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AN INVESTIGATION OF DIFFERENT APPROACHES TO COMPLIANCE ASSESSMENT IN THE AIR QUALITY DIRECTIVE 2008/50/EC

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Executive summary

1. This report investigates different approaches to compliance assessment under the 2008/50/EC Air Quality Directive, focussing on the annual mean limit value for NO_2 of 40 µg m^{-3}.
2. First, the report considers the measured distributions of NO_2 and PM_{10} from the Airbase database for 2010 for the UK, Germany, France and Italy. It is shown that in the case of annual mean NO_2 concentrations, the distributions of concentration are similar across the four countries. Furthermore, adjusting for the proportions of different site types improves the agreement between the distributions. It is also found that the UK has a similar relationship between NO_x and NO_2 concentrations compared with other countries. These results show that the UK measurement network for NO_2 is similar to other large member states with respect to capturing the concentration distributions. Supplementary evidence from emission inventories and satellite data confirms these findings.
3. Currently the UK supplements measured data with modelled predictions in its compliance assessments, which is equivalent to monitoring everywhere across the UK. This approach results in the UK reporting that 40 out of 43 (93%) zones exceed the annual mean NO_2 Limit Value for 2010; a proportion that is much higher than other large Member States such as France (30%), Italy (36%) and Germany (62%). A key question addressed in this report is how the number of zones exceeding differ between the two approaches to compliance assessment – using monitoring data only, or supplementing monitoring with modelling.
4. Simulations have been undertaken to address this issue using the UK as an example. An approach has been developed based on supplementing existing measurements with additional predictions drawn from the UK compliance assessment model (Pollution Climate Mapping (PCM)). The combination of existing measurements and model predictions simulates the effect of the UK having a larger measurement network, which would be required were a monitoring-only approach to be used.
5. Based on the UK network for compliance assessment in 2010 it is shown that 8 zones out of 43 would exceed the annual mean limit value based on a 90% data capture threshold. It can be shown that if the UK were to increase the number of measurement sites to 153 (the minimum required by the Air Quality Directive criteria in the absence of supplementary assessment methods, such as modelling, being available) then it would be expected that 13 zones (range 8 to 21) would exceed the limit value.
6. If the UK had a similar number of measurement sites to other large European countries (400 to 500 sites) the expected number of zones exceeding would be 22

(range 14 to 32 for 400 sites) or 26 (range 16 to 34 for 500 sites), respectively. For all these scenarios, the number of zones exceeding the limit value is far fewer than the current UK situation of relying on *all* modelled data to make up the number of sites.

7. Expressed another way, the use of modelled data to supplement monitored data potentially reveals much more information about the totality of concentrations across the territory of a Member State and hence more information on potential exceedances of the limit value than from monitoring alone, even if the monitoring requirements of the Directive are complied with. Moreover, another important aspect of these findings is that the use of modelling in compliance assessment potentially gives a more robust assessment of the time period for which one or more parts of a zone are in exceedence than a monitoring approach alone.
8. A more limited assessment of PM_{10} concentrations has been undertaken. These results reveal how sensitive the number of zones exceeding is to how close measurement sites are to the limit value. In the case of PM_{10}, the number of zones exceeding an annual mean concentration of 40 µg m^{-3} is not sensitive to the simulated number of measurement sites because they all recorded concentrations <40 µg m^{-3} – and hence adding more sites would not change the number of zones exceeding.
9. The analysis presented here, combining the use of modelling and monitored data with the spatial analysis by zones also provides a potentially valuable tool for the optimisation of current network structures. It provides valuable information on optimal locations for any extensions to existing networks which can be used alongside other site selection criteria such as overall network design and the availability of suitable sites.

Contents

1. Introduction

The EU Air Quality Directive 2008/50/EC, in Article 6.2, permits Member States to assess compliance using monitoring of air pollutant concentrations, supplemented by modelling and/or the use of 'indicative' measurements, in zones and agglomerations where levels exceed the upper assessment threshold for a given pollutant.[1] The use of modelling to supplement monitoring will, in general, cover more of the territory of a Member State in those zones and agglomerations, and will therefore tend to reveal higher areas of exceedance of thresholds than information derived purely from monitoring. This report assesses the implications for compliance assessment of using (a) monitoring data only and (b) a combined approach using modelling to supplement monitoring. The work will focus largely on the UK since the UK is the main Member State to assess compliance using the modelling option. In the last year, the Netherlands has also assessed compliance using a model as well as monitoring data, and some information is also available from this source.

The Directive also allows Member States discretion in defining the 'zones' in each Member State where compliance assessments and reporting have to be carried out. The number and size of zones across the 27 Member States therefore varies considerably which complicates any comparative assessment of the two approaches to compliance assessment across the EU.

This factor, together with the fact that a single 'hot spot' exceedance in one zone renders the whole zone non-compliant further complicates a comparative assessment and can give a misleading impression of the extent of a Member States compliance across its whole territory. However, a potentially more important factor in determining the 'headline' figure of the number of zones exceeding limit values is the choice between compliance assessments based purely on monitoring and those using supplementary modelling. The adoption of these different approaches can lead to a distorted picture across Member State which may not reflect the reality of the comparative levels and distribution of air quality in the respective Member State.

This report further seeks to address the way in which air quality levels and distributions across major Member State are different in reality compared with the differing impressions given by the 'headline' figure of zones in exceedance.

The two approaches have their strengths and weaknesses. Monitoring data are generally a more accurate measure of air quality at a specific point than is modelling. Models will, in general need some form of calibration, or an alternative evaluation of accuracy and performance to ensure they are sufficiently robust to use. Monitoring however is expensive and it inevitably is unable to cover the whole of the territory of a Member State. Models are

[1] A combination of fixed measurements and supplementary methods may also be used in zones where the levels are between the upper and lower assessment thresholds. Modelling or objective estimation are sufficient if levels are below the lower assessment threshold.

capable of covering the whole territory of a Member State and can offer an assessment of compliance 'throughout their zones and agglomerations' as required by Article 13 of the Directive as noted above. Although models are usually limited by grid size, they can be supplemented by small-scale models to adequately model concentrations around busy roads. Having considered these issues, the FAIRMODE[2] group has recently published a document on the use of models for regulatory purposes and for air quality policy, in which they recommend the use of models for "Assessment of air quality levels to establish the extent of exceedances and establish population exposure".

This report addresses both PM_{10} and NO_2, the two pollutants where compliance across the EU is most difficult to achieve. The report is based on a detailed analysis of the Airbase database for 2010, and comparisons are made for the 4 largest Member States, namely the UK, France, Germany and Italy. The PM_{10} analysis has been complicated to an extent by the different measurement methods in use across the EU Member States. The analysis has also compared the distributions of different site types – urban background, suburban, traffic and industry in the four Member States. A comparison of the distributions of modelled and measured concentrations gives a good indication of the extent to which modelling might affect the extent of non-compliance.

Emission inventory and satellite data potentially provide further useful information which can supplement that obtained from analysis of the measured data. In a short project such as this the extent of the analysis that can be undertaken is limited, but a comparison is made between emission inventories in Member States (particularly for road transport) and satellite data to assess differences between the Member States.

2. A comparison of the two approaches to compliance assessment for NO_2

This section brings together various pieces of information relating to the differences between compliance assessments based on a combination of measurements and modelling and assessments based on measurements only for NO_2. The UK is used as an example as detailed data are available. Comparisons are presented of annual mean compliance assessment reported for 2009 with an assessment based on a combination of measurements from UK (AURN)[3] monitoring stations and monitoring stations identified with overall suitability rating A in the 2009 suitability assessment report[4].

Table A1 (see Annex A) shows this comparison. A total of 40 zones were identified as in exceedance in the assessment reported for 2009 (i.e. monitoring plus modelling approach). A total of 13 zones would have been identified as in exceedance if measurements including those identified in the suitability assessment had been used as the sole source of information i.e. a monitoring approach only. A total of 9 zones would have been identified as in exceedance if measurements from the AURN only had been used as the sole source of

[2] Forum for Air quality Modelling (http://fairmode.ew.eea.europa.eu/)
[3] Automatic Urban and Rural Network – the main network used for compliance reporting against the Ambient Air Quality Directives
[4] Local Authority monitoring stations that broadly satisfy the location requirements of the Directive but are not in the formal UK monitoring network.

information. The compliance gap (maximum annual mean NO_2 concentration minus 40 µg m^{-3}) is also shown.

To make preliminary comparisons with the compliance situation and NO_2 concentrations in other Member States, information from the '461' EU annual reporting questionnaire for 2010 has been collected from all of the questionnaires available on the EU Central Data Repository on 8 December 2011. Questionnaires were found for all countries except Finland and Malta.

The following tables summarise the reported compliance status for the 1-hour and annual mean limit values for NO_2 for each member state.

Table 1 shows the compliance status by zone for both limit values. Only the UK has made extensive use of supplementary assessment methods for the annual mean limit value. (Slovakia reported 'm' for one zone; The Netherlands revised their '461' EU annual reporting questionnaire for 2010 to include model results for several zones on 15/12/2011, which was after this analysis was carried out, see section 3). Austria, Germany, Sweden and the UK have the largest percentages of zones with reported exceedances of the annual mean limit value but note that zones may have been assigned in different ways in Member States. Bulgaria and Denmark have the largest percentages of zones with reported exceedances of the 1-hour limit value. The information in this table has been derived from Form 8b of the questionnaire.

Table 2 summarises the information provided in form 11e on measured exceedances of the **1-hour limit value**. The Member States with the largest number of stations with exceedances of this limit value are Germany, France and the UK, but note the large number of monitoring sites in Germany and France. The maximum number of exceedances recorded was also largest in these Member States.[5]

Table 3 summarises the information provided in form 11f on measured exceedances of the **annual mean limit value**. The Member States with the largest number of stations with exceedances of this limit value are Germany, Italy, France and Spain, but note the large number of monitoring sites in these Member States. The Member States with the largest percentage of stations with exceedances of this limit value are Sweden and Germany. The highest maximum concentrations were reported in Italy, Germany, the UK and France. Most of the exceedances of the annual mean limit value have been assigned to either S2 (Proximity to a major road), S1 (Heavily trafficked urban centre) or a combination of S1 and S2. Poland also reported some exceedances due to S9 (winter sanding of roads), which looks like a mistake. Italy reported some exceedances due to various combinations of combination of S1, S5, S6 (Accidental emission from industrial source), S7 (Accidental emission from non-industrial source) and S11 (Local petrol station). Latvia also reported exceedances due to S3 and S10 (Transport of air pollution originating from sources outside the Member State). Belgium reported exceedances due to S3, S10 and locally defined

[5] Slovakia appears to have filled in this form incorrectly in that fewer than the 18 permitted exceedances are reported.

codes. The Czech Republic and Slovakia also reported exceedances due to locally defined codes.

Table 1 Summary of exceedance status in 2010 for 1-hour and annual mean NO_2 concentrations from available '461' questionnaires. Compiled 8/12/2011.

