Faraday Discussions

Accepted Manuscript

Faraday Discussions

ARTICLE

Verifiable emission reductions in European urban areas with air-quality models

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

A. N. Skouloudis,[a] and D. G. Rickerby[b]

The first and second AutoOil programmes were conducted since 1992 as a partnership between European Commission and the automobile and oil industries. These have introduced emission reductions in Europe based on numerical modelling for a target year. These aimed to identify the most cost-effective way to meet desired future air quality over all European Union. In their time, these regulatory efforts were considered an important step towards a new approach for establishing European emission limits. With this work, we review the effectiveness of forecasts carried out with numerical modelling and compare these with the actual measurements at the target year, which was the year 2010. Based on these comparisons and new technological innovations these methodologies can incorporate new sectorial assessments for improving the accuracy of the modelling forecasts and for examining the representativeness of emissions reductions, as well as for the simultaneous assessment of population exposure in cocktails of toxic substances under realistic climatological conditions. We also examined at the ten AutoOil domains the geographical generalisation of the forecasts for CO and NO_2 at 1065 European urban on their basis of urban population and the local population density.

Introduction

The key elements of utilising modelling for demonstrating compliance with the requirements of European Environmental Policy are not new.[1] The use of these models for regulatory purposes requires the coherent coupling of many disciplines relating to anthropogenic and natural processes. For policy purposes, these are then linked to economic data for identifying cost-optimised solutions achieving maximum pollutant reductions over regional and urban domains. This has been the case when industrial partners participated in common actions with regulatory authorities for achieving the best air-quality outcomes over large regional territories. In the past, vehicle emission limits have been set using the 'best available technology' approach. As standards have become increasingly stringent, it will be essential to adopt new approaches for future emission reductions. During the first two AutoOil programmes,[2,3] extensive analysis of emissions reductions based on automotive fuel quality and engine technologies have resulted in several legislative efforts like the so-called Daughter Directives, the Ozone and PM directives and eventually the Clean Air for Europe Programme. All these, had 2010 as the target year and were based on several forecasts for emission reductions.

In their time, these regulatory efforts were considered an important step towards a new approach for establishing European emission limits. Despite various emission reduction efforts, air pollution remains in many areas of Europe above acceptable limits. Since it is not possible to assess if the forecasted emissions were correct at the regulatory base year, we can verify the air-quality concentrations, which is result of the emission reductions at the target year. In this work, we are reviewing the options that were available at the time of the forecasts and we compare these with the actual measurements for the target year 2010.

Since then, we have incorporated several innovations in these methodologies for sectorial assessment and for examining the representativeness of abatement strategies, as well as for the simultaneous assessment of population exposure in cocktails of toxic substances under different climatological conditions. We examine also, why air quality issues have become more complex at regional level with a wider impact of oxidants on population and rural ecosystems. The spatial resolution of an ambient air quality model (that is, the area over which the predicted concentrations are averaged) may vary from several meters to several thousand kilometres.

Evidence is also presented for why integration in regulatory applications is necessary across a range of scales (local, regional), sectors (transport, energy) and issues (ozone, particulate matter) together with health effects as identified in the European Commission Action Plan for Environment and Health (COM-2004-416).

a. *Institute for Environment & Sustainability, European Commission, Joint Research Centre, via E. Fermi 2749, Ispra 21027, Italy.*
b. *Institute for Health and Consumer Protection, European Commission, Joint Research Centre, via E. Fermi 2749, Ispra 21027, Italy.*

Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

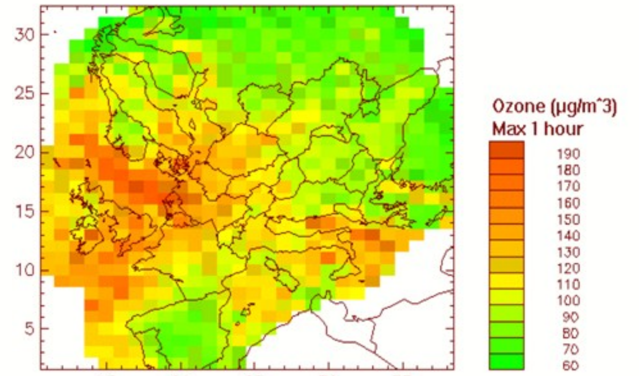

Fig. 1 The grid by the EMEP model with the calculated maximum one-hour ozone concentrations in Europe plotted over the 150x150 km^2 polar-stereographic projection.[5,6]

We also examine what types of numerical modelling innovations can be carried out after incorporating recent advances in distributed data architectures and sensor technologies. We also show what type of integrated new applications can be carried out to understand the hazards at specific urban hot spots and to reduce the burden of human exposure for the local population.

The successes of new regulatory approaches depends on the implementation of new technologies, for setting realistic targets and for monitoring at intermediate steps on how these targets are achieved without the need to look in the long-term future with unverifiable parameters that lead to emission reductions that are beyond the present capabilities.

