Trends in NO_x and NO_2 emissions and ambient measurements in the UK

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Note to readers

This report summarises the main findings from a research project to investigate why recent concentrations of NO_x and NO_2 in the UK have not decreased as anticipated. The work was funded by the UK Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Assembly Government; and Department of the Environment in Northern Ireland.

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Summary key points

Analysis of ambient measurements

1. Trends in ambient concentrations of NO_x and NO_2 in the UK have generally shown two characteristics: a decrease in concentration from ≈1996 to 2002–2004, followed by a period of more stable concentrations from 2002/2004–2009. Concentrations of NO_x and NO_2 from 2004–2009 overall, are best described as having been weakly downward, although there is of course a distribution of trends depending on the site in question. This characteristic is observed for all site groupings and locations considered (UK roadside, UK urban background, UK urban centre, inner London roadside, outer London roadside and UK rural).

   Over the period 2004–2009 the annual percentage reduction in NO_x concentrations has been in the range 1–2%, although trends at motorway sites have been greater ≈3.5%. Corresponding trends in NO_2 have been decreases in the range 0.5 to 1% per year, although rural sites have shown a greater decrease ≈1.4% per year.

2. An analysis of data from *Airbase* of over 2,700 sites shows that a very similar proportion of sites in 2008 exceed the annual mean Limit Value (LV) in the UK and Europe ≈18-19%. Furthermore, most countries in Europe have also shown a levelling off of NO_2 concentrations in recent years. It seems therefore that the UK is similar to many other European countries with respect to NO_2 concentrations.

3. Ambient trends in the concentrations of NO_x and NO_2 have not decreased by as much as suggested by current UK emission factors.

4. Trends in the fraction of primary NO_2 in vehicle exhausts, f-NO_2, estimated from monitoring data have shown a strong increase in the UK and London. In the UK f-NO_2 has increased from around 5–7% in 1996 to 15–16% in 2009. In London the increase has been greater: from around 5–7% in 1996 to 21–22% in 2009. Most of the increase occurred in the years preceding 2004.

Analysis of vehicle remote sensing data and comparison with other emission estimates

5. Emissions data from ≈72,000 individual vehicles have been analysed from a vehicle emission remote sensing detector (RSD) technique based on field campaigns led by the University of Leeds and Enviro Technology plc. The location where these campaigns were conducted means that they best represent urban-type driving conditions and not higher speed driving that would be expected on motorways for example. These data have been compared with current UK emission factors and an alternative emission factor estimates from the 'Swiss/German Handbook on Emission Factors' (HBEFA) and COPERT 4. The RSD provides a clear indication of where there are discrepancies between currently-used emission factors and in-use factors. These are among the most important findings of the work.

6. The NO_x emission factors for diesel cars and LGVs given in COPERT 4 and HBEFA are higher compared with those in the UK emission factors (UKEF) for Euro 3 vehicles onwards. These are vehicles which have entered the fleet since 2000.

7. The remote sensing data suggest much higher NO_x emission factors for Euro 1 and 2 petrol cars than is currently used in the National Atmospheric Emissions Inventory (NAEI).

Agreement is better for Euro 4 petrol cars. For diesel cars and LGVs, the RSD indicate higher emission factors than used in the NAEI across all Euro classes, but the difference gets progressively larger for the later Euro classes as the reduction in emission factors implied by the UKEF does not seem to have occurred. For rigid HGVs, there is reasonable consistency between the RSD and UKEF.

8. A *new* Euro 5 petrol car emits about 96% less NO_x than a pre-catalyst vehicle. However, the RSD data does show that NO_x emissions from Euro 1/2 and to some extent Euro 3 are higher than either the UK emission factor estimates or HBEFA. These results imply that catalyst degradation, or more accurately, the emissions control system used on petrol vehicles as a whole, is more important than previously thought and that older catalyst-equipped cars are important emitters of NO_x.

9. For diesel cars/vans the RSD suggests that there has been little change in total NO_x emissions over the past 20 years or so.

10. NO_x emissions from HGVs were static until Euro IV, where NO_x decreased by about one third. The RSD data does however show that bus emissions of NO_x have been static, or even increasing over the past 10–15 years. However, the bus emissions are affected by specific fleet characteristics.

11. Considering emissions of NO_x as a function of *Vehicle Specific Power* (VSP) shows that under higher engine load conditions there is a clear increasing emission of NO_x for Euro 3–5 diesel cars that is not apparent for older generation vehicles. Indeed, Euro 3–5 diesel cars can emit up to twice the amount of NO_x under higher engine load conditions compared with older generation vehicles; possibly the result of the increased use of turbo-charging in modern diesel cars. The data also show that diesel cars have become increasingly powerful through the Euro classes with pre-Euro to Euro 2 cars having a maximum rated power output of about 70 kW increasing to 85, 98 and 113 kW for Euro 3–5, respectfully. Petrol vehicle maximum rated power has remained about 80 kW through all Euro classes.

12. We find that the *absolute* emission estimates for passenger cars are higher than suggested by currently used emission factors. This finding will therefore have an influence on the relative emissions calculated by vehicle type i.e. these vehicles will be relatively more important emitters of NO_x than previously thought. It may also mean that total road transport NO_x emissions are higher than previously thought; although detailed inventory calculations will be required to confirm this.

13. A potentially important issue to emerge recently is that selective catalytic reduction (SCR) used on HGVs is shown to be ineffective under urban-type (slow speed, low engine temperature) conditions. Currently it is difficult to judge the importance of this issue due to a lack of data concerning the proportion of HGVs with SCR in urban areas. Euro VI legislation will however include a specific slow speed driving cycle that would be expected to address this issue.

Re-analysis of emissions inventory data

14. A considerable amount of work has been undertaken to develop emission inventory scenarios using the findings from the RSD. These scenarios represent a first attempt to understand the likely impact of new assumptions regarding emission factors on inventory trends in NO_x and NO_2 emissions and should not be regarded as complete revised inventories — which will require more work to develop.

The work in this report includes the estimation of new emission factors suitable for use in inventories for both the NAEI and London Atmospheric Emissions Inventory (LAEI). While the straightforward comparison of emission factors described above is revealing in terms of emissions of NO$_x$ from different vehicle types, it is far less straightforward to understand the emission inventories trends. This is because the underlying road vehicle emission factors and the development of emission inventories themselves are now highly complex. There are numerous issues that individually or collectively can influence total emission trends of NO$_x$ at any one time. For this reason, several emission scenarios have been developed for both the NAEI and LAEI.

15. For base case conditions i.e. unadjusted most recent UK/London inventory estimates, the downward trend in NO$_x$ is dominated by reductions in emissions from petrol vehicles. Over the period 2002–2009 the NAEI calculations for UK urban emissions show a reduction in NO$_x$ from diesel vehicles of about 24%. Taking account of the RSD emissions data reverses this downward trend for diesel vehicles to an increase in NO$_x$ emissions of 18% over the same period because of the increase in diesel vehicles (cars and LGVs) together with RSD that suggests that NO$_x$ emissions have not decreased. This is an important change to projected emissions over that period. Nevertheless, this increase in diesel NO$_x$ emissions is still more than off-set by decreases in petrol vehicle NO$_x$ emissions.

16. From a consideration of trends in the NAEI/LAEI it is clear that the assumptions regarding petrol vehicle emissions are very important. In particular, catalyst degradation/failure assumptions used in inventories — and evidence from the RSD that older petrol vehicles with catalysts (Euro 1–3) emit rather more NO$_x$ than was previously thought, are important. Because the RSD only provides a snapshot in time (effectively what was on the road around 2009), we have no observational emissions data relating to what these vehicles emitted when they were new or for the intervening years. For this reason it has been assumed that emission factor estimates for vehicles when they were first introduced are correct and the degradation effect has been linearly scaled from the time of first introduction to 2009.

17. Considering what might be called the ‘central scenario’ for re-calculating inventory NO$_x$ emissions i.e. our best estimate and interpretation of the RSD, the following points can be made. For UK urban areas (2002–2009) the total urban road transport emissions of NO$_x$ reduce on average by 6.0% per annum for the uncorrected case. The trend reduces to a decrease of 4.2% per annum taking account of the RSD emissions. Detailed calculations in London (2003–2008) shows that base case reductions in road traffic emissions are 5.0 and 4.8% per annum for outer and inner London, respectively. The use of the RSD emissions changes these to 3.0 and 2.6%, respectively.

18. Use of factors from COPERT 4 and from the RSD does slow down the rate of decrease in emissions of NO$_x$ from road transport since 2002 compared with the current NAEI trend, but still not enough to bring consistency with the roadside measurements.

19. The RSD data also provides an estimate of the on-road vehicles stock for $\approx$2009. These data effectively provide a distance-weighted estimate of vehicle stock, which is also required input data to emission inventories. The RSD data does indicate that there is a much lower proportion of Euro 4/5 petrol vehicles in service than the inventories assume. This finding would likely have an important influence on NO$_x$ trends beyond that due to new information on emission factors. This is because most of the downward trend in NO$_x$ is driven by petrol vehicle NO$_x$ reductions, which is strongly influenced by significant reductions assumed to be brought about by Euro 4/5 vehicles. It is difficult however to know what the actual vehicle stock was in years prior to 2009 because the RSD only provides a snapshot of

recent vehicle activity. Further analysis and development of the emission inventories is required to understand the impact that these findings have on emissions of NO_x and NO_2.

Whilst there is some evidence that the current emissions calculations assume a 'younger' age profile for cars in the UK than might actually be the case, more work is necessary before definitive conclusions can be drawn. It seems likely therefore that the discrepancy between trends in ambient concentrations of NO_x and NO_2 and emissions estimates lies with both the emission factors used in inventories *and* the underlying assumptions and other data used to compile emission inventories.

20. Before an improved emission inventory calculation methodology can be developed with confidence, further information is necessary. This includes: more sophisticated information on the extent of SCR use in the UK HGV fleet; better information on the changing emissions performance of petrol vehicles over time and more accurate information on the vehicle stock age profile and distance travelled.

Pollution climate mapping

21. The PCM (Pollution Climate Mapping) model has been used to assess compliance limit value status across the UK in 2002, 2008 and for projections to 2010, 2015 and 2020 using both the current emission inventories and the illustrative central scenario for road traffic emissions i.e. our best estimate and interpretation of the RSD.

22. It is clear that the modelled ambient concentrations calculated from the current emission inventory predict a steeper decline in NO_x and NO_2 concentrations between 2002 and 2008 than has been observed at roadside and kerbside monitoring sites. Model results calculated using the illustrative central scenario show better agreement with the observations but still predict a steeper decline than has been observed at many monitoring sites.

23. Projections of future compliance status have previously been calculated using the current baseline emission inventory and a 'calibration year' of 2008. These projections show a steep decline in the extent of exceedance of the annual mean NO_2 limit value at the roadside from 26.6% of the total urban major road length assessed in 2008 to 3.6% in 2015 and 0.2% in 2020.

24. Projections of compliance status have also been calculated using the illustrative central emissions scenario (i.e. our best estimate of re-calculated emission factors using the RSD data) and a calibration year of *2002*, the earliest year for which full emission data are available. The projected extent of exceedance for these calculations in 2008 is 20.4%. This is lower than the extent of exceedance of 26.6% calculated using the model calibrated in 2008. This is consistent with the illustrative scenario showing better agreement with the observed trends between 2002 and 2008 than the current emission inventory but still predicting too steep a decline in emissions over this period.

25. The projected extent of exceedance in 2015 for the illustrative scenario is much higher than for the baseline at 8.8% compared with 3.6%. But note that projections for this illustrative scenario calibrated using data for a more recent year, such as 2008, would be expected to show an even greater extent of exceedance for 2015.

26. Both the current emission inventory and the illustrative central scenario assume large reductions in NO_x emissions for Euro 6 and Euro VI diesel vehicles relative to earlier vehicle standards. Thus the projected extent of exceedance in 2020 is low for all of the scenarios examined (0.2% for the previously calculated baseline and 0.4% for the illustrative scenario). There is considerable uncertainty surrounding the expected NO_x and

primary NO_2 emission factors for Euro 6 and Euro VI. The sensitivity of the projections to the assumptions for these future vehicle standards has not been addressed in this current study, for which the focus has been attempting to understand the observed trends arising from emissions from the current vehicle fleet.

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1. Introduction

This report summarises the main findings from the *Trends in* NO_x *and* NO_2 *Emissions and Ambient Measurements* contract. Recent work shows that concentrations of NO_x and NO_2 in the UK have not decreased as anticipated. Emission inventories for NO_x have led us to believe that emissions of NO_x from road vehicles should have decreased substantially in the past 10 years or so. It is critical that a good understanding is developed of why this disagreement exists. It is also very important that a good understanding is developed of different vehicular source contributions for the past, present and future. This is because measures that aim to reduce ambient concentrations of NO_2 rely on understanding the relative contributions made by different vehicle types etc. This work aims to improve understanding of these issues to provide better scientific evidence on which policy development relies.

The main objectives of this work are:

1. Undertake a detailed analysis of the trends in ambient concentrations of NO_x and NO_2 across the UK and consider in less detail the trends in Europe. In addition, trends in vehicular primary NO_2 emissions, derived through the analysis of ambient measurements, will also be considered.

2. Undertake a detailed analysis of emissions data from recent vehicle remote sensing data from campaigns around the UK. This analysis includes the estimate of new vehicle emission factor estimates for NO_x and a comparison with other recent methods for calculating vehicles emissions in Europe.

3. Using the emission factor estimates above, develop new illustrative road vehicle emissions inventory estimates of NO_x and NO_2 for the NAEI and LAEI. These estimates should cover a range of years from approximately 2002–2009 for comparison with ambient measurements.

4. Using new road vehicle inventories for NO_x, use pollution climate mapping to help understand whether these new estimates of NO_x emissions are more consistent with ambient observations.

5. Finally, drawing on the findings above consider the implications for measures to control emissions of NO_x with respect to meeting European Limit Values for ambient NO_2 concentrations.

2. Trends in NO_x and NO_2 concentrations

2.1. Introduction

In this section we consider the trends in NO_x and NO_2 across the UK until the end of 2009. There are a potentially very large number of sites available at which to consider trends. The focus here is on “long-term” sites i.e. sites that have been running for at least 5 years. By considering these longer-term sites it is possible to provide a more consistent analysis of the trends that is less affected by the addition of many recently started sites that could bias the more recent data.

These trends can be considered in many different ways. To help with interpretation we have categorised the sites as follows: London roadside, London urban background, UK roadside, UK urban background, UK urban centre and UK rural/remote. We have also split the London roadside sites by inner (sites within an area approximately defined by the North/South circular) and outer (the rest within the M25). Note that the UK sites do not include any in London. This split is intended to help determine at a broad level whether there is evidence of different behaviour in different parts of the UK.

2.2. Trends in NO$_x$ concentrations

Trends have been calculated for 11 UK roadside sites, 11 UK urban centre sites and 17 UK urban background sites. In London there were 10 inner London roadside sites, 13 outer London roadside sites and 19 London background sites. In addition, we have considered trends from three Highways Agency motorway sites (M25, M4 and the M60).[1] These data cover the period up to the end of 2008 because 2009 is not yet available. In this respect, the trends calculated for these sites are not entirely consistent with the other areas considered, but this is not thought to have much of an effect on the conclusions drawn. It should also be noted that the M25 site has undergone various moves and that the motorway has been widened over the period considered. For this reason some caution should be applied when considering the trend results from the M25.For clarity the data for these locations have been averaged to give and overview of the typical trends in these locations. However, later in this section the site-specific trends are considered in more detail.

It was clear from an initial consideration of the overall trend at these sites that the trend in NO$_x$ and NO$_2$ has not been linear over time — indeed, most trends can be characterised as having a period where concentrations decreased, followed by a longer period of stability, or at least little change. Most of the trends shown in this section therefore use a non-parametric smoothing technique based on locally weighted regression Cleveland (1979). This technique helps to show the overall shape of the trend and is particularly useful when trends are non-linear. In addition, we consider monthly trends in order to maximise the amount of information shown. However, because there is a sometimes strong seasonal effect (particularly at background sites), the data have been de-seasonalised using the technique of Cleveland et al. (1990).

At most site types there was a clear reduction in NO$_x$ concentrations through to around 2002, followed by a period of more stable concentrations from 2002-2009 (Figure 2.1). At urban centre and background sites the initial decrease is less striking compared with the roadside site locations. In both cases however, the more stable trend in recent years is also apparent, as shown in Figure 2.1. Because there were only three motorway sites available to analyse, the trend for these sites will be affected more by individual site characteristics.

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[1] Data were obtained from `http://www.trl.co.uk/research_development/sustainability/environmental_assessment_/air_quality/air_quality_archive.htm`.

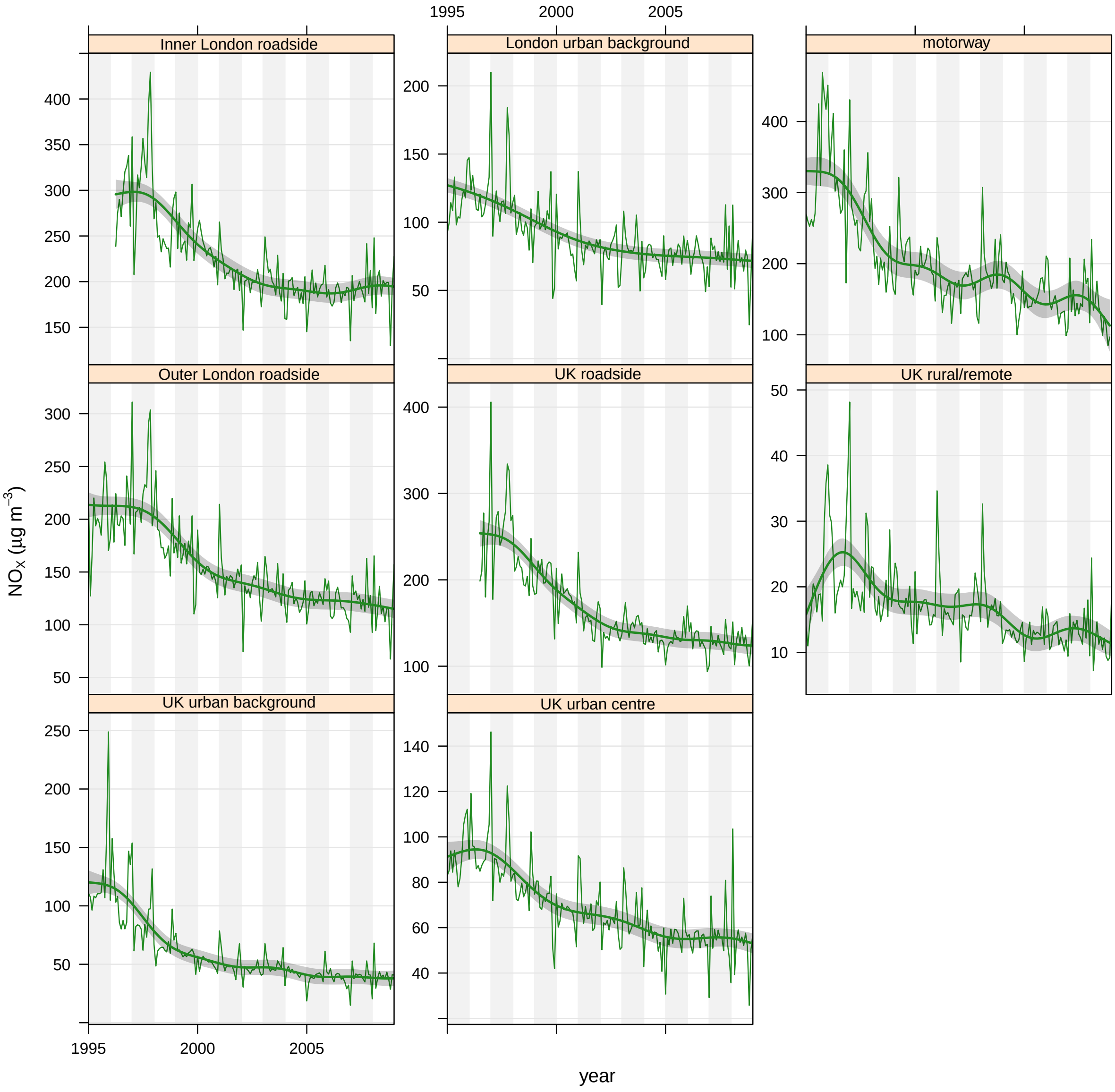

Figure 2.1: Trend in NO_x concentrations by site location type. Monthly data from each location type were averaged and de-seasonalised. A smooth trend line was then fitted and the 95% confidence intervals in the fit calculated as shown by the shading.

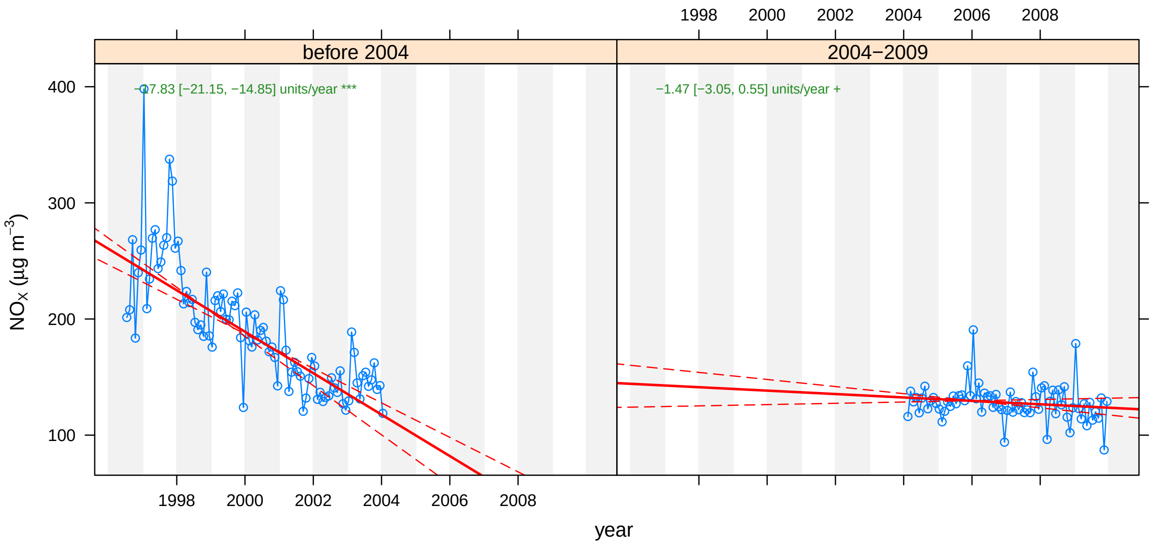

Figure 2.2: Mann-Kendall trend analysis of roadside AURN sites split by two periods (before 2004 and 2004-2009). The estimated slope with uncertainty is given for each period.

To provide a more quantitative understanding of more recent trends we have used the Mann-Kendall/Sen approach to estimate the trends over the past six years (2004–2009), corresponding approximately to the period where concentrations have levelled off. This is also a period that can usefully be compared with emission inventory trends. An example of the analysis is given in Figure 2.2, where the trend for each period is -17.8 and -1.5 µg m^{-3}/year respectively. Note there is only weak evidence of a downward trend in NO_x for 2004–2009 shown by the 95% uncertainty interval from -3.0 to +0.6 µg m^{-3}/year.

It is also important to consider trends at individual sites because there is a reasonably large inter-site difference in the trend estimates. Furthermore, the aggregated analysis shown in Figure 2.1 could be affected to some extent by sites with much higher (or lower) concentrations. This is also an important step when considering the linkage with road traffic information. Figure 2.3 shows the individual sites (2004–2009) trends in an ordered way: categorised by location and then ordered by slope estimate. There are of course differences between the sites, but the trend estimates when considered by individual site broadly reflect the conclusion that taken overall there is generally a mix of sites showing upward and downward trends such that the overall effect is that there is little evidence of a consistent downward trend in NO_x concentrations. Note that in Figure 2.3 the trends are reported as percentage change per year. The trend, T is defined as:

$$T[\%.yr^{-1}] = 100.\left(\frac{C_{Dec.2009}}{C_{Jan.2004}} - 1\right) \Big/ N_{years} \tag{1}$$

where $C_{Dec.2009}$ and $C_{Jan.2004}$ are the mean concentrations in December 2009 and January 2004, respectfully. N_{years} is the number of years the time series spans i.e. 6 in this case.

On this basis, the *median* trends by location for NO_x are shown in Table 2.1.[2] These trends can be thought of as representing a typical site within each site type. For the urban/roadside locations in London and the UK trends typically vary from around -0.5%/year to about -2%/year. It is these numbers which can be compared with trends over the same period from the emissions inventories. The trends are also shown quantitatively in Appendix B.

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[2] Expressing trends as the median avoids the effects of any anomalous sites overly affecting the overall trend for a group of sites.

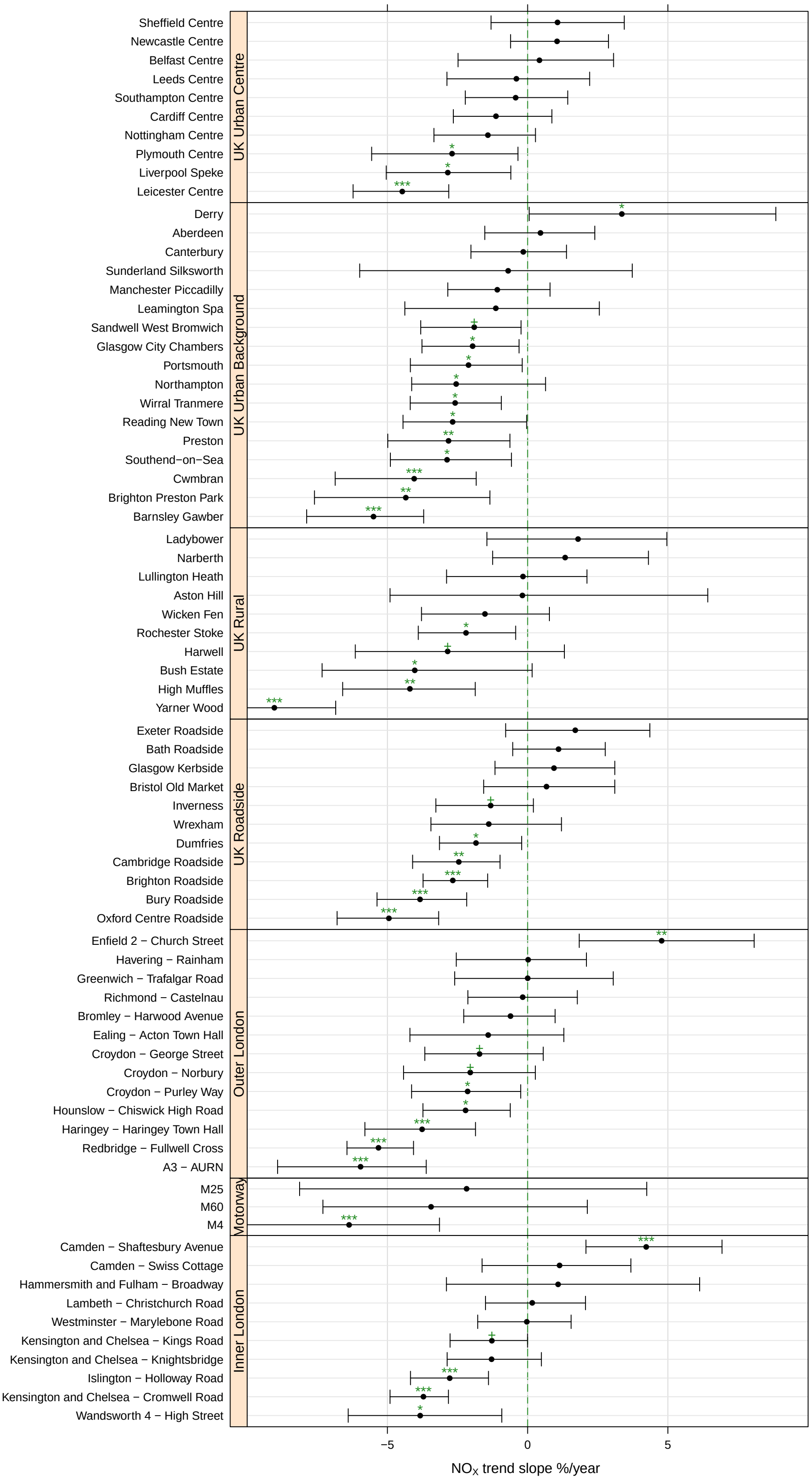

Figure 2.3: NO_x Mann-Kendall trend analysis of roadside sites in the UK for data from 2004–2009. The uncertainties shown relate to the 95% confidence intervals in the slope. Data have been split by UK region and then ordered by slope. Note also that the symbols shown next to each trend estimate relate to how statistically significant the trend estimate is: $p < 0.001$ = $***$, $p < 0.01$ = $**$, $p < 0.05$ = $*$ and $p < 0.1$ = $+$.

Table 2.1: Trends in NO_x concentration by site type/location expressed as percentage change per year calculated according to Equation 1. The median trend is shown in each case.

Location	trend (2004–2009)
Inner London	−0.6
Motorway	−3.4
Outer London	−1.7
UK roadside	−1.4
UK rural	−1.9
UK urban background	−2.1
UK urban centre	−0.8

Taken overall NO_x trends are reasonable consistent across the UK when expresses as a percentage change per year. Urban centre and inner London sites do however show weaker trends compared with other areas.

2.3. Trends in NO_2 concentrations

Similar to the previous section, trends have also been calculated in NO_2 concentrations using the same methods. Figure 2.4 shows the deseasonalised trends in monthly mean NO_2 concentration by site type. There are some similarities with Figure 2.1 as expected. For example, at UK roadside locations the trend in NO_x and NO_2 show similar patterns of decrease to around 2003. However, in London there is more evidence at roadside sites that NO_2 concentrations have not responded in a similar way to NO_x e.g. the initial decrease in NO_x concentrations to around 2003 is not observed for NO_2.

Considering the trends expressed as a percentage change per year (Table 2.2) it can be shown that NO_2 concentrations have typically reduced by about 0.5 to 1% per year — typically about half that for trends in NO_x. This behaviour is consistent with the reductions in NO_x concentrations. One might also expect that primary NO_2 emissions are important, which are considered later in section 3.

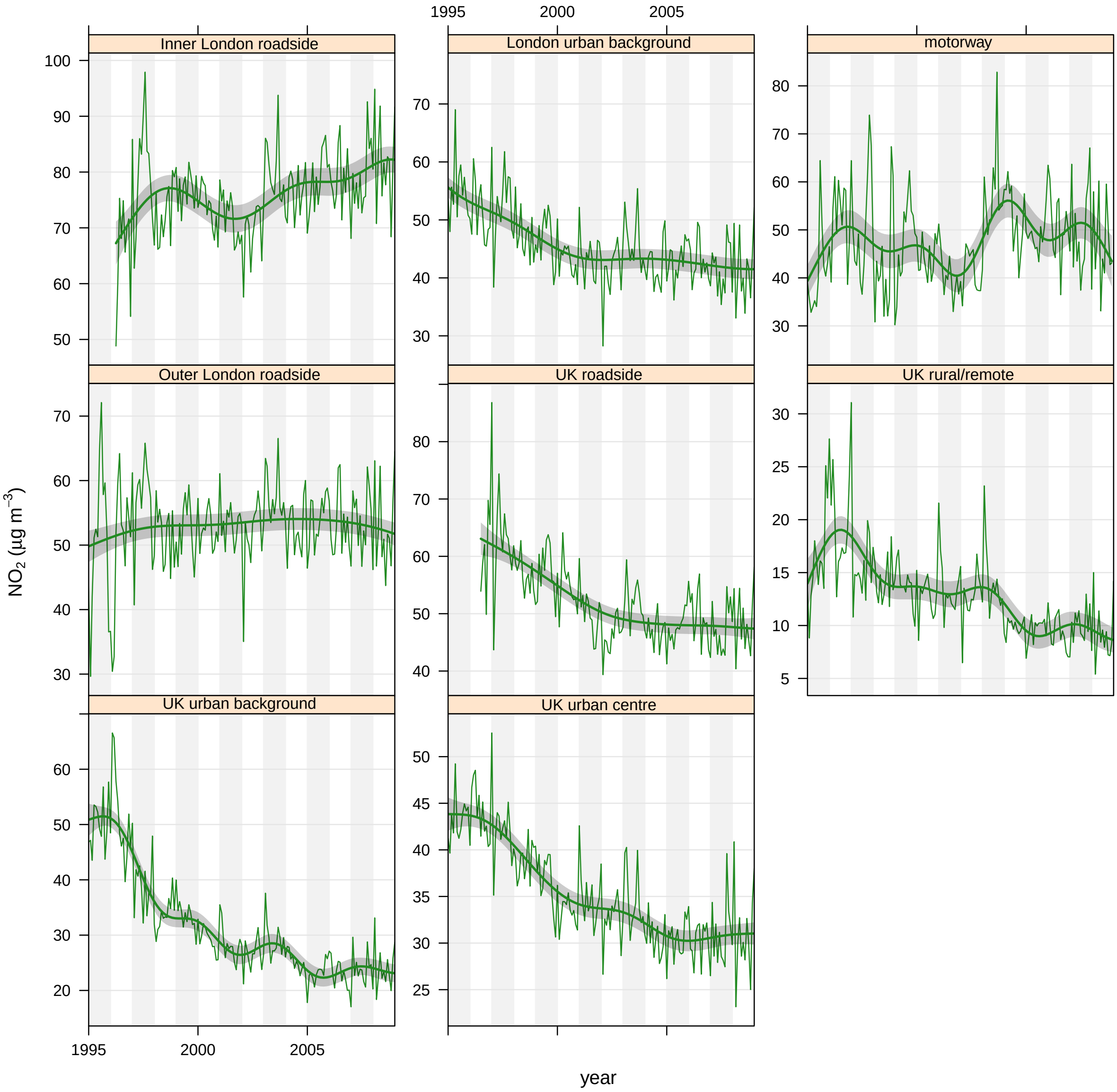

Figure 2.4: Trend in NO_2 concentrations by site location type. Monthly data from each location type were averaged and de-seasonalised. A smooth trend line was then fitted and the 95% confidence intervals in the fit calculated as shown by the shading.

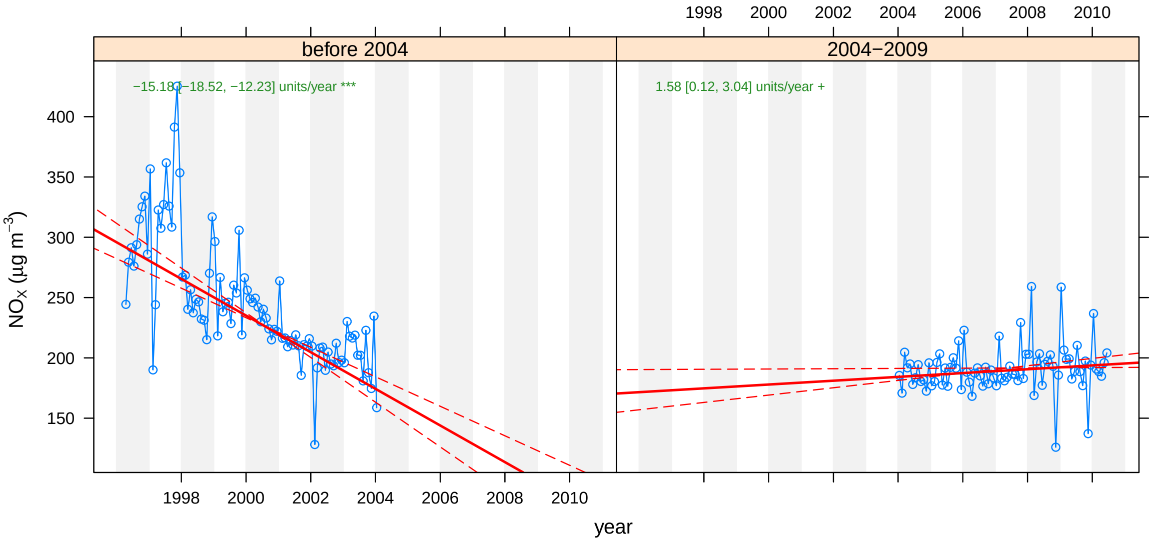

Figure 2.5: Mann-Kendall trend analysis of inner London roadside sites split by two periods (before 2004 and 2004-2009). The estimated slope with uncertainty is given for each period.

Table 2.2: Trends in NO_2 concentration by site type/location expressed as percentage change per year calculated according to Equation 1. The median trend is shown in each case.