Member State	Code	Count of zones	Zones with 1-hour exceedance	Zones with annual exceedance	Percentage of zones with 1-hour exceedances	Percentage of zones with annual exceedances
Austria	AT	11	0	9	0%	82%
Belgium	BE	11	0	3	0%	27%
Bulgaria	BG	6	2	2	33%	33%
Cyprus	CY	1	0	0	0%	0%
Czech Republic	CZ	15	1	4	7%	27%
Denmark	DK	3	1	1	33%	33%
Estonia	EE	4	0	0	0%	0%
Finland	FI	-	-	-	-	-
France	FR	76	4	23	5%	30%
Germany	DE	98	5	61	5%	62%
Greece	EL	4	0	1	0%	25%
Hungary	HU	10	0	2	0%	20%
Ireland	IE	4	0	1	0%	25%
Italy	IT	128	3	46	2%	36%
Latvia	LV	2	0	1	0%	50%
Lithuania	LT	3	0	0	0%	0%
Luxembourg	LU	3	0	1	0%	33%
Malta	MT	-	-	-	-	-
Netherlands*	NL	9	0	9	0%	100%
Poland	PL	46	0	3	0%	7%
Portugal	PT	20	1	3	5%	15%
Romania	RO	21	1	2	5%	10%
Slovakia	SK	10	0	2	0%	20%
Slovenia	SI	6	0	0	0%	0%
Spain	ES	134	1	9	1%	7%
Sweden	SE	6	0	4	0%	67%
United Kingdom	UK	43	3	40	7%	93%

461 questionnaires for 2010 were not available on the CDR for Malta and Finland at time of compilation. Revised results reported on 15/12/2012.

Table 2 Summary of number of NO_2 stations with exceedances of the 1-hour limit value in 2010 from available '461' questionnaires. Compiled 8/12/2011.

Member State	Code	Count of NO_2 stations	Count of stations with exceedance of annual mean limit value	Percentage of NO_2 stations with annual mean exceedance	Maximum concentration at stations with exceedance ($\mu g\ m^{-3}$)	Mean concentration at stations with exceedance ($\mu g\ m^{-3}$)	Maximum number of exceedances at stations with exceedance	Average number of exceedances at stations with exceedance
Austria	AT	158	0	0%	n/a	n/a	n/a	n/a
Belgium	BE	76	0	0%	n/a	n/a	n/a	n/a
Bulgaria	BG	25	2	8%	365.6	250.8	34	32.0
Cyprus	CY	2	0	0%	n/a	n/a	n/a	n/a
Czech Republic	CZ	89	1	1%	281.6	223.0	56	56.0
Denmark	DK	13	0	0%	n/a	n/a	n/a	n/a
Estonia	EE	9	0	0%	n/a	n/a	n/a	n/a
Finland	FI	-	-	-	-	-	-	-
France	FR	457	6	1%	333.0	223.8	181	72.0
Germany	DE	510	7	1%	413.0	226.3	379	131.1
Greece	EL	24	0	0%	n/a	n/a	n/a	n/a
Hungary	HU	24	0	0%	n/a	n/a	n/a	n/a
Ireland	IE	13	0	0%	n/a	n/a	n/a	n/a
Italy	IT	555	4	1%	353.7	222.7	88	44.3
Latvia	LV	5	0	0%	n/a	n/a	n/a	n/a
Lithuania	LT	14	0	0%	n/a	n/a	n/a	n/a
Luxembourg	LU	6	0	0%	n/a	n/a	n/a	n/a
Malta	MT	-	-	-	-	-	-	-
Netherlands	NL	70	0	0%	n/a	n/a	n/a	n/a
Poland	PL	138	0	0%	n/a	n/a	n/a	n/a
Portugal	PT	56	1	2%	255.3	217.9	21	21.0
Romania	RO	78	2	3%	358.0	243.8	45	34.5
Slovakia	SK	18	2	11%	221.6	208.1	5	3.0
Slovenia	SI	11	0	0%	n/a	n/a	n/a	n/a
Spain	ES	551	4	1%	435.0	234.1	76	38.8
Sweden	SE	10	1	10%	337.0	233.5	80	80.0
United Kingdom	UK	116	5	4%	1209.0	240.4	539	168.4

461 questionnaires for 2010 were not available on the CDR for Malta and Finland at time of compilation

Table 3 Summary of number of NO_2 stations with exceedances of the annual mean limit value in 2010 from available '461' questionnaires. Compiled 8/12/2011.

Member State	Code	Count of NO_2 stations	Count of stations with exceedance of annual mean limit value	Percentage of NO2 stations with annual mean exceedance	Maximum concentration at stations with exceedance ($\mu g\ m^{-3}$)	Mean concentration at stations with exceedance ($\mu g\ m^{-3}$)
Austria	AT	158	19	12%	67.5	49.6
Belgium	BE	76	7	9%	54.0	44.9
Bulgaria	BG	25	2	8%	53.4	51.0
Cyprus	CY	2	0	0%	n/a	n/a
Czech Republic	CZ	89	8	9%	67.3	48.8
Denmark	DK	13	1	8%	56.0	56.0
Estonia	EE	9	0	0%	n/a	n/a
Finland	FI	-	-	-	-	-
France	FR	457	46	10%	96.0	55.0
Germany	DE	510	183	36%	100.0	53.5
Greece	EL	24	5	21%	83.0	53.0
Hungary	HU	24	2	8%	49.4	48.6
Ireland	IE	13	0	0%	n/a	n/a
Italy	IT	555	98	18%	102.0	52.5
Latvia	LV	5	1	20%	41.7	41.7
Lithuania	LT	14	0	0%	n/a	n/a
Luxembourg	LU	6	1	17%	59.5	59.5
Malta	MT	-	-	-	-	-
Netherlands	NL	70	4	6%	50.9	44.1
Poland	PL	138	3	2%	70.4	66.8
Portugal	PT	56	8	14%	64.9	47.7
Romania	RO	78	4	5%	65.0	51.2
Slovakia	SK	18	2	11%	62.5	55.7
Slovenia	SI	11	0	0%	n/a	n/a
Spain	ES	551	42	8%	68.0	47.0
Sweden	SE	10	7	70%	59.4	46.1
United Kingdom	UK	116	20	17%	98.0	57.6

461 questionnaires for 2010 were not available on the CDR for Malta and Finland at time of compilation

It is clear from Table A1 that the use of modelling to supplement the UK monitoring data greatly increases the number of zones which are non-compliant.

The robustness of these conclusions has been assessed through more detailed analysis of the actual concentrations and their distribution in the UK and other Member States through use of the Airbase data base. Moreover, the use of these data has allowed further conclusions to be drawn regarding the use of modelling and monitoring for compliance assessment and these are described in the following sections.

3. Distributions of monitoring site types in Member States for NO_2

The relative impact of the two approaches to compliance assessment will depend amongst other things on the distribution of monitoring site types in a given Member State. An important issue is whether there is evidence that there are differences between the distributions of site types in Member States. To understand this issue more, AURN measurements for 2010 have been compared with measurements from other countries. For 2010, data from 81 AURN sites were available with at least *90% data capture* for NO_x and NO_2. Data from other European countries were obtained from Airbase (http://acm.eionet.europa.eu/databases/airbase/). Note that France only reports NO_2 concentrations and not NO_x. While data for all European countries were available, the focus here is on the four largest countries: the UK, France, Italy and Germany.

Figure 1 shows the proportion of sites by site type in each country (background, industrial and traffic). It is clear that France has a much higher proportion of background sites compared with other countries (over three quarters of the total). The UK also has a higher proportion of background sites compared with Italy and Germany. Note that the Air Quality Directive requires that the number of urban background and traffic stations in Member States should not differ by more than a factor of two[6].

[6] Annex V, A, 1 footnote (1) to table.

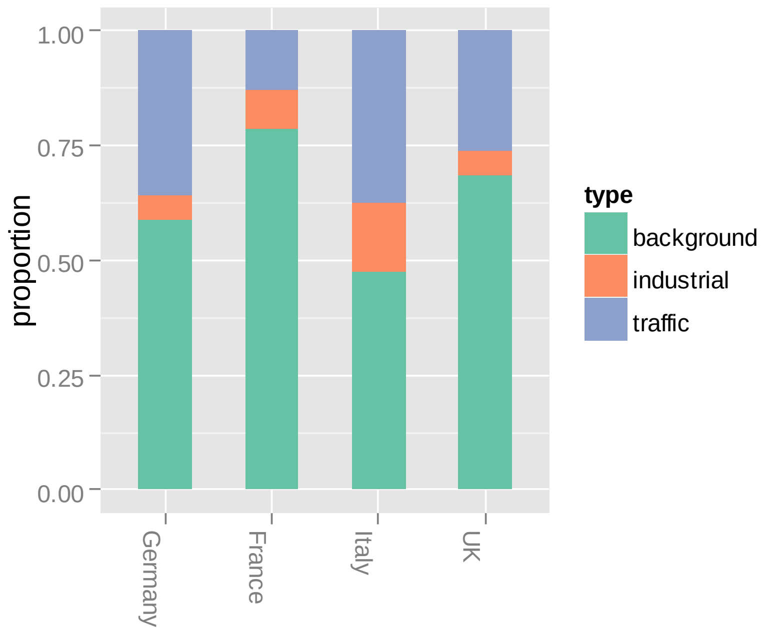

Figure 1 Proportion of sites by site type and country for NO_2.

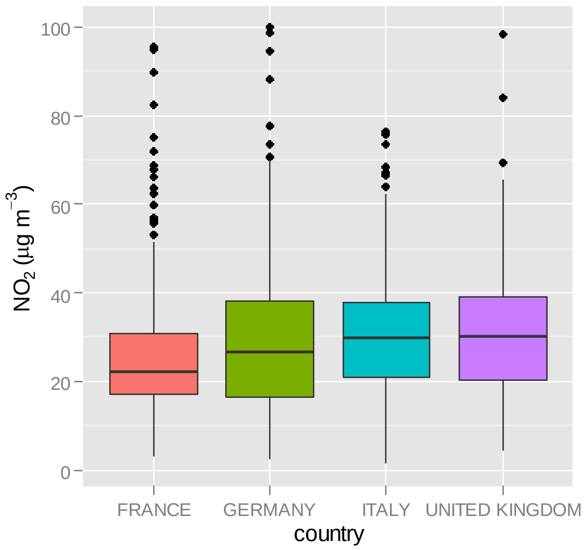

Figure 2 Box and whisker plot of NO_2 concentrations for four European member states.

One of the most useful ways to compare the distribution of concentrations is to use a box and whisker plot as shown in Figure 2. This Figure shows that the range in concentrations across the different countries is very similar e.g. up to a maximum concentration of about 100 µg m^{-3}). The distributions of the UK, Germany and Italy are very similar, but in France there is a higher proportion of sites recording lower NO_2 concentrations, which is due to the higher proportion of background site for France in the AIRBASE database. This finding is also confirmed by considering a density plot of concentrations, as shown in Figure 3. Overall the mean concentrations across all sites is as follows: UK: 31.7, Germany 29.1, Italy

30.7 and France 25.3 µg m^{-3}, which shows that the UK has a *slightly* higher overall NO_2 concentration across all its sites than Germany or Italy, while France is somewhat lower.