The AutoOil approaches

In planning for the abatement and control of air pollution in regional and urban domains several complex issues might arise. The aim of the first AutoOil programme was to achieve compliance with the EU and WHO air-quality standards by looking into classical urban pollutants (such as CO, SO_2, NO_2 and C_6H_6) over seven urban domains and by looking into regional photochemical pollution over the whole Europe. The seven cities studied were Athens, Cologne, the Hague, London, Lyon, Madrid and Milan. These cities were considered representative in terms of air quality, location and size. Since measurements are not possible at all location and at all times, simulations were carried out by three models using 3D Eulerian models for meteorology coupled also with dispersion models without allowing for chemical reactions.[2,4] This assumption was necessary because of the large number of emission scenarios that were required. In addition, the period of simulation in each city domain was restricted to four days. Several urban background locations were used for identifying the four-day interval when the measured concentrations were close to the annual averages simultaneously for all four pollutants. For establishing this period the measured concentrations were analysed over several years.[4] In each city, the size of each urban domain was 100x100 km^2 and the size of each grid was 2x2 km^2.

For establishing the emission reduction targets for ozone were utilised another approach. It was considered necessary to look into regional simulations over the whole Europe. The simulations were carried out over a year but by assuming that ozone concentrations are highest during afternoon hours, the 8-hour averaged concentrations were estimated by taking the mean of the calculated concentrations at 12:00 and 18:00. The calculated ozone concentrations over Europe are shown in Fig. 1. Simulations were carried out with a single layer Lagrangian model[5]. The advantage of this model is its simplicity for calculating over long time-periods nevertheless there were still computational difficulties so the model was applied every six hours on a scale of each grid was 150x150 km^2.

Ideally, it is essential to relate the ozone concentrations to emissions on a finer grid. In the past, this problem was prohibitive in terms of computational times and for this reason today the EMEP grids became three times finer.[6] Nevertheless whenever a large geographical area is projected in a grid based on km the spacing will change with latitude. This is only due to the mathematical projection of the spherical coordinates over a flat Eulerian map. As such, it means that in northern latitudes, there is 27% more area averaging than in south grids. While this is perhaps acceptable for emissions due to small spatial variations in rural uninhabited areas, it introduces significant underestimation of concentrations emitted and transported due to large area averaging for each grid cell.

Recent advancements in computational speeds coupled with the reduced costs of electronic storage have resolved some of these limitations in the second AutoOil programme. The spatial resolution of an ambient air quality model (that is, the area over which the predicted concentrations are averaged) may vary from one to several km. However, the projection of the spherical geographical coordinates in a flat Eulerian grid expressed at km was abandoned. Due to vastness of the overall European domain a grid based on geographical degrees was utilised. The partial differential equations are solved numerically for the ten domains shown in Fig. 2 as well as in the whole European domain. Twenty levels were considered in vertical domain up to 13 km for the meteorological calculations and up to 4 km for the dispersion model. For the latter, calculations were carried out with appropriate chemical scheme. Apart from the improved

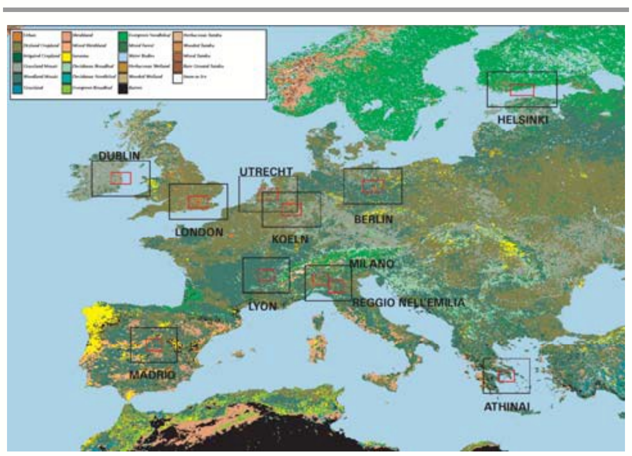

Fig. 2 The three levels of two-way nested domains used for the second AutoOil programme. With red is the inner urban domain, with black is the outer domain and the overall image is the European regional domain. The colours in the legend show the corresponding CORINE land cover.

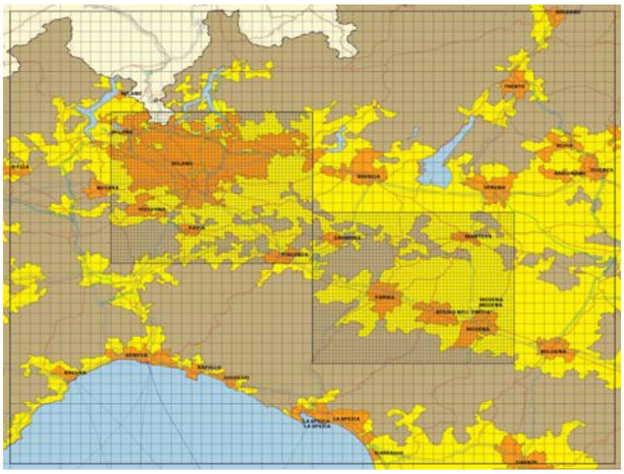

Fig. 3 Detail of the three levels of grid in Milano and Reggio Nel Emilia with the urban (orange) and suburban (yellow) landscape areas at the background. These areas are identified from the CORINE categories for land-cover categorisation.

treatment of the boundary, the other obvious advantage of these models is that the coarser domains allow simulations to be carried out over long modelling periods (several months).

The choice of the spatial grid on which the equations are solved is governed by the degree of spatial detail in the emissions inventory and the accuracy of the meteorological variables. Sometimes it is desired to predict pollutant concentrations in the immediate vicinity of sources, in city centre as well as the greater downwind area. In such cases the spatial resolution of the concentrations might be as little as a few km at the centre but coarser in the outer regions. The coupling of these resolutions in multi-nested layers and the online interaction of the solution schemes (two-way nesting) provides the basis for accurately examining the impact of man-made emissions and their impact in larger geographical areas. A typical outer domain with two inner domains is depicted at Fig. 3 with information about the urban and suburban territories aggregated from the detailed CORINE categories of land-cover shown at Fig. 2.