Location	trend (2004–2009)
Inner London	-0.5
Motorway	-0.8
Outer London	-0.8
UK roadside	-0.6
UK rural	-1.4
UK urban background	-0.8
UK urban centre	-0.4

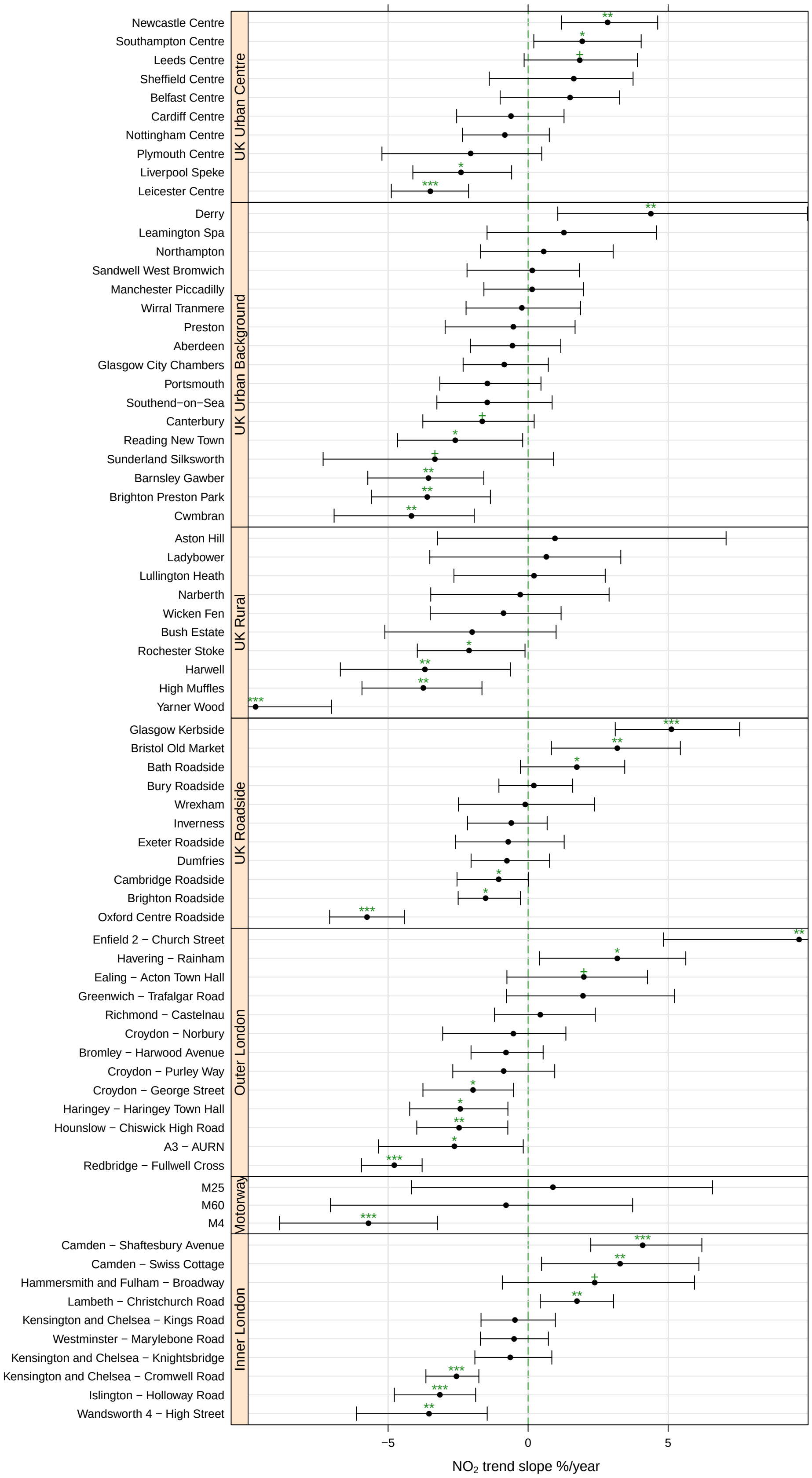

Figure 2.6: NO$_2$ Mann-Kendall trend analysis of roadside sites in the UK for data from 2004–2009. The uncertainties shown relate to the 95% confidence intervals in the slope. Data have been split by UK region and then ordered by slope. Note also that the symbols shown next to each trend estimate relate to how statistically significant the trend estimate is: $p < 0.001 = ***$, $p < 0.01 = **$, $p < 0.05 = *$ and $p < 0.1 = +$.

2.4. Trends in Europe

2.4.1. Overview of annual mean NO_2 exceedances in the UK and Europe

An important consideration is understanding how the UK compares with the rest of Europe with respect to NO_x and NO_2 trends and exceedances of limit values. We have analysed hourly data from 2728 NO_x-NO_2 sites across Europe for 2008 (the most recent year available) using data available in *AirBase*[3]. These data are summarised in Figure 2.7.[4] The Figure clearly shows the influence of site classification: with rural locations having the lowest NO_2 concentrations and roadside sites with the highest concentrations. In Europe 18.9% of all sites exceeded the annual mean NO_2 limit value in 2008, which is very similar to that in the UK of 18.0%. Indeed, this consistency between UK and the rest of Europe is also seen across different site types, as shown in Figure 2.7. It is interesting to note that the site with the highest annual mean NO_2 is Marylebone Road in London — easily seen on the 'roadside' panel in Figure 2.7.

Aggregated trends in NO_2 concentrations for a range of European countries is shown in Figure 2.8, again based on the Airbase data. The plot shows that while there are different behaviours across different countries e.g. Greece and Italy showed stronger initial downward trends in NO_2, concentrations over the past few years have tended to level off.

For almost all cities for which data are readily available, trends in NO_x and NO_2 are similar to those in London and elsewhere in the UK. This section shows trend data from a selection of major European cities, from both traffic-orientated sites and urban background locations.

Appendix C provides a survey of recent trend analyses from European cities.

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[3] `http://air-climate.eionet.europa.eu/databases/airbase`

[4] There are actually many more sites that measure NO_2 than NO_x because it seems many countries only report the NO_2 data. Currently the analysis is considering sites where there are NO_x and NO_2 measurements. However, for completeness we will likely report trends for more countries using only the NO_2 data.

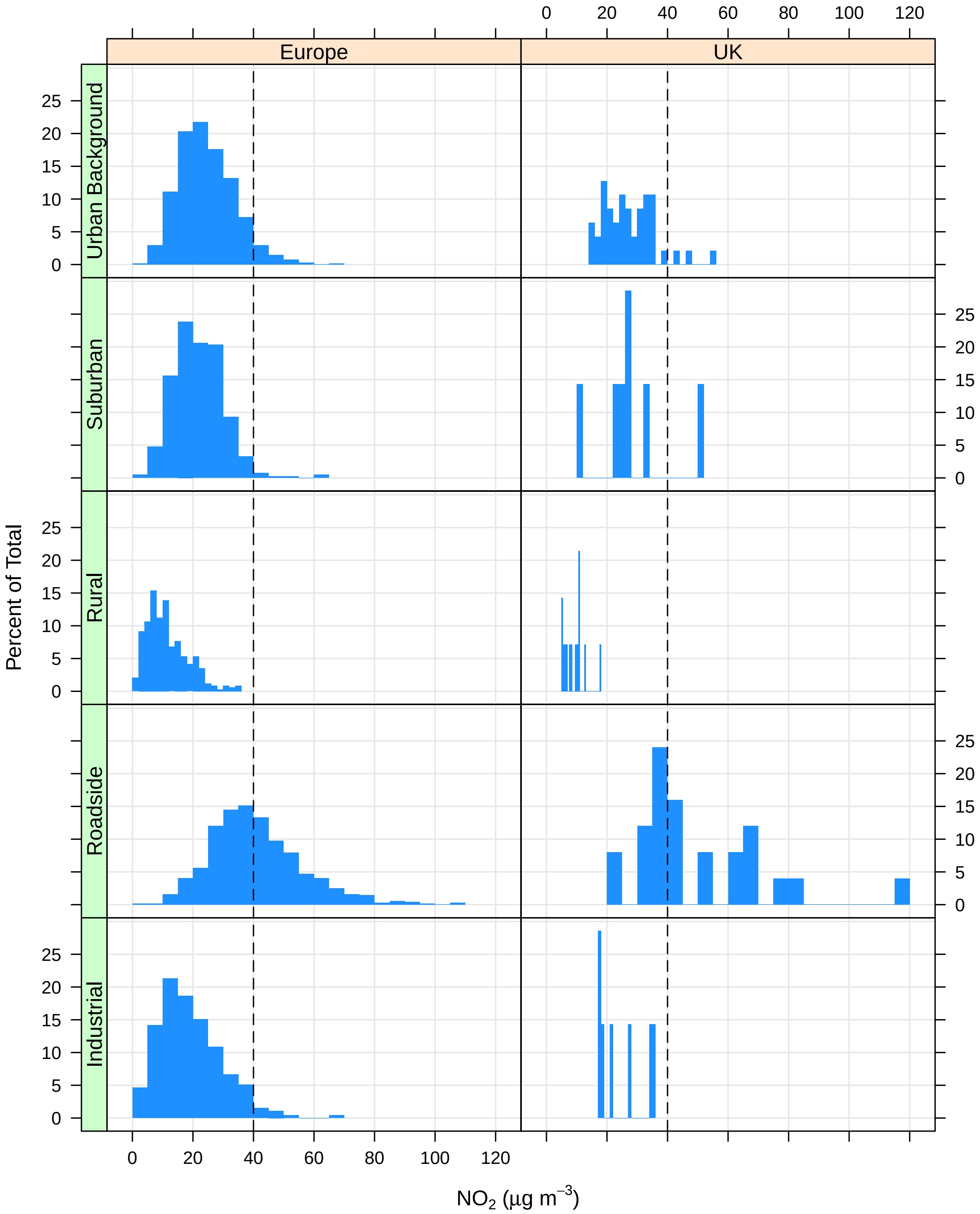

Figure 2.7: Histogram of annual mean NO$_2$ concentrations across the UK and Europe for 2008 for sites with a data capture rate $>$75%. A total of 2728 were analysed and the data split by site location type e.g. 'roadside'. The vertical dashed line shows the 40 µg m^{-3} annual mean limit.

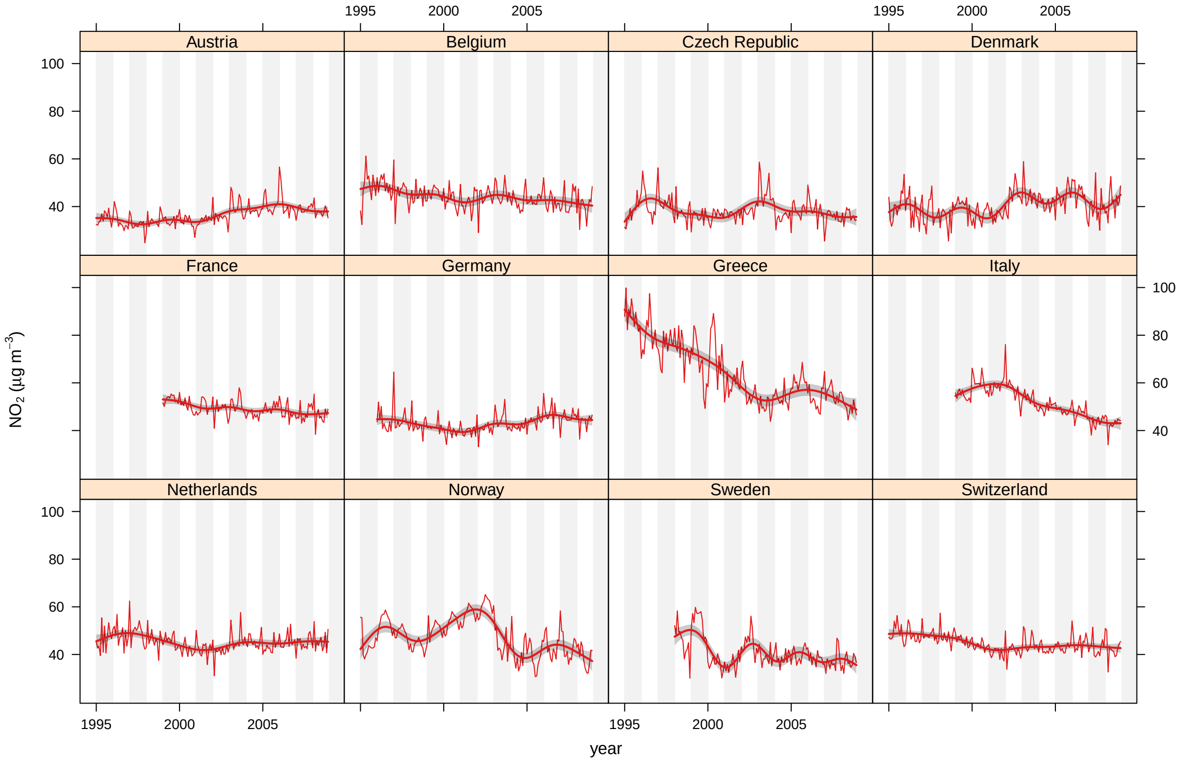

Figure 2.8: Monthly de-seasonalised trends in NO_2 at roadside sites for select European Countries.

2.5. Trends based on satellite measurements

This section addresses the issue of deriving estimates of emissions of NO_x for areas of the UK from satellite measurements of NO_2 columns, and in particular, whether any further useful information can be derived on the emission trends in the last few years. The text reports the work of Konovalov and co-workers[5,6], who have used measurements of the column burden of NO_2 from the GOME and SCIAMACHY satellites with horizontal resolution of 320 km x 40 km and 60km x 30 km respectively, combined with results from the CHIMERE chemistry and transport model. Earlier work of this group has reported NO_x emission trends for countries and compared them with officially reported trends. More recently the group has focussed on so-called 'mega-cities' in Europe, including London. The process derived an estimated emission trend for specific grid squares; that relevant to 'London' has co-ordinates 51° to 53° and -2° to 3° covering an area up to the Midlands and down to the south coast. As a validation exercise, the derived trends were compared with surface measurements by Konovalov and co-workers.

2.5.1. Decadal trends

Figure 2.9 shows satellite-derived results for London for the period 1996-2008. The results show the downward trend in estimated NO_x emissions for London, Berlin and the Ruhr area of Germany over the whole period, along with the similar downward trend in emission inventory reports to EMEP. Taking the decade or so as a whole there is reasonably good agreement between the satellite derived trends and those officially reported.

The results from Paris, Milan and Madrid (not shown but plots available) show much more scatter and do not appear to show clear linear downward trends.

Figure 2.10 shows comparisons (reported by the Konovalov group) of the satellite/modelled results with surface measurements. For London the measurement sites chosen by the Konovalov group were Bexley, Bloomsbury, North Kensington, Eltham, Rochester, Leicester and Southampton. The satellite passes over the UK once a day so concentrations for hour 10:00 LST were used, and the data averaged over June to August. A weighting procedure was used to combine the UK sites to produce an overall normalised trend. Since precise details of this process are not available, the present analysis has not attempted to reproduce this. No information is available at present on the sites used for the other European cities.

Over the decade or so studied, the trends in the surface measurements are in broad agreement with the trends in emissions derived from the satellite/modelled data, even if for some cities (Madrid, Milan and Paris) the trends are not linear.

This might seem surprising given the fact that the surface measurements are for one hour each day in the three summer months when surface concentrations of NO_x are generally lowest. This subset of data is about 1% of the full hourly data over a year. To check the extent to which the trends in this subset mirror the full annual trends, analyses have been carried out by King's College London using the full annual data set for the sites used by Konovalov et al. The overall trends (see Table 2.3) from both data sets are similar, although in some cases the magnitude of the slope differs by a factor of two.

The average of the slopes derived from the full surface data set (i.e. all hours in each year) in Table 2.3 is -3.84%/yr which compares very well with the satellite-derived value obtained by Konovalov et al shown in Figure 2.9, of $\sim$3.9%/year.

The satellite retrievals are likely to measure total NO_x emissions and thus the derived trends will be a composite of all sources. This reinforces the conclusion that while satellite data are a potentially useful source of independent information on the broad features of emission trends

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[5] Konovalov, I.B., Beekman, M., Burrows J.P., Richter A., (2008) Satellite measurement based estimates of decadal changes in European nitrogen oxides emissions, Atmos. Chem. Phys., **8**, pp. 2623–2641.

[6] Konovalov, I.B., Beekman, M., Richter, A., (2009), Estimation of NO_x emission trends in megacities from satellite measurements, poster at Global Emission Inventory Activity/ACCENT Workshop, Oslo, 26-28 October 2009.

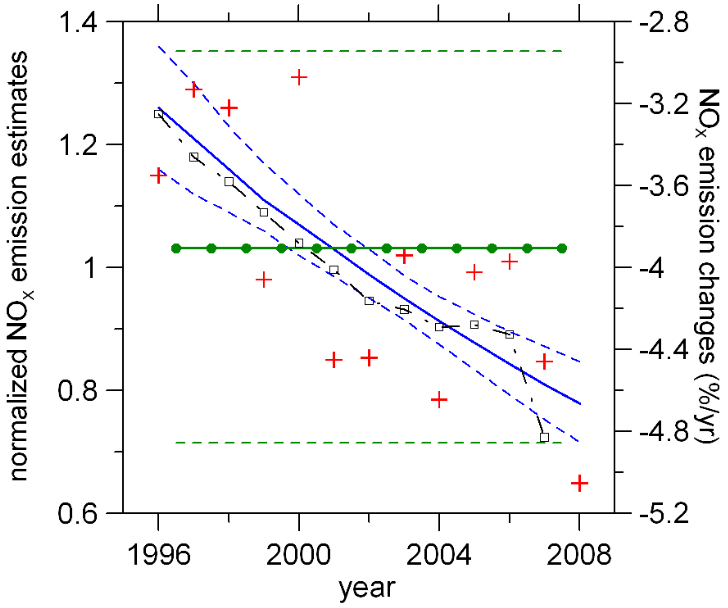

Figure 2.9: Normalised Emission Trend for 'London' grid square from satellite data. Personal communication I. Konovalov; Red crosses-raw satellite-derived data, open squares EMEP reported data, green is interannual change in %/yr, blue is derived trend).

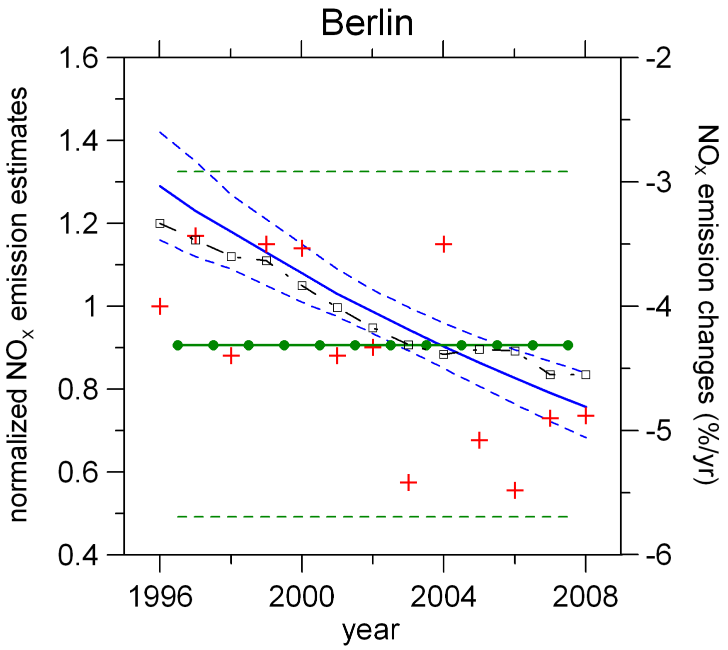

Figure 2.10: Normalised Emission Trend for 'Berlin' grid square from [6]; Red crosses-raw satellite-derived data, open squares EMEP reported data, green is interannual change in %/yr, blue is derived trend).

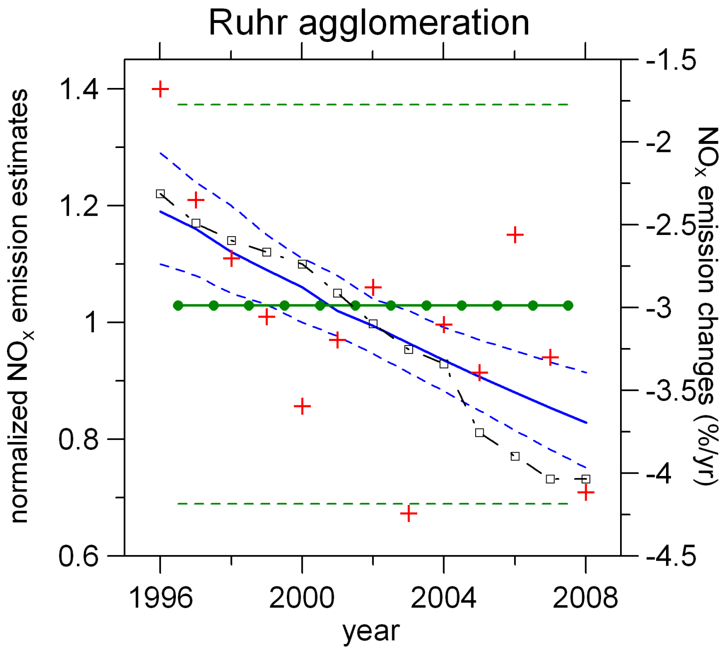

Figure 2.11: Normalised Emission Trend for 'Ruhr' grid square from [6]; Red crosses-raw satellite-derived data, open squares EMEP reported data, green is interannual change in %/yr, blue is derived trend).

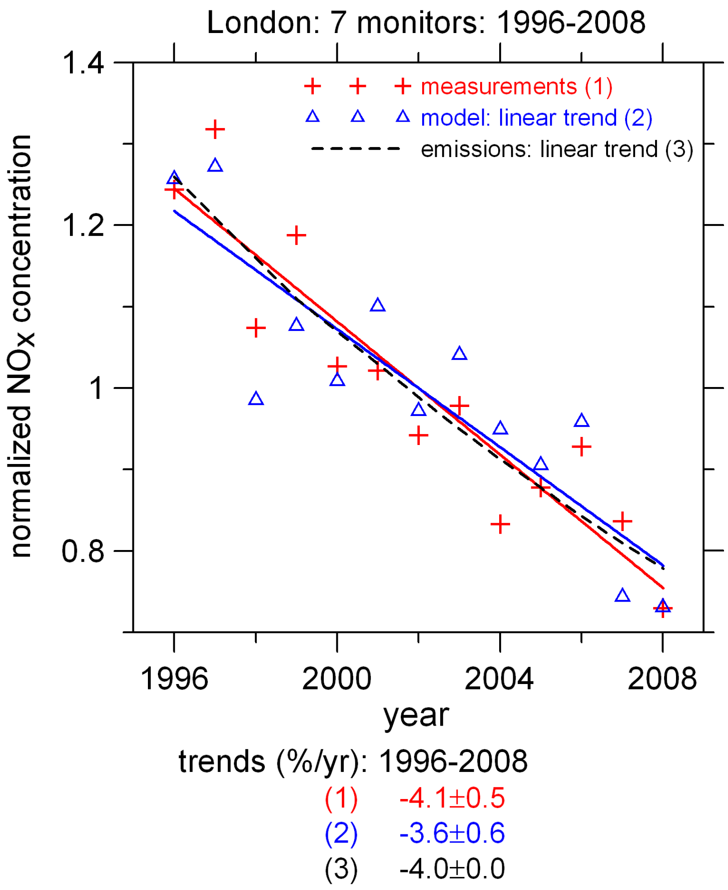

Figure 2.12: Validation of satellite-derived trends from surface monitors.

Table 2.3: Trends (in ppb/yr with 95% confidence intervals) from Mann Kendall analysis of the June-August hour 10:00 data and the full set of annual means.

	Site	JJA Hour 10 data set	Full annual means	% per year (slope/mean over whole period of full data)
1	Bexley	−0.55(−1.04, −0.16)*	−1.06(−2.04, −0.4)**	−2.95
2	Bloomsbury	−1.47(−2.92, −0.7)**	−1.92(−2.96, −1.11)**	−3.04
3	Eltham	−1.0(−1.2, −0.52)***	−1.57(−2.08, −0.95)***	−6.28
4	Harwell	−0.44(−1.1, −0.09)*	−1.34(−1.78, −0.43)**	−6.31
5	Leicester	−1.19(−1.37, −1.02)***	−1.14(−1.40, −0.75)***	−3.38
6	North Ken	−0.801.55(−1.17, −0.3)**	−1.50(−2.6, −0.75)***	−4.14
7	Rochester	−0.25(−0.39, −0.06)**	−0.23(−0.38, −0.11)**	−1.53
8	Southampton	−1.11(−1.64, 0.10)*	−1.8(−2.50, −1.05)***	−4.38
9	Thurrock	−0.97(−1.3, −0.64)***	−0.9(−2.53, −0.42)***	−2.53

for NO_x, they are unlikely on their own to provide sufficient detail to assess trends in emissions from individual sectors such as road transport.

The conclusion from the work of Konovalov et al and the additional analysis here therefore is that satellite data appear to be able to describe broad decadal trends in NO_x emissions with reasonable accuracy. It is worth noting that the original authors make no claims of accuracy for the absolute magnitude of the emissions.

2.5.2. Trends in more recent years

Given the potential problems with the apparent mismatch between the UK emission inventory for NO_x and surface measurements, an important question is whether or not satellite-derived emission data can provide an independent check on recent emission changes in the UK.

Looking first at Figure 2.9, the satellite data (red crosses) from ∼2003/4 onwards for London, Berlin and the Ruhr area suggest an indication of a levelling off, although there is much scatter in the data, and there are fewer points to draw on. The data for the other cities show no clear overall downward trend anyway so there is no 'levelling off' apparent; equally however there is no clear sign of a downward trend in the last few years either. With few data points, and only one data point per year, a more rigorous assessment of trends in the satellite data is not feasible. However the technique shows promise and with longer runs of data even the sparse temporal coverage looks to be capable of delivering useful additional information on NO_x emission trends in the UK, in the rest of Europe and also in other areas of the world.

3. Trends in primary NO_2 in London and the UK

A key component to understanding trends in ambient NO_2 concentrations is the effect that primary NO_2 has. It is now well documented that the proportion of NO_2 to total NO_x in the exhausts from vehicles has been increasing in recent years (AQEG, 2008; Carslaw, 2005). It is therefore very important to understand how trends in primary NO_2 have changed in the UK over the past few years and to reconcile these changes with changes in vehicle stock and vehicle emissions. The proportion of NO_2 to total NO_x expressed as a volume ratio is referred to as *f-NO_2* .

There are various ways in which estimates can be made of f-NO_2, including a consideration of total oxidant (sum of NO_2 and O_3) gradients (Clapp and Jenkin, 2001). However, the principal interest here are roadside locations because of the interest specifically in vehicle emissions. Only a few roadside monitoring sites measure O_3, which restricts the direct usefulness of the total oxidant technique. For this reason the approach of Carslaw and Beevers (2005) has been

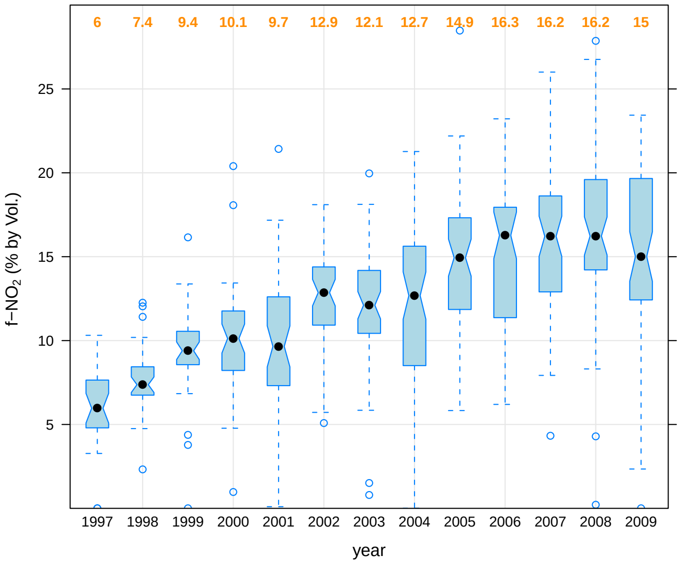

Figure 3.1: Estimated trend in f-NO_2 at AURN roadside sites in the UK. The black dot shows the median monthly estimate of f-NO_2 (also shown as numbers at the top of the plot) and the shaded areas the 25th and 75th percentile values. The hollow circles show points lies outside ≈99th of the data for a particular year.

used. This approach estimates the likely contribution to roadside NO_2 concentrations from the NO + O_3 reaction from the vehicle plume mixing with background air and the direct contribution from primary NO_2. The technique requires hourly NO_x and NO_2 at a roadside site and NO_x, NO_2 and O_3 at a background site together with meteorological variables.

Twelve (non-London) roadside sites were analysed from the AURN and monthly estimates made of the f-NO_2 value. The results are shown in Figure 3.1. There is a clear increase in the estimated value of f-NO_2 over the past decade — increasing from around 5–7% in 1997 to about 15–16% in 2009. In more recent years (2005–2009) there is some evidence to suggest that f-NO_2 values are levelling off.

The increase in f-NO_2 in London has been more marked that other UK locations, as shown in Figure 3.2, based on 23 long-running roadside sites. Here, f-NO_2 has increased from around 5% in 1998 to about 21% in 2009. Note that there were fewer sites used in the analysis in the first five or so years and hence the f-NO_2 estimates will be more uncertain.

The principal factor accounting for the increase in the observed f-NO_2 values shown in Figure 3.1 and Figure 3.2 is considered to be the increased use of oxidation catalysts and particle filters on light duty diesel vehicles (AQEG, 2008). Higher values in London are consistent with a large fraction of the London bus fleet using continuously regenerating particle filters. The levelling-off of the f-NO_2 values in recent years could be due to vehicle fleets reaching saturation with respect to vehicles fitted with oxidation catalysts and particle filters.

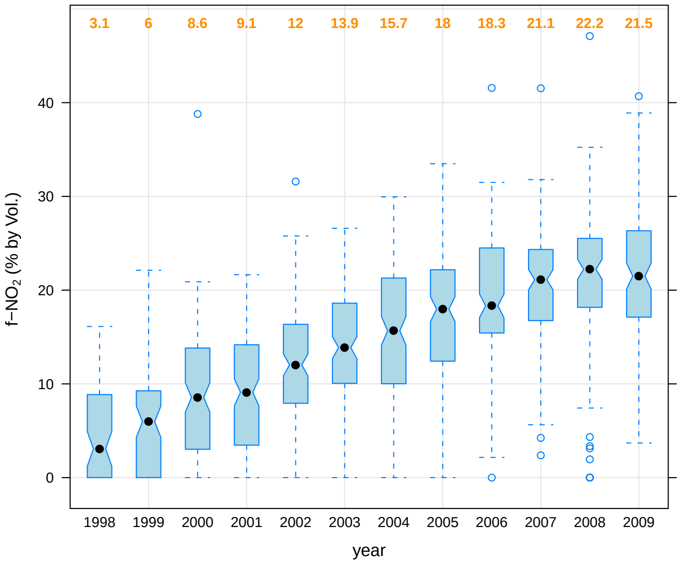

Figure 3.2: Estimated trend in f-NO_2 at London roadside sites. The black dot shows the median monthly estimate of f-NO_2 (also shown as numbers at the top of the plot) and the shaded areas the 25th and 75th percentile values. The hollow circles show points lies outside ≈99th of the data for a particular year.

4. Vehicle emissions remote sensing data

4.1. Introduction

This section summarises some of the data analysed from several vehicle emission remote sensing campaigns carried out over the past three years by the University of Leeds and Enviro Technology plc. The remote sensing measurements were made using the RSD-4600 supplied by Environmental Systems Products (ESP, Arizona, US) as a dedicated across-road vehicle emissions monitoring system. Individual vehicle plumes are measured from passing vehicles by shining a UV/infrared beam of light across the plume. The measurements include the concentration ratio of NO, CO, HC and a measure of "smoke" to the concentration of CO_2.

A record is defined as a beam block (by a vehicle) followed by a half second of data collection. If the data collection is interrupted by another beam block, i.e. a following vehicle with a headway less than 0.5 seconds, the measurement attempt is aborted. The capture of a valid record does depend on several factors. These include the size of the observed CO_2 emission plume is sufficient to allow emission ratios to be calculated, and the vehicle speed is in the range 5 to 60 km h^{-1}, and a clear digital image of the vehicle's number plate is captured.

The collection of a *high* proportion of 'valid' measurements requires:

- The remote sensing beam to be located in a position where it will intersect a significant proportion of exhaust gas. It is typically aligned less than 300 mm from the road surface. Emissions from vehicles with elevated tail-pipes, cannot be studied in this configuration;
- Selected study sites are restricted to single lane operation;
- The optical beam path distance is limited to less than 10 m;
- The majority of vehicle engines being under load as they drive through the measurement site. This is to ensure significant emission plumes are available for measurement. Sites should therefore have an uphill grade; and
- Weather and environmental conditions to be favourable. High wind speeds rapidly disperse exhaust plumes. The equipment is also not weather-proof, so cannot be operated in rain or snow.

There are several characteristics or limitations of the RSD that should be noted. First, the measurements represent a mix of urban-type conditions and not roads such as motorways etc. However, given that most NO_2 exceedances of the LV are in urban areas, this is not considered to be a significant limitation. The RSD measures *ratios* of pollutant concentrations to CO_2 and therefore does not provide an absolute emission measure as used in emission inventories i.e. in g km^{-1}. However, pollutant ratios are very useful measures and can be used to derive absolute emissions given an estimate of an emissions of CO_2 in g km^{-1}. The equipment used here only measures NO and not NO_2. The assumptions regarding the proportion of NO_2 for different vehicles is considered in subsection 4.2. The equipment was set up to measure exhaust from vehicle plumes at a height of 30 cm. As such, the measurements will not include vehicles where the exhaust exits at height; such as on large HGVs. This again is not considered to be a significant limitation because there tend to be few of these vehicles in urban areas.

Another potential disbenefit is that a bias is introduced due to vehicles being sampled while the engine is under load. It should be noted however that the requirements of a vehicle being under load are to do with maximising the probability of a satisfactory measurement i.e. there is a plume sufficient enough to detect. The RSD data itself covers vehicles decelerating as well as accelerating. The mean speed of 31 km h^{-1} is also typical of urban-type driving. Furthermore, the mean slope of roads on which the RSD applied was only 1% (the median was 0.7%). None

Table 4.1: Numbers of vehicles sampled by vehicle type.

Year	Car	HGV	LGV	PSV
1980	2	0	0	0
1981	1	0	0	0
1982	3	0	0	0
1983	9	0	0	0
1984	6	0	0	0
1985	16	0	1	0
1986	22	0	3	0
1987	34	0	0	0
1988	69	0	4	0
1989	126	0	4	0
1990	173	0	10	0
1991	225	0	9	0
1992	337	0	14	0
1993	667	0	11	0
1994	987	8	36	0
1995	1263	9	59	0
1996	2031	31	172	14
1997	2616	13	199	35
1998	3341	7	288	20
1999	3714	20	407	114
2000	3992	24	469	315
2001	4692	36	616	30
2002	5164	46	707	362
2003	5240	88	913	37
2004	5304	78	1073	26
2005	4979	75	1384	32
2006	5036	68	1524	36
2007	4884	80	1509	97
2008	3001	71	920	43
2009	1655	333	360	23
2010	223	0	23	0

of these characteristics suggest that the RSD data are significantly different to typical ‘real’ driving conditions.

Despite some of the limitations listed above, these data fill an important gap in information between emission inventories where data tend to be collected on rolling roads. Perhaps the two key benefits of the RSD are that measurements are made under actual (sometimes called ‘real-world’) conditions and that samples sizes are or can be very large. In this respect, the RSD does not provide all the information required to understand vehicle emissions, but provides important, complimentary data.

The data comprise six separate campaigns carried out across several areas in the UK including York (2007, 7731 records), Halifax (2009, 8149 records), Shropshire (2010, 17481 records), London (2008, 24861 records) and Devon (2008, 16392 records).

Individual vehicle number plate information was captured by photographing individual vehicles and post-processing the data to obtain number plate information, or through the use of an ANPR (Automatic Number Plate Recognition) camera to record the number plate directly.

The number plate information can be used to query databases that contain information on individual vehicles. We commissioned *Carweb* (`http://www.carwebuk.co.uk/`) to match the RSD number plate information with specific vehicle characteristics. Note that Carweb are able to provide over 100 different variables related to vehicle information e.g. relating to physical characteristics (length, width, engine size, number of gears etc.), performance characteristics (e.g. time taken to accelerate from 0-60 mph etc.) and many other items of information. Also available was the Euro class designation of the vehicle where available.[7] One advantage of using the CarweB data is that manufacturer databases are queried and cross-checked for quality assurance purposes. It is our understanding that these data are the most comprehensive, reliable data available in the UK. We have used these data extensively in the analysis of the vehicle emissions information e.g. for Euro class designation.

The complete data set from all campaigns has been compiled and "cleaned up"; providing a total of around 72,000 valid measurements – see Table 4.1.