In terms of the proportion of sites exceeding 40 µg m^{-3}, the UK and Germany have 22%; Italy has 21% and France 11%. Again, the UK seems to be very similar to Germany and Italy, whereas France has a significantly lower proportion of sites exceeding the limit value.

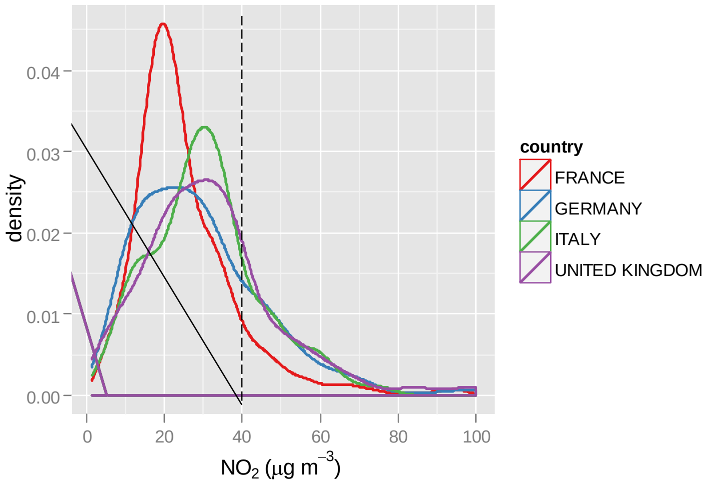

Figure 3 Distribution of NO_2 concentrations across four EU member states.

As noted in Figure 1 each country has a different proportion of site types. In particular, France has a much higher proportion of background sites compared with the other countries. We have re-analysed the distributions of NO_2 concentrations by accounting for the proportion of each site type in each country. Equal numbers of batches of random samples of background and traffic sites were taken in a proportion 2:1 to ensure there were the same numbers of background and traffic sites for each country. This analysis therefore gives an indication of the distribution of NO_2 expected if each country had one third traffic sites and two thirds background sites.

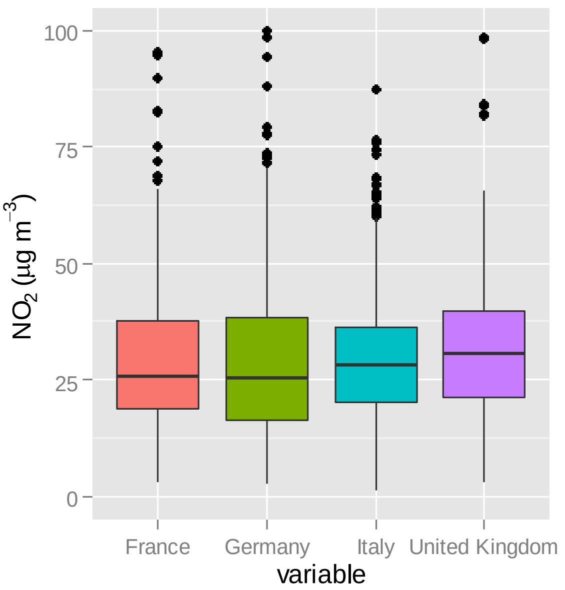

Figure 4 Distribution of NO_2 concentrations from a re-sampling approach that ensures the same proportion of background: traffic sites (2:1) in each country.

The distributions are shown in Figure 4 and can be compared with Figure 2. The distributions are much more even – in particular the mean values for France have now increased markedly. The means across the countries are France = 30, Germany = 29, Italy = 30 and UK = 32 µg m^{-3}. Furthermore, it can be shown in terms of the proportion of sites exceeding 40 µg m^{-3} the sites are very similar: Germany, France and the UK have 23% and Italy has 17% exceeding the limit value). **These results show that all four countries would be expected to have very similar distributions of NO_2 concentration if they had similar proportions of site type – and a very similar number of *measured* exceedances.**

Another important issue is whether for a particular concentration of NO_x the Member States have similar concentrations of NO_2. If any Member State was influenced by higher primary NO_2 road vehicle emissions, then such a relationship would help reveal these differences. Figure 5 shows the NO_2/NO_x ratio as a function for NO_x concentrations for the UK, Germany and Italy (the shading shows the uncertainty in the line fit). Overall, the three countries have very similar NO_2/NO_x ratios. France was not included in this plot as it doesn't report NO_x or NO data.

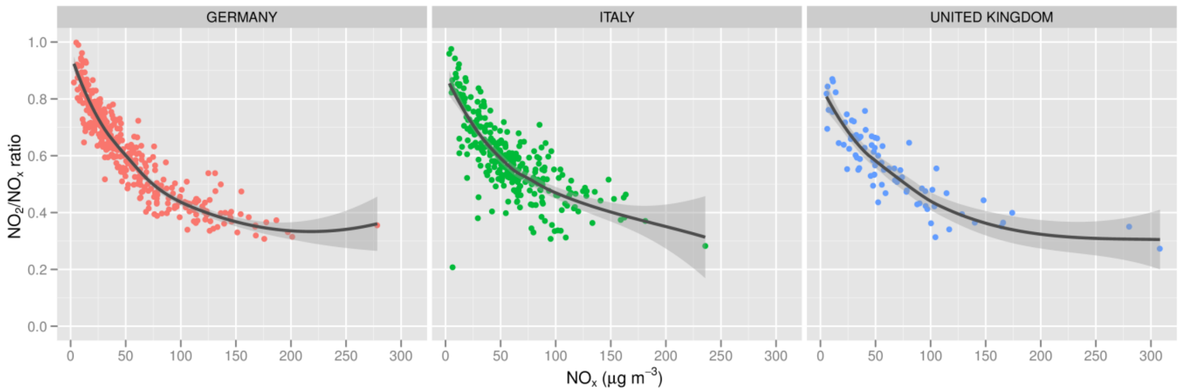

Figure 5 NO_2/NO_x ratios across three different EU member states.

What effect does the use of modelled data have on the number of zones exceeded?

This is a key question and is analysed here using the UK as an example. The analysis of measured data suggests there is little obvious difference between the four Member States as far as NO_2 and NO_x measured concentrations are concerned, with the exception of France which has a higher proportion of background sites measuring low values of NO_2.

We have investigated this issue in a comprehensive way through simulations which aim to quantify these effects. The data used in this analysis includes the measurement data from 81 UK measurement sites described above and the UK compliance assessment model roadside and background predictions for NO_x and NO_2 for 2010 (the version of the model recalibrated to incorporate revised emission factors for road traffic NOx emissions and fleet compositions data, known as 2010b). The UK compliance assessment model produces separate 'roadside' and 'background' predictions and is the model used by Defra for compliance purposes. Note that this analysis is based on 2010 meteorology and that there is some indication that this was a 'high' year for NO_x and NO_2 due to increased emissions and poor dispersion associated with cold weather. An assessment of measurements and modelling for another year would help confirm the extent to which this is the case. For these three data sources (measured values, modelled roadside and modelled background predictions) the zone id has been included to help express the results in terms of the zones exceeding the limit value. The data from the UK compliance assessment model provides predictions for 9,263 road links and over 250,000 background km^2 grids. The UK annual compliance assessment for 2011 reported 40 zones that exceed the annual mean NO_2 limit value out of a possible 43.

Note that the measurements alone would provide 8 unique zones exceeding the NO_2 limit value. Recall also that a 90% data capture threshold was used in this analysis.

The question addressed in this section is "***what is the likely number of zones that would have at least one exceedance if one were to rely solely on monitoring data?***" For comparison, Germany, Italy and France have between 400-500 monitoring sites.
Table 4 shows an estimate of the minimum number of monitoring stations that each of these member states needs for compliance if fixed measurements are used as the sole source of information. The number of stations required is a function of the way that the Member State has been split into zones and the levels of pollutants in the zones. These estimates have been calculated based on the populations of zones for NO_2 assessment reported in the 2010 '461' questionnaires as summarised by Jimmink et al, (2012)[7] and the number of stations required per zone listed in Annex V of the Air Quality Directive. In the absence of detailed information about the concentrations of pollutants in each zone we have made a worst case assumption that levels were above the upper assessment threshold in all zones. Note that since the UK also makes use of model results in the assessment, the minimum number of stations required in this case is lower. This analysis indicates that:

[7] http://acm.eionet.europa.eu/reports/ETCACM_TP_2012_10_AQQ2010

- Having more zones tends to lead to increases in the number of stations required (e.g., Italy)
- Germany, France and Italy probably have rather more monitoring stations than the minimum required by the Air Quality Directive.

Table 4 Estimated minimum number of NO_2 monitoring stations required if fixed monitoring is the sole source of information for the air quality assessment

Member State	Reported population (millions)	Estimate of number of NO_2 stations required
France	62.4	206
Germany	82.5	256
Italy	56.6	282
UK	58.8	153

The approach adopted here to combine measured data with modelled predictions is as follows. First, all 81 monitoring sites are used in the analysis to which additional sites are added from the modelled data to simulate the effect of the UK having an increased number of monitoring sites. The additional sites are added by taking random samples from the UK compliance assessment model roadside and background predictions. The samples are randomly drawn from the background/roadside predictions *by zone* in a way that ensures the overall mean concentration of all sites is close to the measurement site mean (about 32 µg m^{-3}). This sampling strategy is necessary because of the very large number of background predictions compared with roadside predictions. A purely random sample would bias the overall mean low compared with the measurement network. Note also, this sampling process yields very similar distributions to those shown in Figure **3** and therefore produces distributions of NO_2 that are similar both to existing UK measured distributions and those of Germany and Italy.

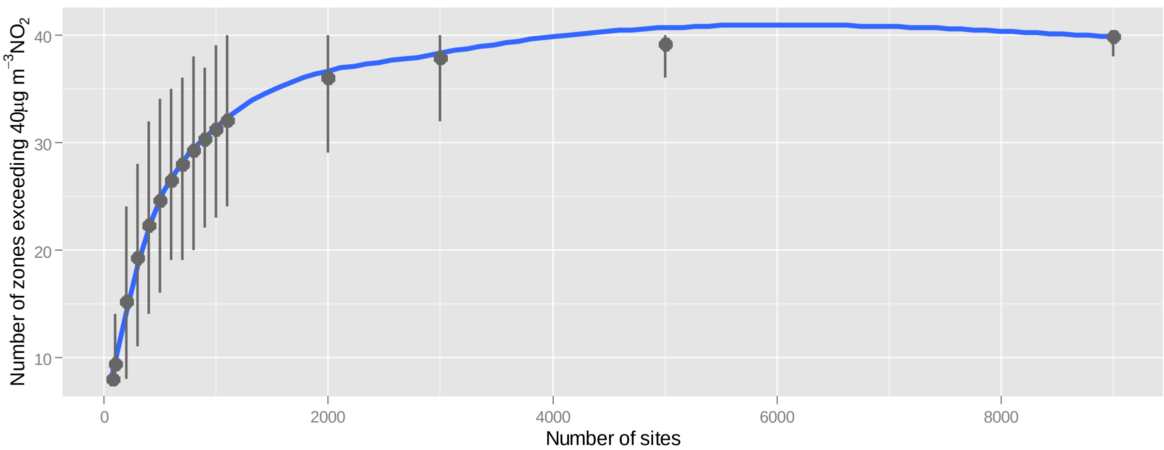

Figure 6 Simulations showing how the number of monitoring sites in the UK is likely to affect the number of zones exceeding in 2010.