In regulatory applications, spatial resolution is frequently considered of secondary importance in favour to provide simulations over long modelling periods. However, for verifying the effectiveness of regulatory assessments, the spatial resolution in the horizontal and vertical directions is a key area that needs to be addressed properly. Assuming that parametrisation of physical and chemical processes is the same, models with the finer resolution in the horizontal direction allow a more accurate spatial representation of the overall processes and is expected to characterise more accurately the size of hot-spot areas. On the other hand, emission of pollutants at different heights from industrial and traffic sources coupled with the vertical atmospheric transport requires that the models have a reasonable number of levels in the vertical direction. The proximity of maximum ozone concentrations near large urban agglomerations in South Europe and the existence of significantly varying conditions in densely populated areas means that average representation in coarse regional grid sizes (more than 50x50 km^2) is rather inappropriate and modelling windows with adequate size need to be utilised.

Yet there remains the problem of the accurate estimation of emissions, which needs to be given at each grid cell for the corresponding temporal resolution, especially for natural sources. The set of emission categories that were taken into consideration were for traffic sources (passenger cars gasoline and LPG, passenger cars diesel, light duty commercial vehicles heavy duty commercial vehicles, buses, two wheeled vehicles, medium areas sources (non-industrial combustion plants, combustion in manufacturing industry, solvent and other product use, extraction and distribution of fossil & other fuels, combustion in energy & transformation industries <50MW, gas turbines, stationary engines), large area sources (combustion in energy & transformation industries 50-300MW, combustion in energy & transformation industries >300MW, production process industries, waste treatment & disposal) and small area sources (other mobile sources and machinery, agriculture, natural emissions).

For the aforementioned emission categories inventories were constructed for NO_x, VOC, CO, SO_2 and PM_{10}. The requirements for implementing a model are strongly governed by its temporal resolution. The temporal resolution of emissions (that is, the time period over which these are assumed constant in the air-quality simulations) may vary from several minutes to one year. Starting from the annual emissions for these inventories were disaggregated to daily and hourly values according to chapter 4.2 of the air-quality report.[3] For assessing the impact of emission reduction under annual mean and the most severe episodic conditions in each urban domain the steps that were followed for were:

- The monitoring sites were characterised as of relevance in representing the domain and the exposure significance.
- Measured data for monitoring sites were used for at least one to five calendars year previously (rolling data, one year before the current calendar date) for examining the temporal trends.
- Statistical analysis were carried out to identify representative periods with air-quality similar to annual mean conditions and for identifying a similar period severe conditions (98 percentile). This step was carried out once for conventional pollutants and once for ozone.
- Forecasts for meteorological parameters are calculated for grid cell on the basis of data obtained from meteorological offices.
- The current air-quality concentrations are calculated and compared with measurements for the base year.
- Emissions are weighted according to anthropogenic and natural estimate for the target year 2010.
- Air-quality concentrations are calculated for 2010.
- Source apportionment simulations are carried out.
- Spatial synthesis of all appropriate parameters from all modelling domains is carried out.
- Spatial generalisation of the results in other urban areas is carried out from the intermediate domain.

These steps, although simplified, required data handling, retrieval and harmonisation as well as computational

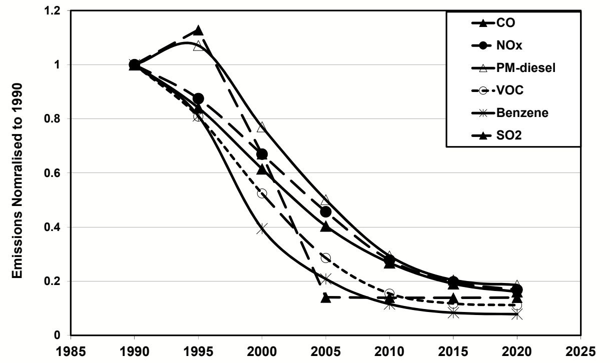

Fig. 4 The forecasted emission for the EU15 member states normalised to 1990.

capacities that resemble big-data and distributed network architectures that only recently are becoming available.

Forecasted concentrations for the target year

The aim of the legislative efforts in the AutoOil programmes was to identify suitable measures that could be introduced in the coming years that will lead in achieving compliance with the desired air-quality standards by 2010. This compliance should be "ideally" achieved for all pollutants and should have an impact both on regional and urban scales.

Certain aspect of the forecasts is the evolution of emissions for the target year and how these will be translated into air-quality concentration especially for chemically reacting pollutants. The evolution of the emissions used in these two programmes are shown in Fig. 4 all by then member states of EU. Despite the fact that the projection of emissions inventories is uncertain due to the complexity of anthropogenic activities and the statistical nature of forecasts, the updating of emission inventories can be described as a purely logistical process. From this figure it is clear that after 2010 will start the period of less possible reductions with all, by then, existing technologies.

The application of regulatory models in this type of long-term forecasts requires, firstly, the suitable updating of emission inventories and, secondly, the identification of suitable emission reductions in order to achieve compliance with specific air-quality targets.