4.2. Assumptions regarding NO_2 emissions for the RSD

Emissions of total NO_x have been calculated by applying the f-NO_2 values from Grice et al. (2009), shown in Table 4.2. These assumptions are broadly consistent with other data sources including AQEG (2008) and recent remote sensing campaigns from Sweden using remote sensing measurements of both NO and NO_2 (Jerksjö et al., 2008). The Grice et al. (2009) and Jerksjö et al. (2008) results are generally consistent with one another. For example, there is good agreement that all petrol cars have very low f-NO_2 values and HGVs are around 10–15%. They are in agreement that early diesel cars (pre-Euro 3) have relatively low f-NO_2 values and that Euro 3/4 are much higher. The bus data are more inconsistent, but these values will depend very much on the specific bus fleet in question and the type of after-treatment used. However, for this report all buses are assumed not to have particle filters, except for several campaigns in London, which are considered later.

Ideally the RSD data used in this report would provide a direct measure of both NO and NO_2. Indeed, one of our recommendations is that future RSD surveys should use RSD equipment that can measure NO and NO_2. For this reason the accuracy of the total estimated emissions of NO_x are dependent on the values of f-NO_2 given in Table 4.2.

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[7] This information was available for almost all cars but was only partially available for HGVs/buses.

Table 4.2: Percentage of NO_2 assumed by vehicle type used to calculate total NO_x emissions from the RSD NO data (Grice et al., 2009; Jerksjö et al., 2008). The numbers in square brackets give the number of vehicles sampled for the Jerksjö et al. (2008) data. Note that for diesel LGVs the Grice et al. (2009) values are assumed to be the same as for diesel cars.

Vehicle class	Euro class	% NO_2 (by volume) (Grice et al., 2009)	% NO_2 (by volume) (Jerksjö et al., 2008)
Petrol cars			
	All	3	≈1 [12551]
Diesel cars			
	Euro 2 and earlier	11	14 [177]
	Euro 3	30	47 [538]
	Euro 4–6	55	55 [881]
Diesel LGVs			
	Euro 1		10 [42]
	Euro 2	11	20 [179]
	Euro 3	30	30 [816]
	Euro 4–6	55	60 [49]
HGVs			
	Euro II and earlier	11	7 [218]
	Euro III	14	9 [353]
	Euro IV–VI	10	13 [52]
Buses			
	Euro II and earlier	11	10 [78]
	Euro III (no trap)	14	30 [93]
	Euro III (trap)	35	25–52 [45]
	Euro IV–VI	10	48

4.3. Emissions by vehicle class, technology and time

It is useful to consider how the emissions of NO_x have changed over time to help understand whether the changes are consistent with emission inventories or whether there is any unusual behaviour. One of the most useful ways of considering how the emissions have changed over time is to use a *box and whisker* plot, as shown in Figure 4.1 for petrol cars. In Figure 4.1 the horizontal line show the median value, the bottom of the shaded region the 25th percentile and the top of the shaded region the 75th percentile. So, for example, about 25% of the data lies below the bottom of the shaded box (and above the top of the shaded box). The lines extending out from the shaded box are at 1.5 times the inter-quartile range. For normally distributed data about 99% of the data will lie within these "whiskers". In the context of the current work, values at the higher end of the distribution (the upper whisker) should provide a good indication of the emissions characteristics of high-emitting vehicles. It might further be expected that the highest emitting petrol vehicles since 1993 will tend to represent vehicles where the emissions control system has degraded — including catalyst failures.

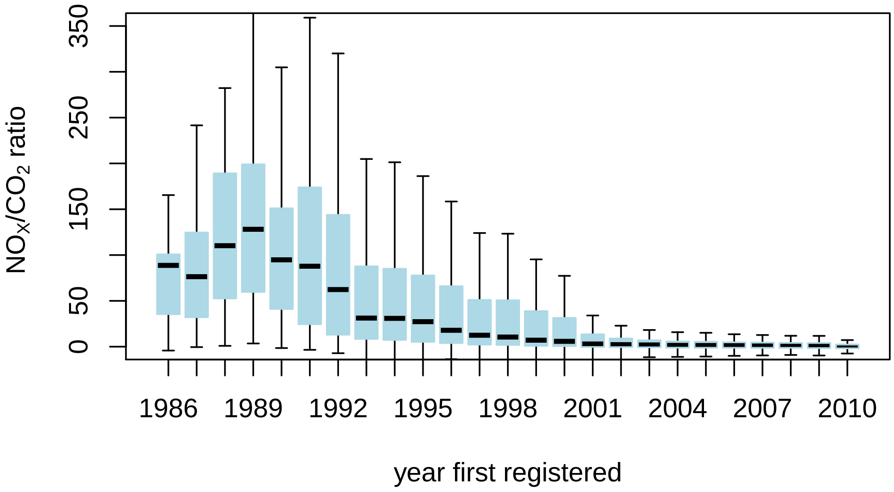

Figure 4.1: Box and whisker plot of the volume ratio of NO_x/CO_2 for petrol cars.

In Figure 4.1 there is clear evidence that median NO_x emissions decreased from 1992–1993 – coinciding with the introduction of 3-way catalysts on petrol vehicles. This reduction is also clearly shown in the 75th and upper whisker. There then seems to follow a gradual decrease in NO_x emissions from 1993–2000. The only other obvious decrease in NO_x emissions is from 1999–2000, which is seen in the 75th percentile and the upper whisker. This change corresponds to the introduction of Euro 3 petrol cars.

The changes in NO_x emissions from petrol cars are seen more clearly in Figure 4.2. We have also taken the opportunity to plot the other pollutants (CO, HC and 'smoke') — also expressed as a ratio to CO_2. In this plot it is apparent that from Euro 3 to Euro 5, emissions of NO_x are very well controlled. For vehicles older than Euro 3 (about 10 years old), there is much more of a spread in NO_x emissions shown by the width of the shaded box. Note also that cars without catalysts (E0) tend to have a symmetric distribution shown by the median being located in the middle of the shaded box, whereas Euro 2/3 vehicle emissions tend to be asymmetric — with a higher number of vehicles showing higher emissions. This characteristic is again what would be expected from either failed catalysts or inefficient catalysts.

Very similar trends are also observed for CO and HC, consistent with the effective introduction

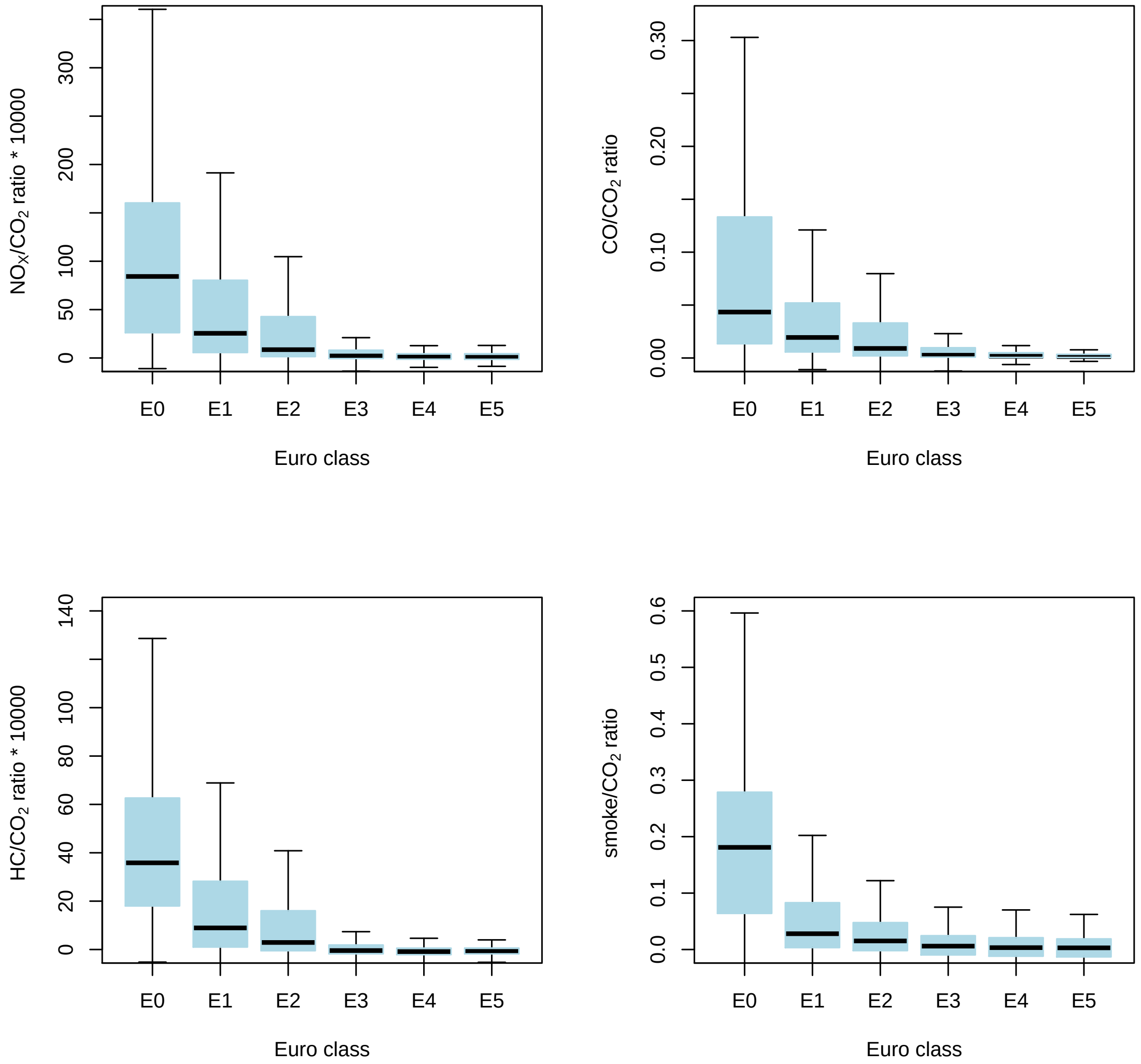

Figure 4.2: Box and whisker plots for petrol cars by Euro class.

of catalysts, particularly from Euro 3 onwards.

To understand the performance of the emissions control system on petrol vehicles further, we have considered how the distribution of NO_x emissions from these vehicles has changed over time. Figure 4.3 shows several percentile emission levels over time. It is apparent for the median emission level i.e. the 50th percentile, that emissions decreased considerably from pre-catalyst vehicles to post catalysts vehicles. Note that the vertical dashed line shows when catalyst vehicles were introduced to the UK.

The introduction of catalyst vehicles to the UK is most apparent for the 75th, 90th and 95th percentile emissions. For the higher percentile levels the shape of the relationship over time differs from the median line. For example, considering the 99th percentile line the emission level is relatively constant from 1986–2000. This behaviour suggests that there has been little change in the level of emissions for the highest emitting vehicles for pre Euro 3 cars. Despite being equipped with catalysts these vehicles behave like non-catalyst vehicles, which would be consistent with emissions control system degradation in these vehicles. However, Figure 4.3 shows that similar patterns are also observed for the other high percentile levels (90th percentile

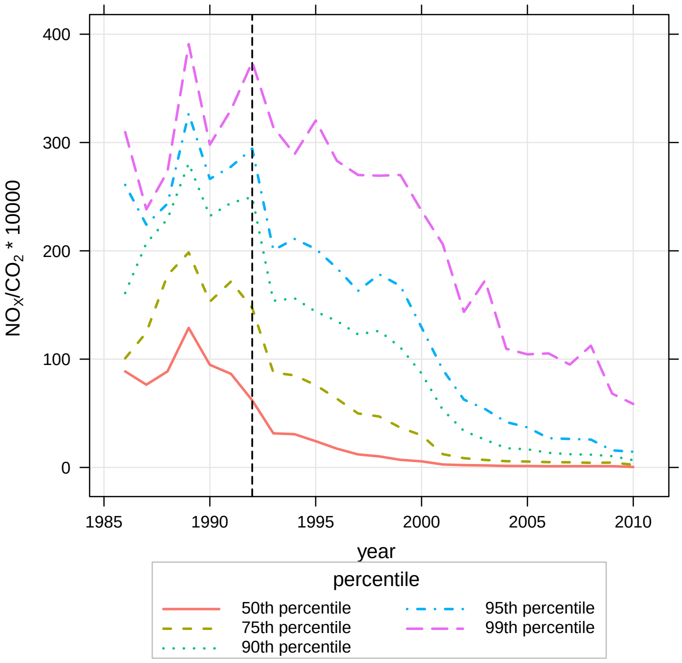

Figure 4.3: Different percentile emissions of the NO_x/CO_2 ratio for petrol cars. The dashed vertical line shows the date when catalysts vehicles were introduced to the UK.

and higher). There is therefore a distribution of emissions control equipment degradation.

Also shown is a box and whisker plot for diesel cars by Euro class (Figure 4.4). There are several important differences compared with the same plot for petrol vehicle (Figure 4.2). First, there is very little evidence that emissions of NO_x from diesel cars have changed by much from pre-Euro to Euro 5. Second, the distribution of emissions has tended to widen across the Euro classes (for example, compare the width of the shaded boxes); opposite to the behaviour of petrol vehicles. Furthermore, the distributions are mostly symmetric, as shown by the central location of the median in each case. This feature of diesel cars is very different to Euro 1/2 petrol cars with catalysts, which again supports the view of a catalyst effect for older catalyst-equipped petrol cars.

For HC and CO there is some evidence that emissions have decreased through the Euro classes, although the decrease seems to have been modest. Interestingly, ‘smoke’ emissions from diesel cars show a stronger decrease since Euro 2, presumably due to the increased use of oxidation catalysts and particle filters. Further analysis of these other species is beyond the scope of this work but would be useful.

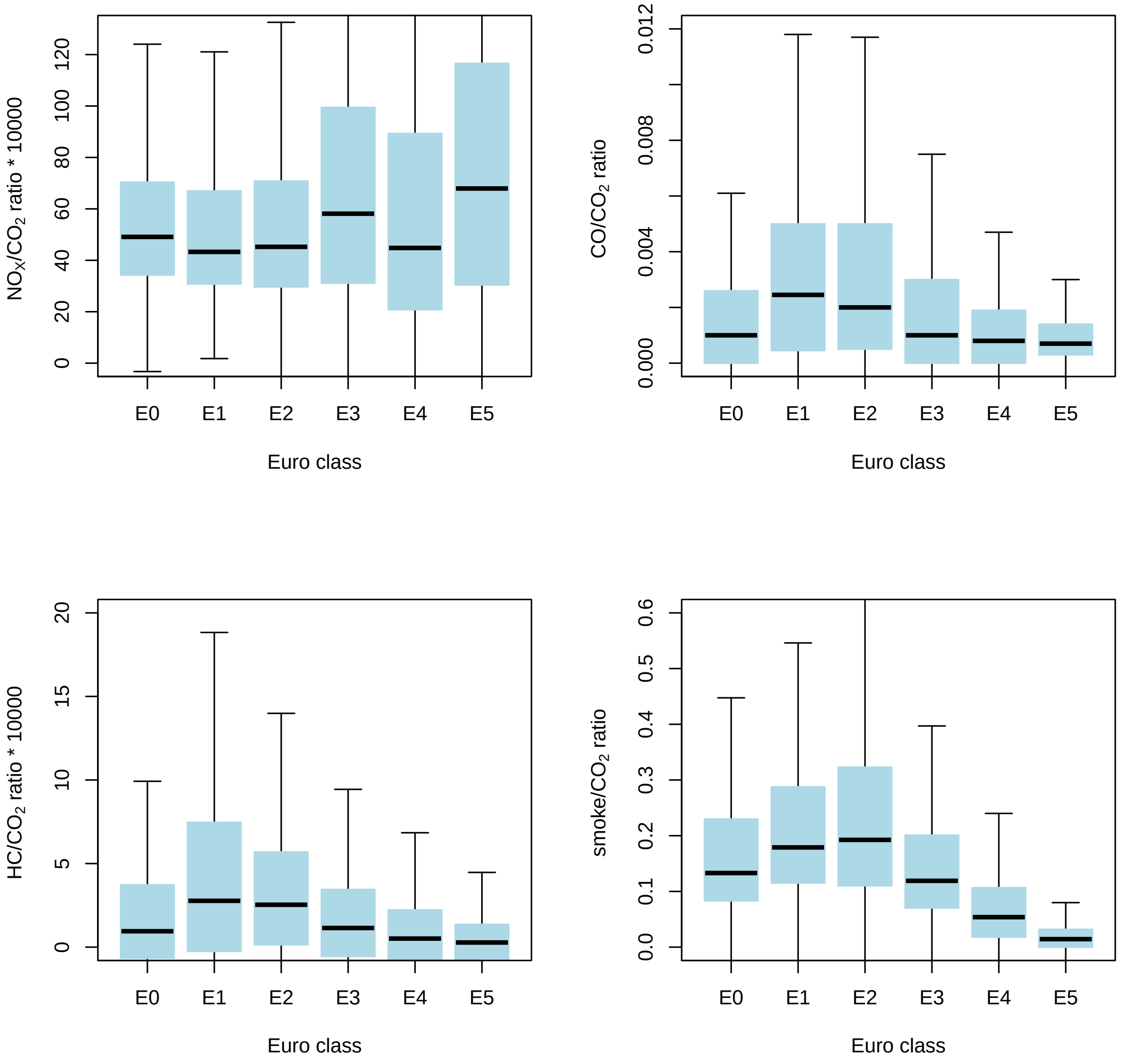

Figure 4.4: Box and whisker plots for diesel cars by Euro class.

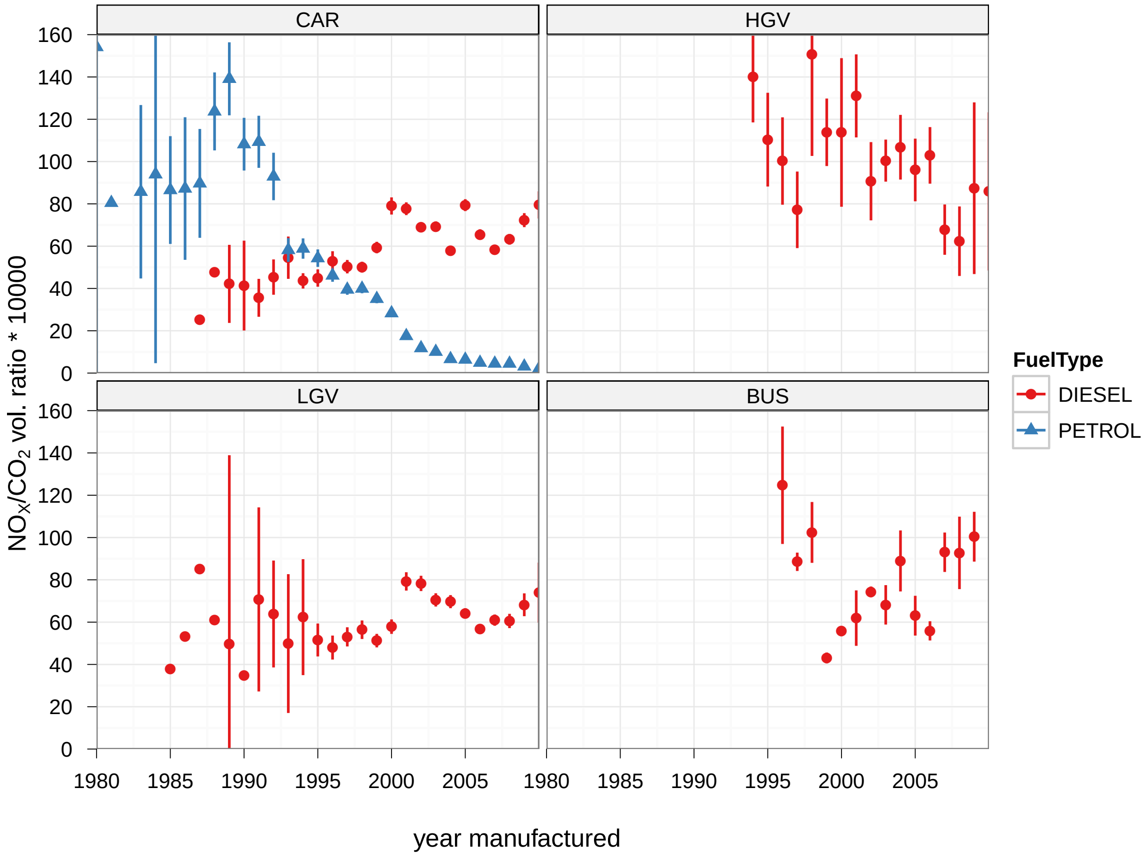

Figure 4.5: NO_x/CO_2 ratio for major classes of vehicle based on the analysis of the remote sensing data. The error bars show the 95% confidence interval in the mean.

The NO_x/CO_2 ratio for petrol and diesel vehicles highlight some important features (Figure 4.5). Note that the wider uncertainty levels in the estimated mean emission is due to the smaller sample sizes for very old (or new) vehicles. The effect of introducing various Euro standards is very apparent for petrol vehicles. For example, there is a steep drop in emissions going from pre-Euro to Euro 1 from 1992–1993 and from 2000–2001.

The situation for diesel vehicles is very different. Emissions of NO_x appear to peak in 2000 and then decrease slightly to 2010. However, vehicles registered from 2005–2010 emit similar or higher levels of NO_x compared with vehicles prior to 1995. In this respect, NO_x emissions from diesel cars have changed little over a period of about 20 years. The trend for LGVs shown in Figure 4.5 is similar to diesel cars.

The HGV trend (Figure 4.5) is relatively flat but there is evidence of a decrease in emissions from 2006–2007. The timing of this decrease is again consistent with emissions legislation for Euro IV HGVs where type approval was set for October 2005 with in-service vehicles entering the market about 1 year after that.

The trend for buses is again different to other vehicles types as shown in Figure 4.5, where there has been a steady increase in emissions over time. However, there are a couple of points to note. The sample size is not high for buses (see Table 4.1) and bus stock and hence emissions could be determined by very local factors. These issues will be considered in greater detail when comparisons are made with other data sources.

Also shown (Figure 4.6) is the NO_x/CO_2 ratio by Euro classification for petrol and diesel cars. The decrease in emission through the Euro classes is clear for petrol vehicles. Emissions for diesel cars have been much more constant. Note that for diesel and petrol cars the CarWeb

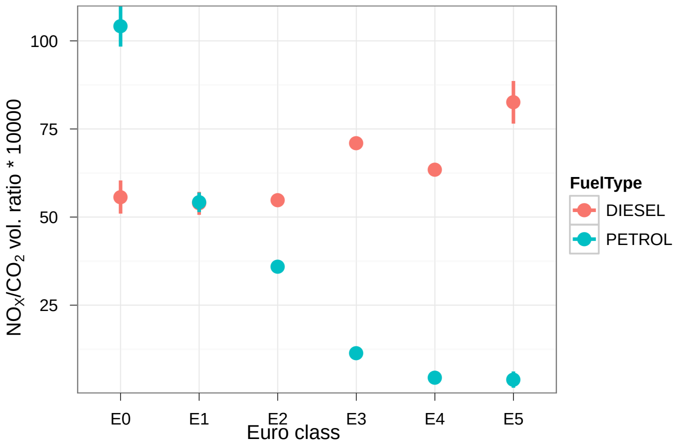

Figure 4.6: Volume ratio of estimated NO_x/CO_2 for petrol and diesel cars by Euro classification. The error bars show the 95% confidence intervals in the mean.

derives its Euro classification from manufacture databases and will be more accurate than any year-based approach.

4.4. Effect of driving conditions on emissions from light duty vehicles

There are many approaches available that aim to characterise how emissions from vehicles vary by various metrics such as vehicle speed. This is an important issue for several reasons, including the extent to which the RSD data reflects actual driving conditions. One commonly used approach to characterise vehicle operating conditions and relate them to emissions is to use *Vehicle Specific Power*, VSP (Jiménez et al., 1999). VSP is a measure of the power required by an engine to overcome forces including friction, aerodynamic drag, internal engine friction and the effect of road gradient. VSP is expressed in kW/tonne and simple analytical expressions have been derived for different categories of vehicle. VSP has the advantage over other metrics such as vehicle speed in that it is based on engineering principles concerning the forces a vehicle must overcome. It should be noted that VSP forms the basis of the new US-EPA Motor Vehicle Emission Simulator (MOVES) approach, which replaced the older MOBILE emission estimate approaches.[8]

The relevance of VSP to this report is mostly in understanding how emissions of NO_x vary as a function of VSP. The Jiménez et al. (1999) approach provides a simple algorithm for calculating VSP for light duty vehicles:

$$VSP = \frac{Power}{Mass} \approx 0.22 \cdot v \cdot a + 4.39 \cdot sin(slope) \cdot v + 0.0954 \cdot v + 0.0000272 \cdot v^3 \qquad (2)$$

VSP is in kW/Metric tonne, v is the vehicle speed in mph, a is the vehicle acceleration in mph/sec and the $slope$ is expressed in degrees. In the RSD surveys used in this report, the slope mean slope was 1 degrees and the median slope 0.7 degrees, and these data have been used in evaluating Equation 2.

Jiménez et al. (1999) provides some examples of vehicle usage and typical VSP values. For example, a car accelerating from 0–60 mph in 15 seconds requires a VSP of 33 kW/t. The mean value from the RSD data was 6.7 kW/t (typical of RSD surveys). By contrast the urban part of the ARTEMIS cycle with a mean speed of 17 km h^{-1} is 0.9 kW/t and the urban-regional cycle with a mean speed of 57 km h^{-1} is 5.1 kW/t. However, a typical value for *actual* urban-type

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[8] See `http://www.epa.gov/oms/models/moves/movesback.htm` for information on the use of VSP by the US EPA MOVES.

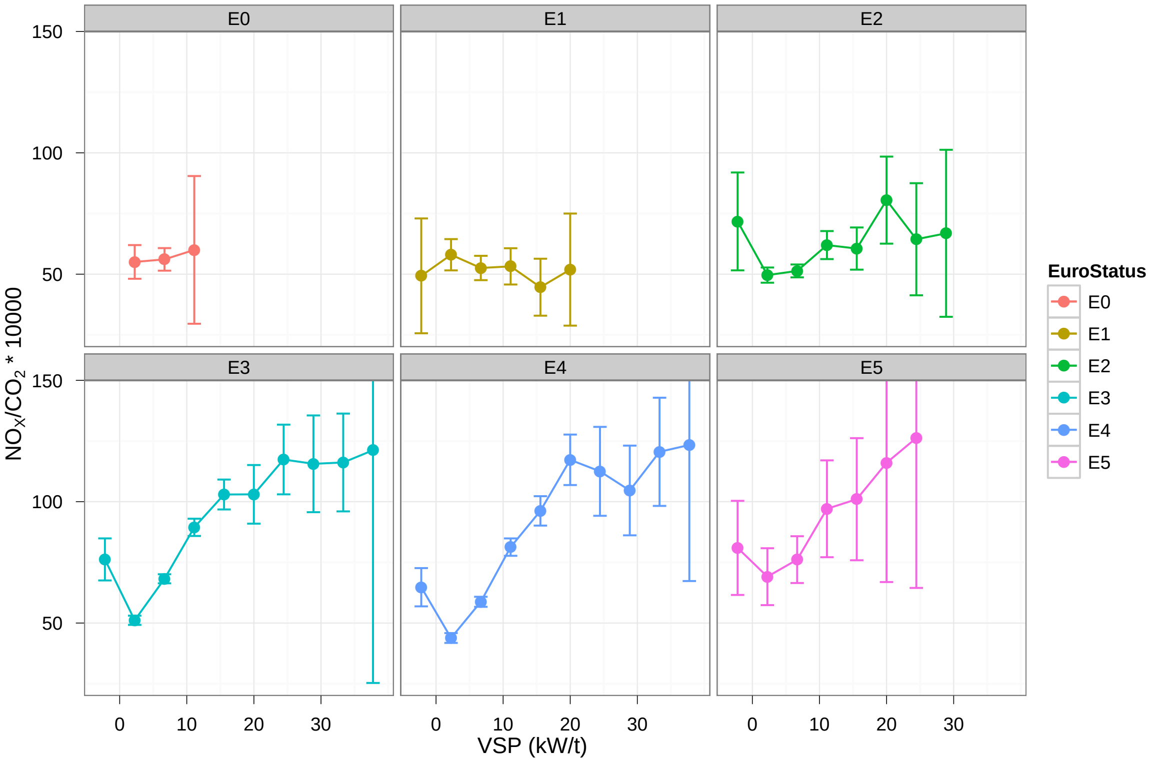

Figure 4.7: VSP vs. NO_x/CO_2 ratio for diesel cars split by Euro status. The error bars show the 95% confidence interval in the mean.

driving is not known. As it will be shown, modern diesel cars tend to emit high NO_x/CO_2 ratios as the VSP increases. Therefore, it is not sufficient to know what a 'typical' or 'average' VSP value is because of the disproportionate effect that higher engine loads have on emissions of NO_x. For example, a small proportion of higher load conditions e.g. through 'aggressive' driving could have an important effect on overall emissions of NO_x.

Figure 4.7 show the results for diesel cars. It is clear that there has been a tendency for NO_x/CO_2 ratios to *increase* with increasing VSP for newer model diesels. There is little evidence that the NO_x/CO_2 ratio increased for Euro 1 vehicles with increasing VSP and only weak evidence for Euro 2 vehicles. However, for Euro 3–5 there is a clear increasing relationship between NO_x/CO_2 and VSP. These relationships for diesel vehicles could have important implications for emission trends. The results show that under higher engine loads, modern diesels (Euro 3–5) can emit considerably higher NO_x/CO_2 ratios than older vehicles. The data show that diesel cars have become increasingly powerful through the Euro classes with pre-Euro to Euro 2 cars having a maximum rated power output of about 70 kW increasing to 85, 98 and 113 kW for Euro 3–5, respectfully. Petrol vehicle maximum rated power has remained about 80 kW through all Euro classes. Note also that under higher loads the absolute emission of CO_2 would also be higher and hence the absolute emission of NO_x would also be proportionately higher.

The results for petrol vehicles do not tend to show an increasing NO_x/CO_2 ratio with increasing VSP as shown in Figure 4.8. In the case of diesel LGVs it is Euro 4 vehicles that show a strong increasing relationship between the NO_x/CO_2 ratio and VSP — see Figure 4.9.

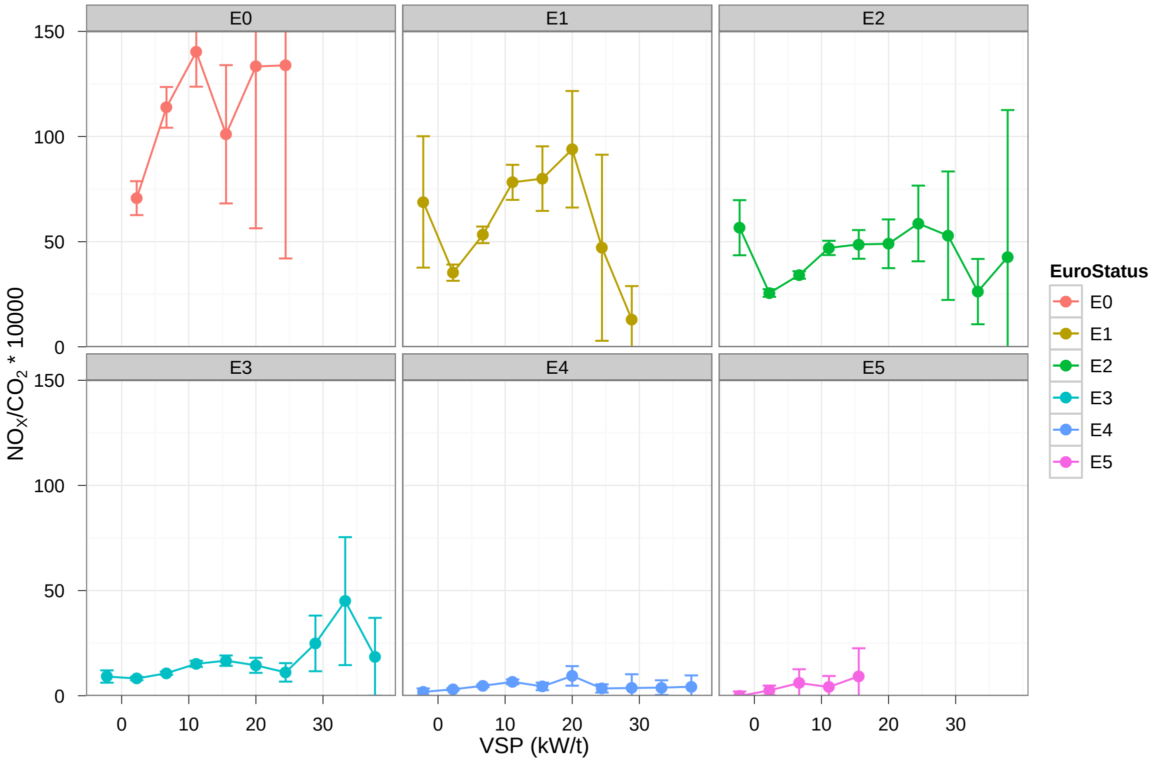

Figure 4.8: VSP vs. NO_x/CO_2 ratio for petrol cars split by Euro status. The error bars show the 95% confidence interval in the mean.

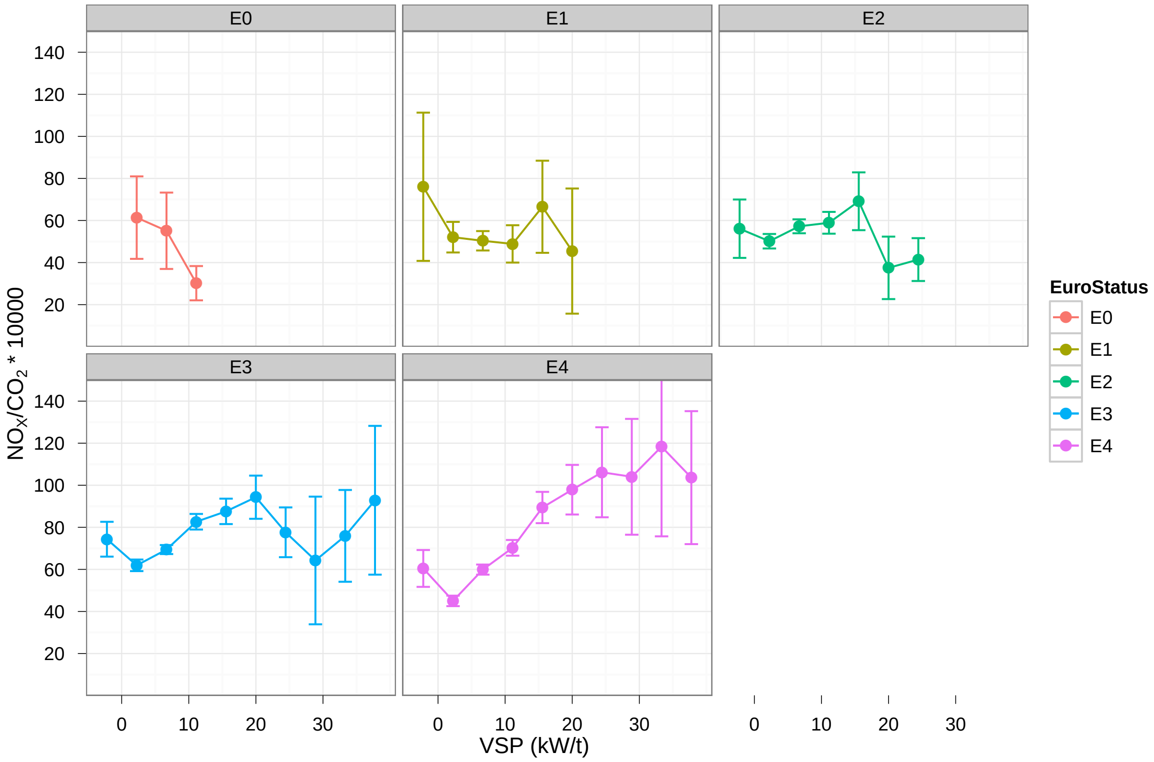

Figure 4.9: VSP vs. NO_x/CO_2 ratio for diesel LGVs split by Euro status. The error bars show the 95% confidence interval in the mean.

4.5. Effect of vehicle speed and engine size on emissions of NO_x

The relationship between the NO_x/CO_2 ratio and vehicle speed as shown in Figure 4.10. The strongest relationship is for diesel cars where the NO_x/CO_2 ratio increases with vehicle speed. It should be remembered that the absolute CO_2 emission (in g km^{-1}) will tend to increase as the vehicle speed decreases. Therefore, given an estimate of the CO_2 emission for a particular vehicle class, it would possible to calculate a speed-emissions relationship as used in standard UK emission factors.