The process described above was repeated for 10,000 simulations for different numbers of total sites (81 measured + additional modelled). The results are shown in Figure 6. The results highlight some potentially important findings. First, in order to replicate the UK assessment outcome, i.e. 40 zones exceeding the annual mean limit value, the UK would need around 9,000 sites, using a monitoring only strategy. There is a range because the exceedance zone statistics depend on exactly where the site is located. It can be shown that if the UK were to increase the number of measurement sites to 153 (the minimum required by the Air Quality Directive criteria in the absence of supplementary assessment methods, such as modelling, being available) then it would be expected that 13 zones (range 8 to 21) would exceed the limit value. Moreover, if the UK had a similar number of measurement sites to other large European countries (400 to 500 sites) the expected number of zones exceeding would be 22 (range 14 to 32 for 400 sites) or 26 (range 16 to 34 for 500 sites), respectively. For all these scenarios, the number of zones exceeding is far fewer than the current UK situation of relying on *all* modelled data to make up the number of sites.

Put another way, the use of modelled data to supplement monitored data potentially reveals much more information about potential exceedances of the limit value across the territory of an Member State than from monitoring alone, even if the monitoring requirements of the Directive are complied with.

Distributions have also been calculated for 2015 and 2020 for the UK as shown in the following plots. Recalling that 153 sites in 2010 would typically result in 13 zones exceeding (range 8 to 21), the corresponding values for 2015 and 2020 are as follows: 8 (range 2 to 15) for 2015, and 2 (range 0 to 5) for 2020. As the concentration of NO_2 reduces in future, the relationship between the number of sites and the number of exceedance zones also changes. The analysis of future years also highlights another important issue: the effect of how close monitoring sites are to the limit value and how this affects the relationship between number of sites and the number of zones exceeding. This issue is particularly important for PM_{10}, as will be shown later.

Another important aspect of these findings is that the use of modelling in compliance assessment gives a more robust assessment of the time period for which one or more parts of a zone are in exceedence than a monitoring approach alone.

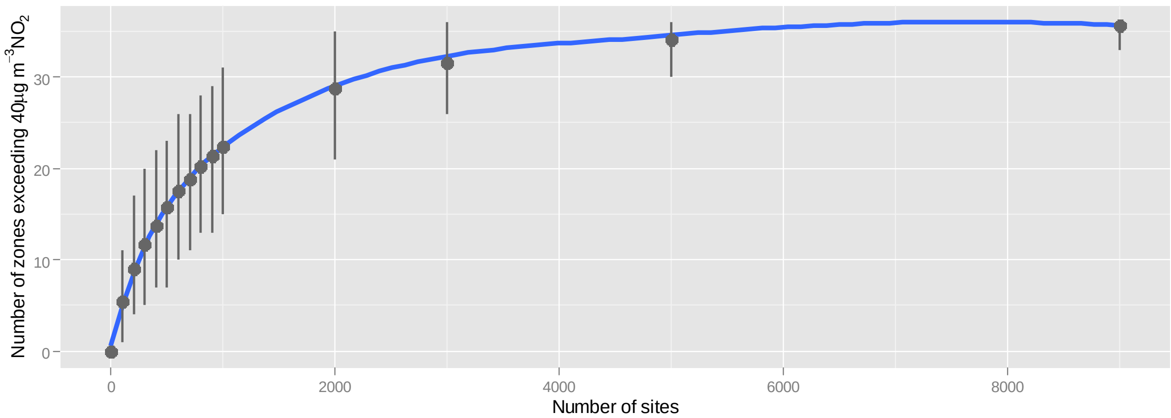

Figure 7 Simulations showing how the number of monitoring sites in the UK is likely to affect the number of zones exceeding in 2015.

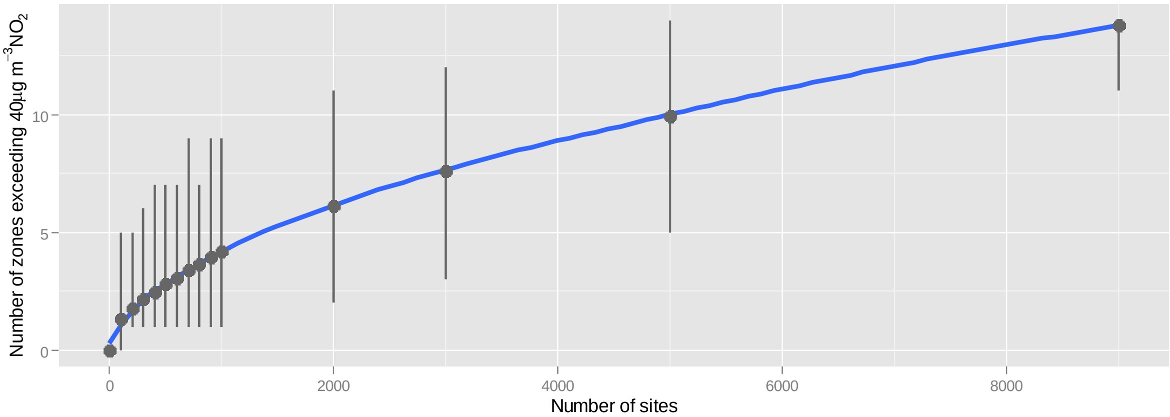

Figure 8 Simulations showing how the number of monitoring sites in the UK is likely to affect the number of zones exceeding in 2020.

In terms of the number of *zones* exceeding the limit value it can be shown that France, Italy and Germany have 30%, 36% and 66% respectively. Based on the simulations above, if the UK had 153 sites, we estimate the number of zones exceeding the limit value to be 30% (range 19 to 49%), which is consistent with the range reported by other European countries.

A direct indication of the impact of including modelling data on the results of an air quality assessment is provided by a comparison of the NO_2 results initially submitted by the Netherlands for 2010 based on measurements alone and the revised results for 2010 submitted on 15/12/2011, which were based on a combination of measurements and model results. The assessment based on measurements alone reported that four out of nine zones exceeded the annual mean limit value for NO_2. The revised assessment based on a combination of measurements and model results reported exceedances in all nine zones.

This information supports the view that it is very likely that the use of modelling would provide much more detailed information on potential limit value exceedances than relying purely on monitoring.

Annex B considers the modelled and measured distributions in more detail.

4. PM_{10} concentrations

In this section consideration is given to concentrations of PM_{10} and a similar analysis has been undertaken to that for NO_2. The Airbase 2010 data has been analysed to first consider how concentrations in the major European countries compare, and second, to consider the implications for compliance assessment.

Compared with NO_x, PM_{10} concentrations require a more detailed consideration because of the many different ways in which PM_{10} is measured. Table 5 shows a summary of the main instrument types used across different European countries. These data were compiled and simplified from multiple instrument descriptions in Airbase to three main types. The Table also shows that other major European countries rely more on the Beta attenuation method for measuring PM_{10} compared with the UK.

Table 5 also includes an estimate of the minimum number of PM_{10} monitoring stations required in each of the member states. These estimates have been calculated in the same way as those presented in Table 4 for NO_2. Annex V of the Air Quality Directive specifies the total number of PM_{10} and $PM_{2.5}$ measurements that are required and states that the total number of measurements for each should not differ by more than a factor of 2. For this analysis we have made the simplifying assumption that the number of PM_{10} and $PM_{2.5}$ measurements will be the same as each other. As with NO_2, this analysis indicates that France, Germany and Italy probably have rather more monitoring stations than the minimum required by the Air Quality Directive. Remember that the requirement in the UK is reduced because of the use of modelling.

Table 5 Main instrument types used to measure PM_{10} in Europe according to Airbase (2010).

Country	Beta attenuation	Gravimetry	TEOM	Total	Estimate of minimum requirement[8]
France	43	0	280	323	101
Germany	192	56	69	317	127
Italy	288	36	34	358	121
Netherlands	45	0	0	45	11
United Kingdom	1	9	36	46	77

It is useful to consider how concentrations of PM_{10} differ across the different countries at specific site locations. Figure 9 shows a map of site concentrations for five of the countries. The map helps to show both the number of sites and their associated concentration.

[8] If only monitoring used.

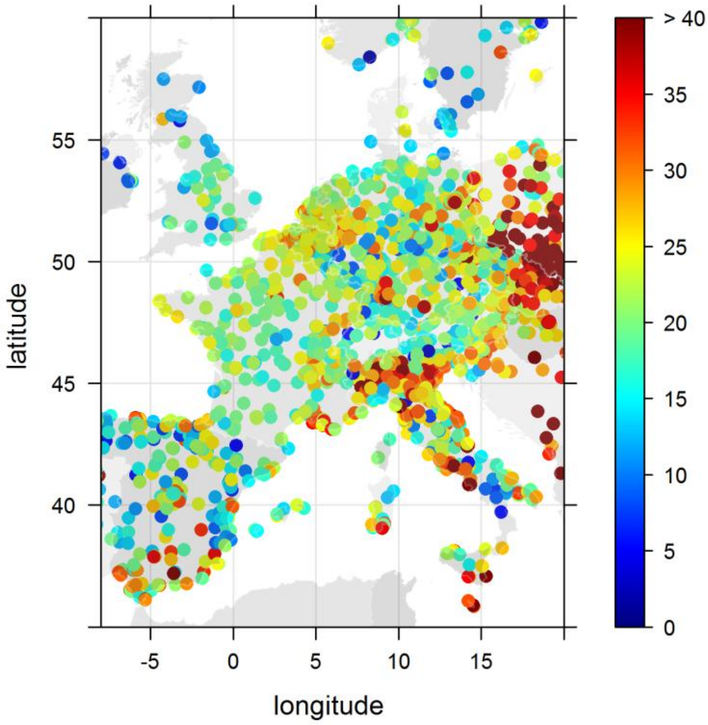

Figure 9 Distribution of annual mean PM_{10} concentrations across for 2010 using Airbase data.