Regional scale forecasts

A typical example is ozone. Taking into consideration the already agreed technological measures until 2010 and photochemical calculations carried out in the first AutoOil with EMEP were generated maps like those shown in Fig. 1. From these maps with GIS processing was deduced the percentage of the EU15 area exposed by each ozone concentration as in Fig 5; by this time there were only 15 member states in EU. The reduction of emissions will improve the percentage of the European area which achieves compliance, but with varying impact as shown in the same figure. The straight line in the figure shows the limit values.

The intersection of the distribution curve with the limit value indicates the percentage of the area above which the limit value is exceeded. It is evident that the limit values of the 1-hour maximum values of ozone and the 8-hours average values are different. The latter is practically exceeded all over Europe. The same figure shows that 73% of the European territory was exposed to 1-hour average concentrations of 180 μg/m³ in 1990 but this will be reduced to 47% by 2010.

In order to improve the compliance area further reductions in NO_X and VOC emissions are needed. Sensitivity calculations for 2010 have shown in Fig. 6 that, despite significant improvements in the area the European territory experiencing high one-hour concentrations, there are still areas where the targets are exceeded even for reductions of NO_X emission reductions between 60%, 70% and 80%. Of course these are results from simulations with a coarse geographical grid and a single vertical layer. Even, ignoring the uncertainty of numerical simulations, it is clear that uniform reductions over necessary and these reductions might not be translated with the same level of success in other target limits for the same air pollutant.

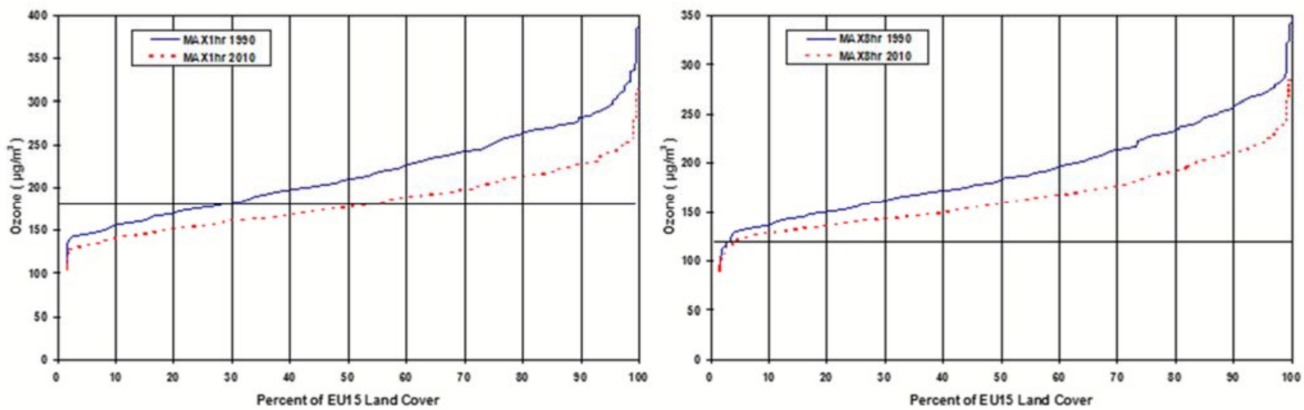

Fig. 5 Ozone concentrations in the EU15 states from EMEP simulations after the impact of agreed measures on emissions until 2010. The horizontal axis shows the percent of EU15 land area effected from these concentrations for the 1-hour maximum values (left), and the 8-hours maximum values (right). The desirable limit values are also indicated with the horizontal lines.

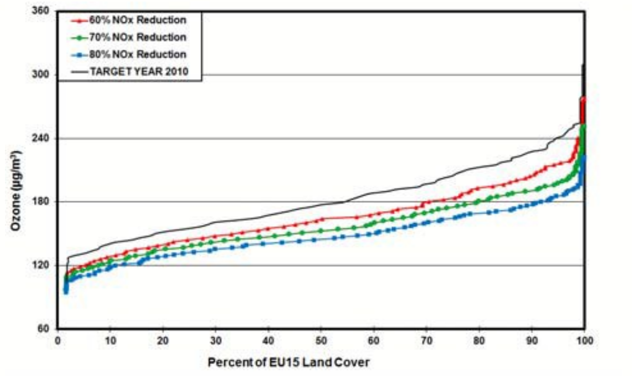

Fig. 6 Ozone concentrations and the percent of EU15 area effected. Impact of 60%, 70% and 80% NOx emission reductions on maximum 1-hour values.

Forecasts for urban areas

Article 4 of the European Directive on passenger car emissions designed to produce effects to meet the requirements of the EU air-quality standards and related objectives at least cost". However, the major challenge of the AutoOil-2 programme was to take account of all emission sources in an integrated manner and. For this reason the Working Group for air-quality decided to proceed without the use of attenuation factors (deduced from emission ratios) for projecting the results of air-quality to other pollutants. For assessing the impact of emission reduction in metropolitan areas the existing and projected air-quality conditions were analysed with 3D photochemical models.

Following the emission projections for the target year, the photochemical simulations produced spatial contours maps showing the detailed areas of exceedance over the target year. On the basis of these, in the second AutoOil programme were calculated: (a) the maximum and (b) mean concentrations in each domain, (c) the area of exposure for the population and the (d) percentage of the urban area above the WHO target values. The simulations were repeated for examining the source apportionment for different emission categories so the last option offered by this programme was (e) break down of pollutant concentrations at each grid cell according to the real emission sources.