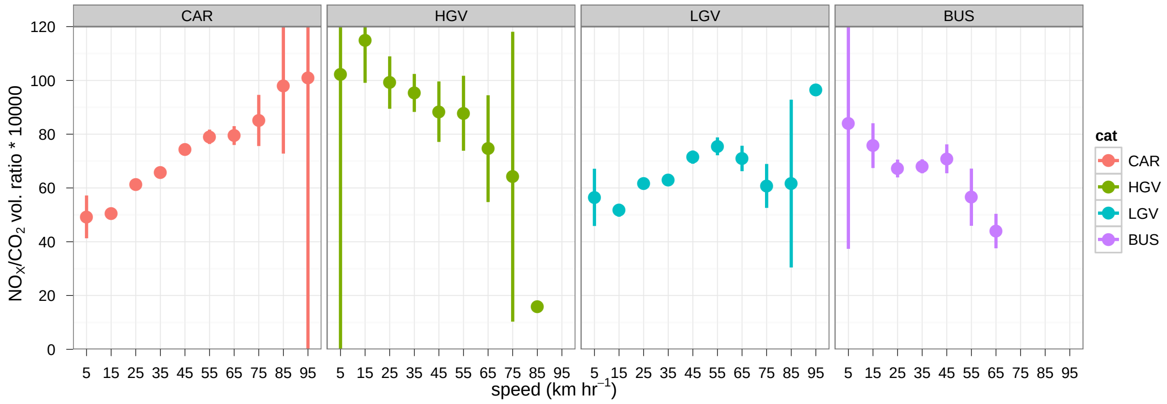

Figure 4.10: Vehicle speed- NO_x/CO_2 relationship by major *diesel* vehicle classes. The error bars show the 95% confidence interval in the mean.

There is some evidence for diesel cars that the NO_x/CO_2 ratio *decreases* with increasing engine size, as shown in Figure 4.11. However, the relationship does not appear to be strong. As with Figure 4.10 it should be remembered that as the engine size increases then so too will the absolute emission of CO_2 and hence NO_x.

These data may prove useful in any subsequent work used to compile vehicle emission inventories for NO_x and NO_2.

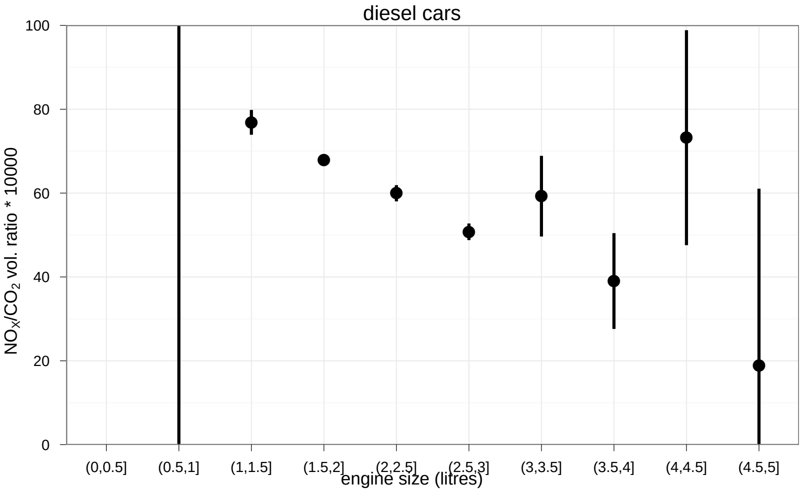

Figure 4.11: Engine size- NO_x/CO_2 relationship for diesel cars.

5. Emission factor comparison

5.1. Comparison of UK emission factors with the HBEFA and RSD

This section considers the emissions from different vehicle and Euro classes for three data sources. These emission factors are the building blocks for emission inventories and are therefore an important consideration. This section does not consider the effect of fleet mix etc., which depends on many other factors e.g. the time and location being considered.

An analysis of the Swiss/German Emission factors for road transport (HBEFA, version 3.1, released January 2010, HBEFA (2010)) has been carried out together with the analysis of the RSD and UK emission factors. The HBEFA provides an alternative approach to that used for the NAEI/LAEI and has the benefit that it is up to date.

It is not possible to compare these data sources on exactly the same basis due to different methodologies used in both measurement (RSD) and approach. We have however taken care to ensure that the emissions are as consistent as possible. The RSD has been taken as the basis of comparing the emissions. These emissions best represent urban-type driving conditions and the mean speed across all campaigns was 31 kph. While covering only a limited set of conditions, urban areas are most important with respect to exceedances of the NO_2 limit values. This speed was used directly in the UK emission factor calculations since these factors use speed as an input. The HBEFA data is somewhat more complex because the emission depends on one of many “traffic situations”. We have chosen “URB/Trunk-City/50/Satur” where the average speed is 36 kph (and 29 kph for HGVs). These types of road and traffic condition are most likely consistent with the RSD and UK emission factor estimates and represent main urban roads. While HBEFA does allow for road gradients to be considered, zero gradients have been assumed throughout. This assumption was to allow direct comparison with UK emission factors. As mentioned previously, the median slope used for the RSD surveys was only 0.7 degrees.

The other calculation to be made is the *absolute* estimate (in g km^{-1}) of NO_x from the RSD. What is required is a way of estimating total NO_x emissions from the calculated RSD NO_x/CO_2 emission. We have used the UK emission factor estimate of CO_2 in g km^{-1} as a means of estimating the total NO_x emission in g km^{-1}. The key assumption therefore is that the UK emission factor estimates are accurate. While there is likely to be some uncertainty in these factors, the estimates for CO_2 should be more reliable than those for other non-fuel related emissions such as NO_x. The emission factors for CO_2 for most classes of vehicle do tend to show progressive reductions in CO_2 emissions through the Euro classes. These reductions in CO_2 also mean that total emissions of NO_x reduce in a proportionate way.[9] The CO_2 values are shown later in Table 5.1.

For the HBEFA data we have used emission factors relevant for EGR and not SCR.

There are several limitations of this analysis, which are mostly related to the RSD:

1. The RSD does not include a sufficiently large sample of articulated HGVs from which conclusions can be drawn. Part of the difficulty in capturing enough of these vehicles is due to the elevated height of the exhaust, which the RSD was not set up to deal with. However, there are few of these vehicles in urban areas.

2. Similar to the above point, there is also insufficient data for petrol LGVs (again — there are very few of these vehicles.)

3. The bus emissions are dominated by two campaigns in London. However, sense can be made of the emissions by considering the campaigns in more detail as described below.

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[9] For example, a small diesel pre-Euro passenger car emits 186 g km^{-1}, whereas a small Euro 4 diesel car emits 152 g km^{-1} based on a speed of 31 kph.

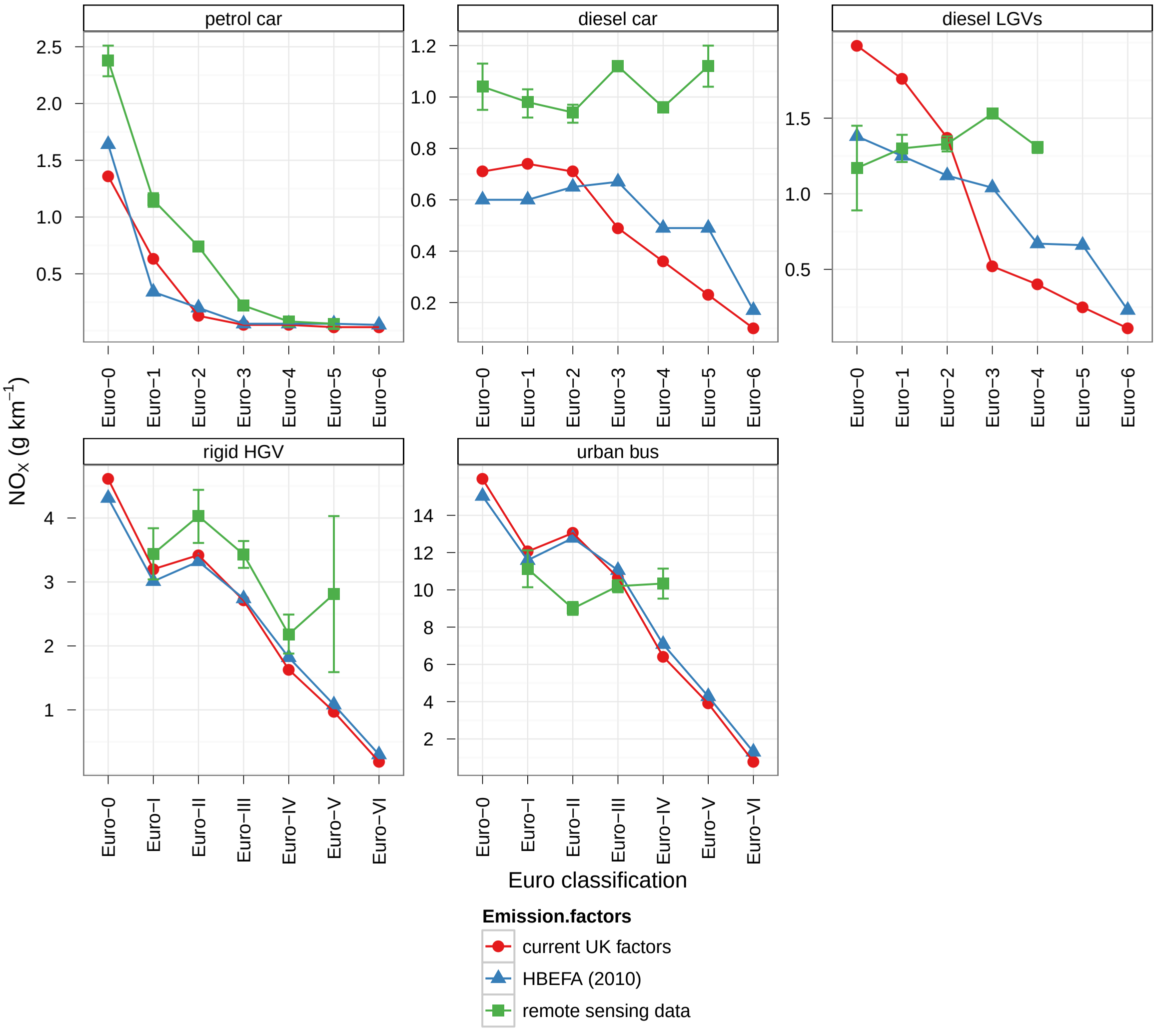

Figure 5.1: Comparison of different emission factor estimates. Three emission sources are compared: current UK factors, HBEFA (2010) and estimates based on the analysis of remote sensing data. The uncertainties for the remote sensing data are the 95% confidence intervals in the mean.

These limitations should be borne in mind when considering how the RSD compares with other data sources.

Figure 5.1 shows the g km^{-1} estimates of total NO$_x$ for the three data sources. There are several important differences in these emission estimates that are considered next. First, the rigid vehicle emission estimates are very consistent across the three data sources. In the case of HBEFA and the UK emission factor estimates this may be because they are reliant on the same source of emissions data. However, it is reassuring that the totally independent RSD agrees very well in both magnitude and trend with the other two data sets. In other words, emissions of NO$_x$ from Euro I to Euro III show little difference, while Euro IV emissions are approximately one third less than earlier Euro classes.

As mentioned previously there were insufficient articulated HGV data available from the RSD to allow similar comparisons. However, it does appear that the trend through the Euro classes is very similar to that for the rigid vehicles. It would also seem likely that similar conclusions would be drawn for these vehicles compared with the rigid HGVs.

The bus emissions will be affected by local factors due to the specific fleets used in urban areas. A consideration of the data shows that 98% of the Euro II buses were sampled from two campaigns in London. For Euro III approximately half the buses were from London, whereas for Euro IV only 6% were from London. All Euro II buses in London have been fitted with particle filters. Previous work e.g. AQEG (2008) suggests that Euro II f-NO_2 values for London buses were ≈40%. The bus emissions were therefore considered specifically to account for these fleet characteristics i.e. buses known to have been fitted with particle filters were assumed to emit a NO_2/NO_x ratio of 40%. The Euro IV emissions would be expected to be more in line with buses without particle filters. To our knowledge, the local bus fleets for the other locations (notably York and Shropshire) do not use particle filters.

Considering the results in Figure 5.1 it is clear that most of the disagreement among the emission factor estimates is for light duty vehicles.

There is large disagreement between the UK emission factors compared with the other data sources for diesel LGVs and cars i.e. two very important vehicle classes in urban areas. For diesel LGVs the UK emission factors suggest that emissions of NO_x should have fallen substantially from pre-Euro to Euro 4 (approximately 80% reduction). By contrast, there is little evidence of any decrease in NO_x emissions from the RSD. HBEFA suggests emissions should have fallen by ≈40% — still half that suggested by the UK emission factors. This is clearly one class of vehicle where there is substantial disagreement with the RSD data.

The picture for diesel cars is similar to LGVs. First, however, the RSD emissions tend to be higher compared with either the HBEFA or UK estimates. For this particular comparison we have assumed “small” (<2.0 l) cars, as these comprise the largest numbers on the road. The RSD does suggest that the NO_x/CO_2 ratio is higher than the other data sources; and this is then reflected in the absolute emission estimate. Applying the RSD factors to emission inventories would therefore tend to increase the importance of diesel car emissions overall. The second feature to note is that the UK emissions show that from Euro 2 onwards NO_x emissions decrease almost linearly with time. Both the RSD and HBEFA show that Euro 3 emissions are similar (or higher) than older Euro classes. While all data sources show a decrease in NO_x from Euro 3 to 4, the RSD and HBEFA show that Euro 5 emissions are very similar to Euro 4. Further, the pattern of emission changes through the Euro classes is most similar for HBEFA and the RSD. The net affect of these differences would be (assuming RSD emissions are used) is that diesel cars are more important for NO_x emissions than previously thought and the effect of newer Euro classes less important than previously thought.

A summary of the current UK, HBEFA and RSD emission factors for NO_x is given in Table 5.1.

Superficially the emissions change from petrol vehicles are very similar: there has been a very large reduction in emissions of NO_x from pre-Euro vehicles classed to Euro 4/5 — more than 95% in all cases. Nevertheless there are differences that are likely important with respect to recent trends. The key difference is that between the RSD and the UK/HBEFA emissions for pre-Euro 4 vehicles. In particular, the RSD suggests petrol car emissions of NO_x are much higher for Euro 2/3 vehicles compared with the other data.[10] Indeed, the RSD suggests that Euro 2/3 petrol car emissions are similar to diesel car NO_x emissions. It is interesting to note that the remote sensing results from Sweden are similar in this respect i.e. emissions have not decreased as much as the emission factors suggest for Euro 1-3 vehicles (Jerksjö et al., 2008). The reason is mostly likely related to emission system degradation discussed in subsection 4.3, where is shown that for Euro 2/3 catalyst-equipped vehicles the emissions are significantly skewed towards higher emissions.

The following plots highlight some of the important comparisons for diesel vehicles. In general, the HBEFA trend in time (by Euro class) is more pessimistic than the emission factors used in the UK inventories. It is interesting to note that HGV emissions tend to be similar between the two methods for higher speed driving. Also important is the high NO_x emissions seen for

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[10] Pre-Euro emissions are also higher, but there are far fewer of these vehicles and the uncertainty in the RSD emissions greater, as shown in Figure 4.6.

Table 5.1: Emission factor estimates based on current UK emission factors, HBEFA and those estimated from the RSD. The CO_2 values shown relate to those currently used in UK emission factor estimates and have been used to scale appropriate NO_x/CO_2 estimates from the RSD to derive absolute g km^{-1} estimates of NO_x. The RSD uncertainties relate to the 95% confidence intervals in the mean.

Vehicle type	Euro	CO_2	NO_x emission factor (g km^{-1})		
	classification	(g km^{-1})	UK	HBEFA (2010)	RSD
diesel LGV	Euro-0	203	1.98	1.38	1.17 ± 0.28
diesel LGV	Euro-1	250	1.76	1.25	1.3 ± 0.09
diesel LGV	Euro-2	240	1.37	1.12	1.33 ± 0.05
diesel LGV	Euro-3	216	0.52	1.04	1.53 ± 0.03
diesel LGV	Euro-4	216	0.40	0.67	1.31 ± 0.04
diesel LGV	Euro-5	216	0.25	0.66	NA
diesel LGV	Euro-6	216	0.11	0.23	NA
diesel car	Euro-0	186	0.71	0.60	1.04 ± 0.09
diesel car	Euro-1	181	0.74	0.60	0.98 ± 0.06
diesel car	Euro-2	171	0.71	0.65	0.94 ± 0.04
diesel car	Euro-3	158	0.49	0.67	1.12 ± 0.02
diesel car	Euro-4	152	0.36	0.49	0.96 ± 0.02
diesel car	Euro-5	136	0.23	0.49	1.12 ± 0.08
diesel car	Euro-6	122	0.10	0.17	NA
petrol car	Euro-0	228	1.36	1.64	2.38 ± 0.14
petrol car	Euro-1	212	0.63	0.34	1.15 ± 0.06
petrol car	Euro-2	204	0.13	0.20	0.74 ± 0.03
petrol car	Euro-3	193	0.05	0.06	0.22 ± 0.01
petrol car	Euro-4	178	0.05	0.06	0.08 ± 0.01
petrol car	Euro-5	159	0.03	0.06	0.06 ± 0.04
petrol car	Euro-6	143	0.03	0.05	NA
rigid HGV	Euro-0	425	4.61	4.31	NA
rigid HGV	Euro-I	340	3.20	3.01	3.44 ± 0.4
rigid HGV	Euro-II	321	3.42	3.32	4.03 ± 0.42
rigid HGV	Euro-III	342	2.71	2.74	3.43 ± 0.21
rigid HGV	Euro-IV	321	1.63	1.82	2.18 ± 0.3
rigid HGV	Euro-V	327	0.97	1.08	2.81 ± 1.22
rigid HGV	Euro-VI	327	0.19	0.30	NA
bus	Euro-0	1277	15.95	15.03	NA
bus	Euro-I	1132	12.06	11.59	11.13 ± 0.99
bus	Euro-II	1110	13.05	12.78	9 ± 0.34
bus	Euro-III	1164	10.66	11.05	10.2 ± 0.33
bus	Euro-IV	1102	6.42	7.08	10.34 ± 0.81
bus	Euro-V	1143	3.90	4.28	NA
bus	Euro-VI	1143	0.78	1.30	NA

SCR-equipped vehicles under urban-type driving conditions. Higher NO_x emissions from HGVs with SCR have also been observed in work conducted by TNO (in Finland, reference required) and as commented by Finn Coyle from TfL.

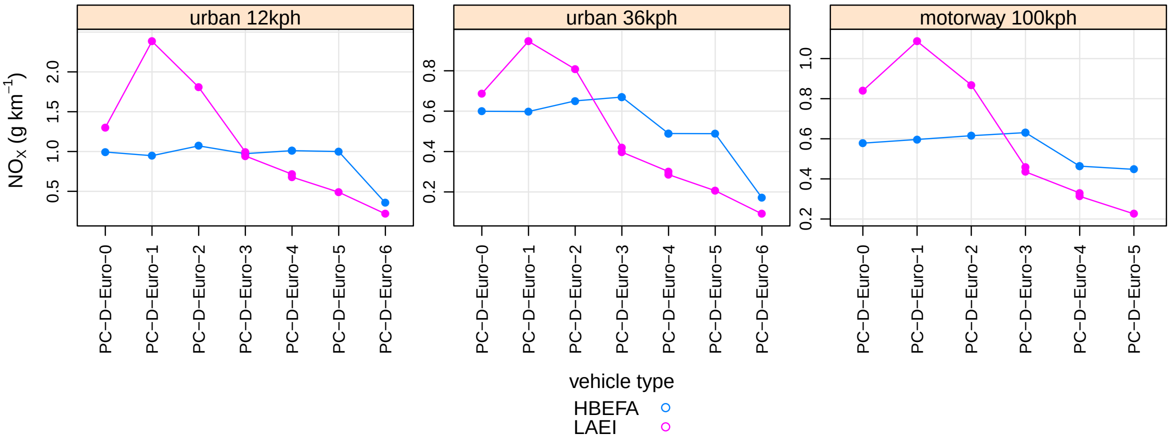

Figure 5.2: Comparison between LAEI and HBEFA emission factors for diesel cars.

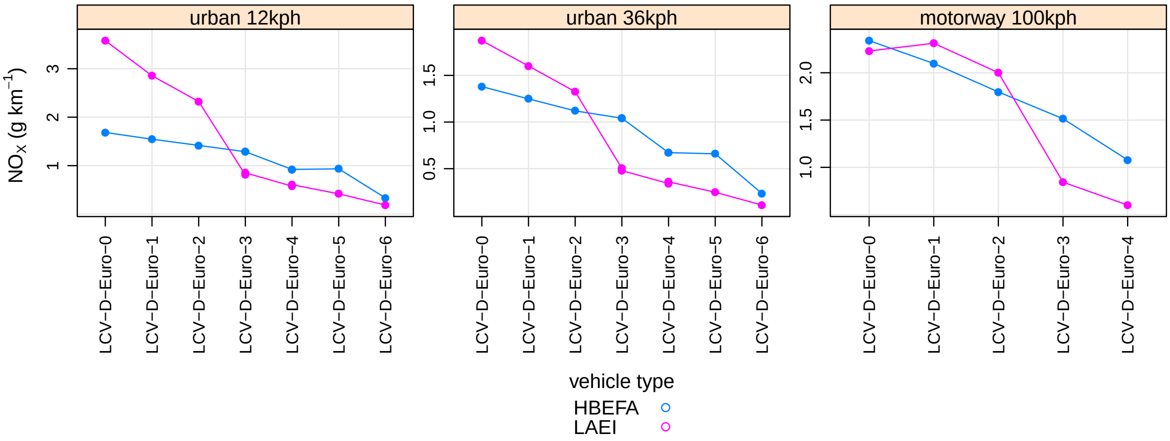

Figure 5.3: Comparison between LAEI and HBEFA emission factors for diesel LGVs.

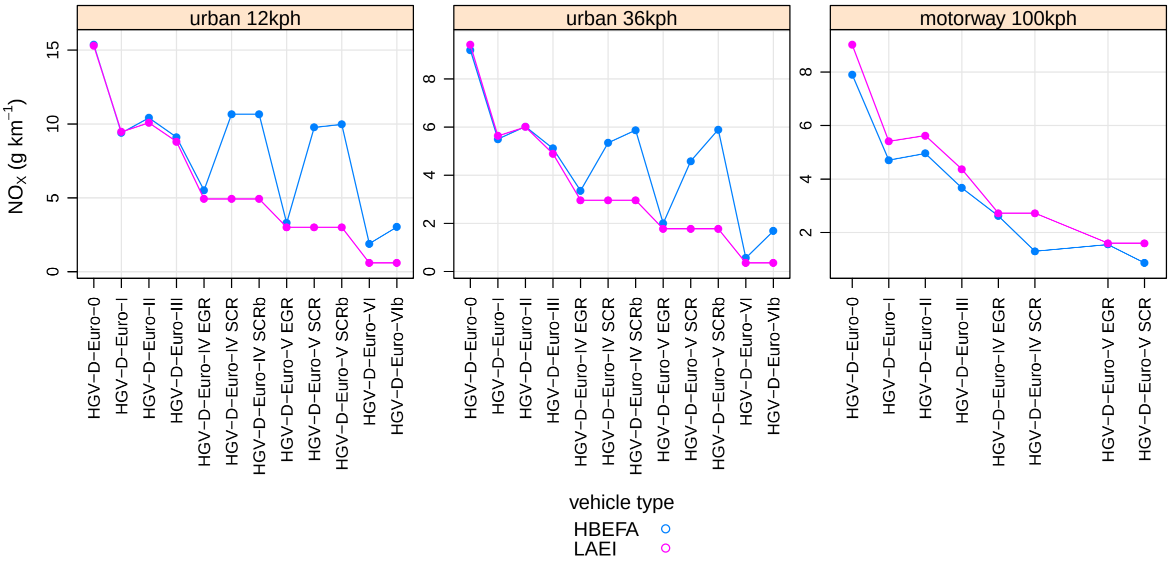

Figure 5.4: Comparison between LAEI and HBEFA emission factors for diesel HGVs.

5.2. Comparison of type approval emissions for diesel cars with legislated limits

This section briefly considers the legislated limits for NO_x emissions for diesel cars and the emission measurements undertaken as part of the type approval process. The Vehicle Certification Agency (VCA) makes available emissions information for all new models of vehicle that have been tested for type approval purposes, consisting of thousands of vehicles. These emissions can usefully be compared with the legislative limits, as shown in Figure 5.5.

Figure 5.5 shows the steep decline in legislated emissions from Euro 2 to Euro 5, in stark contrast to Figure 5.1.[11] It is also clear from Figure 5.5 that the measured values track the emission limits very closely and are consistently slightly lower. The close correspondence between the two suggests that vehicle manufacturers have been able to meet Type Approval limits in a consistent way when tested over the legislated test cycle.

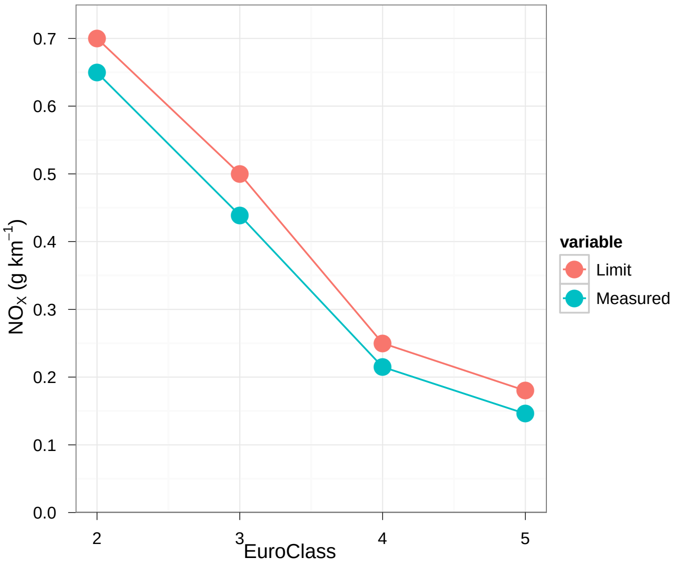

Figure 5.5: Comparison of Type Approval limits and actual measured emissions as part of the Type Approval process for diesel cars (Euro 2–5). The emissions of NO_x from each Euro class were averaged. The sample sizes were as follows: Euro 2 = 400;, Euro 3 = 3788; Euro 4 = 6559 and Euro 5 = 881.

5.3. Selective Catalytic Reduction used on HGVs and buses

An important development in recent years has been the use of selective catalytic reduction (SCR) on HGVs and buses. This technology along with Exhaust Gas Recirculation (EGR) is described in AQEG (2004).

In a recent study using PEMS (portable emission monitoring system), Ligterink et al. (2009) report the performance of SCR for a range of HGVs using a portable emissions monitoring system (PEMS). Seven common distribution and national long-haul trucks were tested on the same route and under similar circumstances. Each vehicle was tested with at least two different payloads. One vehicles was fitted with EGR while the others used SCR. These vehicles are thought to be typical of the types of vehicle also driven in the UK with GVW of 5.8 and 17.8 t.

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[11] Although there was no separate legal limit on NO_x for Euro 2 vehicles, a 'limit' was estimated from a consideration of the HC+NO_x ratios for Euro 3 when NO_x was reported along with HC+NO_x to give a figure of approximately 0.7 g km^{-1}.

The Ligterink et al. (2009) and Velders et al. (2011) showed that vehicles fitted with SCR did result in considerably reduced NO_x emissions for motorway-type driving, but much higher emissions for urban driving. For example, compared with a Euro III truck, emissions of NO_x from SCR trucks on motorways was reduced from 11 g $kg^{-1}CO_2$ to 4 g $kg^{-1}CO_2$. However, in urban areas the emissions changed from 13 to 10 g $kg^{-1}CO_2$. NO_x emissions from the SCR trucks generally started decreasing to approach the regulatory level at speeds of 60 to 80 km h^{-1}.

The EGR truck produced lower NO_x than the SCR trucks.

TfL has also considered the use of SCR on the bus fleet in London. This work is interesting because some effort was made to optimise the SCR system for use under urban driving conditions i.e. addressing the issue mentioned above. Results from the TfL work show that SCR reduces NO_x emissions by about 65%. However, this reduction is seen as a "best case" because the bus in question had a small engine that would have been put under higher load than a larger bus engine.[12]

Data relating to the use of SCR on HGVs in the UK is scarce. Currently it is thought about 20% of the HGV fleet in UK use SCR, although these estimates are considered approximate.[13] The proportion using SCR in urban areas will be somewhat lower than 20% due to the types of HGV fleet in urban areas. It is thought that about 80% of new vehicles in the long-haul sector are vehicles with SCR. However, it seems that manufacturers frequently offer EGR (Exhaust Gas Recirculation) on their distribution and delivery vehicles for Euro IV/V i.e. lorries of the type typically used in urban areas. Below 16 tonnes GVW about 80% of new sales are for vehicles with EGR.

It is clear from the data above that specific, reliable information is required for used in emission inventories concerning the use of SCR/EGR on HGVs. Given the evidence concerning the current poor performance of SCR under urban driving conditions, it will be essential to know the current and future number of SCR-equipped HGVs in urban areas. On the one hand it is concerning that the emissions performance for NO_x is poor for urban driving conditions, but on the other, this effect may be small overall because there are so few of these vehicles in urban areas.

6. Re-calculated emission inventories

6.1. Alternative emission factor scenarios for the UK national emissions inventory for road transport

6.1.1. Introduction

This section considers the implications of the emission factors for NO_x implied by the remote sensing data to trends in UK emissions from the road transport sector as modelled by the NAEI. A comparison was also made with alternative compilations of emission factors from European programmes published since the current set of DfT/TRL emission factors used in the NAEI were published in 2009 (hereafter referred to in this chapter as the UK emission factors, UKEF). The focus was on the emission factors for COPERT 4 as these are in a format quite similar to the UKEF and are designed to be used with similar activity data sets for national emission inventories, but cross-reference was also made to the factors HBEFA (2010).

It should be stressed that the inventories developed and used in this section are illustrative and do not represent complete, finalised inventories of the sort routinely published for the UK (NAEI) or London (LAEI). This is because while we have attempted to develop robust emission estimates, these are incomplete and further work would be required to produce final, consistent emission estimates.

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[12] Personal communication with Finn Coyle, TfL.

[13] Personal Communication. Simon Davies, Cleaner Fuels and Vehicles, Department for Transport, 28th May 2010.

It is important to appreciate that the speed-related factors in UKEF and COPERT 4 are designed to be used in conjunction with emission degradation functions and potentially other important parameters such as catalyst failure rates so differences in the basic emission factors for different Euro classes calculated at a particular speed need to be viewed in the context of differences in degradation patterns associated with each set of basic factors. This is all the more important when trying to interpret the factors developed from Remote Sensing Data (RSD) which offer a 'snapshot' of the emission performance of the vehicle fleet at a particular moment in time. Therefore consideration needs to be given to what the RSD might be telling us about emission degradation and catalyst failure assumptions as well as about the basic speed-related emission factors themselves. The aspect of emission degradation is key to determining potential trends in vehicle emission factor for a given Euro class over time and hence trends in the emissions inventory over time could be as sensitive to degradation rates as it is to how the basic emission factors change between successive Euro classes.

Based on the factors given in COPERT 4 and those implied by RSD a number of alternative NO_x emission factor and degradation scenarios have been modelled by the NAEI's road transport emissions model maintaining all other assumptions, for example vehicle kilometres and fleet composition, the same. The trends in total UK NO_x emissions from road transport were modelled for each scenario and compared with those derived in the current NAEI using the UKEF.

The section concludes with a brief discussion on the assumptions used in the NAEI that define the fleet composition at national level and how temporal and spatial variability in some of these assumptions derived from national statistics could have a bearing on the validity of the UK's national inventory trend in emissions to interpreting trends at specific locations.

6.1.2. Comparison of UK emission factors with factors in COPERT 4

The UKEF are from the set of speed-related emission factor equations developed by TRL on behalf of DfT published in 2009. These cover a detailed range of vehicle and engine sizes and Euro standards from pre-Euro 1/I to Euro 6/VI. The factors are available at http://www.dft.gov.uk/pgr/roads/environment/emissions/report-3.pdf. Emission factors calculated from the speed-equations are normalised to an accumulated vehicle mileage of 50,000 km and linear degradation rates are provided for each Euro class of light duty vehicle. For NO_x, some Euro standards have positive degradation rates (i.e. emissions deteriorate with mileage) and others have negative degradation rates (i.e emissions improve with mileage). Additional correction factors account for changes in fuel composition. The application of the emission factors to the NAEI are described in the methodology annex to the UK Greenhouse Gas Inventory report at http://www.airquality.co.uk/reports/cat07/1010151420_ukghgi-90-08_Annexes_Issue3_r.pdf. The annex describes the activity data used with the emission factors, namely the vehicle kilometre and fleet composition data, and other assumptions for estimating UK emissions.

COPERT 4 is a computer programme and compilation of emission factors developed for estimating emissions from road transport (http://lat.eng.auth.gr/copert/). Its development has been financed by the European Environment Agency for use by National Experts to estimate emissions from road transport to be included in official annual national inventories. The COPERT 4 methodology is also part of the EMEP/CORINAIR Emission Inventory Guidebook. The Guidebook, developed by the UNECE Task Force on Emissions Inventories and Projections, is intended to support reporting under the UNECE Convention on Long-Range Transboundary Air Pollution and the EU directive on national emission ceilings. The COPERT 4 methodology and emission factors are documented in the 2009 Guidebook (http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-transport.pdf)

The COPERT 4 factors are similar to the UKEF in terms of format in the sense that they also

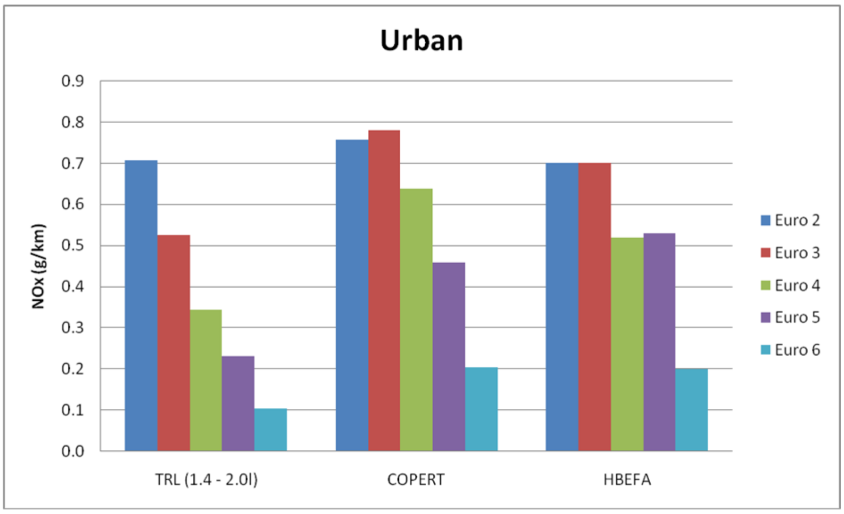

Figure 6.1: Comparison of NO_x emission factors for diesel cars from UKEF, COPERT 4 and HBEFA at urban speeds.

use a series of average speed-related polynomial equations for different vehicle sizes and Euro classes to calculate emission factor in g km^{-1} combined with degradation rates and fuel quality correction factors. The vehicle classifications by engine size or vehicle weight are slightly less detailed than used in the UKEF.

The COPERT 4 equations and UKEF speed equations were used to calculate NOx emission factors for each vehicle type at a common speed for comparison. For some vehicle classes, for example diesel cars and LGVs, the UKEF are available for different engine size or vehicle weight ranges whereas COPERT 4 provides a single factor. In this situation, the UKEF factors for different vehicle sizes were weighted according to the proportions of each size range in the fleet for comparison with the COPERT factor or the most representative size class was chosen. Where relevant, the factors from both sources were normalised to a common accumulated mileage to take account of emission degradation.

For light duty vehicles, the UKEF and COPERT 4 factors differed. For petrol cars, the differences were relatively small, but for diesel cars and LGVs, the differences were marked. Figure 6.1 compares NO_x factors from the UKEF and COPERT equations for diesel cars at urban speeds. Also shown are factors from HBEFA. It can be seen that while the factors are similar for Euro 2 cars, they deviate for higher Euro standards, with both COPERT 4 and HBEFA giving significantly higher factors for vehicles from Euro 3 onwards compared with UKEF.

A similar trend is apparent for diesel LGVs with COPERT and HBEFA producing higher factors than UKEF for Euro 3 onwards. For HDVs, all sources give very similar emission factors. This is because all come from a common source, namely the ARTEMIS programme.

A further difference between UKEF and COPERT 4 is apparent when considering the effects of emission degradation on diesel cars. UKEF assume a negative emission degradation for Euro 3 diesel cars and LGVs whereas COPERT 4 does not assume any degradation. This compounds the differences between UKEF and COPERT 4 because it means that not only are the basic factors in UKEF lower than COPERT 4, but they diverge further going forward in time as the UKEF factors decrease with increasing mileage. This is demonstrated in Figure 6.2.