It is also useful to gain a more general impression of the distribution of PM_{10} across Europe. Figure 101 shows the smoothed variation in *rural* PM_{10} concentrations across Europe using all Airbase country data. This Figure shows very clearly the areas of elevated concentration e.g. the Benelux countries, northern Italy. It also highlights the lack of rural PM_{10} measurements in the UK and northern Europe in general. It does indicate though the concentrations of PM_{10} do tend to decrease with increasing latitude. The map also perhaps reveals that rural PM_{10} concentrations in Germany appear to be lower than neighbouring countries.

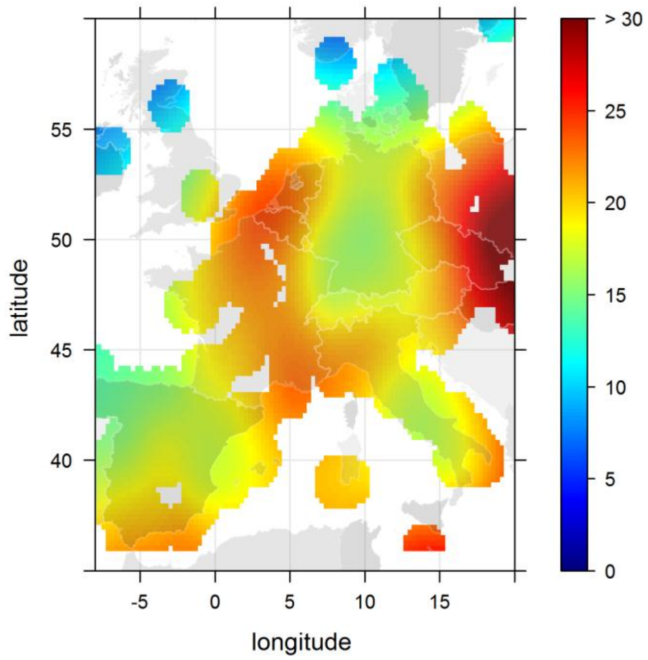

Figure 10 Smoothed distribution of PM_{10} concentrations across Europe using all Airbase countries for sites classified as rural.

The distributions of PM_{10} across the different countries are shown in Figure 11 and Figure 12. These Figures show that the UK tends to have lower PM_{10} concentrations compared with other countries. It is also important to understand the types of site that are used in deriving these Figures. Table 5 shows the breakdown of the sites with a data capture rate of >75%. Clearly, in terms of total number the UK has far fewer sites than the other countries considered in Table 5 except the Netherlands. Similar to the situation for NO_2, France tends to have a higher proportion of background PM_{10} measurement sites and fewer roadside sites. Despite France having fewer roadside sites compared with the UK, the PM_{10} concentrations are on average higher, which was not the situation for NO_2.

Table 5 Number of PM_{10} sites by site location type according to Airbase (2010).

Country	Background	Industrial	Traffic	Total
France	237 (73%)	41 (12%)	45 (14%)	323
Germany	150 (47%)	25 (8%)	142 (45%)	317
Italy	164 (46%)	55 (15%)	139 (39%)	358
Netherlands	28 (64%)	1 (1%)	15 (34%)	44
United Kingdom	26 (57%)	6 (13%)	14 (30%)	46

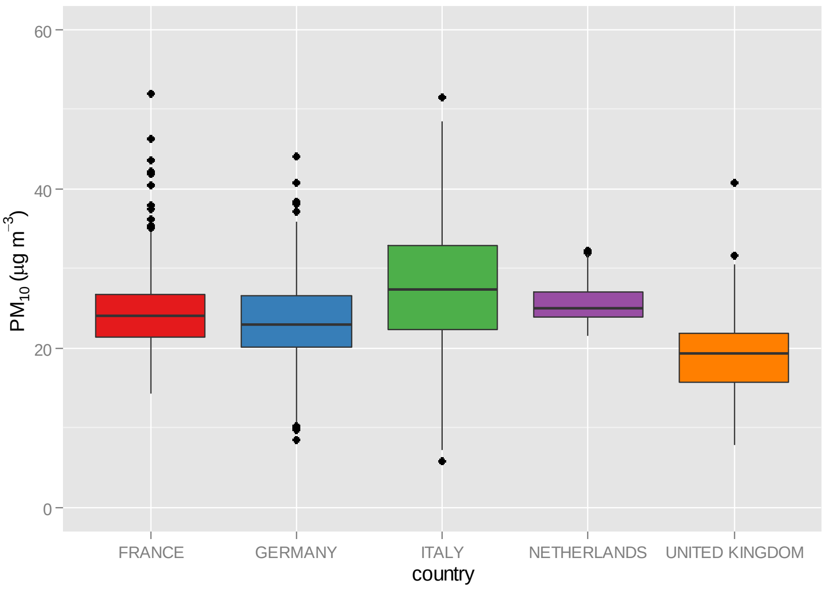

Figure 11 Box and whisker plot showing distributions of PM_{10} across five European countries.

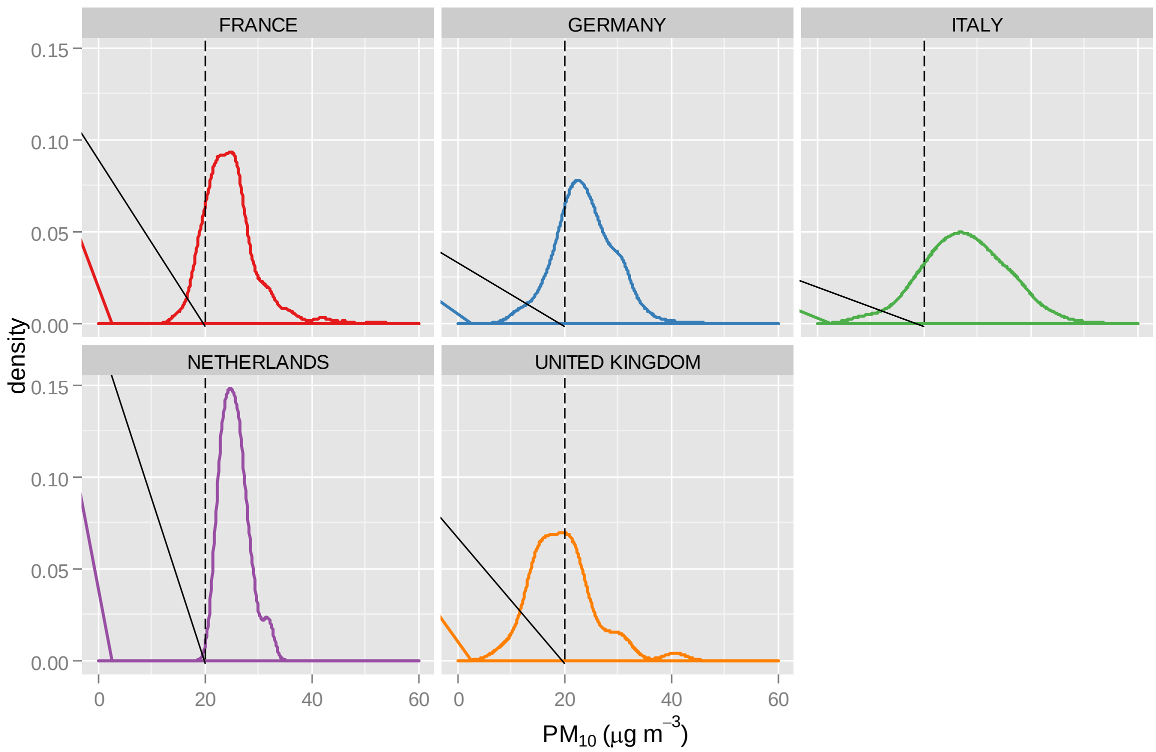

Figure 12 Distributions of PM_{10} across different European countries for 2010. The vertical dashed line is shown simply as a reference point to help compare the different countries.

The analysis of NO_2 was able to quantify the likely number of zones that would exceed the limit value given different numbers of sites assumed in each zone. The situation for PM_{10} is different in an important way in that according to the modelled concentrations from the UK compliance assessment model there are no locations (background or roadside) that exceed the annual average limit value of 40 µg m^{-3} (the highest concentration location was 34 µg m^{-3}). However, it is still useful to demonstrate how sensitive the number of zones above a given threshold is to the number of sites. For illustrative purposes a 20 µg m^{-3} threshold has been used for the analysis, close to the mean of measured values in 2010.

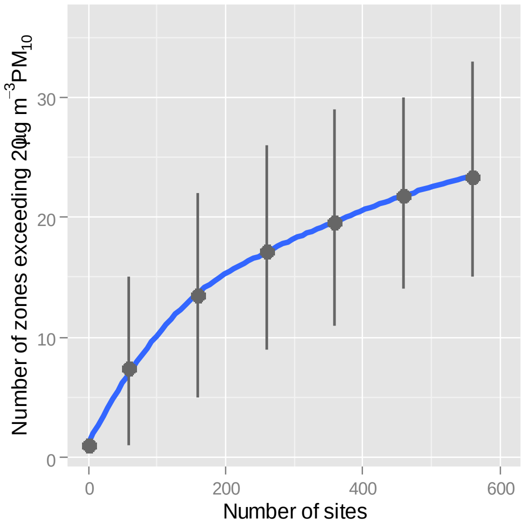

Figure 13 Simulations showing how the number of monitoring sites in the UK is likely to affect the number of zones exceeding an annual average of 20 µg m^{-3} PM_{10} in 2010.

Figure 13 shows the relationship between the number of zones exceeding an annual average of 20 µg m^{-3} PM_{10} against the number of monitoring sites (i.e. measured + modelled) for the UK. Similar to the situation for NO_2, for a 20 µg m^{-3} PM_{10} threshold the number of zones exceeding is very sensitive to the total number of monitoring sites. Therefore, increasing the number of sites measuring PM_{10} would lead to an increase in the number of zones exceeding the 20 µg m^{-3} PM_{10} threshold.

The results for NO_2 and PM_{10} are both highly dependent on the threshold considered. For NO_2 there are a relatively large number of sites that are close to 40 µg m^{-3} and hence it would be expected that the zones exceeding would be sensitive to the total number of sites. However, as the PM_{10} results show, if there are no sites predicted to be above a threshold then the number of sites becomes irrelevant. For a threshold of 30 µg m^{-3} it can be shown between 1 to 2 zones would exceed, and this number is insensitive to the total number of sites. This is because only one zone (London) has locations that are above 30 µg m^{-3} and therefore regardless if the number of additional sites added in other zones, only one zone will exceed the threshold.

A further indication of the impact of including modelling data on the results of an air quality assessment is provided by a comparison of the PM_{10} results initially submitted by the Netherlands for 2010 based on measurements alone and the revised results for 2010 submitted on 15/12/2011, which were based on a combination of measurements and model results. The assessment based on measurements alone reported that none of the nine zones exceeded the daily or annual mean limit values for PM_{10}. The revised assessment based on a combination of measurements and model results reported exceedance of the annual mean limit value in one zone and of the daily limit value in six zones.

Taken together, the analysis of NO_2 and PM_{10} shows that the quantification of zones exceeding a limit value is very sensitive to how close the measurements are to that threshold.