Two of these terms (a and d) are shown all ten domains in the Fig. 7. GIS was used for the evaluation of (d) on the basis of maps similar to those shown in Fig. 3. A similar process was used for the population exposure (c) whereas maps similar to those of Fig. 3 were used but with the population density in each grid cell. This population density maps were unique at its time because they were based on census data in high spatial resolution and disaggregated to local grid cells according to land-cover and light intensity consumption from satellite images. This process resulted in annual mean projections that were closer to physical and chemical reality than the projections forecasted by the extrapolations of only the emission as was done in the first AutoOil.

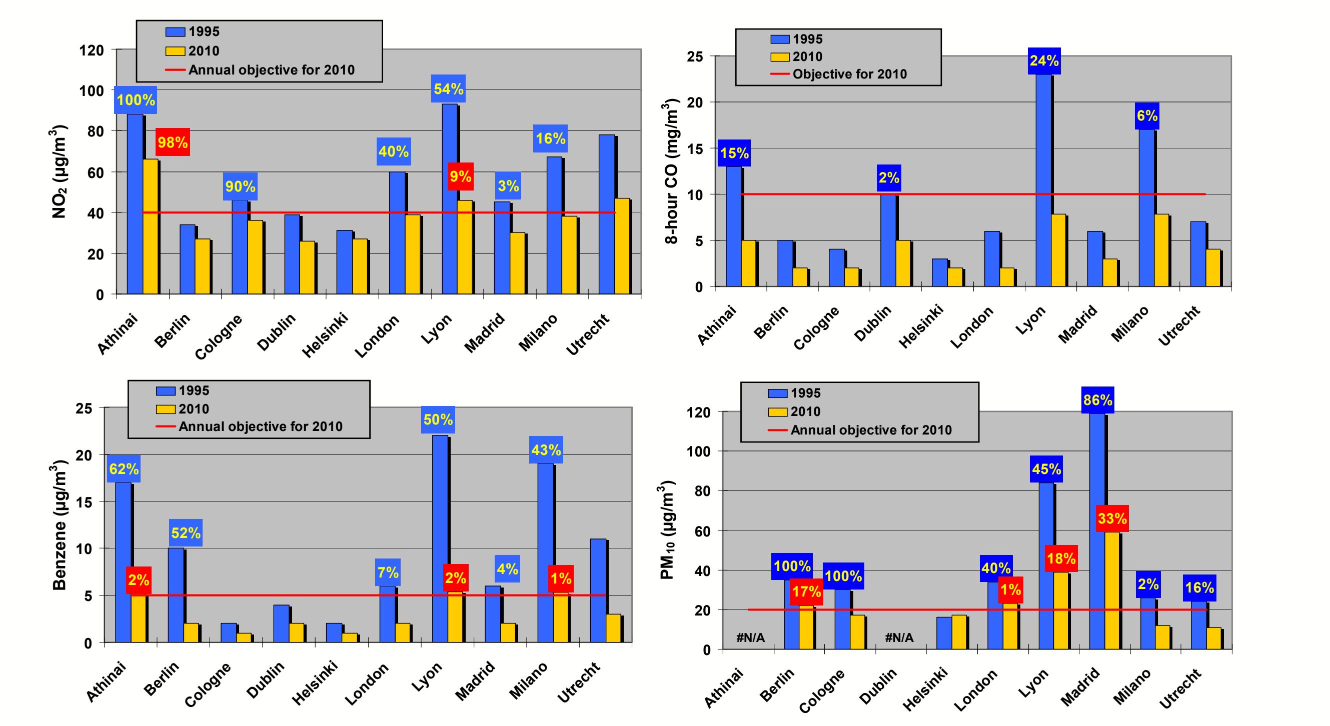

Fig. 7 Maximum predicted values at each at the ten AutoOil-2 domains for the annual mean concentrations of NO_2, CO, C_6H_6 and PM_{10}. The urban area above the 2010 target values is indicated by the percentages calculated from the GIS maps shown in Fig. 3. For PM_{10} the calculations are for limited measurements only where available in 1995.

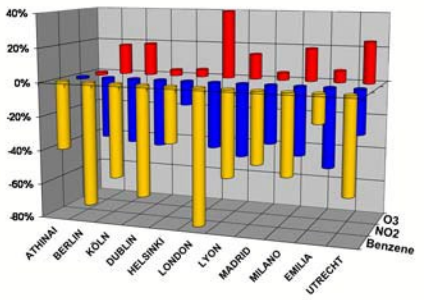

Fig. 8 The percentage of change between 1995 and 2010 for the mean air-quality concentrations in each of the urban inner domains of the second AutoOil on the basis of numerically calculated values.

The mean concentrations (b) for three pollutants in the inner urban domains are shown at Fig. 8. The vertical axis shows the values normalised against the values obtained for the base year 1995 at the same domain. Worth noticing the increase of the ozone values in view of the local emission inventories provided by the local authorities.

For assessing pollutants that depend on the dispersion of several precursors and that are subject to chemical transformations it is necessary to establish an accurate relationship between air-quality concentration and emissions (e). Despite the complexity of establishing this link (especially for photochemical processes), additional simulations were carried for source apportionments in characterising the "reality "in each grid cell. Naturally, the emission inventories need to be sufficiently disaggregated into the same source categories.

Because in the second AutoOil simulations were carried out separately for 18 categories it was possible to identify directly the attribution of Traffic Sources (CAT_20), the Elevated Area Sources (CAT_21), the Large Point Industrial Sources (CAT_22), the Other Area Sources & Nature (CAT_23) as well as the Non-Attributable Secondary Concentrations (NASC) part of primary emissions, which was due to the chemical reaction potential of the different portions of the concentration originating from natural background and the portion originating from the boundaries (i.e. the imposed lateral boundary concentrations).