6.1.3. Comparison of UK emission factors with factors implied by remote sensing data

The UKEF speed equations were used to derive NO_x emission factors for each vehicle class that could be directly compared with those implied by the remote sensing data on a common basis.

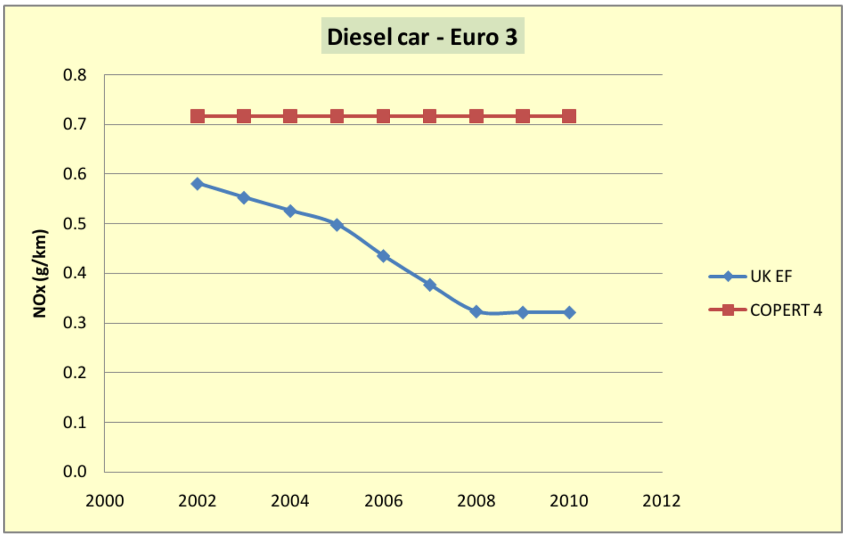

Figure 6.2: Change in emission factor with year due to emission degradation with accumulated mileage for a Euro 3 diesel car implied by UKEF and COPERT 4.

As explained earlier, the RSD provide ratios of NO/CO$_2$ for each vehicle exhaust plume sampled. This was converted into ratios of NO$_x$/CO$_2$ for each vehicle type by taking into account the relative additional amount of NO$_x$ emitted as NO$_2$. The average speed of the vehicles sampled in the RSD is 31 km h^{-1} so this speed was used to calculate the corresponding factors for NO$_x$ and CO$_2$ given by the UKEF speed equations. The ratio NO$_x$/CO$_2$ implied by the UKEF at 31 km h^{-1} was compared with the ratio NO$_x$/cotwo implied by the RSD. Assuming the UKEF factors for CO$_2$ are representative of the vehicles sampled by the RSD then the difference in the two ratios (NO$_x$/CO$_2$) UKEF and (NO$_x$/CO$_2$) RSD represents the difference in the NOx emission factors sampled by the RSD relative to the UKEF. The RSD ratio was invariably higher than the UKEF ratio implying the NO$_x$ factors sampled by the RSD were higher than those implied by the UKEF of a given vehicle type. The relative difference between the two ratios was used to re-scale the UKEF speed-equations for NO$_x$ making the implicit assumption that the shape of the NO$_x$ curve is the same for vehicles of the same type. The new set of RSD-based speed-emission curves were then fed into the inventory.

The following charts show a comparison of emission factors at the RSD speed of 31 km h^{-1} from the RSD results, from COPERT 4 and from the UKEF. Factors are compared for each Euro class 1(I) to 4(IV). The figures effectively repeat the observations on the RSD discussed in a previous section, but allow a clear comparison with COPERT as well as UKEF.

Figure 6.3 shows the comparison for petrol cars. It is very evident here how the factors for Euro 1 and 2 cars implied by the RSD are several times higher than those from UKEF and COPERT 4. There is some convergence between factors for the higher Euros. This implies that according to the RSD, the early Euro standards were not delivering the reductions in NO$_x$ emissions first believed. The question here is whether these vehicles were always emitting higher than expected under real world conditions (i.e. the technology had never been performing well) or whether it reflects a deterioration in emissions over the period of time from when they were first measured on dynamometers tests to the recent past of the RSD measurements.

Figure 6.4 shows the corresponding factors for diesel cars indicating that not only are the factors higher than those based on UKEF and COPERT, but that the trend is fairly flat across the Euro standards. The Euro standards appear to have done little in achieving NO$_x$ reductions in the real world according to the RSD.

A similar situation seems to be evident for diesel LGVs (Figure 6.5) with good agreement for the early Euro standards, but poor agreement (higher emissions) for the recent Euro 3 and 4

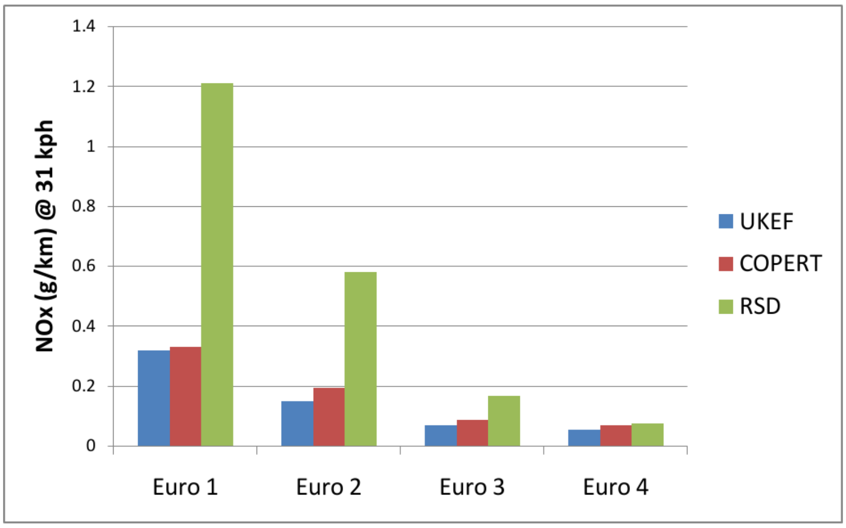

Figure 6.3: Emission factors for petrol cars.

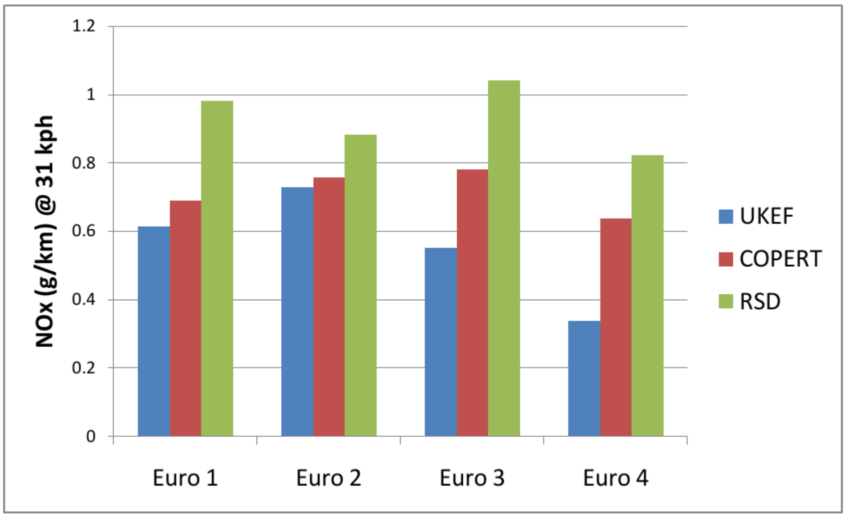

Figure 6.4: Emission factors for diesel cars.

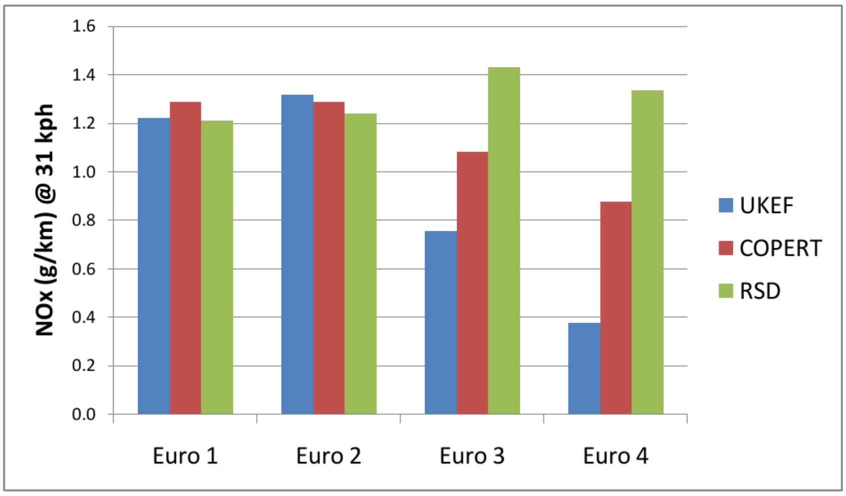

Figure 6.5: Emission factors for diesel LGVs.

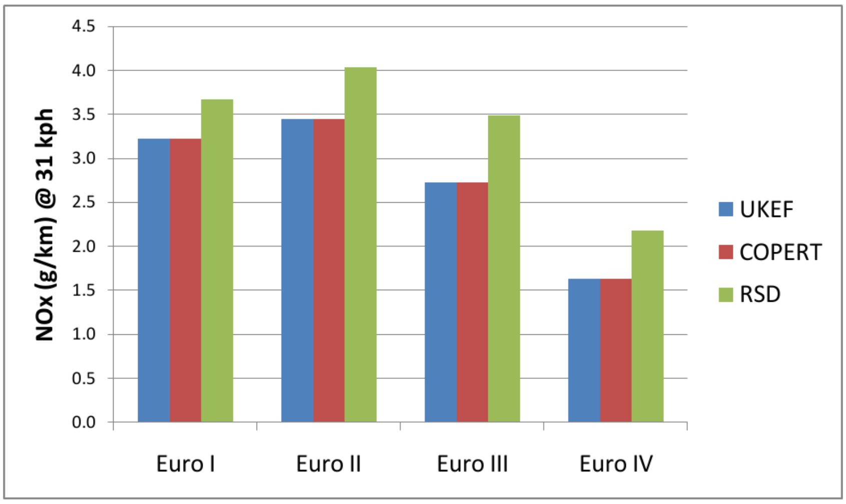

Figure 6.6: Emission factors for diesel rigid HGVs <7.5t.

vehicles.

Figure 6.6 shows the trend in NO$_x$ emissions for small rigid HGVs. Although the RSD factors appear to be somewhat larger than COPERT and UKEF factors, they do follow a similar pattern across the Euro range.

6.1.4. Trend comparison of UK emission factors with factors implied by remote sensing data

The NAEI road transport emissions model was used to model the trends in UK emissions of NO$_x$ for a number of different emission factor scenarios based on the evidence from the above two sections. As well as using different speed-emission factor relationships consistent with COPERT 4 and the remote sensing data, different assumptions were also made about emission degradation and catalyst failure as seemed appropriate.

The base case uses the current UKEF and assumptions about catalyst failure and emission degradation as used in the NAEI.

Scenario 1 uses the UKEF, but excludes any emission degradation functions for petrol and diesel cars and LGVs. Emission factors are normalised to 50,000 km

Scenario 2 uses the COPERT 4 factors for all vehicle types and assumptions about emission degradation. These imply no degradation at all for diesel cars in contrast to the base where different (positive and negative) rates of emission degradation are assumed for each Euro standard.

Scenario 4 uses speed-related factors re-scaled for consistency with the RSD. No catalyst failure or emission degradation is assumed, in other words the higher factors associated with the RSD have been assumed to always have applied throughout the history of the vehicles.

Scenario 5 uses speed-related factors based on RSD for all vehicle types EXCEPT Euro 1 and 2 petrol cars. For these petrol cars, the lower emission factors taken from COPERT 4 are assumed to represent emissions when the vehicles are new (i.e. low emission factors in the early to mid-1990s) which gradually degrade to the high levels implied by the RSD in 2009.

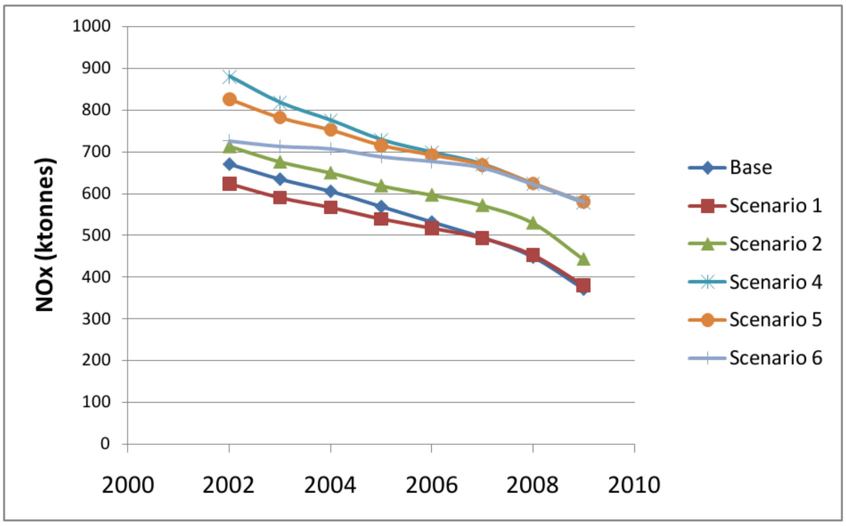

Figure 6.7: UK NO_x emissions for road transport as modelled for the different emission factor scenarios.

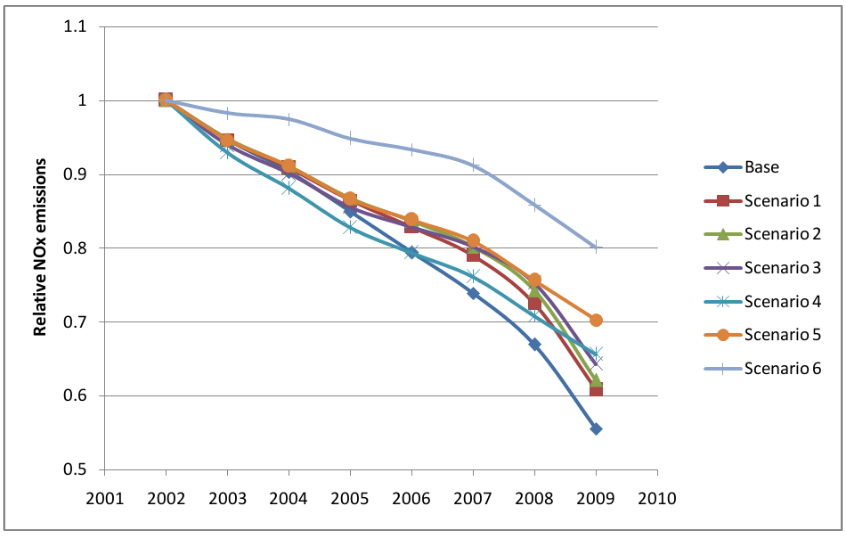

Figure 6.8: UK NO_x emissions for road transport as modelled for the different emission factor scenarios relative to emissions in 2002.

Scenario 6 is similar to Scenario 5 except that the lower COPERT factors for Euro 1 and 2 petrol cars are assumed to hold until 2002 after which a very rapid rate of degradation is assumed to bring the factors up to the higher levels implied by the RSD in 2009.

The results are shown in two forms in Figure 6.7 and Figure 6.8. Figure 6.7 is the total UK emissions from road transport for each scenario in ktonnes/year over the period 2002-2009. Figure 6.8 shows the trend in emissions relative to 2002 levels for each scenario (i.e. emissions in 2002 = 1). With the exception of the slower rate of change in emissions evident in Scenario 6, the trends for all scenarios are roughly in parallel to each other, but it is evident that in absolute terms emissions vary considerably. Thus in 2009, emissions are lowest for the base (372kt), but are some 210kt higher for Scenarios 4, 5 and 6 ($\approx$580 kt). This result is significant in the context of the UK's ability to meet the national emissions ceiling. Figure 6.8 shows that each scenario does slow down the rate of decrease in emissions since 2002 when compared with the base, but with the possible exception of the rather extreme Scenario 6, the trends are still not as flat as the roadside measurements of NO_x suggest.

6.2. LAEI

6.2.1. Introduction

This section considers the trends in emissions from road traffic at 23 site locations in London between 2003 and 2008. Whilst it is based upon the methods used in compiling the London Atmospheric Emissions Inventory (LAEI), additional complexity has been considered. Briefly, the emission calculations were hourly (rather than annual) and were based upon hourly traffic and vehicle speed data. The emissions model also used Automatic Number Plate Recognition (ANPR) data as well as vehicle stock which varied month by month.[14] This meant that the hourly emissions accounted for the large variation which exists by time of the day and day of the week, seasonal variation, in particular during Christmas, as well as the continually changing vehicle fleet throughout the study period.

The reason for developing an advanced method for emissions calculations was to ensure that the results were related as closely as possible to the roadside measurements at the 23 sites considered in the London trend analysis summarised in section 2.

The emissions calculations are a significant step forward in our ability to analyse the performance of emissions inventories with measurements. However, prior to beginning the analysis, the methods were updated to include the most recent DfT vehicle emissions factors (DfT, 2009) as well as adding hourly predictions for the year 2008. As the work programme developed other assumptions were used in the emissions model, including the HBEFA as well as a large data set of roadside (RSD) measurements. Finally, several sensitivity tests were undertaken using alternative assumptions in the emissions model. The most important of these was the calculation of a new catalyst degradation rate for petrol vehicles, based upon results from the RSD data. The change in degradation assumptions proved to be highly influential in the emissions trends.

The following section steps through a number of alternative emissions scenarios beginning with the use of current UK emissions factors and working towards our current best estimate of the NO_x emissions trends, which used a combination of HBEFA factors, RSD factors and a revised petrol vehicle degradation rates.

6.2.2. Emissions predictions at roadside sites in London

The trend analysis used 23 roadside sites in London shown in Figure 6.9. Measurements from these sites typically began in the 1990s, however the comparison between measurements and hourly emissions results was limited to the period 2003 to 2008. The reason for the shortened study period was because of limited access to Automatic Traffic Count (ATC) data prior to 2003. The sites are geographically spread and are associated with some of the largest roads in London, including the North Circular road, Cromwell Road and Marylebone Road.

The hourly emissions were calculated for 11 vehicle types including cars, motorcycles, taxis, bus and coaches, LGVs, 3 sizes of Rigid HGV and 3 sizes of articulated HGV. In addition, petrol and diesel emissions were calculated separately for the car and LGV categories.

A typical hourly emissions trend is given in Figure 6.10 and is based upon the current set of UK emission factors, combined to give a total for all vehicles. The results show a strong downward trend over the period as well as a distinct hour of day and weekday profiles and seasonal effect, such as the summer holiday period and at Christmas-New Year.

6.2.3. Emissions trend results using the current UK emission factors

The hourly emission results, created using the UK factors were averaged for each year and normalised so that the first year begins with a value of one (Figure 6.11 and Table 6.1). This

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[14] The ANPR data was used to estimate stock changes by day weekend/weekday and not to estimate vehicle specific stock profiles from 2003–2008 for which these data are unavailable.

Figure 6.9: The location of roads used to compare with the 23 London roadside measurement sites.

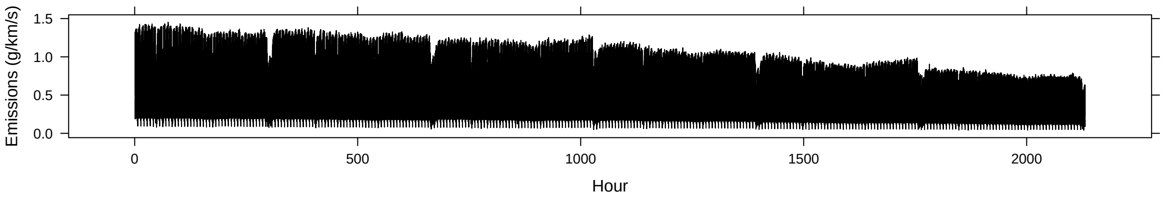

Figure 6.10: Typical time series plot of total hourly NO_x emissions.

allows a quick and easy comparison between the years. Using the UK factors, results in a ≈5%/annum reduction in total vehicle emissions between 2003 and 2008 for both outer and central London sites.

As a consequence an alternative to using UK emissions factors has been investigated in order to develop a more realistic set of assumptions and a more comparable NO_x emission trend. The first step in this process was to investigate the impact of using the HBEFA as a replacement of the UK emissions factors.

Table 6.1: Normalised annual emissions results between 2003 and 2008, using different emissions factors/assumptions. Note *new det.* — Use of the revised deterioration factors for petrol vehicles for emissions trends; *no mileage* — Use of no deterioration factors for emissions trends and, *SCR* — assumes all HGVs are equipped with SCR. The 'mean' value shown is the mean percentage change in emission from 2003–2008 according to Equation 1.

	HBEFA		RSD		UK factors			HBEFA	
	base	new det.	base	new det.	base	new det.	no mileage	SCR	SCR no det.
Outer									
2003	1	1	1	1.00	1	1.00	1.00	1	1.00
2004	0.97	0.98	0.96	0.99	0.96	0.98	0.97	0.97	0.98
2005	0.92	0.94	0.9	0.95	0.91	0.93	0.92	0.92	0.94
2006	0.88	0.90	0.85	0.91	0.84	0.87	0.87	0.88	0.90
2007	0.83	0.85	0.8	0.86	0.77	0.81	0.81	0.84	0.86
2008	0.77	0.8	0.75	0.80	0.70	0.74	0.75	0.80	0.82
mean	−3.8	−3.3	−4.2	−3.3	−5.0	−4.3	−4.2	−3.3	−3.0
Central									
2003	1	1	1	1.00	1	1.00	1.00	1	1.00
2004	0.95	0.96	0.94	0.97	0.95	0.96	0.95	0.95	0.96
2005	0.92	0.94	0.9	0.95	0.92	0.94	0.94	0.92	0.94
2006	0.88	0.89	0.85	0.91	0.85	0.88	0.88	0.88	0.90
2007	0.83	0.85	0.8	0.86	0.77	0.80	0.82	0.84	0.86
2008	0.79	0.81	0.77	0.82	0.71	0.75	0.77	0.82	0.84
mean	−3.5	−3.2	−3.8	−3.0	−4.8	−4.2	−3.8	−3.0	−2.6

6.2.4. Incorporating HBEFA emission factors

As an alternative approach to calculating the NO_x emissions trends, several model runs were undertaken after replacing the UK emissions factors with the equivalent HBEFA emissions factors. The choice of HBEFA as a source of vehicle emissions information resulted from a comparison between the HBEFA and UK factors for diesel and petrol cars, diesel LGVs, Buses and HGVs between pre Euro and Euro 6/VI vehicles. The comparisons showed that the HBEFA factors had less pronounced downward trends in NO_x moving from pre Euro to Euro 6 and this was especially so for some light duty vehicles. It was important therefore to establish the influence that these new factors could have on the NO_x trends overall.

In undertaking these comparisons, the use of SCR devices on UK HGVs, another potentially important issue was also highlighted. The UK emissions factors have a single emission rate for each of six HGV types and for each Euro class. However, the HBEFA has three emissions rates for each vehicle and Euro class combination; an EGR equipped HGV and two SCR equipped HGVs (SCR and SCR*). The comparison provided in Figure 6.11 and Table 6.1 shows that adopting SCR HGVs in the fleet rather than EGR HGVs they follow a very different emissions trend. The reason for the difference is that some doubt exists as to the efficiency of NO_x removal using SCRs during low load/temperature/speed operation and that these conditions typically occur in urban areas. This is also of importance in calculating emissions trends and was included as a sensitivity test of the emissions model. The SCR issue is discussed more in subsection 5.3.

To incorporate the HBEFA emission factors into the emission inventory calculations a link was made between the vehicle types in the UK and HBEFA data sets. Both sets of emissions factors included useful descriptors with which to undertake this link, although for the most part it was undertaken by hand. The list of HBEFA vehicles is longer than the UK vehicles (584 vs. 386), and so not all could be linked. An example of the vehicles without a link to the UK factors included the SCR equipped HGVs, however, for the most part the unlinked vehicles in

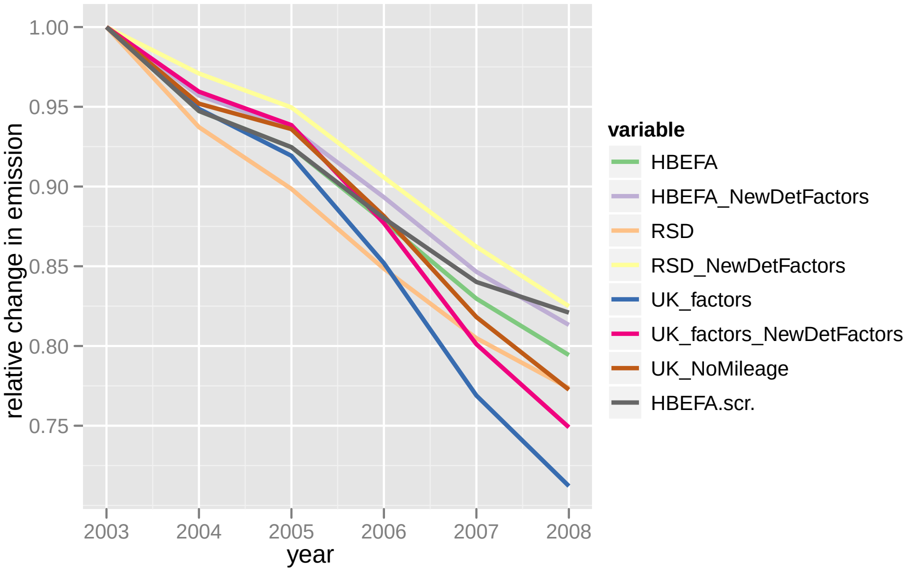

Figure 6.11: Different normalised emission trends in central London according to different input assumptions.

the HBEFA factor list were very old pre Euro vehicles from as far back as the 1950s, alternatively fuelled vehicles and vehicles with diesel particle filters. None of these vehicles were considered to have a significant influence on NO$_x$ emissions between 2003 and 2008.

The HBEFA emission factors differ from those in the UK in one other important respects and this relates to the use of vehicle speed. In the UK, emissions factors are expressed as speed vs. emissions curves. The speed relates to the average speed of the vehicle during its associated real-world test cycle. In contrast, the HBEFA factors use the term 'traffic situation' as a proxy for speed. The user is required to assess the traffic conditions and to pick a 'traffic situation' which is then associated with an emission rate. Whilst it is possible to comprehensively link traffic speed in London with an equivalent 'traffic situation', this would be a large undertaking. So as a first assessment of the impact of using HBEFA factors, a single representative traffic situation was chosen; 'URB/Trunk-City/50/Satur'. This represents an urban A road traffic situation, with a 50 km h^{-1} speed limit, operating under saturated conditions. Clearly this does not represent all road types in London or driving conditions across all hours of the day. However the average speed of ≈36 km h^{-1} is close to the London average of 35 km h^{-1}. Using this 'traffic situation', a NO$_x$ emissions trends was created between 2003 and 2008 and the results summarised Figure 6.11.

By replacing the UK emission factors with HBEFA factors results in closer agreement between the NO$_x$ emissions trends and measurements between 2003 and 2008. The HBEFA trends show a reduction of ≈3.3%/annum over the period compared with ≈5.0%/annum using the UK factors. Central and outer sites show similar trends and differ in 2008 by ≈3.6%/annum. However, this still falls short of the trend in measurements of between ≈1-2%/annum — although it is recognised that a direct comparison between emissions and ambient trends is not consistent.

6.2.5. Incorporating the RSD emissions factors

Whilst important improvements in the emissions trends resulted from using the HBEFA emission factors, there was still a shortfall when compared with the equivalent measurements. To establish whether this gap in the emissions trends could be closed further, another group of emissions factors were applied to the emissions model. These were based upon the roadside measurements described in detail in section 4. In brief, the RSD data provided an estimated NO_x:CO_2 ratio. The NO_x:CO_2 ratios were then applied to CO_2 emissions rates, created using the UK emission factors, to give the equivalent NO_x emissions factors for all vehicle types except for petrol LGVs and articulated HGVs. In London the missing vehicle types represent a relatively small influence on total emissions and for these vehicles the UK factors were retained. Using the RSD factors resulted in emissions trends that reduced by $\approx$3.8%/annum, with central and outer sites differing by only by a small amount in 2008. Note again, however, that this scenario is illustrative because a revised and complete inventory based on the RSD or other data sources is not yet available.

Using either of the alternative methods, HBEFA or RSD, results in an emissions trends that are in closer agreement to the measurements at roadside sites in London. Also, the results of emissions trends using RSD and HBEFA factors agree to within a few percent of each other.

However, in both alternative cases there remains the need to further reduce the emissions trends before it can be concluded that a realistic emissions model has been established. Therefore the next area of analysis was on the role that petrol vehicles have on emissions trends.

6.2.6. Calculating a new degradation factor (NDF) for petrol vehicles

The alternative approaches to using UK emissions factors have resulted in smaller reductions in NO_x emissions trends between 2003 and 2008. From NAEI and LAEI emissions estimates it is clear that the most important influence in the downward trend in emissions in the last 15–20 years has been associated with the petrol cars and is the result of introducing the 3-way catalyst. Given the influence of these vehicles, a further investigation was undertaken using RSD data to establish the NO_x performance of petrol cars with increasing age.

The current UK emission factors account for increasing age of vehicles within the fleet using a combination of degradation in emissions performance with time and catalyst failure rate. Both of these factors have changed as a consequence of updates to the UK factors in 2009. In particular catalysts failure rates have increased from their historic value of $<$3% up to 15% and this has proved to be important in increasing the tonnage of NO_x emitted in London for the recent LAEI 2008, although it was less influential in the NO_x trends.

The influence of vehicle age (as a proxy for mileage) on NO_x emissions has also changed as part of the update. To establish what the RSD data indicated about petrol car NO_x emissions as a function of age, a sample of the emission rates from Euro 2 and Euro 3 petrol vehicles was taken during the year that they were first introduced into the fleet. This was compared with the emissions rate of the oldest vehicles, some of which were 12 years old. Both of the vehicles types showed an increase in NO_x emissions over time.

Comparing this with the equivalent assumptions in the emissions model was considered to be an essential diagnostic test. However, it is not straightforward to directly obtain the emissions degradation rate of a single vehicle as it ages in the fleet. To do this we used a combination of vehicle stock and the fleet emissions rate to track each vehicle from its introduction until it was 12 years old. The years of introduction into the fleet were assumed to be 1997 (Euro 2) and 2001 (Euro 3).

In essence, a new vehicle when first introduced was assumed to emit levels of NO_x according to the inventory assumptions for a new vehicle; but was assumed to degrade according to the RSD data linearly between the year of its first introduction to 2009 (the year representing most of the RSD data). Note that the RSD data encapsulates both catalyst degradation and failure as no distinction is made between the two.

Using the Euro 2 vehicle as an example, the yearly degradation rate was calculated as follows. First, the emission rate from a new vehicle was estimated; in this case the value in 1997. Then taking the fleet emission rate for the next year (1998), this was expressed in the equation below as a combination of new and 1 year old vehicles, weighted by their stock proportions. The

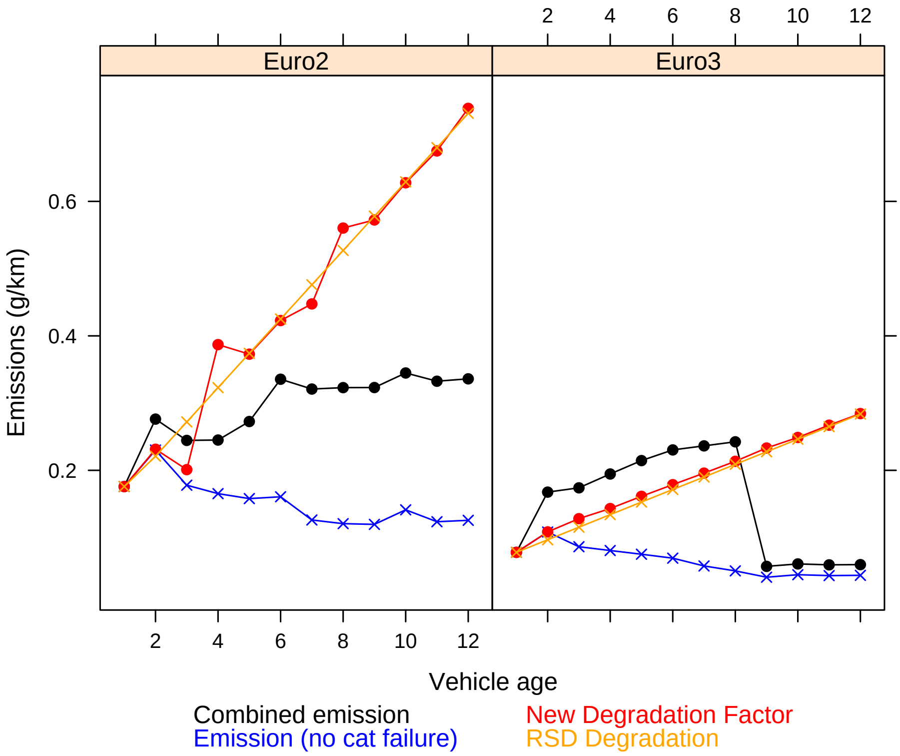

Figure 6.12: The degradation of emissions of a typical Euro 2 and Euro 3 petrol vehicle according to different assumptions.

equation for 1998 only includes the first two terms; new and one year old vehicles and the only unknown is NO$_x$ 1, the emission rate of a 1 year old vehicle. This process is continued for the next year to establish the emission rate of a 2 year old vehicle and so on to 12 years.

$$NO_{x[fleet]} = NO_{x[year\ 1]}.stock_{[year\ 1]} + \ldots + NO_{x[year\ 12]}.stock_{[year\ 12]} \qquad (3)$$

$NO_{x[fleet]}$ = emissions rate for the combined Euro 2 fleet in any year $NO_{x[year\ n]}$ = emissions rate for a new vehicle (year n) and $stock_{[year\ n]}$ = stock proportions for each year.

The resulting emissions rate over time is given as the blue line in Figure for both Euro 2 and Euro 3 vehicles. Overall the blue line shows a reduction of 30% for Euro 2 and $>$ 40% for Euro 3 petrol vehicle emissions from new to 12 years old.

Catalyst failure rates also need to be included in the calculations for base case LAEI emissions. The effect of catalyst failure was included by using the UK estimates for failure rate within each Euro class and by assuming that these vehicles have the same emission rate as a pre Euro vehicle. Combining the two values gives the emissions trend as each vehicle ages and results in an increase in NO$_x$ emissions of 91% for a Euro 2 car between new and 12 years old and a factor of 3.1 increase in NO$_x$ emissions for a Euro 3 car between new and 8 years old. Note however that assumptions for catalyst failure rates introduced in 2009 reduce the emissions from Euro 3 vehicles considerably and by 12 years old the NO$_x$ emissions for a Euro 3 car are 25% less than when new.

The evidence provided by the RSD measurements provides some agreement with the model estimates and some conflicting evidence. Taking Euro 2 vehicles first, the increase in emissions between new and 12 year old vehicles from RSD is a factor of ≈4.1 and for Euro 3 vehicles is a factor of ≈3.6. The latter degradation rate is in reasonable agreement with the Euro 3 modelled effects until the rapid reduction in catalyst failure rates assumed in 2009, where the estimates diverge considerably. For the Euro 2 case the RSD degradation rate is considerably higher than that assumed in the model.

Prior to rerunning the emissions a new degradation rate was calculated for each vehicle type and replaced the combined effect of vehicle age and catalyst failure rate. Note also that the Euro 2 rate was applied to Euro 1 vehicles and the Euro 3 rate applied to Euro 4 vehicles.

For each of the emission factor sets, UK, HBEFA and RSD an equivalent emissions model run was undertaken using the New Degradation Factor (NDF). In all cases the use of the NDF reduced the trend in emissions by between 3 and 5%. Of each method used the RSD approach yields the smallest reduction ($\approx -19\%$) in emissions between 2003 and 2008 and the UK factors, the greatest ($\approx -25\%$). However, the HBEFA and RSD results are very similar. Finally, outer and central London reductions agreed to within about 2%.

6.2.7. Vehicle emission trends — summary of other sensitivity tests

As a final analysis of possible alternative assumptions two additional emissions runs were undertaken. They address the problem identified for the UK emissions factors, i.e. that Euro 1 and 2 vehicle emissions improve with age, whilst Euro 3 and 4 vehicles, deteriorate with age. Such conflicting evidence may be difficult to reconcile and to establish a scaling factor with any certainty, impossible. To test the effect of removing the age related scaling factor a run was undertaken where the emissions performance of petrol vehicles would depend solely on catalyst failure rates. This emissions run was given the name 'UK_NoMileage'.