5. Comparison of emission estimates across EU Member States

This section compares emission estimates for NO_x across EU Member States in order to assess the extent to which Member States might be underestimating the totality of high NO_2 concentrations by relying solely on monitoring which is unlikely to capture all the locations of elevated concentrations. It should be noted that NOx emission inventories as currently published are subject to some uncertainty given the recent findings regarding real-world vehicle emissions, although in a comparative exercise such as this one, this may not represent a significant problem. Notwithstanding this, NO_x is used as an example as the other important pollutant, PM_{10}, is subject to significant contributions from secondary aerosols which are not captured by emission inventories.

A comparison of total NO_x emissions per capita for 2009 for the EU-27 Member States as reported to EMEP is shown in Figure 15. The major Member States are clearly not out of line with each other in terms of per capita emissions. A similar plot of total NO_x emissions (not shown) also demonstrates that the large Member States have similar NOx emissions. (Note that Luxembourg has been removed from this graph. That country has a high per capita value due to the large amount of through traffic on that country's roads).

Ambient NO_2 concentrations, and particularly those in locations where compliance with limit values is an issue, are largely determined by road transport NO_x emissions and these are shown in Figure 16. Not all Member States report gridded emission data to EMEP to the same extent, so the data in Figure 16 are the data used in the EMEP modelling work, as produced by the EMEP Centre for Emission Inventories and Projections. The data in Figure 16 show that there are equally high grid squares in many Member State including the UK, the Benelux/North East Germany area, the Po Valley in Italy, and cities like Paris, Warsaw, Vienna, Madrid and Barcelona. The UK however has a larger area of contiguous grid squares with higher emissions than most Member State, apart from the Benelux/NW Germany area and the Po Valley. This is borne out by Figure 17 which plots the highest 30 50km x 50 km grid squares in the EMEP Road Transport inventory. Of the top 30, the UK has the highest number of grid squares in the top 30 with a total of 8; Italy has 5 and France 3 of the large Member State. The Benelux region (excluding Brussels) has 6 grids in the top 30 but Germany does not feature.

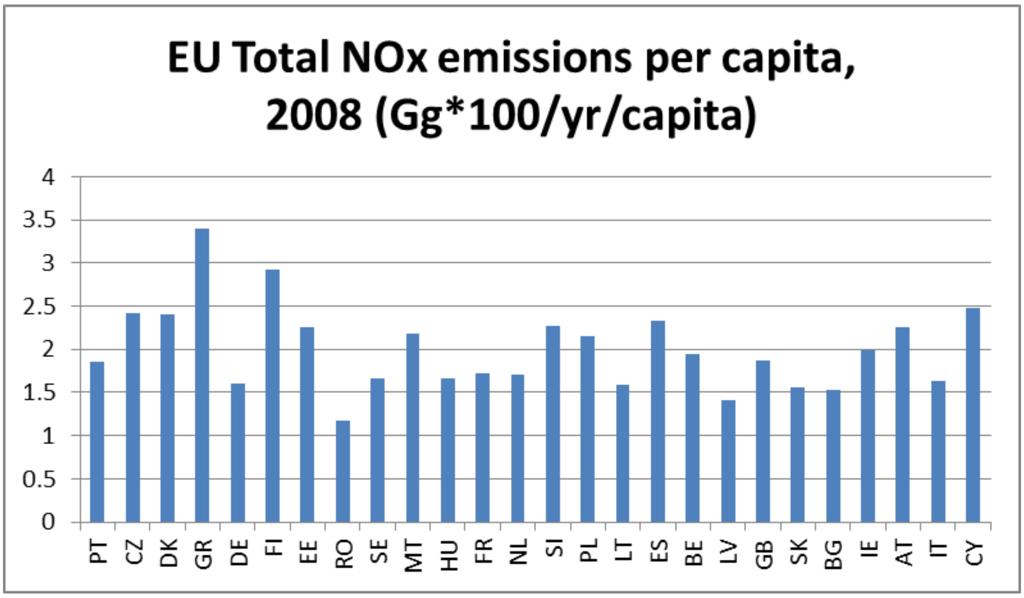

Figure 14 Total NOx emissions per capita from EU Member States for 2009 as reported to EMEP. (source: EMEP CEIP). Note Luxembourg has been excluded as that Member State has a misleadingly high amount of non-national through traffic.

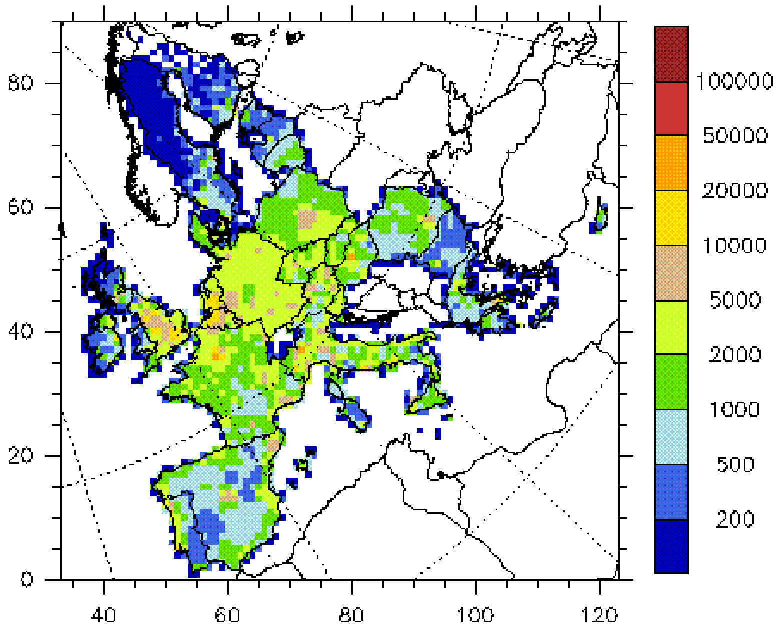

Figure 15 NOx emissions from Road Transport for 2010, data as used by the EMEP model (source: EMEP CEIP; units Mg NO_x as NO_2 in 50km grid squares).

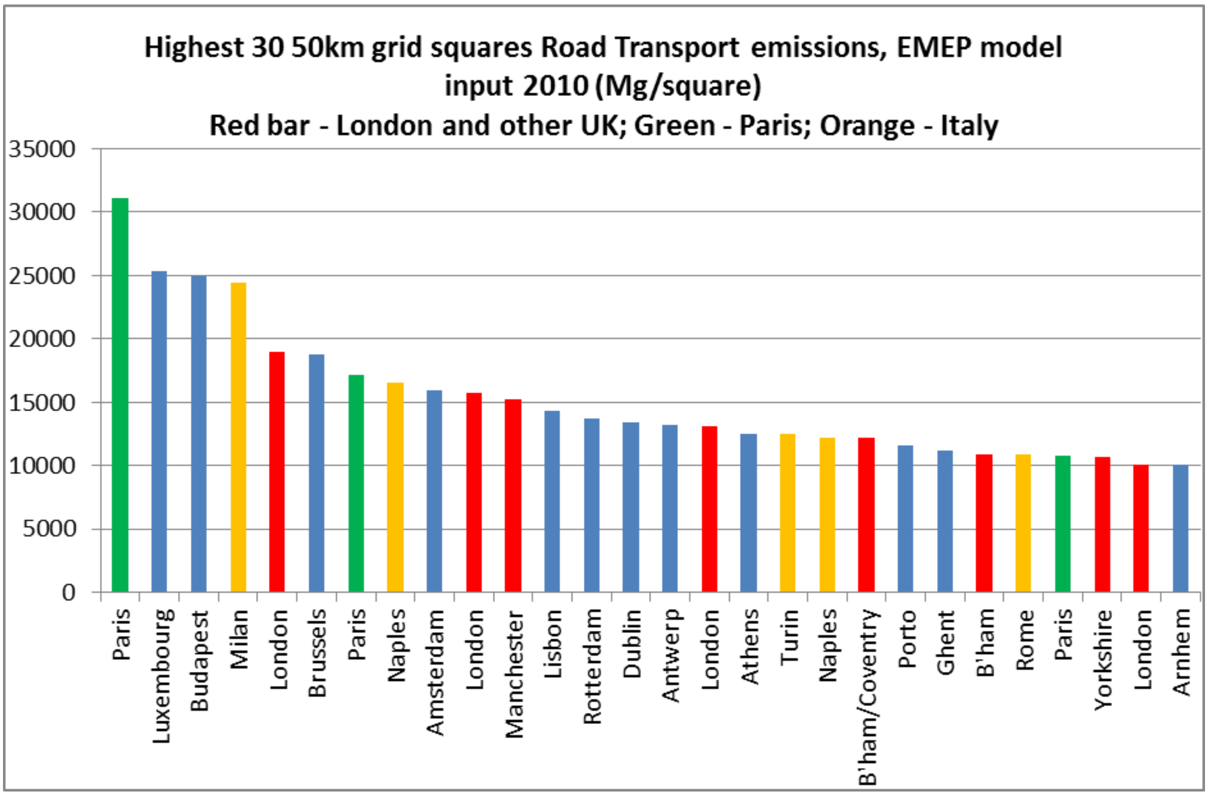

Figure 16 NOx emissions on the highest 30 grid squares in the EMEP Road transport inventory (source: EMEP CEIP).

6. Comparison of London and Paris NO_x emissions

The analysis in the previous section is inevitably limited to data of fairly corase spatial resolution. To assess the extent to which monitoring alone might understimate the extent of non-compliance more detailed comparisons are needed. One detailed comparison which is feasible within this work is an analysis of the relative emissions in London and Paris, the latter having the single highest NO_x emission in the EMEP grid as displayed in Figure 17. Published plots, shown in Figures 18 and 19, suggest that London might have a larger number of contiguous squares with high emissions (in this case greater than 40 tonnes/km^2/yr) than does Paris. Both maps show 1km grid squares.

However, rather than relying on subjective impressions, this question is addressed quantitatively in Figure 20 comparing the frequency distribution of 1km NOx emissions in Greater London and the Paris region (Ile-de-France).

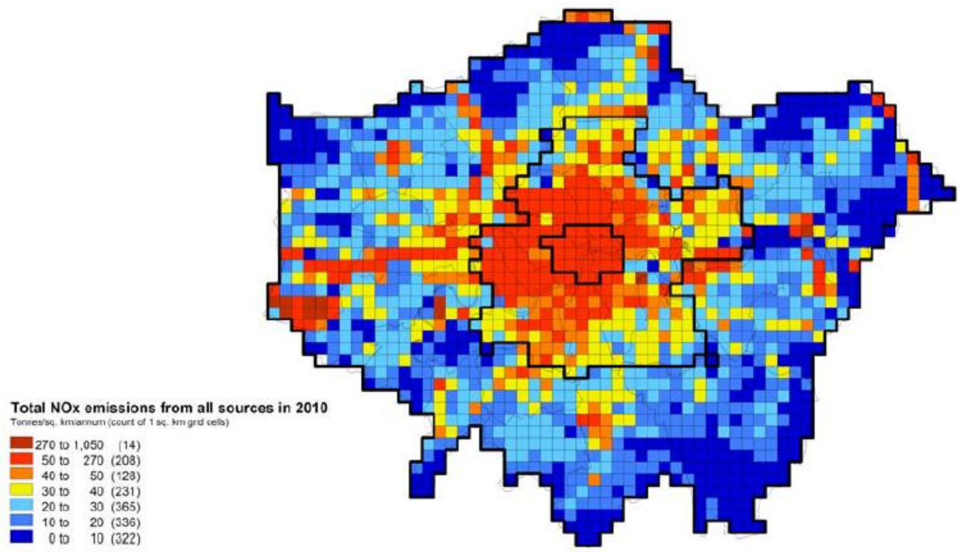

Figure 17 NOx emissions in London, 2010 (source: GLA).