Fig.9 shows the breakdown of the 40 highest pollutant concentrations at the inner domains for Athens, Lyon and Milan. This figure also contains a portion of "non-attributable" concentrations with the green colour which is not directly attributable to anthropogenic sources. In reality this portion is the portion is the reason why simple emission reduction approaches based on simple attenuation of "base year" air-quality from factors derived on emission with have unpredictable consequences. This is also the case with cost-effective models that utilise emissions only and air-quality concentrations are utilised off-line after optimising on emission files only.

Although for many years in scientific literature are carried out comparisons with measurements, these usually are not focused or are not general. Hence, they do not help in increasing the confidence on modelling data, especially if these conveniently examine only one component (e.g. ozone) and ignore evaluations for the precursors or the meteorology. The next section shows comparisons with measurements at the target year and generalisations over large geographical areas.

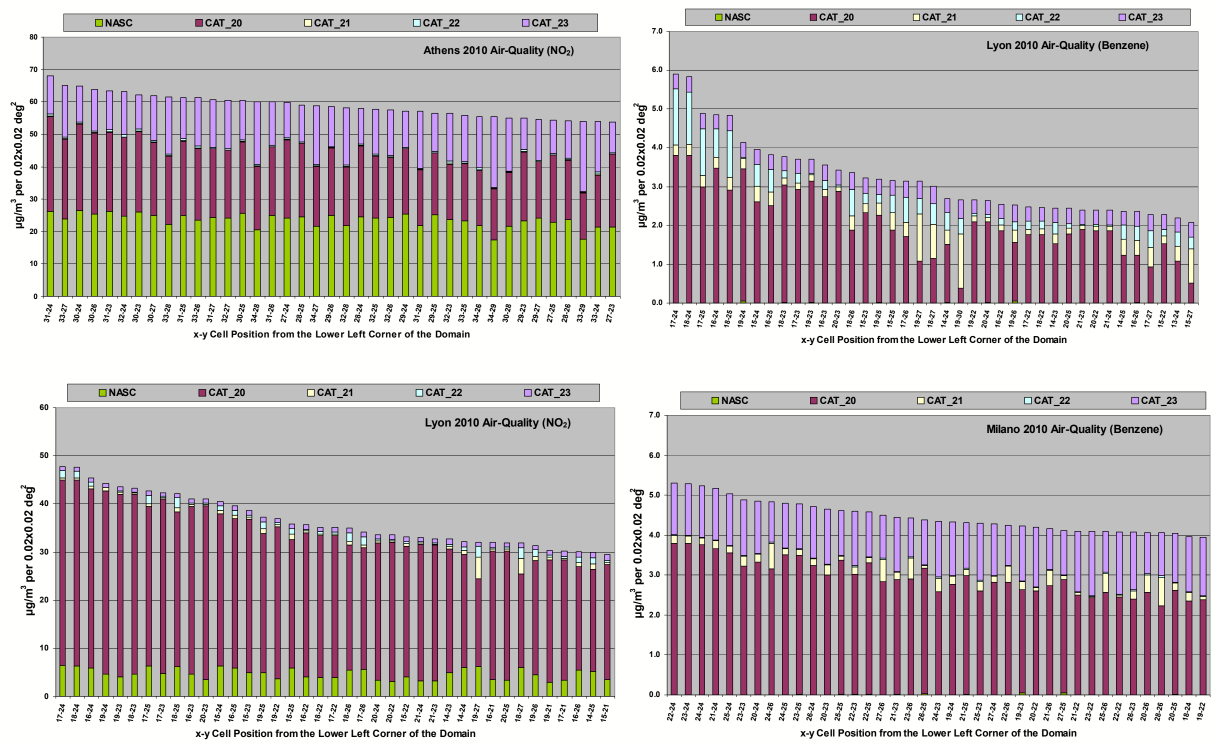

Fig. 9 Emission Source attribution of air-quality for 40 grid-cells with the largest concentrations of NO_2 and C_6H_6 in the city domains of Athens, Lyon and Milan.

Actual measurements at the target year

Most urban domains contain a number of air-monitoring stations, operated under the auspices of the local authorities, at which average pollutant concentrations levels are reported at times ranging from minutes to hours. By looking into the actual measurements at the target year we can see how much of this process has been successful.

Between 1995 and 2010 the number of monitoring stations operating at the ten AutoOil domains changed significantly. In 1995, 242 monitoring stations reported ozone in the black rectangles shown in Fig. 2 (outer domains). Out of these 242 stations, 73 operated at the red rectangles (inner domains). In 2010, the corresponding number of stations were 529 and 195 respectively. Consequently, we are able to look relatively accurately what was the effectiveness of the emission reductions introduced between the 1995 and 2010. At Fig. 10 are shown the comparison of measured concentrations between the base and the target year. The comparisons show the comparisons for O_3 and NO_2, but similar figures have been generated for CO, C_6H_6 and PM_{10}. The stations reporting within the AutoOil domains (both inner and outer) are shown separately for each modelling domain. With triangles are shown the values for all other European stations which are in the European grid but outside the AutoOil domains. The diagonal line divides the graph in two parts. The top-left area where are represented the monitoring stations with deterioration in 2010 of the annual mean values of 1-hour maximum concentration for O_3 and the 1-hour averaged concentration for NO_2. The lower right area below the diagonal line shows the stations with improvements in 2010.