The second run addressed the importance of SCR use in the urban HGV fleet and its implications for NO_x emissions trends. Accepting the fact that the proportion and use of SCR within the HGV fleet is highly uncertain the scenario assumed was that all HGVs beyond Euro 3 were fitted with SCR devices. This represents the maximum influence of this technology using current emission factors and has been named 'HBEFA_SCR'. Finally, the effects of 'HBEFA_SCR' and 'HBEFA_NDF' were combined. All influence the NO_x emission trends and reduce it further. The change in emissions trend using no mileage effects was similar to using the combined new deterioration factor, and gave NO_x reductions for outer and central London of 23% and 25%, respectively. Finally, by assuming widespread use of HGV SCRs in urban areas and combining this with the NDF assumptions pushed the central emissions estimates towards a 15% reduction or half that predicted using the current UK emission factors alone. The HBEFA+SCR+NDF scenario is much closer to the actual measured trend, although it is accepted that to get to this point required some unrealistic assumptions regarding SCR to be adopted.

6.2.8. Vehicle emission trends — discussion

The NO_x emissions trends in this section represent a step by step investigation of UK emissions inventory performance. The diagnostic value in this case was the NO_x trend between 2003 and 2008 compared with an equivalent trends in NO_x ambient measurements. This was undertaken using detailed hourly emissions estimates and was made at 23 roadside air pollution monitoring stations throughout London.

Alternative emission factors such as those from the HBEFA were also adopted, and as a consequence of assuming smaller NO_x reductions especially in light diesel vehicles, smaller and more realistic emissions trends were evident ($\approx$25%), especially in central London. New on-road measurement data (RSD) also provided emission factors for use with the emissions model and also produced emissions trends that represented an improvement over current UK factors. However, the RSD data also allowed further insight into the emissions inventory calculations and resulted in an important improvement of the assumptions surrounding petrol car deterioration with age. Specifically, the RSD data suggested that the emissions inventories were overly optimistic about the ageing effects of the petrol car fleet, especially Euro 1/2 vehicles, and that their emissions performance deteriorated to a much greater extent than had been assumed so far in the emissions calculations. Adoption of the new deterioration factors resulted in NO_x trends that were closer to those of measurements.

However, a final question was still to be addressed and this was associated with the assumptions about SCR use in the HGV fleet. As knowledge of SCR use is highly uncertain a sensitivity test was chosen, assuming that all of the HGVs operated with an SCR device and that this represented a maximum possible effect. The SCR assumption, combined with the use of the NDF and the HBEFA emission factors resulted in NO_x emission reductions of $\approx$15% between 2003 and 2008, still short of the measurement trend but half that calculated using the UK factors.

6.3. Vehicle stock assumed in emissions inventories

Much of the work in the preceding sections has considered in detail, the emission factors by vehicle type and attempted to re-estimate UK emission factors based on the RSD. While these calculations have been very illuminating e.g. suggesting where the major discrepancies lie, it has also become clear that the current work raises more fundamental questions concerning how emission inventories are compiled.

A key issue that has emerged that is likely to be important are the assumptions related to vehicle stock in the inventories. Vehicle stock assumptions in the NAEI and largely the LAEI are based on national statistics. DfT's National Travel Survey data are used to estimate the mean mileage of a vehicle dependent on its age. This is not updated annually and a general 'mileage by age' profile is applied to all years. Combining population with age and mileage with age as done in the NAEI model effectively defines the probability of 'seeing' a vehicle being used on the road.

A side effect of the RSD data is that because number plate data are collected for using ANPR, it effective captures a distance-weighted vehicle stock profile. As mentioned previously, this information is biased towards urban-type driving. The number plate data is matched by CarweB to details concerning the vehicles. CarweB query manufacturer databases to derive Euro classification and many other variables. It is possible therefore to compare the distance-weighted Euro class split used in the inventories with those observed during the RSD surveys.

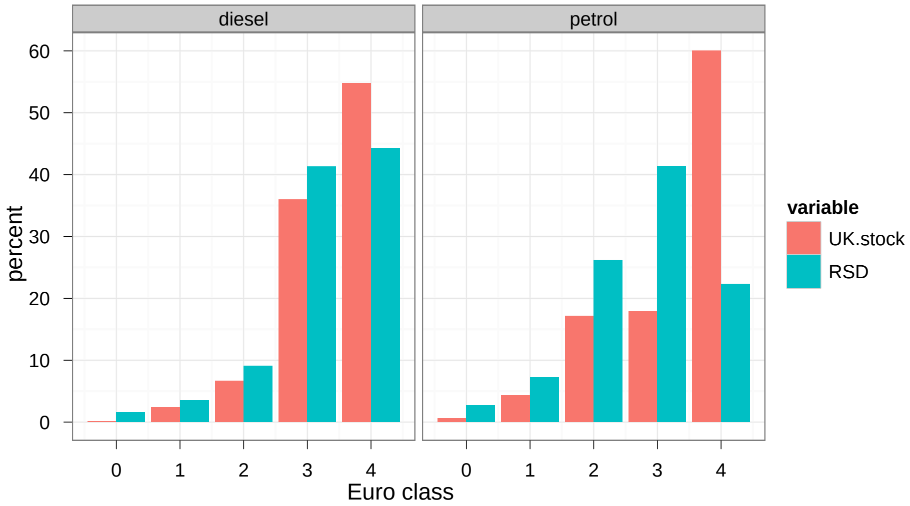

Figure 6.13: Comparison between national estimates of vehicle stock for cars in 2009 with that derived from the RSD data.

Figure 6.13 shows the comparison for cars and highlights some potentially important issues. First, there is reasonable agreement between national statistics and the RSD data for diesel

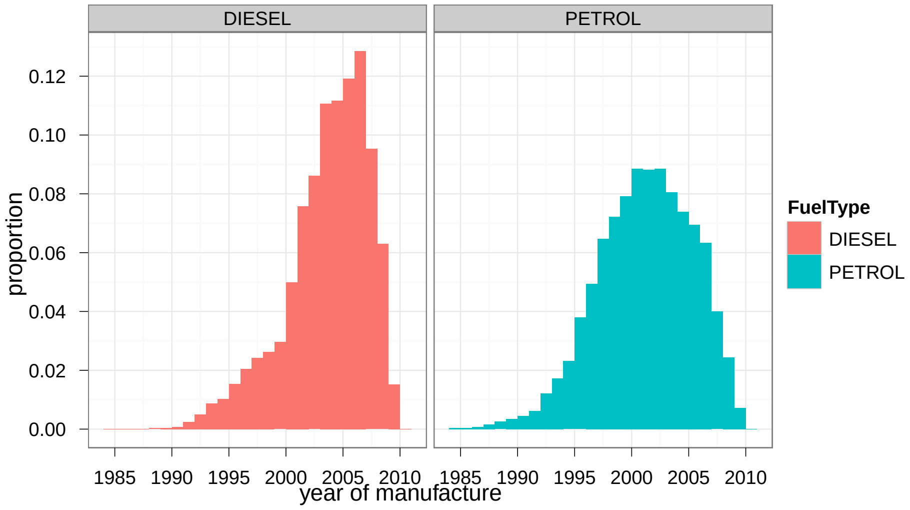

Figure 6.14: Passenger car vehicle age profiles according to the RSD data.

cars. However, there is a considerable disagreement between the two data sets for petrol cars: the RSD data suggests there are far fewer newer vehicles on the road (e.g. compare the Euro 4 data) than is assumed in the inventories. Furthermore, if one considers the age profile of vehicles shown in Figure 6.14, then it is clear that there are significant differences between diesel and petrol cars. Figure 6.14 shows that the most common age for a diesel car on the road in 2009 was 2 years i.e. the vehicle was manufactured in 2007. By contrast, petrol vehicles are much older and vehicles from around 2000–2002 are most common.

These differences could have important effects on estimated inventory trends, irrespective of the actual emission factors. In essence, there are a large number of modern diesel in the vehicle fleet, which are relatively high emitters of NO_x *and* NO_2; and there is a relatively large number of older petrol cars which have also shown to be important emitters of NO_x. Because the inventories assume that over the past few years, most older petrol cars have been removed from the fleet, this would drive the trend in NO_x emissions downward more than should perhaps be the case. In other words, estimated downward trends in vehicle NO_x emissions would be greater than they should be.

Clearly, this is an issue that needs to be considered in more detail and calculations made to estimate the effect on trends. It is however difficult to re-calculate vehicle stock profiles based on observed data due to the absence of ANPR data in previous years. Also, care would be needed to understand how vehicle stock varies by location, road type and so on. Nevertheless, given that recent downward trends in vehicular NO_x in the UK inventories is driven by petrol vehicles, it is likely these effects could have an important effect on NO_x trends in recent years.

7. Effect of new emissions assumptions on ambient concentrations

7.1. Introduction

Defra's Pollution Climate Mapping (PCM) models have been used to estimate the impact that the use of the illustrative road traffic emission inventory calculations would have on modelled ambient concentrations. The models provide estimated background concentrations of NO_x (as NO_2) and NO_2 on a 1km x 1km grid for the UK. Estimated roadside concentrations are modelled on a road link specific basis for 9553 major urban road links in the UK. The NO_x and NO_2

modelling methodology used is explained in detail by Grice et al. (2010).[15] Emission projections were based upon the UK national inventory (NAEI07), detailed in Murrells et al (2009).[16] Three scenarios were modelled and are summarised below.

Scenario 1

- Baseline model run. Using existing model results produced for Defra and reported to the Commission for 2008.
- Projections to 2010, 2015 and 2020 were already available for this scenario
- Uses baseline road traffic emission factors
- The calibration was based on the 2008 base year.
- An additional projection was added going back to 2002 from the 2008 base year.

Scenario 2

- Uses baseline road traffic emission factors
- The calibration was based on a 2002 base year with projections for 2008, 2010, 2015 and 2020

Scenario 3

- Uses the revised road traffic emission factors developed within this project. This scenario is our current best estimate and interpretation of the RSD. These assumptions are consistent with those shown for *Scenario 5* on page 57. As noted previously, further work would be required to formally produce a new inventory.
- The calibration was based on a 2002 base year with projections for 2008, 2010, 2015 and 2020

Scenario 1 is the baseline scenario which reflects the results that have been formally reported to the European Commission for 2008 on behalf of Defra. This scenario has been calibrated using 2008 monitoring data and projected to all other years using 2007 NAEI emissions data. Scenario 2 uses the same parameters as the baseline model runs but is calibrated using 2002 data and then projected forwards from that base year. Scenario 3 is the scenario that uses the illustrative emission factors determined within this project and based on new data (for example from remote sensing of vehicle emissions). This scenario, like Scenario 2 was calibrated using monitoring data from 2002 and projected forwards.

Scenario 1 projections back to 2002 were calculated in order to investigate the ability of the current baseline emissions inventory to account for the observed changes in ambient NO_x concentrations between 2002 and 2008. Scenarios 2 and 3 were calculated in order to investigate the ability of the current baseline and illustrative emission inventory scenarios to predict the the trends in measured concentrations going forwards from 2002 and to provide illustrative projections for these scenarios for concentrations in 2015 and 2020. Scenario 1 is consistent with the 2008 air quality assessment and the projections to 2015 and 2020 currently (2010) being used to develop air quality plans for NO_2.

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[15] Grice, S. E., Cooke, S. L., Stedman, J. R., Bush, T. J., Vincent, K. J., Hann, M., Abbott, J. and Kent, A. J. (2010). UK air quality modelling for annual reporting 2008 on ambient air quality assessment under Council Directives 96/62/EC, 1999/30/EC and 2000/69/EC. Report to The Department for Environment, Food and Rural Affairs, Welsh Assembly Government, the Scottish Government and the Department of the Environment for Northern Ireland. AEA report. AEAT/ENV/R/2859 Issue 1. `http://www.airquality.co.uk/reports/cat09/1007201636_dd122008mapsrep_v4.pdf`

[16] Murrells, T.P., Passant, N.R., Thistlethwaite, G., Wagner, A., et al., (2009). UK Emissions of Air Pollutants 1970 to 2007. National Atmospheric Emissions Inventory, AEA Technology. Report AEAT/ENV/R/2856. `http://www.naei.org.uk/reports.php`

Scenario 3 has been calibrated for 2002, which is the earliest year for which a full NAEI road traffic emission inventory consistent with currently published inventories is available. Since we are aware of inconsistencies between current inventories and recent measurement trends, it makes sense to calibrate the model runs for scenario 3 for the earliest year for which data are available. Scenario 2 is required in order to provide a direct comparison for the two emission inventories with a consistent starting point. Scenario 1 and scenario two are based on the same emission inventory but have been calibrated for different base years.

The choice of these scenarios illustrates some of the complexity of using models to attempt to link emission inventory and measurement trends. Care is needed in the selection of scenarios for modelling using the PCM model because of the calibration step. A benefit of the PCM approach is, however, that this calibration step is explicit and the implications are understood. The use of a model without a calibration step when attempting to reconcile measurements and inventories would be likely to lead to similar complexity but perhaps without the clear understanding of the fixed points at which the model has been calibrated.

7.2. Model results and verification

The model results have been compared against monitoring data in the trends analysis below and the NO_2 model results assessed against the European annual limit value of 40 µg m^{-3} in the exceedance statistics analysis in order to represent the impact of the illustrative emission factors from a policy perspective.

Verification plots have been produced for each scenario to show how the PCM model has performed compared with measurements in background and roadside locations. These plots show the modelled NO_x concentration plotted against the measured NO_x concentration at each AURN monitoring site in both 2002 (the calibration year for scenario 2 and 3) and 2008 (the calibration year for scenario 1). Separate plots have been produced for background and roadside sites because concentrations at these two different types of locations are modelled differently within the PCM model.

The advantage of looking at all sites across the network for background and roadside locations for a snapshot in time like this is that this makes it possible to pick out systematic under or over prediction of the model across the network in a given year. Hence, we can tell which scenario produces the best results when compared with real world data. For each scenario, either 2002 or 2008 measurement data has been used to calibrate the model. The model results should therefore agree well with the measurements in this calibration year (i.e. there should be no systematic under or over-prediction for this calibration year). Hence, the model projection year (2002 for scenario 1 and 2008 for scenarios 2 and 3), rather than the calibration year is the most relevant place to look for systematic bias in terms of understanding whether the road transport emissions projections used cause significant under or over prediction in the NO_x model results.

Figure D.1 shows the verification plots for background sites, in Appendix D. Roadside verification plots are shown in Figure D.2.

7.2.1. Scenario 1

Scenario 1 background verification plots (Figure D.1) show that in 2008, which is the calibration year, the majority of the points sit within the ±30% Data Quality Objective (DQO) lines shown on the graph and there does not seem to be much evidence of systematic under or over-prediction. In the 2002 projections, by contrast, the model over-predicted by more the 30% at 11 out of 62 sites and only under-predicted by more than 30% at three sites. All three of the sites that were under % predicted by over 30% were also under-predicted by over 30% in the other scenarios suggesting that the issue at these sites may be that the model fails to characterise them well, rather than being related to the road traffic emissions projections used. The remaining 48 sites all fall within the DQO. This suggests that overall the model projections may be slightly over-predicting compared with measurements in 2002, but generally at background locations this over-prediction is not large.

Scenario 1 roadside verification plots (Figure D.2) also show that in the calibration year of 2008 there is little evidence of any systematic over or under-prediction by the model across the network. By contrast the verification plot for the 2002 model projections shows that the model predicted higher NO_x concentrations than the measurements at 14 out of 18 roadside sites considered. Half of the 18 roadside sites had modelled NO_x concentrations over 30% higher than the measured concentrations. This suggests that in 2002 the model projections significantly over-predicted at the roadside compared with measurements for scenario 1.

The findings from the verification plots for scenario 1, described above, suggest that the road transport emissions projections used in this scenario may have too steep a decline with time. This is because going backwards in time from a 2008 baseline, the emissions projections increase too steeply, which causes the over prediction in the 2002 model projections. Going forwards in time from 2008, this overly steep trend is likely to cause modelled NO_x concentrations to be under-predicted. The reason that this incorrect trend is more apparent from the concentration results at roadside locations, where there is a significant over-prediction in 2002, than background locations, where only a slight over prediction is evident, probably relates to the proportion of the overall source apportionment that is traffic. At background locations, the proportion of traffic contributions to the overall total concentration is much less than at roadside locations, where contributions from the road that the site is located on generally make up a high proportion of the total NO_x concentration. Hence the overall emissions trend at background locations is more driven by non-road transport emissions projections, for which large trends are not expected and we are not currently aware of any problems.

7.2.2. Scenario 2

Scenario 2, which is also uses baseline road transport emissions factors from a PCM 2002 base year, re-enforces the message from scenario 1 that the baseline emission factors cause too steep a decline in road transport emissions with time. This can be seen from the verification plots for background (Figure D.1 c and d) and roadside locations (Figure D.2 c and d). As for scenario 1, the plots for the calibration year (in this case 2002) show no systematic over or under-prediction of the model results compared with measured concentrations. However, in the 2008 model projections, there is evidence that the background NO_x model results slightly under-predict compared with measurements (48 out of 70 sites with modelled concentrations lower than measured concentrations and eight out of 70 sites with modelled concentrations more that 30% lower than measured concentrations) and that the roadside model significantly under-predicts (15 out of 20 sites with modelled concentrations lower than measured concentrations and seven out of 20 sites with modelled concentrations more that 30% lower than measured concentrations). This under-prediction for projecting from 2002 to 2008 indicates the same overly steep decline in road transport emissions that is evident in Scenario 1 from the over-prediction when projecting back in time from 2008 to 2002.

7.2.3. Scenario 3

For scenario 3, which uses the illustrative road transport emissions factors developed within this project, background verification plots are shown in Figure D.1 (e and f) and roadside verification plots are shown in Figure D.2 (e and f). Similar to the other scenarios, the background and roadside verification plots for the calibration year (in this case 2002) show little evidence of systematic over or under-prediction of the model results compared with measured concentrations. For the scenario 3 model projections to 2008 at background locations (Figure D.1 f), there is some evidence that the model is slightly under-predicting compared to the measurements, as for example 44 out of the 70 sites have higher measured than modelled NO$_x$ concentrations for this scenario. However, this under prediction is less than the under prediction shown by scenario 2 in 2008 (Figure D.1 d). Similarly, for the scenario 3 roadside projections to 2008, there is evidence of some under prediction of the model compared to the measurements, but to a lesser extent than for scenario 2. This can be seen by comparing the scenario 3 roadside model verification plot for 2008 (Figure D.1 f) with the same plots for 2008 for scenario 1 (calibrated in 2008 and hence no systematic over or under-prediction) and 2 (significant under prediction). The points on the scenario 3 plot fall somewhere between the points on the two other plots.

7.2.4. Scenario summary

In summary, the verification plots in Figure D.1 and Figure D.2 suggest the following conclusions:

- Any differences between real life trends in road transport emissions and modelled trends in road transport emissions will have a bigger impact on PCM model projections at roadside locations than at background locations where non-road transport emissions make up a higher proportion of the total.
- As expected, there is little evidence that the PCM model systematically over or under-predicts NO$_x$ concentrations for the year for which the model has been calibrated. Hence it is only projected model results where incorrect emission factors may cause systematic errors in the PCM modelled NO$_x$ concentrations. This is because the model is calibrated for a specific base year and should therefore always show good agreement with measurements in that year.
- The baseline road transport emissions projections (generated using baseline road transport emissions factors) probably have a steeper decline in emissions with time than has actually happened/is happening in reality. This is shown by the systematic bias of modelled NO$_x$ concentrations away from the measured NO$_x$ concentrations for the projection years for scenarios 1 and 2.
- The illustrative road transport emissions projections (generated using illustrative road transport emissions factors) are closer to reality than the baseline road transport emissions projections, but still may have a steeper than realistic decline with time. This is shown by the scenario 3 PCM model projections being closer to measured data in 2008 than the scenario 2 PCM model projections.

7.3. Comparison of trends for measured and modelled concentrations

The PCM model results for the three different scenarios have been plotted against monitoring data from the AURN that is available across the period reviewed (i.e. operating in 2002 and still operational in 2010). The monitoring data presented are annual means with a 75% data capture threshold. The 2010 concentration is a partial year and is calculated from provisional data. Nine urban background sites were selected for comparison, whilst all comparisons for all roadside sites with model available results (those situated on A roads or Motorways classified as urban) are presented. Modelled projections to 2010, 2015 and 2020 are also shown. Whilst the PCM models do not show any bias in the calibrations year (2008 for scenario 1 and 2002 and scenarios 2 and 3) the modelled values for some monitoring site locations do show a consistent bias for all scenarios. This is because the model is calibrated for the network as a whole, and not at individual monitoring sites.

Figure D.3 to Figure D.5 shows the comparison of the modelled and measured time series for NO$_x$. As expected, scenario 3 shows the least decline in projected concentration between

2002 and 2010. The difference between the projected trends for the different scenarios is not very great for the background sites as was indicated by the comparison of the verification plots. The modelled decline in concentration at background sites is reasonably consistent with the trends in measurements at some sites, while at other sites the model predicts a decline and the measurements show little or no trend.

It is clear that the PCM model tends to systematically under predict the measured concentration at some roadside sites, such as Bath Roadside and Oxford Centre Roadside and over predict at other sites, such as Haringey Roadside. The agreement in the scenario base year is better at some sites including Bury Roadside, London Marylebone Road, London Cromwell Road 2, Tower Hamlets Roadside and Wrexham. Scenarios 1 and 2 systematically over predict the decline in measured concentrations between 2002 and 2010. The decline in concentrations is predicted well by the scenario 3 results for some sites including Bury Roadside, Haringey Roadside, London Cromwell Road 2 and Tower Hamlets Roadside. The agreement is, however, poor at the sites with very little observed trend, such as London Marylebone Road and Bath Roadside.

Figure D.6 to Figure D.8 shows similar time series comparison for measurements and PCM model results for NO_2 concentrations. Annual mean NO_2 has been calculated from annual mean NO_x using the oxidant partitioning model, as described by Grice at al.[17] The expected changes in f-NO_2 between 2002 and 2020 have also been incorporated. Evidence presented elsewhere in this study suggests that the current emission inventories can provide a reasonably good description of the trends in f-NO_2 for road traffic emissions between 2002 and 2010. Projections of f-NO_2 to 2020 are likely to be less certain. At present both the baseline and illustrative emission inventory scenarios project a steep decline in road transport NO_x emissions to 2020 as a result of the impact of Euro 6 for light vehicles and Euro VI for heavy vehicles. A low f-NO_2 for Euro V and Euro VI heavy vehicles is also assumed with the projections. This is in contrast to a high f-NO_2 for Euro 5 and Euro 6 light vehicles.

As expected, both the measured and modelled declines in NO_2 are less steep than for NO_x. Overall the conclusions from the NO_2 time series analysis analyses are similar to the conclusions for the NO_x time series. There is considerable site to site variation in the observed trends and the best agreement between the model results and the measurements is obtained for scenario 3.

7.4. Exceedance statistics for NO_2

The model results for the three scenarios were assessed against the European annual mean limit value (LV) of 40 µg m^{-3} and the total area (km^2), population and urban road length (km) were calculated for each of the 43 zones and agglomerations in the UK.

The number of zones with modelled roadside exceedances of the annual mean LV for each scenario in each of the years are listed in Table 7.1. These data are also illustrated in Figure 7.1, which shows that there is a large variation between the scenarios for 2015, which is a significant year in terms of policy application with respect to the end of any time extension (TEN) granted for NO_2. In general Scenario 3 shows the lowest rate of decline to 2015 with Scenario 2 showing the highest.

The 2008 assessment for scenario 1 is the reported air quality assessment for 2008. A steep decline in the number of zones with exceedances between 2008 and 2010, 2015 and 2020 is projected for scenario 1. The results for scenario 2 are already more optimistic in 2008 than the

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[17] Grice, S. E., Cooke, S. L., Stedman, J. R., Bush, T. J., Vincent, K. J., Hann, M., Abbott, J. and Kent, A. J. (2010). UK air quality modelling for annual reporting 2008 on ambient air quality assessment under Council Directives 96/62/EC, 1999/30/EC and 2000/69/EC. Report to The Department for Environment, Food and Rural Affairs, Welsh Assembly Government, the Scottish Government and the Department of the Environment for Northern Ireland. AEA report. AEAT/ENV/R/2859 Issue 1. `http://www.airquality.co.uk/reports/cat09/1007201636_dd122008mapsrep_v4.pdf`

Table 7.1: The number of UK zones where roadside modelled concentrations of NO_2 exceeded 40 µg m^{-3}.

Scenario	2002	2008	2010	2015	2020
1	43	40	37	20	1
2	40	37	31	6	1
3	41	40	38	30	3

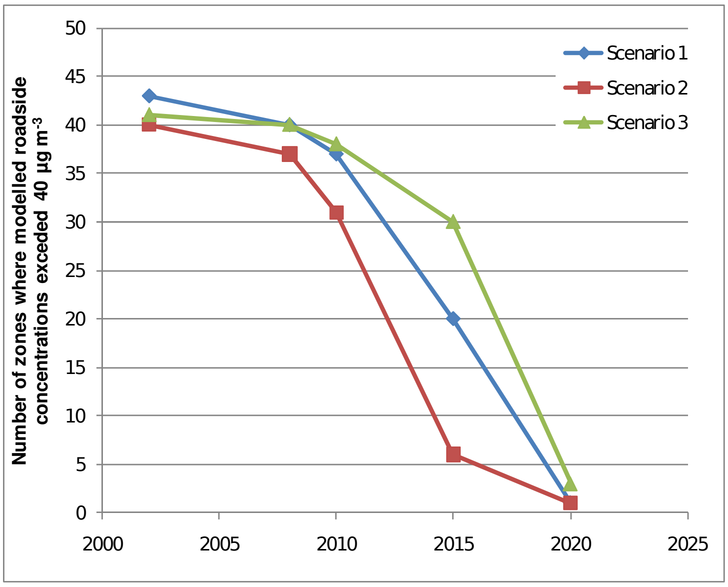

Figure 7.1: The number of UK zones where roadside modelled NO_2 concentrations exceed 40 µg m^{-3}.

results reported in the assessment for 2008 and are projected to show an even steeper decline in the number of zones with exceedances than the results for scenario 1. The number of zones with projected exceedances for scenario 3 is higher in 2015 than for the other scenarios but only a small number of zones are projected to still have exceedances in 2020 as a result of the sharp declines in road traffic emissions assumed for Euro 6 and Euro VI vehicles.

Table 7.2 presents the extent of exceedances of the annual mean LV for both background and roadside model results. Under all three scenarios there are estimated background exceedances in 2015 when the LV at 40 µg m^{-3} would come into force after a time extension period. Of the scenarios presented here, Scenario 2 provides the lowest number of exceedances in terms of all four metrics (area, population and road length).

In addition to Table 7.2, the total road length within the UK exceeding 40 µg m^{-3} have been plotted for all scenarios (see Figure 7.2). This shows that the decline in road length exceeding is least for Scenario 3 which exhibits a reasonably linear decline from 2008. Scenarios 1 and 2 exhibit a steeper decline to 2010 (most prominent in Scenario 1) before the trend progressively flattens off to 2020. The projected 2008 data for Scenario 2 and 3 are both notably lower than the baseline modelling calibrated using monitoring data from that year.

Remember that the scenario 1 results for 2008 represent our best estimate of the extent of exceedance in 2008. There are clearly uncertainties surrounding the trends in road traffic emissions within the baseline emission inventory used in this air quality assessment. The calibration of the model fir 2008 has ensured that the model result are unbiased for this year. Thus projections forward for scenario 2, which also used the current baseline emission inventory, result in an underestimate of the extent of roadside exceedance in 2008 of only 2159 km (15.9%

Table 7.2: Summary of background and roadside exceedances.

Scenario	2002	2008	2010	2015	2020
Total area (km^2) with modelled concentrations exceeding 40 µg m^{-3} (253,729 km^2 assessed)					
Scenario 1	356	74	33	11	0
Scenario 2	145	34	19	1	0
Scenario 3	128	36	28	5	0
Total population exposed to modelled concentrations exceeding 40 µg m^{-3} (58,729,386 assessed)					
Scenario 1	1796580	499244	174813	21069	0
Scenario 2	800235	176567	80360	32	0
Scenario 3	615637	205161	143647	20448	0
Total road length (km) with modelled concentrations exceeding 40 µg m^{-3} (13,610 km assessed)					
Scenario 1	7590	3623	2163	492	24
Scenario 2	4682	2159	122	128	1
Scenario 3	4770	277	5 2373	1197	73

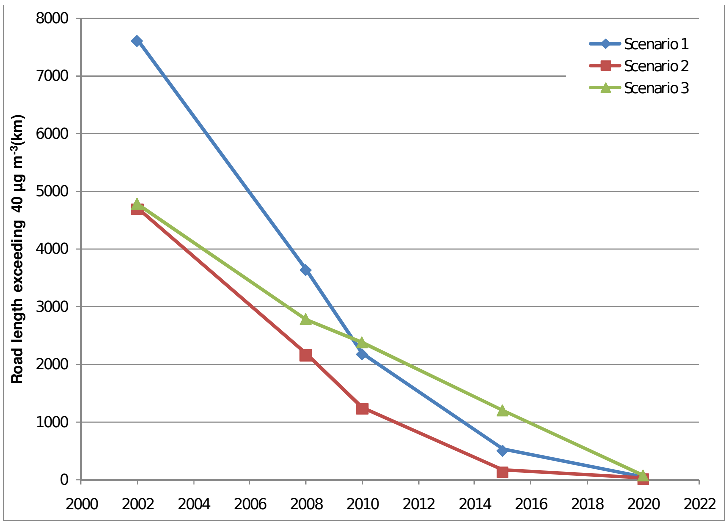

Figure 7.2: Road length where modelled concentrations exceeded 40 µg m^{-3} NO_2.

of the total assessed) compared with the value report for 2008 of 3635 km (26.8%). The projection forward from 2002 to 2008 for scenario 3 using the illustrative emission factors and inventory result in a smaller underestimation of the extent of roadside exceedance of 2275 km (20.4).

The projected length of road exceeding is higher in 2010, 2015 and 2020 for scenario 3, although all scenarios project only a small extent of exceedance in 2020. Both scenarios 2 and 3 have been projected forward from a calibration year of 2002 in order to provide an assessment for comparison with measured trends that starts off with good agreement with measurement data for 2002. Scenario 1 is less easy to interpret in terms of recent trends because it is calibrated to be in agreement with 2008 measurements, rather than at the start of the period studied. A projection forward using the illustrative emission factors and inventory from a calibration year of 2008 has not been carried out as part of this current study. Such a scenario would provide our best estimate of the extent of exceedance in 2015 and 2020 for this emission scenario but the results would need to be interpreted with care because of the inconsistency between the measured trends and the results obtained from our scenario 3 calculations. If the results of the scenario 3 calculations showed better agreement with the trends in measurement data between 2002 and 2008 then we would have more confidence in the projected future trends for this scenario. The ultimate goal of the inventory and modelling studies is, of course, an assessment that shows good agreement with measured trends in order to provide confidence in the projections for future years. With the currently available emission inventories this additional scenario with a calibration in 2008 could provide further useful information.

Table D.1 provides a full list of the results for each scenario in each year in terms of the extent of roadside exceedance.

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A. Implications for measures to meet EU Limit Values for NO_2

The findings of this report have implications for policies aimed at reducing NO_x emissions and achieving compliance with the EU LVs for NO_2. These are set out below. They are the authors' own views and do not represent UK Government policy.

1. Current methods used to estimate compliance with air quality limit values for NO_2 and with national emission ceilings for NO_x are erroneous. The reasons for the mismatch between the observed and modelled behaviour need to be fully understood before projections of future compliance can be made with confidence.

2. It is clear from the RSD and the HBEFA that **new** petrol vehicles (Euro 4/5) result in very low emissions of NO_x and NO_2. The data suggest that NO_x emissions from new Euro 5 petrol vehicles have reduced by $\approx$96% since pre-Euro (non-catalyst) vehicles. This is the case for all engine sizes. However, while it is expected that Euro 4/5 vehicles will not deteriorate as quickly as older catalyst vehicles (Euro 1–3), this cannot be known with certainty until these vehicles are older. It will be important therefore to continue to monitor the in-use emissions of the vehicles as they age to ensure they continue to emit low amounts of NO_x.

   - **Provided that Euro 4/5 do not deteriorate in the same way as older catalyst vehicles, policies that incentivise small, modern (Euro 5/6) petrol vehicles, petrol hybrids and electric vehicles in urban areas in place of diesel (5 and probably Euro 6) vehicles should be incentivised, and measures on low-emission vehicles announced in July 2010 will be helpful. Their uptake should be monitored.**

   The analysis of inventory trends using the RSD shows that older petrol vehicles (Euro 1-3) emit higher emissions of NO_x than previously thought and that these vehicles still make up a considerable amount of total NO_x emissions in urban areas (about half based on 2009 data).

   - **Therefore measures that encourage the removal of these vehicles from the fleet (to be replaced by modern petrol vehicles, or petrol hybrids etc.) or which ensure their maintenance at a higher level, would be beneficial.**

   We note that the *Regulations Controlling Sale and Installation of Replacement Catalytic Converters and Particle Filters for Light Vehicles* for Euro 3 petrol cars[18] or LDVs (or above) after June 2009 should ensure that replacement catalysts on vehicles are of a higher standard. It is difficult, however, to know how effective these regulations are in practise. In addition they do not cover Euro 1/2 vehicles which remain important NO_x emitters.

   - **Consideration should also be given to tightening the MOT, which currently only provides a measure of CO/hydrocarbons. High emitters of NO_x (but low emitters of CO/HC) would not be captured by the MOT.**

3. We find that diesel cars and LGV emissions of NO_x have not decreased for the past 15–20 years; even for Euro 5 vehicles.

   - **It will be essential to ensure that Euro 6 vehicles result in a considerable reduction in NO_x emissions, particularly under urban driving conditions. Defra and other relevant agencies should monitor the implementation of Euro 6 vehicles through European emission standards to ensure there is sufficient evidence to support claims of significantly reduced NO_x emissions under 'real-world' driving conditions.**

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[18] These regulations also apply to diesel particulate filters for diesel cars/vans.

4. The research has shown that the current light-duty test cycle is inadequate to ensure that real world emissions of NO_x, particularly from diesel vehicles, decrease in line with emission limits. Discussions on a new world-wide harmonised light duty test cycle are already under way within GRPE in the UNECE.

   - **Defra and DfT should ensure that any agreement on such a cycle is capable of ensuring real-world decreases in NO_x emissions in the UK in line with future emission limits.**

5. Evidence from a range of sources strongly suggests that SCR is ineffective on HGVs for urban conditions due to low operating temperatures. This will likely remain the case until Euro VI vehicles are introduced and where there will be a slow speed element to the test cycle.

   - **The accelerated introduction of Euro VI diesel HGVs should be considered beyond the incentive already in place through the RPC.**
   - **Alternative technologies such as hybrids, electric, even hydrogen could offer advantages and should be considered as serious alternatives to conventional fuels.**

   Note that currently in UK urban areas it is thought that only a small fraction of HGVs use SCR. This is because SCR tends to be fitted to larger (articulated) vehicles and these vehicles contribute about 4% of UK urban road vehicle NO_x emissions (based on re-calculated emissions using the RSD). However, as time goes on the proportion using SCR will increase and so too will the issue of SCR performance in urban areas.

6. In terms of retrofitting it is the heavy duty fleet (buses and HGVs) that are important because it is more practicable to retrofit fewer of these vehicles rather than numerous light vehicles.

   - **Targetting of specific fleets e.g. urban bus fleets for retrofitting does have the potential to reduce NO_x emissions. However, it would be important in the case of SCR that the technology is matched to specific duty cycles e.g. optimised to deal with lower engine-out temperatures.**

   The retrofitting of the wider, older HGV fleet could also reduce NO_x emissions. However, if the emphasis is on meeting limit values for NO_2, which are most problematic in urban areas, such retrofitting may not be as effective as one might think. This is because in urban areas the vehicle km driven by these vehicles is relatively low. It would be necessary to consider the specific traffic composition by urban or regional area. Any increased use of SCR on rigid vehicles through retrofitting would need to ensure their efficacy under urban conditions.

7. It remains the case that policies that result in an absolute reduction in traffic volume will result in corresponding reductions to vehicular NO_x and NO_2, provided that changes to vehicle operation do not offset the emission reductions e.g. if there was a significant change in vehicle speed.

8. Finally, an essential tool for understanding the discrepancies between emission inventories and ambient measurements has been the RSD. Without the RSD it would have been very difficult or impossible to understand these issues.

   - **We strongly believe that Defra should consider the use of such as system in the coming years as a way of ensuring emissions change as expected. In addition, the use of more recent RSD instruments that measure NO *and* NO_2 would further enhance these possibilities.**

In the absence, for example, of MOT or other in-service NO_x emissions information for large numbers of vehicles, remote sensing offers a robust approach for the regular assessment of in-service emissions of a large number of vehicles at comparatively little cost.