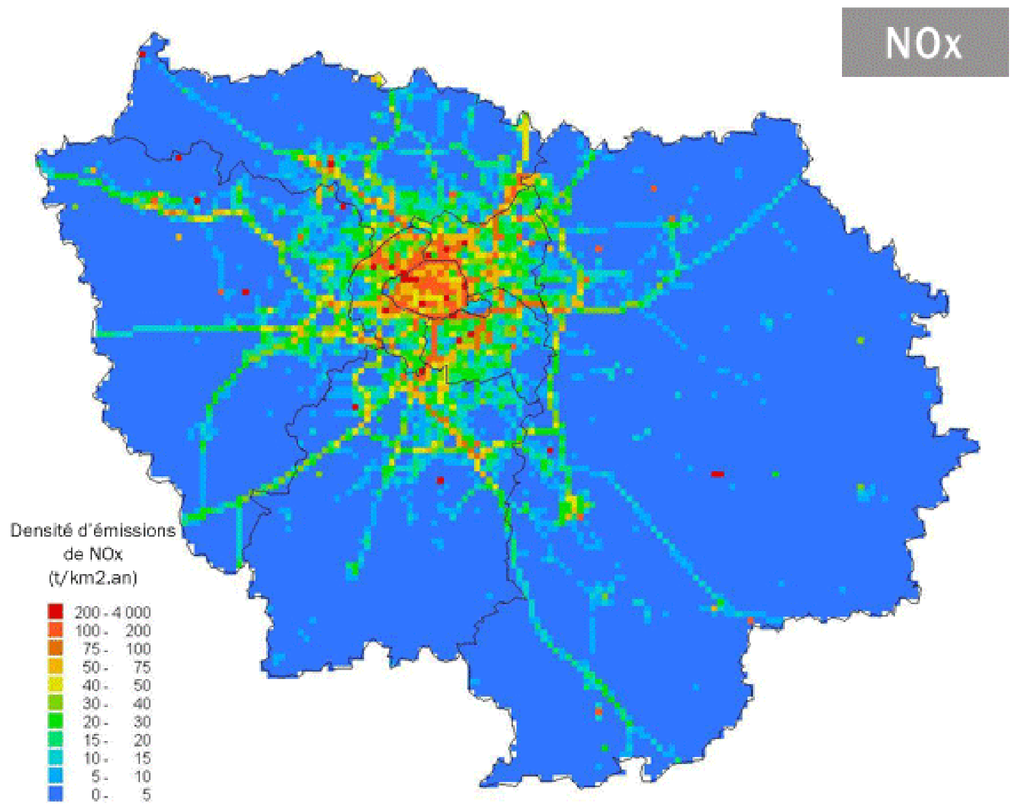

Figure 18 NOx emissions in the Paris region, 2008. (Source: AirParif).

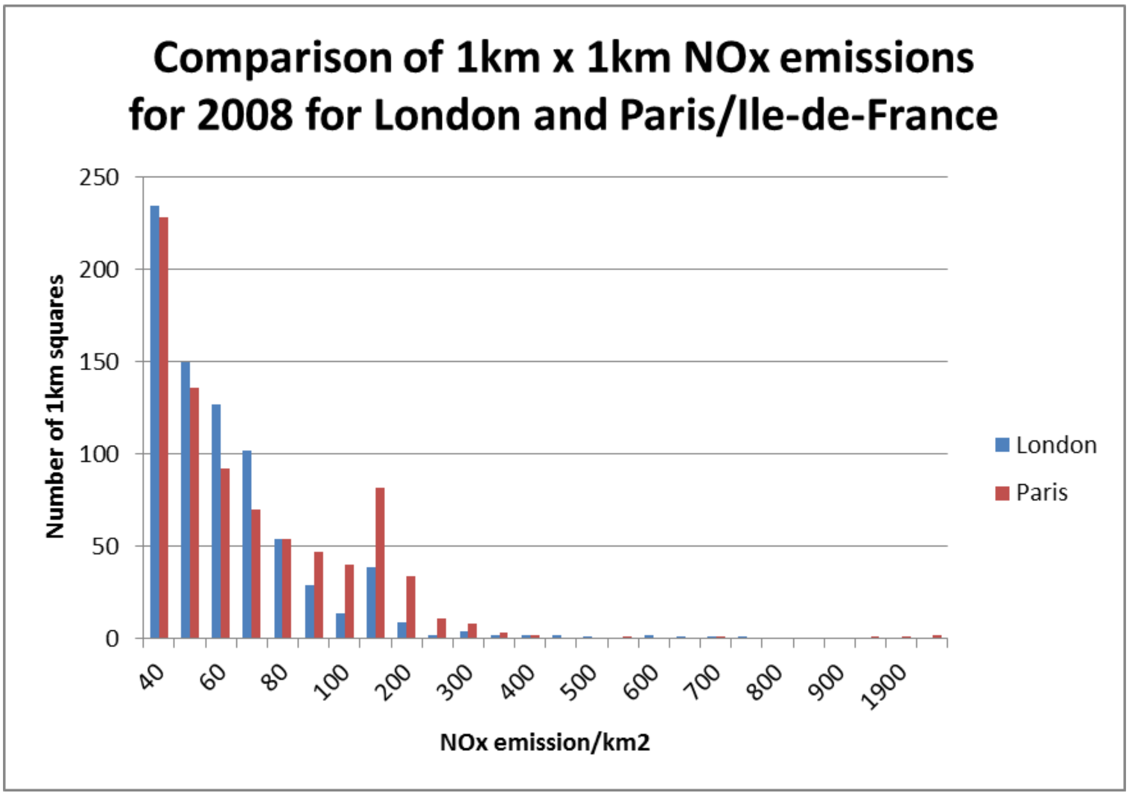

Figure 19 Frequency distribution of 1km emissions in London and the Paris region.

Although the two areas are different in size (Ile de France is 12012 km^2 compared with the LAEI area of 2466 km^2) there are significantly more low NOx emission squares in the former region. Hence Figure 20 has compared the distributions of squares greater than or equal to 40 t/km^2. This analysis suggests that while London has more squares in the range 40-80 t/km^2, Paris has more than London– but fewer in absolute terms – in the range 80 – 300 t/km^2. Overall there is no suggestion from these data that London should have higher NO_2 concentrations than Paris. This suggests that, with a full assessment of compliance using both modelling and monitoring, London and Paris should show similar behaviour. Table 6 shows a comparison of the air quality monitoring results reported in the 2010 '461' questionnaire for the Paris and London air quality zones. In this instance both zones exceed the minimum number of measurements required which is 10 for a zone with a population of greater than 6 million and concentrations greater than the upper assessment threshold.

Table 6. Reported air quality assessment results based for annual mean NO_2 on monitoring for Paris and London in 2010

Zone	City	Area (km^2)	Population (millions)	Number of stations	Number of stations exceeding limit value	Maximum measured annual mean (μgm^{-3})
FR04A01	Paris	2869	10.4	39	10	96
UK0001	London	1618	7.8	14	7	98

7. Satellite data

Satellite data represent a novel way to address the same questions that were addressed in sections 5 and 6 above. They have the advantage that they are potentially measurements of actual concentrations/emissions rather than calculated estimates of emissions as are emission inventories. At present they are limited in their temporal coverage, but their spatial resolution (see below) approaches, or even exceeds, that of European scale emission inventories. Satellite data for annual average NO_2 columns over Europe have been obtained and are presented in Figure 21 for 2010. The maps for the period 2005-2010 are also available and are all very similar in terms of the regional patterns, consistently showing the same regions with higher column densities although the absolute magnitudes vary slightly from year to year. There are some caveats on these data and questions remain about the accuracy of such data: they are derived from the OMI satellite which passes over northern Europe once per day at 13.30 GMT, data are not available when cloud cover is too great, and the data refer to total column amounts with no processing via a model to derive ground level concentrations. Nonetheless they probably provide a reasonable picture of *relative background* levels of NO_2 across the EU – the grid size for these data are 13km x 24 km.

These maps reinforce the conclusions from the emission inventories and suggest that the areas in central and south-east UK, Paris, the Beneulx/Ruhr corridor, the region around Frankfurt, and the Po valley have the highest background levels of NO_2 in Europe. Exceedances of the EU NO_2 limit value are largely near busy roads and as with emissions inventories in section 4 it is difficult, even with a finer grid from satellite data to assess the extent to which other Member States may underestimate compliance by only using monitoring.. Detailed data on traffic activity on the roads in other Member States would be needed to address this issue and is beyond the scope of the current project.

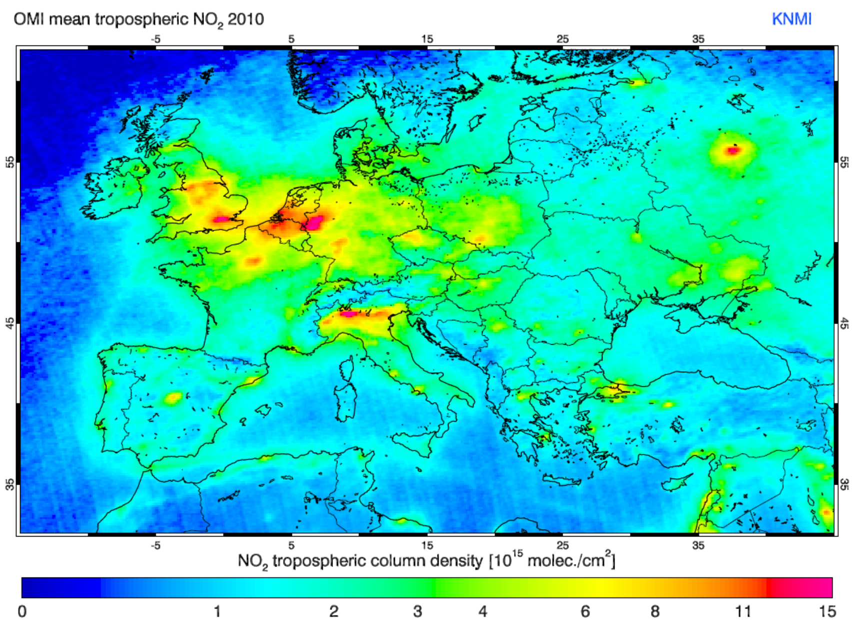

Figure 20 Annual mean NO2 columns from the OMI satellite, 2005-2010.