A seen by the two parts of Fig. 10 for O_3 and NO_2 respectively, the expectations of the modelling simulation of Fig. 8 are confirmed. Similar comparisons with the other pollutants confirmed the same trend. These comparisons with measurements implicitly means that the detailed setup with the urban and regional representation of the atmosphere was correct despite being numerically laborious with the ICT tools that were available when these modelling simulations were carried out.

Fig. 11 Meteorological measurements for the national network of weather station in the Athens domain of AutoOil and the surrounding area (the values in each blue box are in degrees C).

Experimental comparisons were also made between measurements and modelled results for the target year. The purposes of these comparisons were to examine at the target year:

- How well the annual average conditions are represented.
- Examine the frequency distribution during the modelled annual-mean period and demonstrate that this is similar to the distribution at the target year.
- Demonstrate spatial variability by looking into several monitoring stations at least for the annual mean and the 98 percentile values.

Unfortunately, the verification of modelling simulations with time-series comparisons for pollutant concentrations and meteorology during the target year were not possible due to

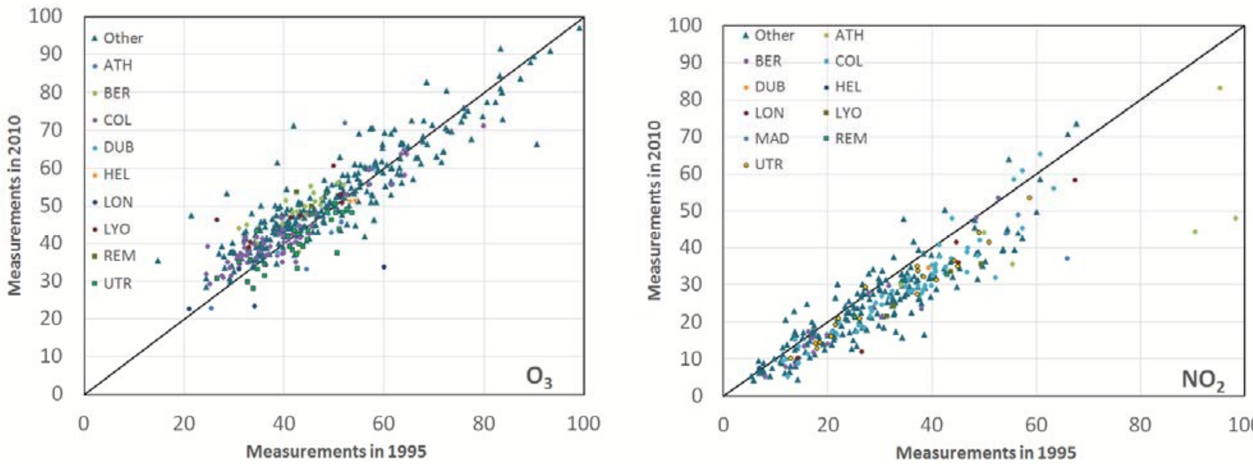

Fig. 10 Comparison of measurements between the base year 1995 and the target year 2010 for O_3 (left) and NO_2 (right). The units are in μg/m^3. The diagonal line indicates no variation in concentrations between 1995 and 2010. The area above this line represents deterioration and the area below the line improvements in the measured concentrations at the target year. With triangles are represented the monitoring stations outside the ten outer AutoOil domains.

the limitations of the modelling methodology in working with surrogate periods. This is because the surrogate annual-mean period and the period for the 98 percentile episodes are occurring at different dates in 1995 and in 2010.

For future regulatory approaches, it is worth mentioning that in the modelling area there has seen significant improvements in numerical tools and in the information available from monitoring and emission databases. The former can already benefit from big data and utilise assimilated techniques for reducing the uncertainty of initial conditions and improve the spatial representativeness. The following areas are now technologically feasible and will contribute in the development of a new generation of modelling methodologies.

First, the increase in the global deployment of compact weather monitoring devices is now capable to provide on real time 10 min averaged values over a dense grid as shown by Fig. 11. This will not only improve the spatial initialisation but because of lowering the temporal interval it will make meteorological tools more suitable to acute episodes.

Second, supplementary to static networks, mobile sensor systems have also become available. These have the advantage of reducing the number of sensor nodes required, at the expense of increasing the complexity of the data processing. Data from vehicle mounted sensors in conjunction with GPS can be used to generate a map of pollution distribution in a specific area wireless sensor networks could potentially fulfil this function by supplementing the data from existing monitoring stations to enable extremely localised mapping of air pollution to analyse peak events and identify hot spots.[7] Their wide scale deployment in densely populated urban areas would allow the spatial and temporal variation of air pollutants.

Third, algorithms have been developed to optimise the sampling rate to obtain the best accuracy while reducing data transmission costs and verified by simulations and tests with a prototype mobile sensor system.[8] Mobile sensor platforms have been designed to be mounted on both public transport and private vehicles. In the latter case individual drivers would have the option of measuring air quality data for private use only or to participate in community based sensing.[9]

Stricter emission regulations will in future also require more efficient on-board diagnosis systems. Aside from monitoring air pollution, metal oxide sensors can also be used to control the levels of pollutants present in exhaust gases.[10] Because of their low cost and the ease with which they can be integrated into mobile devices and networks, these sensor technologies may also find application in variable engine emission monitoring as well as personal exposure to air pollutants.[11]

Geographical generalisation

An important remaining issue for regulatory comparisons remains the geographical representativeness over the domain of interest. Ideally, the model simulations should be repeated in verification runs with the actual meteorology and emission inventories during the target year. Comparison of the forecasted conditions with actual up-to-date conditions from verifications runs could be very useful in further regulatory efforts for 2020 and 2050. This process is laborious even with modern ICT resources due to heterogeneous data structures and data gaps. So it might be useful on the basis of inner and outer modelling windows to propose a geographical generalisation of the simulated concentrations.