B. Trend results for NO$_x$ and NO$_2$ for UK sites

Table B.1: Trend results for NO$_x$ at UK sites (2004-2009). Note the motorway sites are for 2004–2008.

	site type	site	slope (µg m^{-3}/year)	uncertainty (µg m^{-3}/year)	slope (%/year)	uncertainty (%/year)
1	UK Roadside	Oxford Centre Roadside	-9.6	[-13.2, -6.2]	-4.9	[-6.8, -3.2]
2	UK Roadside	Bury Roadside	-8.2	[-11.5, -4.6]	-3.8	[-5.4, -2.2]
3	UK Roadside	Brighton Roadside	-2.2	[-3.1, -1.2]	-2.7	[-3.7, -1.4]
4	UK Roadside	Cambridge Roadside	-2.8	[-4.6, -1.1]	-2.5	[-4.1, -1.0]
5	UK Roadside	Dumfries	-1.8	[-3.1, -0.2]	-1.8	[-3.1, -0.2]
6	UK Roadside	Wrexham	-0.5	[-1.4, 0.5]	-1.4	[-3.4, 1.2]
7	UK Roadside	Inverness	-0.6	[-1.5, 0.1]	-1.3	[-3.3, 0.2]
8	UK Roadside	Bristol Old Market	1.1	[-2.6, 5.1]	0.7	[-1.6, 3.1]
9	UK Roadside	Glasgow Kerbside	2.3	[-2.9, 7.6]	0.9	[-1.2, 3.1]
10	UK Roadside	Bath Roadside	1.9	[-0.9, 4.7]	1.1	[-0.5, 2.8]
11	UK Roadside	Exeter Roadside	1.6	[-0.7, 4.1]	1.7	[-0.8, 4.4]
12	UK Urban Centre	Leicester Centre	-2.6	[-3.7, -1.7]	-4.5	[-6.2, -2.8]
13	UK Urban Centre	Liverpool Speke	-1.1	[-1.9, -0.2]	-2.8	[-5.0, -0.6]
14	UK Urban Centre	Plymouth Centre	-1.1	[-2.3, -0.1]	-2.7	[-5.6, -0.3]
15	UK Urban Centre	Nottingham Centre	-0.9	[-2.0, 0.2]	-1.4	[-3.3, 0.3]
16	UK Urban Centre	Cardiff Centre	-0.6	[-1.3, 0.4]	-1.1	[-2.6, 0.9]
17	UK Urban Centre	Southampton Centre	-0.3	[-1.4, 0.9]	-0.4	[-2.2, 1.4]
18	UK Urban Centre	Leeds Centre	-0.3	[-1.8, 1.4]	-0.4	[-2.9, 2.2]
19	UK Urban Centre	Belfast Centre	0.2	[-1.4, 1.7]	0.4	[-2.5, 3.1]
20	UK Urban Centre	Newcastle Centre	0.5	[-0.3, 1.4]	1.0	[-0.6, 2.9]
21	UK Urban Centre	Sheffield Centre	0.6	[-0.8, 2.0]	1.1	[-1.3, 3.4]
22	UK Urban Background	Barnsley Gawber	-1.9	[-2.8, -1.3]	-5.5	[-7.9, -3.7]
23	UK Urban Background	Brighton Preston Park	-1.5	[-2.7, -0.5]	-4.3	[-7.6, -1.3]
24	UK Urban Background	Cwmbran	-1.0	[-1.7, -0.4]	-4.0	[-6.9, -1.8]
25	UK Urban Background	Southend-on-Sea	-1.0	[-1.8, -0.2]	-2.9	[-4.9, -0.6]
26	UK Urban Background	Preston	-1.1	[-2.0, -0.3]	-2.8	[-5.0, -0.6]
27	UK Urban Background	Reading New Town	-1.1	[-1.8, -0.0]	-2.7	[-4.4, -0.0]
28	UK Urban Background	Wirral Tranmere	-0.7	[-1.2, -0.3]	-2.6	[-4.2, -0.9]
29	UK Urban Background	Northampton	-0.9	[-1.4, 0.2]	-2.5	[-4.1, 0.6]
30	UK Urban Background	Portsmouth	-0.8	[-1.6, -0.1]	-2.1	[-4.2, -0.2]
31	UK Urban Background	Glasgow City Chambers	-2.0	[-3.8, -0.3]	-2.0	[-3.8, -0.3]
32	UK Urban Background	Sandwell West Bromwich	-0.8	[-1.6, -0.1]	-1.9	[-3.8, -0.2]
33	UK Urban Background	Leamington Spa	-0.4	[-1.5, 0.9]	-1.1	[-4.4, 2.6]
34	UK Urban Background	Manchester Piccadilly	-0.9	[-2.3, 0.7]	-1.1	[-2.8, 0.8]
35	UK Urban Background	Sunderland Silksworth	-0.2	[-1.4, 0.9]	-0.7	[-6.0, 3.7]
36	UK Urban Background	Canterbury	-0.0	[-0.5, 0.4]	-0.2	[-2.0, 1.4]
37	UK Urban Background	Aberdeen	0.2	[-0.7, 1.0]	0.5	[-1.5, 2.4]
38	UK Urban Background	Derry	0.6	[0.0, 1.6]	3.4	[0.1, 8.8]
39	Inner London	Wandsworth 4 - High Street	-3.5	[-5.9, -0.9]	-3.8	[-6.4, -0.9]
40	Inner London	Kensington and Chelsea - Cromwell Road	-7.2	[-9.5, -5.5]	-3.7	[-4.9, -2.8]
41	Inner London	Islington - Holloway Road	-5.0	[-7.6, -2.5]	-2.8	[-4.2, -1.4]
42	Inner London	Kensington and Chelsea - Knightsbridge	-2.9	[-6.4, 1.1]	-1.3	[-2.9, 0.5]
43	Inner London	Kensington and Chelsea - Kings Road	-2.9	[-6.2, -0.0]	-1.3	[-2.8, -0.0]
44	Inner London	Westminster - Marylebone Road	-0.1	[-5.3, 4.6]	-0.0	[-1.8, 1.6]
45	Inner London	Lambeth - Christchurch Road	0.2	[-1.8, 2.4]	0.2	[-1.5, 2.1]
46	Inner London	Hammersmith and Fulham - Broadway	2.2	[-5.9, 12.5]	1.1	[-2.9, 6.1]
47	Inner London	Camden - Swiss Cottage	2.0	[-2.9, 6.5]	1.1	[-1.6, 3.7]
48	Inner London	Camden - Shaftesbury Avenue	6.2	[3.0, 10.1]	4.2	[2.1, 6.9]
49	Outer London	A3 - AURN	-10.5	[-15.8, -6.4]	-6.0	[-8.9, -3.6]
50	Outer London	Redbridge - Fullwell Cross	-8.8	[-10.6, -6.7]	-5.3	[-6.4, -4.1]
51	Outer London	Haringey - Haringey Town Hall	-3.7	[-5.6, -1.8]	-3.8	[-5.8, -1.9]
52	Outer London	Hounslow - Chiswick High Road	-3.8	[-6.5, -1.1]	-2.2	[-3.7, -0.6]
53	Outer London	Croydon - Purley Way	-3.1	[-6.0, -0.4]	-2.1	[-4.1, -0.2]
54	Outer London	Croydon - Norbury	-3.8	[-8.3, 0.5]	-2.0	[-4.4, 0.3]
55	Outer London	Croydon - George Street	-2.0	[-4.2, 0.6]	-1.7	[-3.7, 0.6]
56	Outer London	Ealing - Acton Town Hall	-2.1	[-6.3, 1.9]	-1.4	[-4.2, 1.3]
57	Outer London	Bromley - Harwood Avenue	-0.5	[-2.0, 0.8]	-0.6	[-2.3, 1.0]
58	Outer London	Richmond - Castelnau	-0.1	[-1.7, 1.4]	-0.2	[-2.1, 1.8]
59	Outer London	Greenwich - Trafalgar Road	0.0	[-2.7, 3.1]	0.0	[-2.6, 3.1]
60	Outer London	Havering - Rainham	0.0	[-2.2, 1.8]	0.0	[-2.5, 2.1]
61	Outer London	Enfield 2 - Church Street	3.6	[1.4, 6.0]	4.8	[1.8, 8.1]
62	Motorway	M4	-11.3	[-18.6, -5.6]	-6.4	[-10.5, -3.1]
63	Motorway	M60	-4.5	[-9.5, 2.8]	-3.4	[-7.3, 2.1]
64	Motorway	M25	-3.6	[-13.4, 7.0]	-2.2	[-8.1, 4.2]
65	UK Rural	Yarner Wood	-0.9	[-1.1, -0.7]	-9.0	[-11.5, -6.8]
66	UK Rural	High Muffles	-0.4	[-0.7, -0.2]	-4.2	[-6.6, -1.9]
67	UK Rural	Bush Estate	-0.5	[-0.9, 0.0]	-4.0	[-7.3, 0.2]
68	UK Rural	Harwell	-0.4	[-1.0, 0.2]	-2.8	[-6.1, 1.3]
69	UK Rural	Rochester Stoke	-0.6	[-1.1, -0.1]	-2.2	[-3.9, -0.4]
70	UK Rural	Wicken Fen	-0.2	[-0.6, 0.1]	-1.5	[-3.8, 0.8]
71	UK Rural	Aston Hill	-0.0	[-0.4, 0.5]	-0.2	[-4.9, 6.4]
72	UK Rural	Lullington Heath	-0.0	[-0.4, 0.3]	-0.2	[-2.9, 2.1]
73	UK Rural	Narberth	0.1	[-0.1, 0.3]	1.3	[-1.2, 4.3]
74	UK Rural	Ladybower	0.2	[-0.1, 0.5]	1.8	[-1.5, 5.0]

Table B.2: Trend results for NO_2 at UK sites (2004-2009). Note the motorway sites are for 2004–2008.

	site type	site	slope (µg m^{-3}/year)	uncertainty (µg m^{-3}/year)	slope (%/year)	uncertainty (%/year)
1	UK Roadside	Oxford Centre Roadside	-4.2	[-5.1, -3.2]	-5.8	[-7.1, -4.4]
2	UK Roadside	Brighton Roadside	-0.6	[-1.0, -0.1]	-1.5	[-2.5, -0.3]
3	UK Roadside	Cambridge Roadside	-0.5	[-1.1, 0.0]	-1.0	[-2.5, 0.0]
4	UK Roadside	Dumfries	-0.3	[-0.8, 0.3]	-0.8	[-2.0, 0.8]
5	UK Roadside	Exeter Roadside	-0.3	[-1.1, 0.5]	-0.7	[-2.6, 1.3]
6	UK Roadside	Inverness	-0.1	[-0.5, 0.1]	-0.6	[-2.2, 0.7]
7	UK Roadside	Wrexham	-0.0	[-0.5, 0.5]	-0.1	[-2.5, 2.4]
8	UK Roadside	Bury Roadside	0.1	[-0.7, 1.1]	0.2	[-1.0, 1.6]
9	UK Roadside	Bath Roadside	1.1	[-0.2, 2.1]	1.7	[-0.3, 3.5]
10	UK Roadside	Bristol Old Market	1.8	[0.5, 3.1]	3.2	[0.8, 5.4]
11	UK Roadside	Glasgow Kerbside	3.1	[1.9, 4.5]	5.1	[3.1, 7.6]
12	UK Urban Centre	Leicester Centre	-1.2	[-1.7, -0.7]	-3.5	[-4.9, -2.1]
13	UK Urban Centre	Liverpool Speke	-0.6	[-1.0, -0.1]	-2.4	[-4.1, -0.6]
14	UK Urban Centre	Plymouth Centre	-0.5	[-1.4, 0.1]	-2.0	[-5.2, 0.5]
15	UK Urban Centre	Nottingham Centre	-0.3	[-0.8, 0.3]	-0.8	[-2.3, 0.8]
16	UK Urban Centre	Cardiff Centre	-0.2	[-0.8, 0.4]	-0.6	[-2.6, 1.3]
17	UK Urban Centre	Belfast Centre	0.5	[-0.3, 1.0]	1.5	[-1.0, 3.3]
18	UK Urban Centre	Sheffield Centre	0.5	[-0.4, 1.2]	1.6	[-1.4, 3.7]
19	UK Urban Centre	Leeds Centre	0.6	[-0.0, 1.3]	1.8	[-0.1, 3.9]
20	UK Urban Centre	Southampton Centre	0.6	[0.1, 1.3]	1.9	[0.2, 4.0]
21	UK Urban Centre	Newcastle Centre	0.8	[0.3, 1.3]	2.8	[1.2, 4.6]
22	UK Urban Background	Cwmbran	-0.7	[-1.1, -0.3]	-4.2	[-6.9, -1.9]
23	UK Urban Background	Brighton Preston Park	-0.8	[-1.3, -0.3]	-3.6	[-5.6, -1.3]
24	UK Urban Background	Barnsley Gawber	-0.7	[-1.2, -0.3]	-3.6	[-5.7, -1.6]
25	UK Urban Background	Sunderland Silksworth	-0.5	[-1.2, 0.2]	-3.3	[-7.3, 0.9]
26	UK Urban Background	Reading New Town	-0.6	[-1.1, -0.0]	-2.6	[-4.7, -0.2]
27	UK Urban Background	Canterbury	-0.3	[-0.7, 0.0]	-1.6	[-3.8, 0.2]
28	UK Urban Background	Southend-on-Sea	-0.3	[-0.8, 0.2]	-1.5	[-3.3, 0.9]
29	UK Urban Background	Portsmouth	-0.3	[-0.7, 0.1]	-1.4	[-3.2, 0.5]
30	UK Urban Background	Glasgow City Chambers	-0.4	[-1.1, 0.4]	-0.8	[-2.3, 0.7]
31	UK Urban Background	Aberdeen	-0.1	[-0.5, 0.3]	-0.6	[-2.1, 1.2]
32	UK Urban Background	Preston	-0.1	[-0.7, 0.4]	-0.5	[-3.0, 1.7]
33	UK Urban Background	Wirral Tranmere	-0.0	[-0.4, 0.3]	-0.2	[-2.2, 1.9]
34	UK Urban Background	Manchester Piccadilly	0.1	[-0.7, 0.8]	0.1	[-1.6, 2.0]
35	UK Urban Background	Sandwell West Bromwich	0.0	[-0.6, 0.5]	0.2	[-2.2, 1.8]
36	UK Urban Background	Northampton	0.1	[-0.3, 0.6]	0.6	[-1.7, 3.0]
37	UK Urban Background	Leamington Spa	0.3	[-0.3, 1.1]	1.3	[-1.5, 4.6]
38	UK Urban Background	Derry	0.5	[0.1, 1.2]	4.4	[1.1, 10.0]
39	Inner London	Wandsworth 4 - High Street	-1.7	[-3.0, -0.7]	-3.5	[-6.1, -1.5]
40	Inner London	Islington - Holloway Road	-2.4	[-3.6, -1.4]	-3.1	[-4.8, -1.9]
41	Inner London	Kensington and Chelsea - Cromwell Road	-2.1	[-3.0, -1.5]	-2.6	[-3.6, -1.8]
42	Inner London	Kensington and Chelsea - Knightsbridge	-0.6	[-1.7, 0.8]	-0.6	[-1.9, 0.8]
43	Inner London	Westminster - Marylebone Road	-0.6	[-1.9, 0.8]	-0.5	[-1.7, 0.7]
44	Inner London	Kensington and Chelsea - Kings Road	-0.4	[-1.6, 0.9]	-0.5	[-1.7, 1.0]
45	Inner London	Lambeth - Christchurch Road	1.0	[0.2, 1.7]	1.7	[0.4, 3.1]
46	Inner London	Hammersmith and Fulham - Broadway	1.8	[-0.7, 4.4]	2.4	[-0.9, 5.9]
47	Inner London	Camden - Swiss Cottage	2.2	[0.3, 4.1]	3.3	[0.5, 6.1]
48	Inner London	Camden - Shaftesbury Avenue	2.8	[1.5, 4.2]	4.1	[2.2, 6.2]
49	Outer London	Redbridge - Fullwell Cross	-3.3	[-4.1, -2.6]	-4.8	[-5.9, -3.8]
50	Outer London	A3 - AURN	-1.7	[-3.4, -0.1]	-2.6	[-5.3, -0.2]
51	Outer London	Hounslow - Chiswick High Road	-1.9	[-3.0, -0.6]	-2.5	[-4.0, -0.7]
52	Outer London	Haringey - Haringey Town Hall	-1.1	[-1.9, -0.3]	-2.4	[-4.2, -0.7]
53	Outer London	Croydon - George Street	-1.1	[-2.2, -0.3]	-2.0	[-3.8, -0.5]
54	Outer London	Croydon - Purley Way	-0.4	[-1.3, 0.4]	-0.9	[-2.7, 1.0]
55	Outer London	Bromley - Harwood Avenue	-0.4	[-1.0, 0.3]	-0.8	[-2.0, 0.5]
56	Outer London	Croydon - Norbury	-0.4	[-2.0, 0.9]	-0.5	[-3.0, 1.3]
57	Outer London	Richmond - Castelnau	0.2	[-0.5, 1.0]	0.4	[-1.2, 2.4]
58	Outer London	Greenwich - Trafalgar Road	1.0	[-0.4, 2.6]	2.0	[-0.8, 5.2]
59	Outer London	Ealing - Acton Town Hall	1.1	[-0.4, 2.4]	2.0	[-0.8, 4.3]
60	Outer London	Havering - Rainham	1.2	[0.1, 2.1]	3.2	[0.4, 5.6]
61	Outer London	Enfield 2 - Church Street	3.6	[1.8, 5.2]	9.7	[4.8, 14.2]
62	Motorway	M4	-3.3	[-5.1, -1.9]	-5.7	[-8.9, -3.2]
63	Motorway	M60	-0.4	[-3.4, 1.8]	-0.8	[-7.1, 3.7]
64	Motorway	M25	0.5	[-2.1, 3.4]	0.9	[-4.2, 6.6]
65	UK Rural	Yarner Wood	-0.7	[-1.0, -0.5]	-9.7	[-12.4, -7.0]
66	UK Rural	High Muffles	-0.3	[-0.5, -0.1]	-3.7	[-5.9, -1.6]
67	UK Rural	Harwell	-0.5	[-0.8, -0.1]	-3.7	[-6.7, -0.6]
68	UK Rural	Rochester Stoke	-0.4	[-0.8, -0.0]	-2.1	[-4.0, -0.1]
69	UK Rural	Bush Estate	-0.2	[-0.5, 0.1]	-2.0	[-5.1, 1.0]
70	UK Rural	Wicken Fen	-0.1	[-0.4, 0.1]	-0.9	[-3.5, 1.2]
71	UK Rural	Narberth	-0.0	[-0.2, 0.1]	-0.3	[-3.5, 2.9]
72	UK Rural	Lullington Heath	0.0	[-0.3, 0.3]	0.2	[-2.6, 2.8]
73	UK Rural	Ladybower	0.1	[-0.3, 0.3]	0.7	[-3.5, 3.3]
74	UK Rural	Aston Hill	0.1	[-0.2, 0.4]	1.0	[-3.2, 7.1]

C. Trends in NO_x and NO_2 in European cities

Turning to more detailed information for individual cities, Figure C.1 and Figure C.2 show composite plots of NO_x and NO_2 for a range of European cities showing this lack of downward trend clearly, particularly in NO_2. In order to display all sites the data in Figure C.1 and Figure C.2 give a broad overview, showing averages over several sites in each city and only showing data to 2007 as more recent data were not available for all sites. However subsequent figures extend the time series for most of the major cities and display individual sites rather than averages over several stations. The data are discussed below in terms of each country.

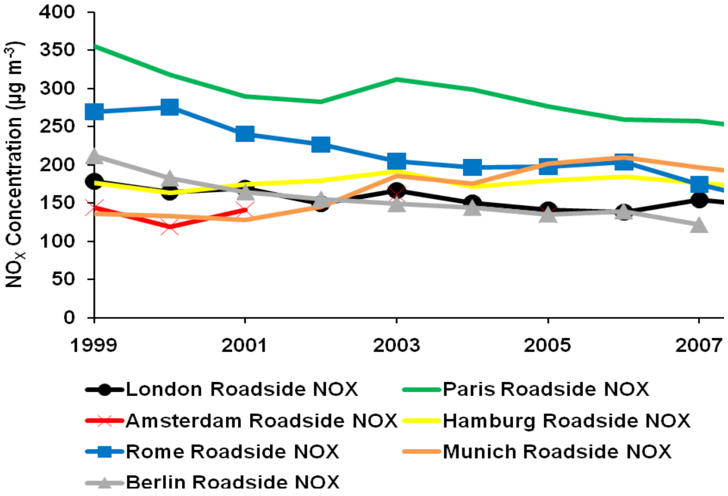


Figure C.1: NO$_x$ trends at roadside sites in European cities.

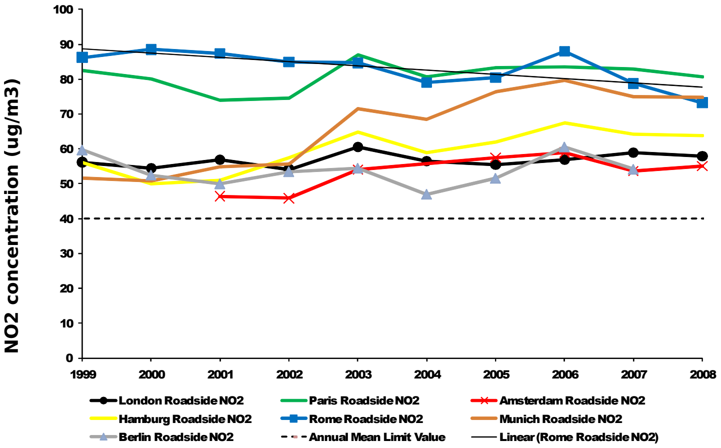


Figure C.2: NO$_2$ Trends at roadside sites in European cities.

C.1. France

The data for Paris are only readily available as averages over groups of sites and trends for more recent years are shown in Figure C.3 and Figure C.4 for traffic and urban background stations respectively.

Trends in NO$_x$ in Paris at both traffic and background stations appear to have continued to decline in more recent years, more so that London or Amsterdam, albeit more slowly, but NO$_2$ levels have remained remarkably constant up to 2009 at the traffic sites. The urban background sites showed a decline in NO$_2$ in the 1990s but in the past five years or so the decline has halted.

C.2. Germany

Data to 2009 are only readily available as averages over types of site as shown in Figure C.5. The trend for the traffic sites (Strasse in Figure C.5) show rising levels in recent years while those for inner city background (Innenstadt) and suburban (Stadtrand) have reained broadly flat since ∼2000.

Data for other cities in Germany all show similar behaviour. Data for NO$_2$ in cities in Baden-Wurttemburg are shown in Figure C.6.

Similar behaviour is also observed in Nord-Rhein-Westfalia, as shown in Figure C.7.

NO$_x$ and NO$_2$ data for sites in Munich are shown in Figure C.8 and Figure C.9 respectively.

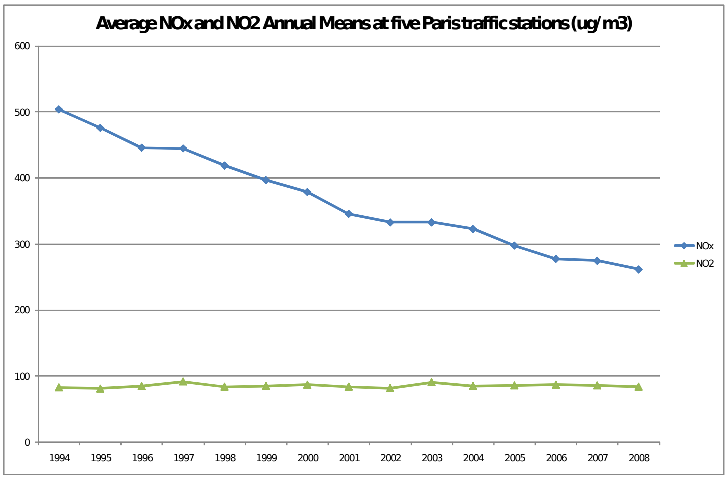


Figure C.3: Paris Traffic Stations (from http://www.airparif.asso.fr/)

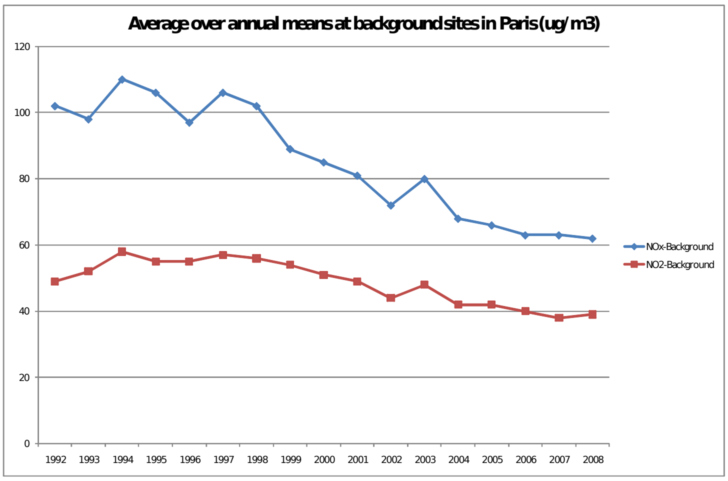


Figure C.4: Paris background stations.

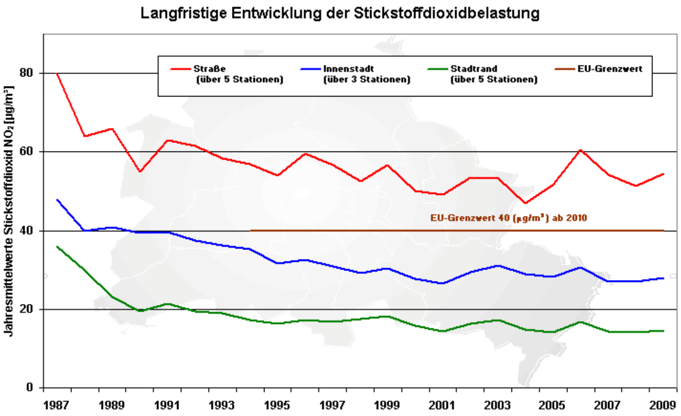
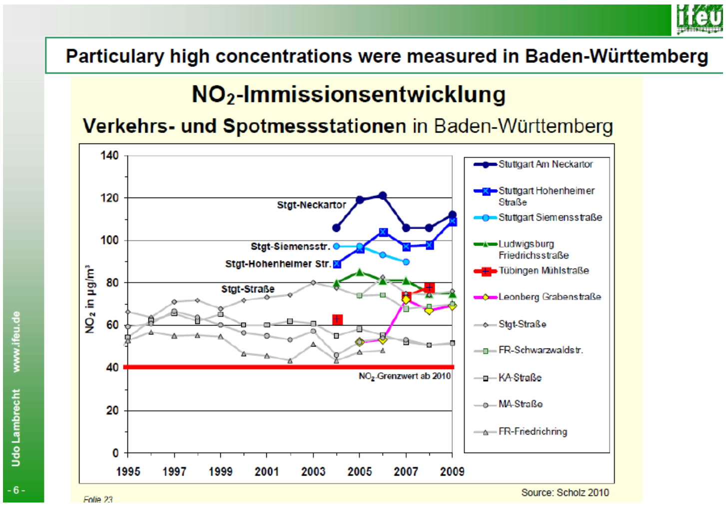


Figure C.5: Berlin Annual average NO_2 at traffic, urban background and suburban sites: (from http://www.berlin.de/sen/umwelt/luftqualitaet/).



Particulary high concentrations were measured in Baden-Württemberg

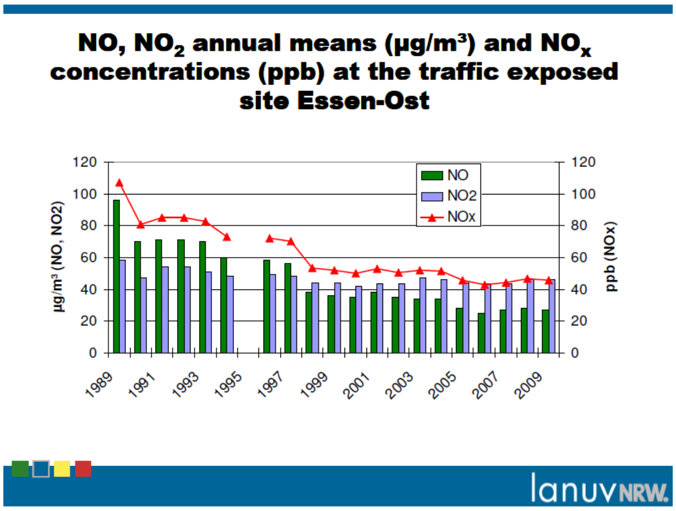
NO$_2$-Immissionsentwicklung

Verkehrs- und Spotmessstationen in Baden-Württemberg

Source: Scholz 2010

Folie 23

Figure C.6: NO$_2$ trends in cities in Baden Wurttemburg.



NO, NO$_2$ annual means (µg/m³) and NO$_x$ concentrations (ppb) at the traffic exposed site Essen-Ost

Figure C.7: NO$_x$ and NO$_2$ trends in Essen, NRW.

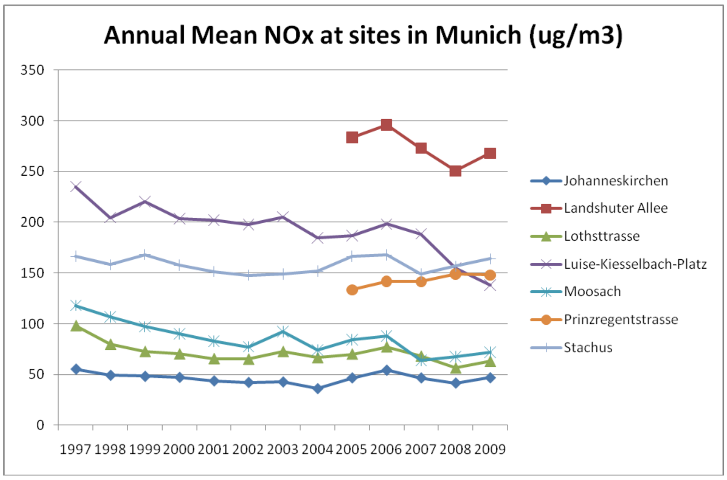


Figure C.8: Trends in NO$_x$ at sites in Munich.

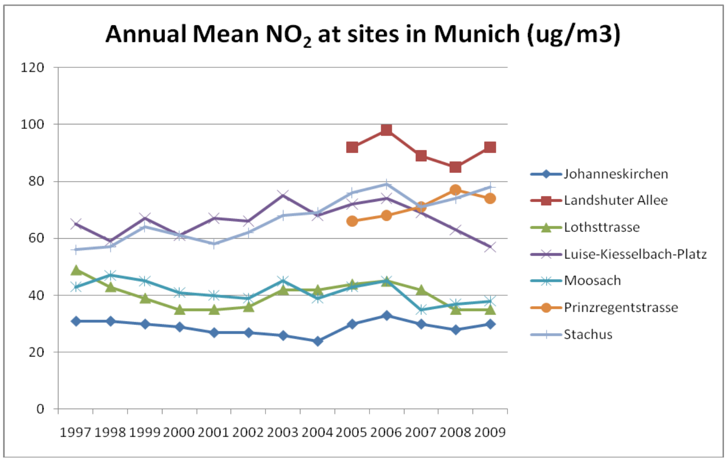


Figure C.9: Trends in NO_2 at sites in Munich.

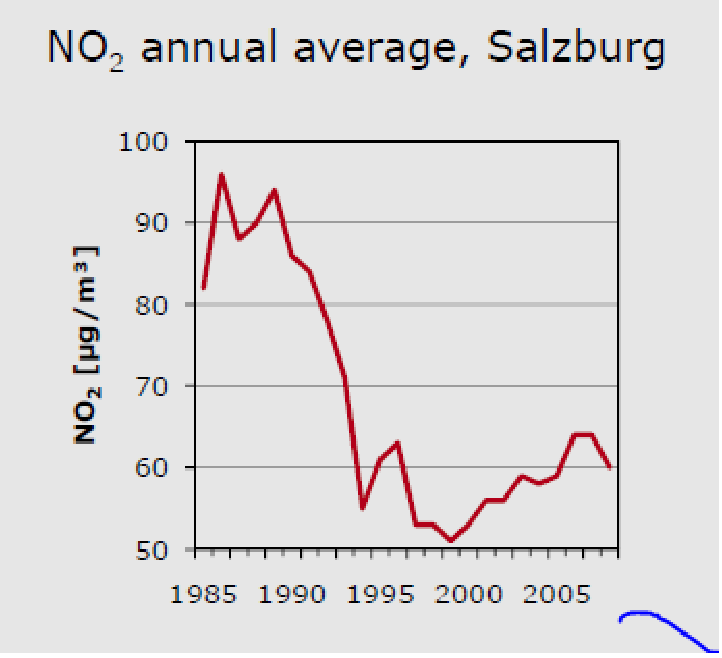


Figure C.10: NO_2 trends in Salzburg, Austria.

Compared with say Paris, even the NO_x levels in Munich appear not to have declined significantly over the past ten years, and NO_2 concentrations at several of the long-running sites have been increasing in the last four years or so.

C.3. Austria

Data are only readily available for Salzburg as a composite plot (source, Schneider, presentation at EU NO_2 Workshop, but again April 2010), a rising trend in NO_2 is apparent from Figure C.10.

C.4. Italy

Data for Rome are shown in Figure C.11 and Figure C.12. The classification of sites into “traffic” and “background” is not clear but what is apparent is that NOx at the most polluted site (Mana Grecia) has declined over the past decade but along with the levels at the other sites , has begun

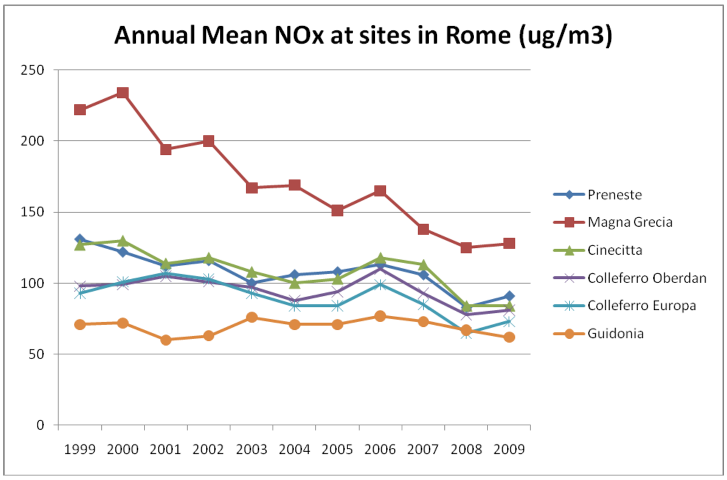


Figure C.11: NO_x levels at sites in Rome.

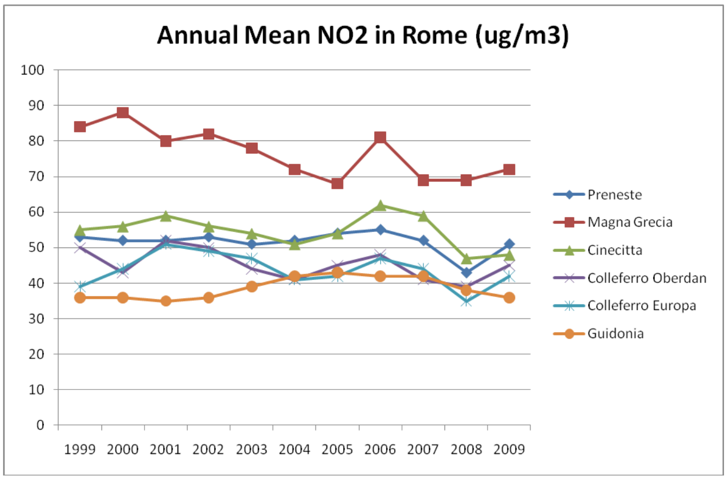


Figure C.12: NO_2 levels at sites in Rome.

to level out. The NO_2 levels at the Magna Grecia site have declined, but in recent years have remained fairly flat, as have levels at the other long-running sites in Rome.

C.5. Sweden

Data from Stockholm, shown in Figure C.13 and Figure C.14, appear to show the most sustained decreases in NO_x and NO_2 of the cities examined in this analysis, particularly for NOx. That said, the decreases in NO_2 are not marked but apart from a small number of sites appear to have maintained a small downward trend. The reasons for this would need further investigation in terms of diesel car penetration and related issues.

D. Pollution climate mapping verification plots and trends

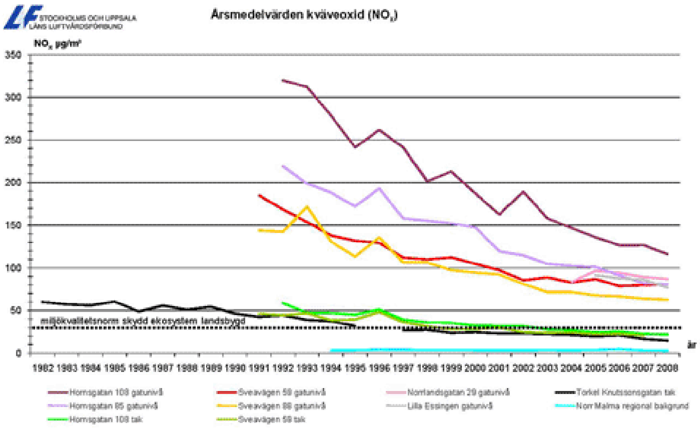


Figure C.13: Annual average NO$_x$ levels in Stockholm.