8. Conclusions

This report has analysed two approaches to the assessment of compliance with the requirements of Directive 2008/50/EC, using nitrogen dioxide (NO_2) and PM_{10} as examples. The Directive allows Member States to supplement air quality monitoring by numerical modelling for compliance assessment, but to date only the UK and the Netherlands have chosen to take this option. In analysing the differences between a monitoring-only and a combined monitoring/modelling approach, data from these two countries, but principally the UK have been used. Comparisons have principally been made between UK data and those from the other large EU Member States, Germany, France and Italy. However, it is very likely that the results and findings have general applicability across the Member States of the European Union.

The principal conclusions from this work are:

- The use of supplementary modelling in addition to monitored data reveals considerably more detailed information on the full distribution of concentrations across a Member State and hence gives a more complete assessment of compliance than monitoring alone, even if the monitoring requirements of the Directive are complied with.
- A combination of modelling and monitoring thus reveals potentially more exceedances in zones and agglomerations compared with monitoring data alone, even if distributions of measured values are similar in each member state.
- The large Member State have similar concentrations and distributions of NO_2 but markedly different levels of exceedances due to the different compliance assessment methods used.
- The proportions of measurement sites of different types (traffic, background etc.) vary between Member States and this could potentially affect the reported number of exceedances based on an analysis of measurements alone.
- The combined use of modelling and monitoring is a valuable tool for understanding monitoring network characteristics and potentially as part of their optimisation.

Annex A Annual mean assessments for NO_2 for 2009

Table A1 . Annual mean NO_2 assessments for 2009

zone	zone name	status of zone AURN measurements only (LV = limit value)	compliance gap (µg m^{-3})	status of zone measurements only including suitability assessment sites (LV = limit value)	compliance gap (µg m^{-3})	status of zone modelling only (LV = limit value)	compliance gap (µgm^{-3})	Compliance gap for model is greater than for AURN + suitability measurements
1	Greater London Urban Area	>LV	67	>LV	67	>LV	123	TRUE
2	West Midlands Urban Area	>LV	7	>LV	15	>LV	49	TRUE
3	Greater Manchester Urban Area	>LV	32	>LV	32	>LV	39	TRUE
4	West Yorkshire Urban Area	>LV	8	>LV	8	>LV	48	TRUE
5	Tyneside	<=LV	0	<=LV	0	>LV	38	TRUE
6	Liverpool Urban Area	<=LV	0	<=LV	0	>LV	38	TRUE
7	Sheffield Urban Area	<=LV	0	<=LV	0	>LV	28	TRUE
8	Nottingham Urban Area	<=LV	0	<=LV	0	>LV	23	TRUE
9	Bristol Urban Area	>LV	23	>LV	23	>LV	21	FALSE
10	Brighton/Worthing/Littlehampton	<=LV	0	<=LV	0	>LV	5	TRUE
11	Leicester Urban Area	<=LV	0	<=LV	0	>LV	27	TRUE
12	Portsmouth Urban Area	<=LV	0	<=LV	0	>LV	26	TRUE
13	Teesside Urban Area	<=LV	0	<=LV	0	>LV	39	TRUE
14	The Potteries	<=LV	0	<=LV	0	>LV	46	TRUE
15	Bournemouth Urban Area	<=LV	0	<=LV	0	>LV	11	TRUE
16	Reading/Wokingham Urban Area	-	-	>LV	5	>LV	10	TRUE
17	Coventry/Bedworth	<=LV	0	<=LV	0	>LV	45	TRUE
18	Kingston upon Hull	<=LV	0	<=LV	0	>LV	39	TRUE
19	Southampton Urban Area	<=LV	0	<=LV	0	>LV	42	TRUE

20	Birkenhead Urban Area	<=LV	0	<=LV	0	>LV	21	TRUE
21	Southend Urban Area*	-	-	-	-	>LV	13	-
22	Blackpool Urban Area*	-	-	-	-	<=LV	0	-
23	Preston Urban Area	<=LV	0	<=LV	0	>LV	6	TRUE
24	Glasgow Urban Area	>LV	38	>LV	38	>LV	51	TRUE
25	Edinburgh Urban Area	<=LV	0	<=LV	0	>LV	15	TRUE
26	Cardiff Urban Area	<=LV	0	<=LV	0	>LV	17	TRUE
27	Swansea Urban Area	<=LV	0	<=LV	0	>LV	17	TRUE
28	Belfast Metropolitan Urban Area	<=LV	0	>LV	26	>LV	26	FALSE
29	Eastern	>LV	6	>LV	6	>LV	63	TRUE
30	South West	>LV	25	>LV	25	>LV	30	TRUE
31	South East	>LV	10	>LV	15	>LV	40	TRUE
32	East Midlands	<=LV	0	<=LV	0	>LV	36	TRUE
33	North West & Merseyside	<=LV	0	<=LV	0	>LV	44	TRUE
34	Yorkshire & Humberside	<=LV	0	<=LV	0	>LV	31	TRUE
35	West Midlands	<=LV	0	<=LV	0	>LV	44	TRUE
36	North East	<=LV	0	<=LV	0	>LV	38	TRUE
37	Central Scotland	<=LV	0	<=LV	0	>LV	27	TRUE
38	North East Scotland	<=LV	0	>LV	16	>LV	16	TRUE
39	Highland	<=LV	0	<=LV	0	<=LV	0	n/a
40	Scottish Borders	<=LV	0	<=LV	0	<=LV	0	n/a
41	South Wales	<=LV	0	>LV	1	>LV	52	TRUE
42	North Wales	<=LV	0	<=LV	0	>LV	23	TRUE
43	Northern Ireland	<=LV	0	<=LV	0	>LV	13	TRUE

*A data capture cut-off of 75% has been applied to the monitoring data

Annex B A closer investigation of modelled – measured NO_2 distributions

It has also been possible to use the UK compliance assessment model results to put the measurements in context. Figure 21 shows the distribution of model predictions at background and roadside locations by zone. Overlaid on these plots are the measured values where they exist. Note that because of the *90% data capture threshold* some sites are absent in some zones. Taking zone 1 as an example (London), it can be seen that there are more measurement sites in this zone compared with others and they cover the distribution of modelled results well (although there are modelled locations with higher concentrations of NO_2 compared with the highest measured value). This analysis is potentially useful in several respects:

- It reinforces the fact that modelling, in addition to monitoring, can provide a far more detailed representation of concentrations across the whole territory of a Member State
- Inevitably in a fixed site monitoring network, sites will never always be in the areas of highest concentration and modelling can provide the additional information to supplement monitoring in these cases
- Were it necessary, modelling can provide valuable information to optimise monitoring network design and to site additional monitors should that be required

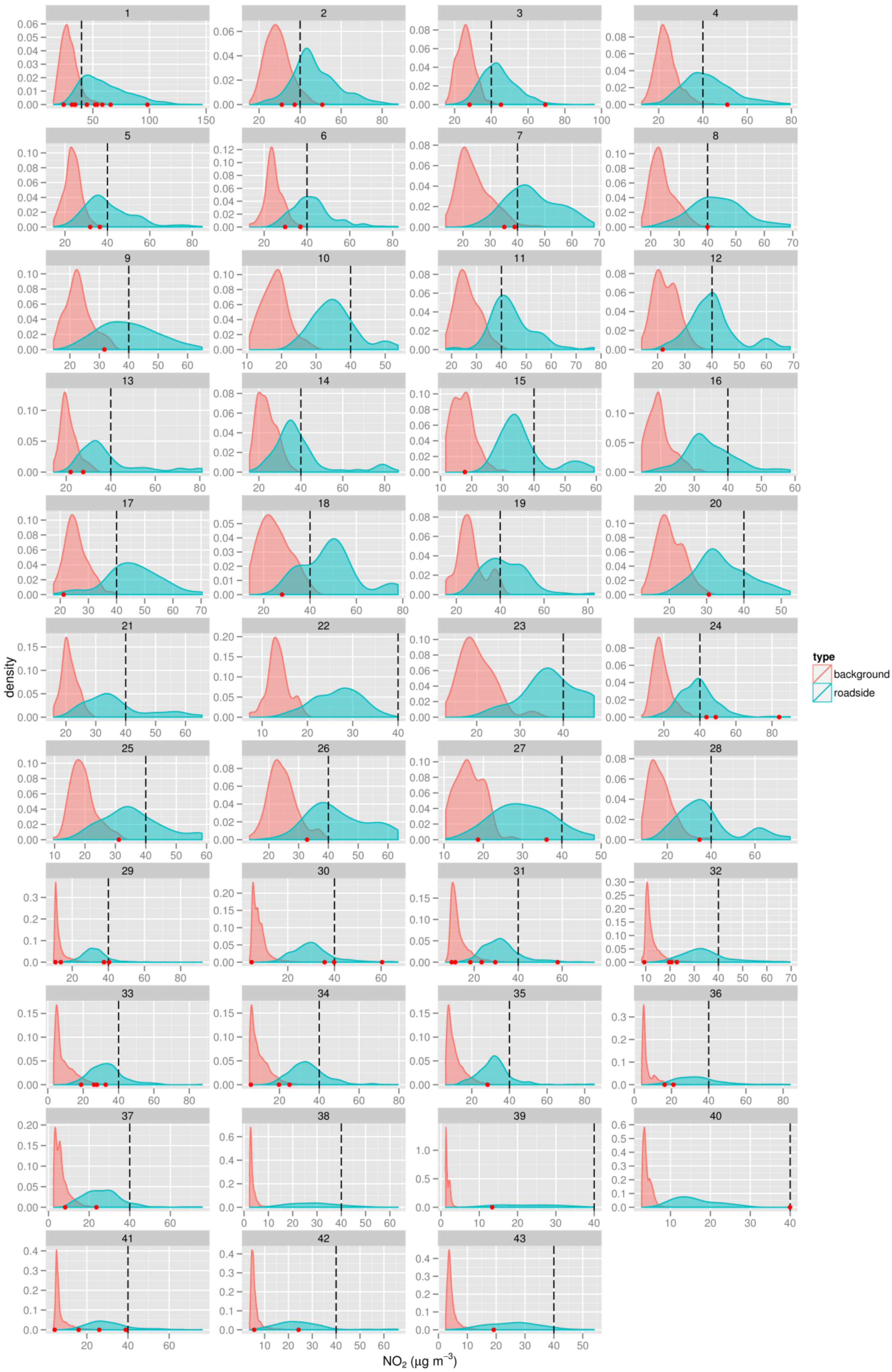

Figure 21 Distribution of modelled roadside and background predictions from the UK compliance assessment model by zone. The red points show the monitoring data available and the dashed line is the annual mean NO_2 Limit Value.