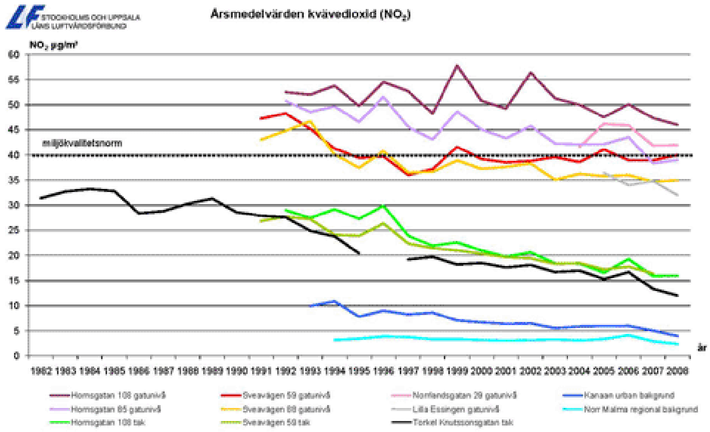


Figure C.14: Annual average NO$_2$ levels in Stockholm.

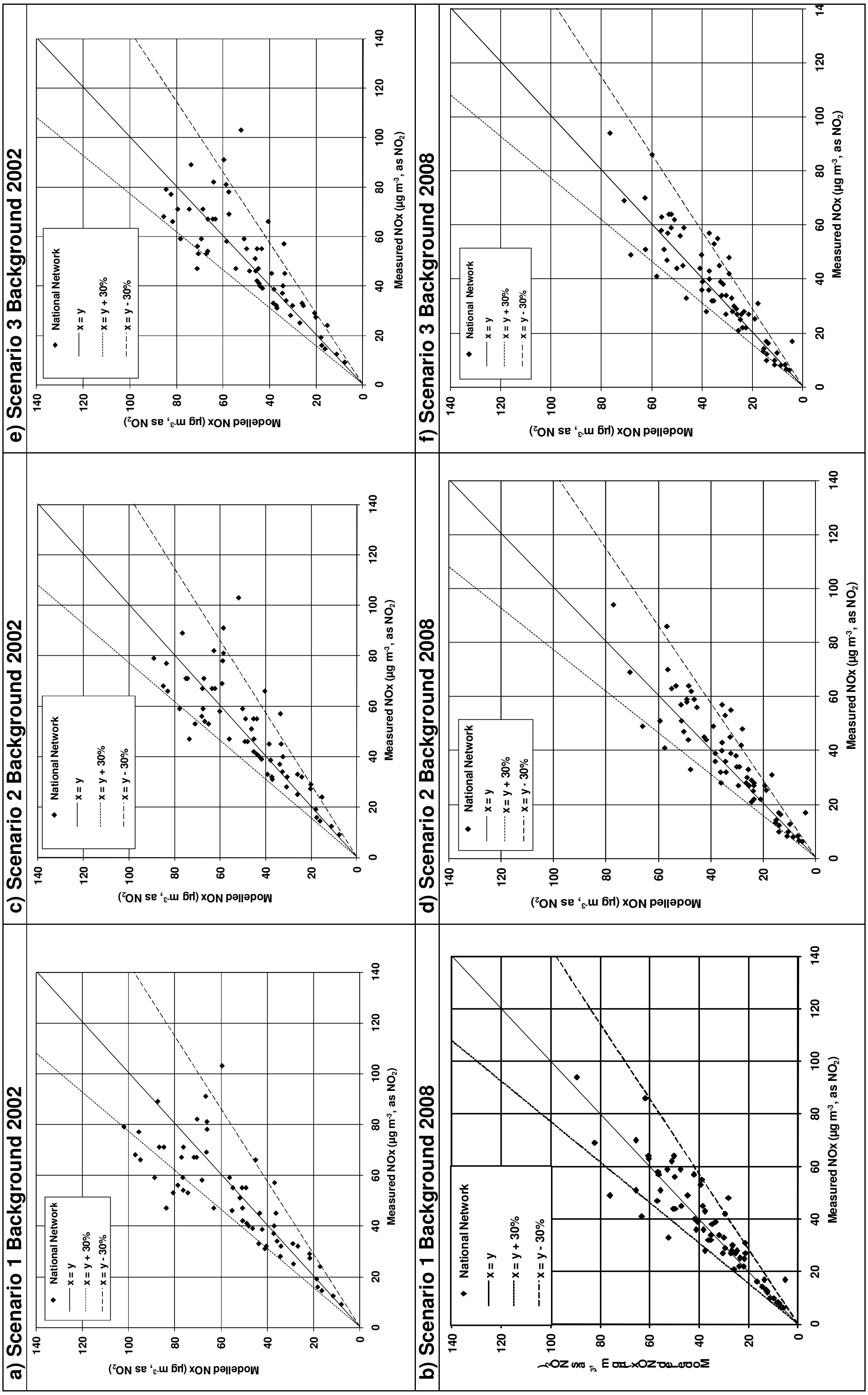


Figure D.1: Model verification plots in background locations.

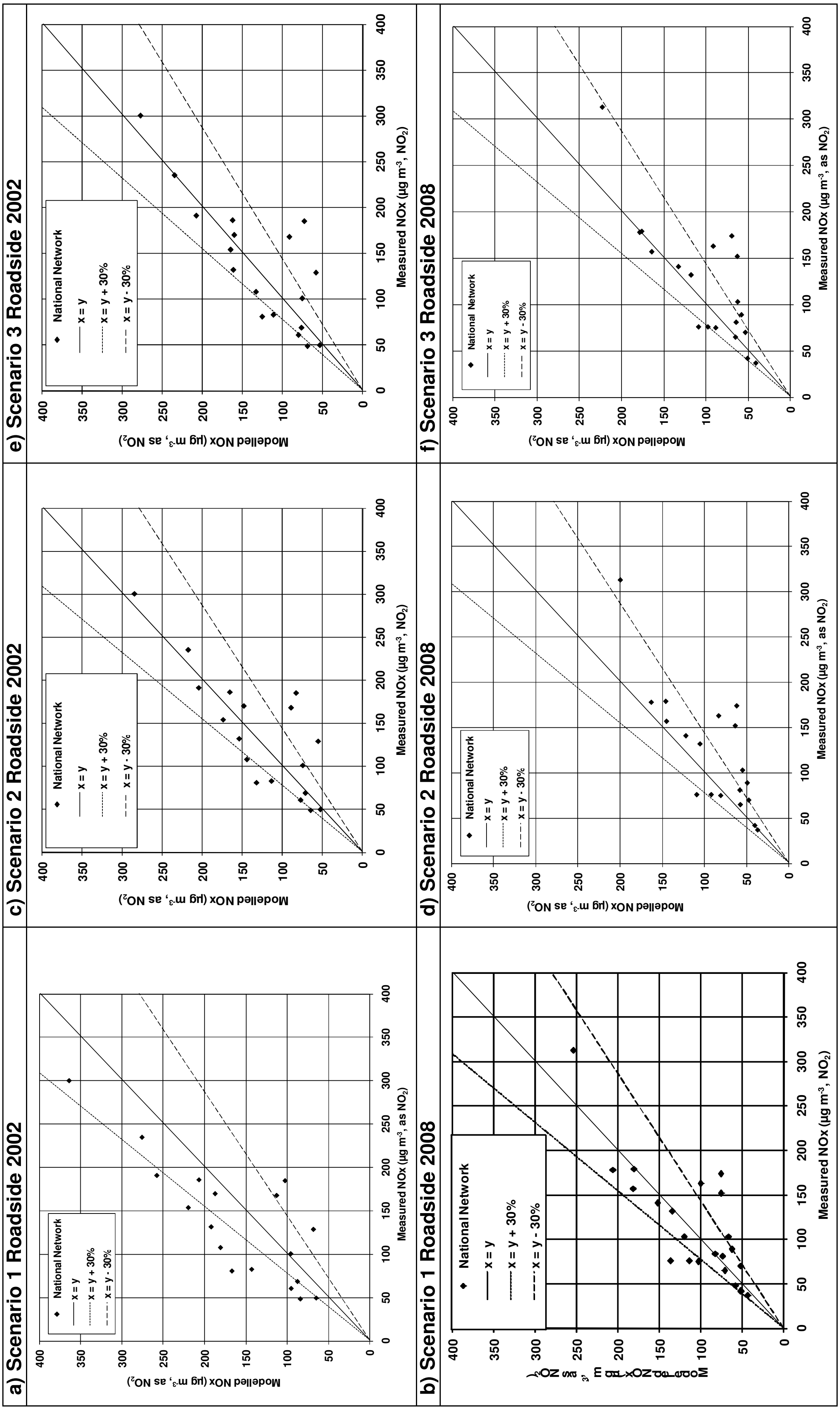


Figure D.2: Model verification plots in roadside locations.

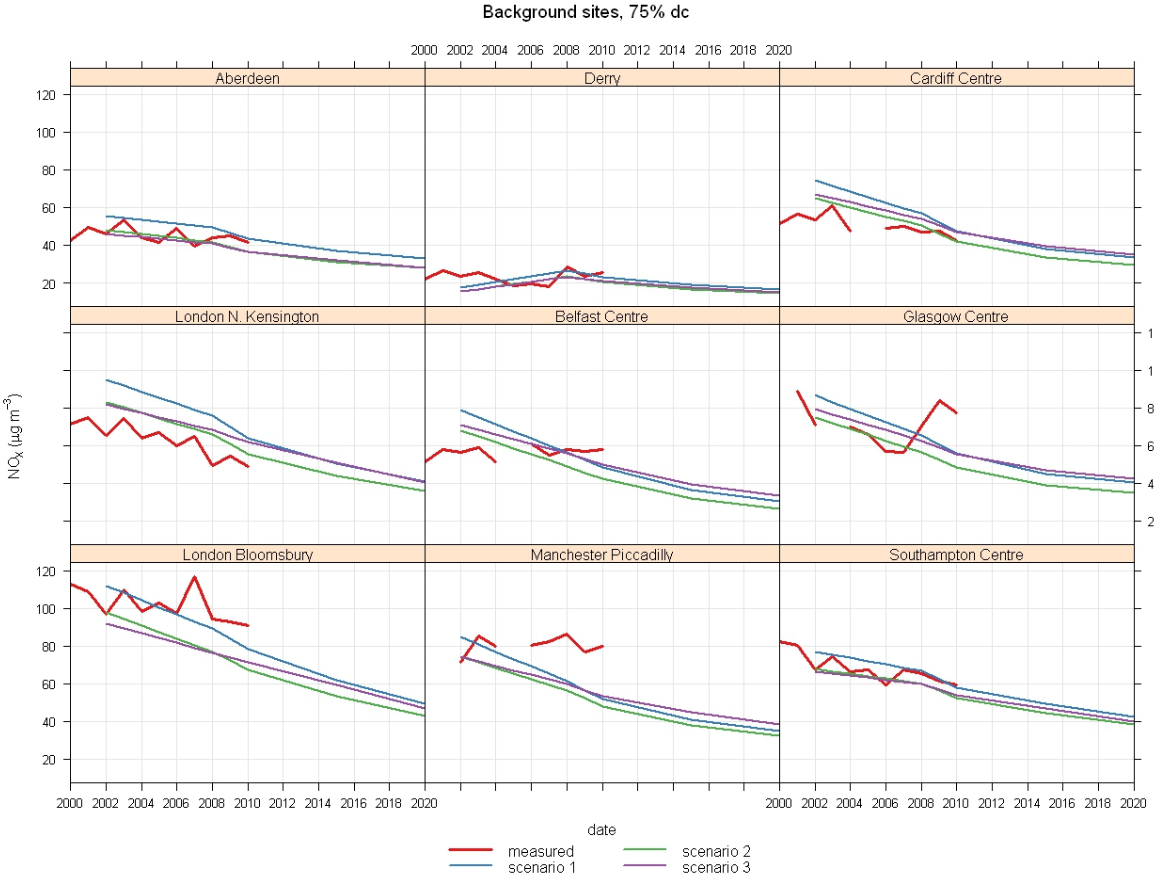


Figure D.3: Comparison of measured and modelled NO_x concentrations for background sites.

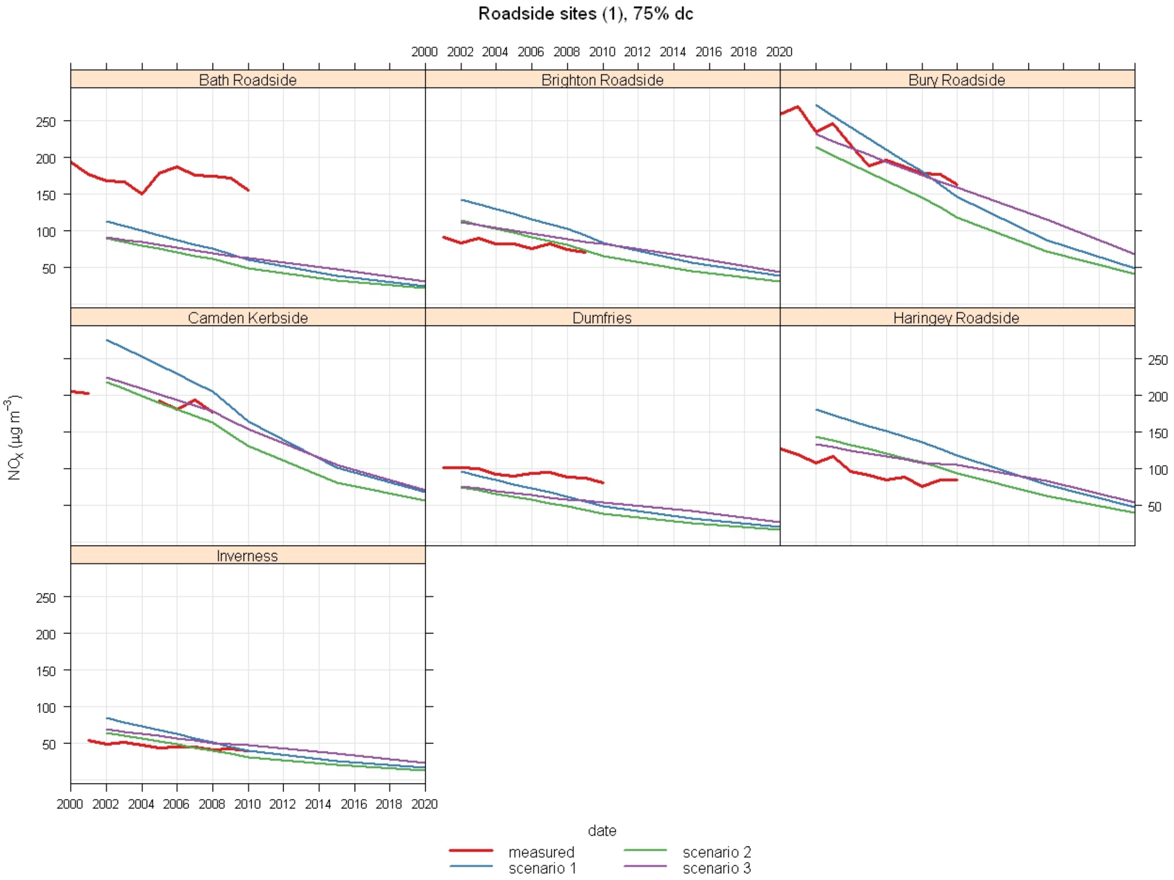


Figure D.4: Comparison of measured and modelled NO_x concentrations for roadside sites.

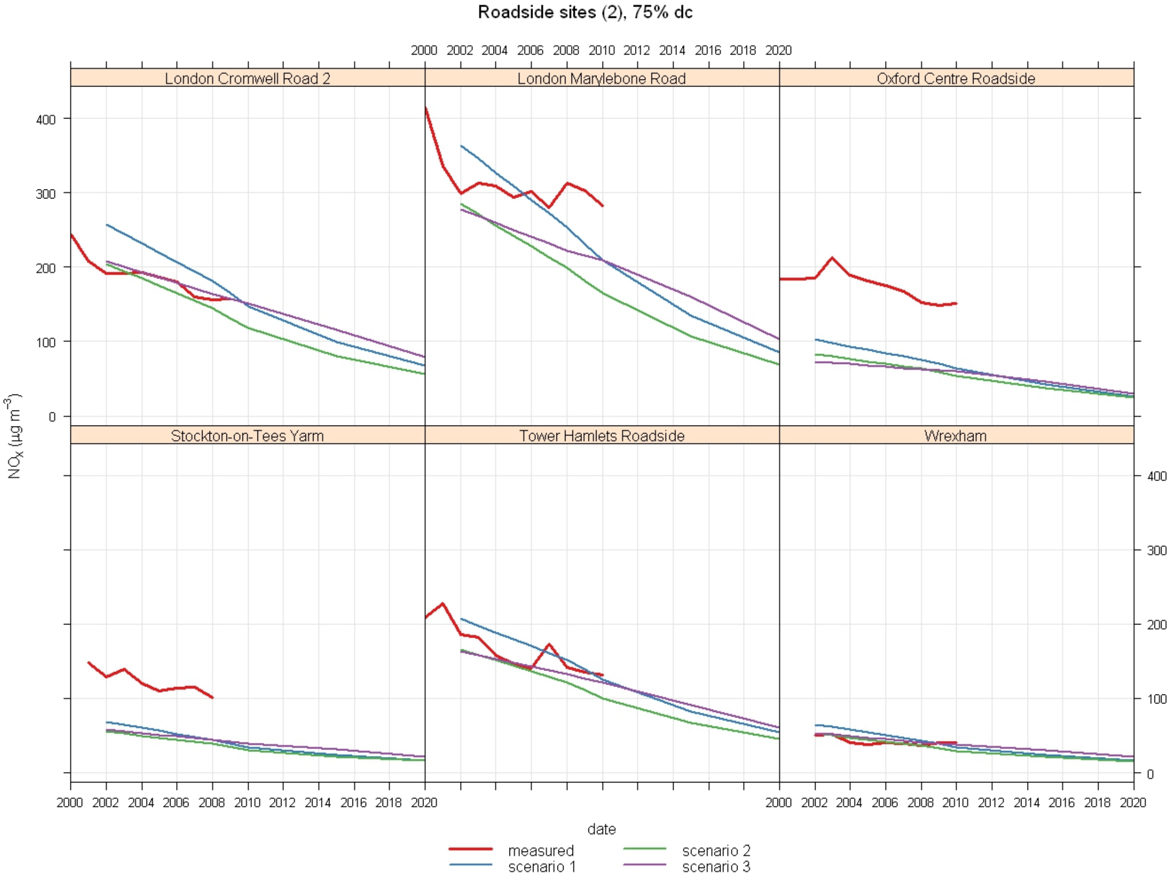


Figure D.5: Comparison of measured and modelled NO_x concentrations for roadside sites (continued).

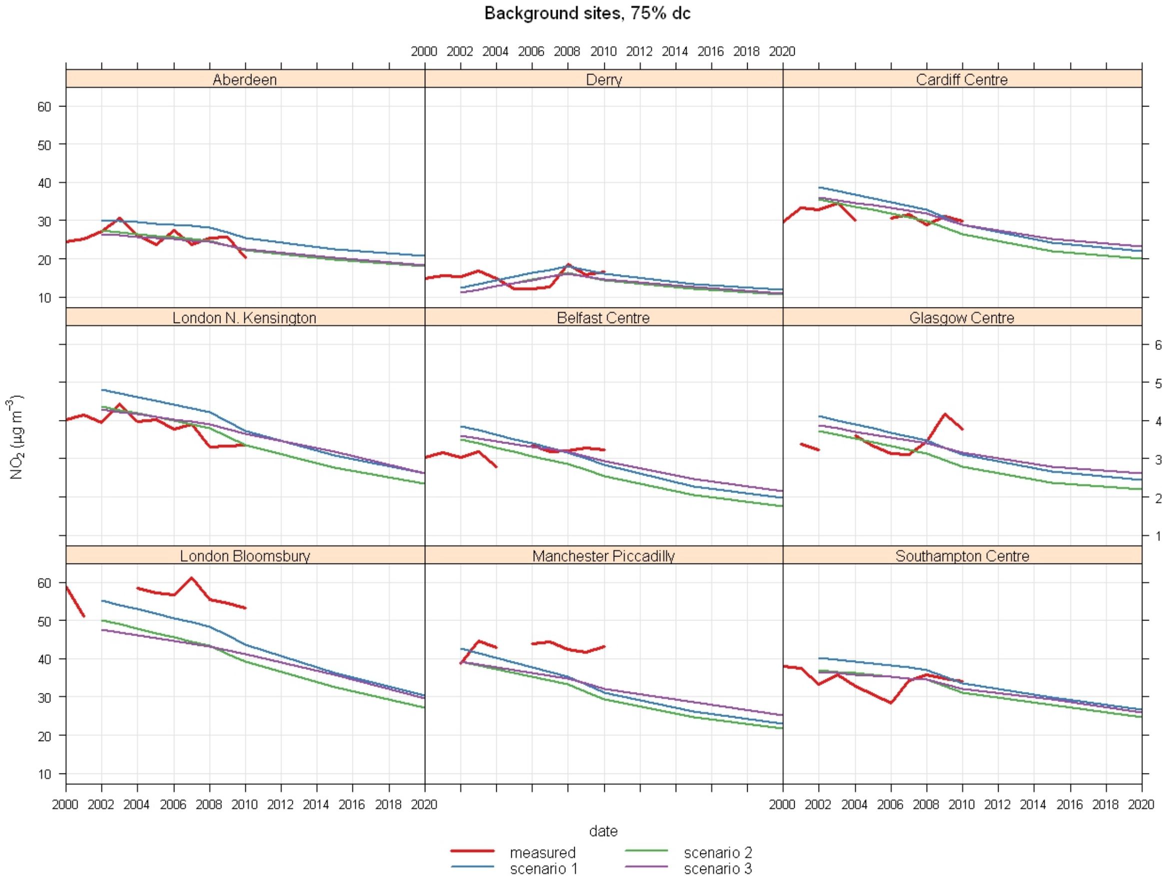


Figure D.6: Comparison of measured and modelled NO_2 concentrations for background sites.

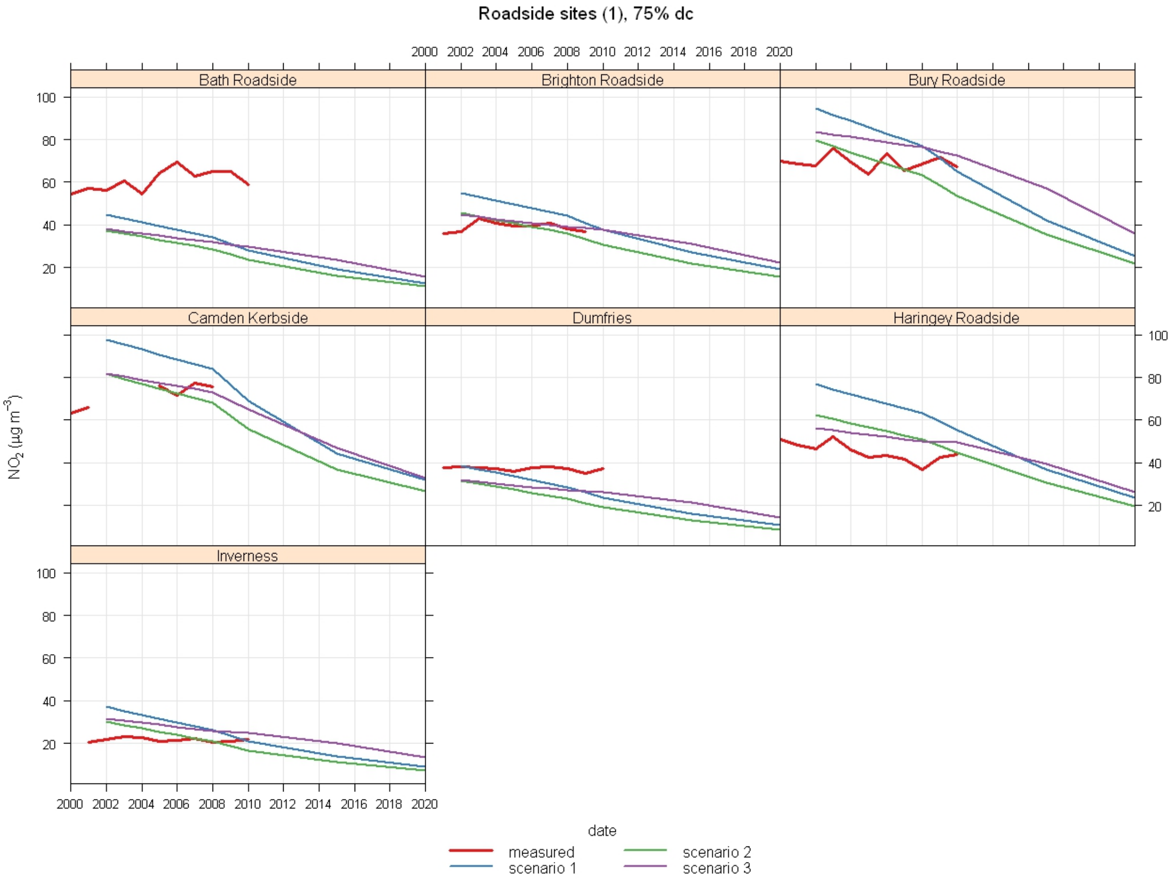


Figure D.7: Comparison of measured and modelled NO$_2$ concentrations for roadside sites.

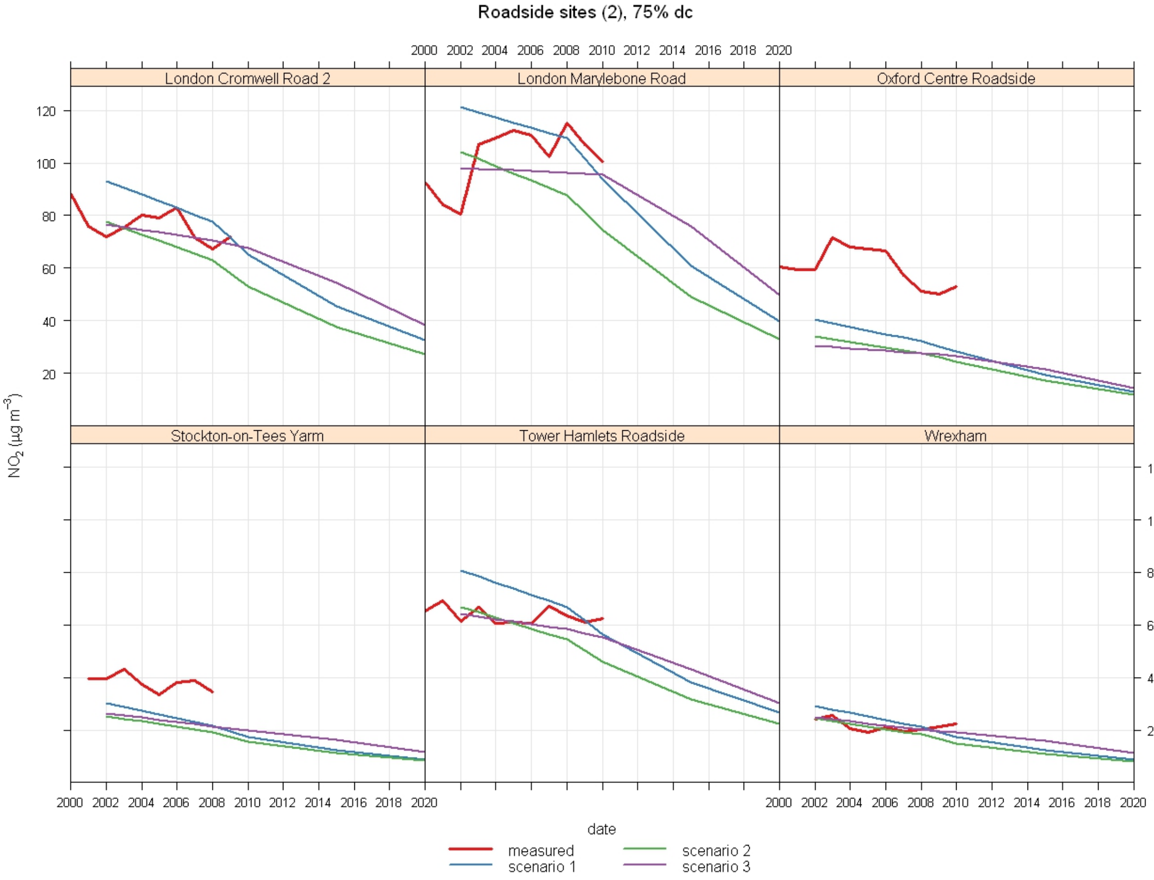


Figure D.8: Comparison of measured and modelled NO_2 concentrations for roadside sites (continued).

Table D.1: Modelled road length (km) exceeding 40 µg m^{-3} by zone and by year.

			Scenario 1					Scenario 2					Scenario 3				
	zone	total assessed	2002	2008	2010	2015	2020	2002	2008	2010	2015	2020	2002	2008	2010	2015	2020
1	Greater London Urban Area	1890.40	1746.10	1286.70	885.30	267.40	23.90	1421.60	847.50	516.60	92.80	0.90	1432.80	991.90	883.80	449.80	67.80
2	West Midlands Urban Area	552.20	496.60	265.30	148.20	35.20	0.00	356.40	155.00	72.10	5.10	0.00	325.50	188.20	147.90	61.50	3.00
3	Greater Manchester Urban Area	661.00	565.40	260.50	107.70	2.70	0.00	404.10	114.40	51.20	0.00	0.00	382.20	164.80	125.50	60.80	0.00
4	West Yorkshire Urban Area	423.90	314.40	109.90	50.10	3.30	0.00	174.10	54.90	18.30	0.00	0.00	163.30	74.00	63.50	24.80	0.00
5	Tyneside	206.00	131.80	55.70	30.90	4.90	0.00	73.20	31.70	13.20	0.00	0.00	71.20	43.30	37.20	14.20	0.00
6	Liverpool Urban Area	216.70	170.40	72.30	36.10	0.20	0.00	103.20	36.20	11.80	0.10	0.00	87.00	43.60	36.80	6.60	0.00
7	Sheffield Urban Area	160.30	143.00	58.20	35.80	0.70	0.00	103.10	40.00	16.50	0.00	0.00	86.50	47.40	38.20	11.10	0.00
8	Nottingham Urban Area	134.00	102.30	45.10	13.20	0.00	0.00	62.00	19.60	3.90	0.00	0.00	71.50	34.80	28.30	4.70	0.00
9	Bristol Urban Area	116.20	82.30	31.80	15.30	0.30	0.00	46.10	15.30	3.00	0.00	0.00	47.10	25.10	17.80	7.30	0.00
10	Brighton/Worthing/Littlehampton	88.90	31.70	3.20	0.00	0.00	0.00	3.50	0.00	0.00	0.00	0.00	12.60	0.60	0.00	0.00	0.00
11	Leicester Urban Area	81.30	75.40	24.10	7.60	0.00	0.00	49.90	8.50	0.60	0.00	0.00	56.70	17.10	11.20	1.40	0.00
12	Portsmouth Urban Area	75.30	46.20	13.60	9.50	0.00	0.00	26.50	9.50	2.90	0.00	0.00	30.30	10.20	9.50	6.70	0.00
13	Teesside Urban Area	73.60	38.20	15.70	13.20	6.10	0.00	21.10	13.80	7.30	1.10	0.00	24.00	13.80	13.80	9.00	0.00
14	The Potteries	129.00	72.80	23.00	17.70	6.10	0.00	39.30	18.30	12.90	0.00	0.00	42.90	18.90	18.30	12.90	0.00
15	Bournemouth Urban Area	72.10	36.10	12.00	5.20	0.00	0.00	13.30	5.20	0.00	0.00	0.00	18.10	10.90	9.80	2.30	0.00
16	Reading/Wokingham Urban Area	76.80	35.70	9.00	1.50	0.00	0.00	16.80	1.50	0.00	0.00	0.00	18.20	4.70	1.50	0.50	0.00
17	Coventry/Bedworth	36.00	31.80	10.60	0.80	0.00	0.00	19.40	1.60	0.00	0.00	0.00	19.00	4.50	1.90	0.00	0.00
18	Kingston upon Hull	60.10	48.90	31.70	19.70	0.00	0.00	39.00	22.10	9.90	0.00	0.00	39.00	29.70	23.10	9.90	0.00
19	Southampton Urban Area	63.70	47.40	21.50	14.90	2.10	0.00	23.60	13.00	10.70	0.00	0.00	27.20	18.80	13.00	11.20	0.00
20	Birkenhead Urban Area	73.40	34.40	13.00	1.50	0.00	0.00	18.30	1.50	1.50	0.00	0.00	14.10	1.50	1.50	0.00	0.00
21	Southend Urban Area	50.60	24.80	8.70	2.90	0.00	0.00	10.90	2.90	0.00	0.00	0.00	10.90	8.70	4.40	0.00	0.00
22	Blackpool Urban Area	64.80	10.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	Preston Urban Area	47.40	31.30	3.50	0.00	0.00	0.00	13.20	0.00	0.00	0.00	0.00	18.50	1.70	1.00	0.00	0.00
24	Glasgow Urban Area	300.60	178.80	75.90	43.90	7.70	0.00	89.50	42.50	16.20	0.00	0.00	76.90	52.20	51.30	30.80	0.00
25	Edinburgh Urban Area	102.30	54.90	13.90	9.40	0.00	0.00	17.00	8.00	6.40	0.00	0.00	17.70	11.20	8.00	0.00	0.00
26	Cardiff Urban Area	59.10	36.70	18.40	9.60	0.00	0.00	21.50	11.10	0.90	0.00	0.00	23.10	16.60	12.50	0.50	0.00
27	Swansea Urban Area	65.10	22.00	2.50	0.00	0.00	0.00	6.70	0.00	0.00	0.00	0.00	9.80	2.50	0.00	0.00	0.00
28	Belfast Metropolitan Urban Area	158.40	68.00	36.40	13.30	0.00	0.00	37.80	13.30	12.40	0.00	0.00	38.20	32.40	24.60	0.00	0.00
29	Eastern	866.00	351.00	110.80	77.60	21.40	0.00	145.90	78.00	44.00	0.00	0.00	162.60	96.50	89.60	50.60	0.00
30	South West	648.90	210.00	62.40	24.80	0.00	0.00	89.20	24.20	5.60	0.00	0.00	107.40	49.10	35.80	9.30	0.00
31	South East	1303.00	495.60	163.10	97.60	4.90	0.00	216.40	98.20	53.40	0.00	0.00	258.40	135.40	111.00	71.80	0.00
32	East Midlands	696.30	260.40	82.50	36.40	1.70	0.00	121.70	38.20	23.60	0.00	0.00	142.00	60.80	46.80	24.70	0.00
33	North West & Merseyside	970.70	487.80	209.70	130.60	26.50	0.00	279.40	132.10	83.40	0.00	0.00	299.20	189.00	167.30	111.10	0.00
34	Yorkshire & Humberside	754.80	409.20	230.50	181.00	82.80	0.00	278.10	184.30	161.80	27.40	0.00	268.30	209.50	188.30	151.70	2.60
35	West Midlands	544.40	217.60	76.30	40.90	11.80	0.00	111.00	40.90	24.70	0.00	0.00	128.20	58.40	57.00	20.80	0.00
36	North East	289.30	149.80	52.70	28.40	5.00	0.00	78.90	27.30	11.30	0.00	0.00	75.90	35.00	32.50	11.30	0.00
37	Central Scotland	360.90	66.40	24.10	7.70	0.00	0.00	29.70	7.70	4.90	0.00	0.00	31.00	10.40	9.30	3.10	0.00
38	North East Scotland	230.40	54.00	18.40	4.80	0.00	0.00	30.40	3.30	0.00	0.00	0.00	30.70	14.00	9.70	0.00	0.00
39	Highland	32.40	3.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.30	0.00	0.00	0.00	0.00
40	Scottish Borders	47.30	1.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41	South Wales	321.10	89.60	32.40	15.70	0.90	0.00	42.20	15.70	9.50	0.90	0.00	48.40	23.30	17.10	12.50	0.00
42	North Wales	156.00	21.20	11.00	10.20	0.00	0.00	11.70	10.20	0.00	0.00	0.00	13.60	10.20	10.20	4.30	0.00
43	Northern Ireland	348.90	94.30	26.70	14.20	0.00	0.00	36.70	11.40	11.40	0.00	0.00	37.30	14.20	14.20	0.00	0.00