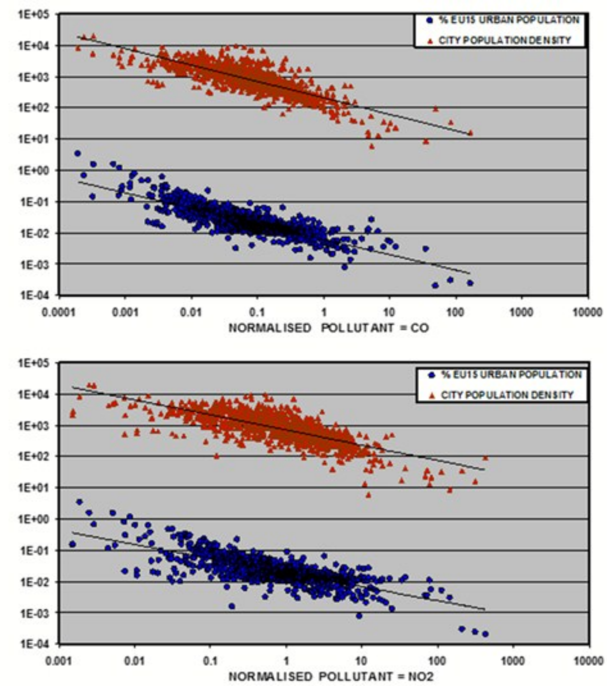

Fig. 12 Normalised maximum 8-hours CO (upper) and the hourly NO_2 concentrations in 1995 (base year). These are expressed in the y-axis against the percentage of EU urban population (circles) and the local population density (triangles) for all settlements in the AutoOil domains.

Within the ten modelling domains shown in Fig. 2 were situated 1065 urban settlements. These represented 46.5% of EU15 urban population. Out of these settlements 281 are within the 11 inner modelling domains and 784 within the ten outer domains. These settlements are located primarily at the states of Belgium, France, Finland, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Spain and United Kingdom, although there are few additional urban settlements from Estonia, Switzerland and Poland. This is a sufficiently large base on establishing a generalisation relationship between air quality concentrations and the local population density.

By normalising local concentrations for each pollutant against the population density and the percentage of EU15 urban population the results for the data set of 1065 settlements are shown in Fig. 12. The local concentrations are extracted from the modelling results in the grid cell where is situated each settlement. The city population density is according to the Eurostat census data in the respective urban areas. The upper part is for the maximum 8-hour averaged CO and the lower for hourly NO_2. The line in these figures is representing the following function:

$$c \approx a\, p_d\, u_p^{b+1}$$

where, "*c*" is the pollutant concentration (expressed in μg/m^3), "p_d" is the population density (expressed as inhabitants/km^2) and "u_p" is the percentage of population against the total EU15 urban population and "*a*" and "*b*" are empirical constants. These take different values for the base year and the target year on the basis of emission reductions and change of the climate. For NO_2 the values of $a= 1.63\ 10^{-4}$ and $b= -2.2124$ in 1995 *and* $a= 1.03\ 10^{-4}$ and $b= -2.2163$ for 2010. For max-8H CO the values of $a= 3.38\ 10^{-2}$ and $b= -2.0255$ in 1995 *and* $a= 2.10\ 10^{-2}$ and $b= -2.0695$ for 2010.

The advantages of this approach are that the sample is large (more than 1000 settlements), consistent geographical grid of at the worst 6x6 km^2 as in Fig. 3, which is by far better than most regional models. The emissions are not directly utilised which might introduce uncertainty or ad-hoc assumptions about the representation of monitoring stations.

Conclusions

In the past, the perception of sustainable urban air-quality conditions led to emission control strategies that were fundamentally linked only to the magnitude of the emission sources and all atmospheric processes were assumed to be static. Subsequently these strategies were coupled with measurements of air-quality through networks of measuring stations, which also had limitations in representing reality over large areas. However, even in the latter case, serious problems might arise when such measurements are extrapolated to locations where data are missing or when interpreting concentration in the proximity of measuring instruments.

With this work we presented a modelling methodology for describing the air-quality in a target year after analysing the current conditions in a base year. Following the validation simulations on the base years emission reductions were introduced with several scenarios aiming to achieve compliance to air-quality limit values. Several such regulatory efforts have been carried out in the past but rarely it has been analysed what was outcome on the planned “target year”. With this work we analysed for the first time measurements over more than 1000 monitoring sites both during the “base year” as well as the “target year”. These demonstrate the effectiveness of emission reductions in Europe in achieving compliance to well-known air-quality standards. Concerning modelling, since air-quality problems have become more complex at regional and local level with a wider impact of oxidants on population and rural ecosystems, it is essential to carry out the simulations with sufficient physical, geographical and temporal details.

It is evident that not all emission reductions will work everywhere and at all temporal scales. Even more, compliance to targets with different temporal weighting might not necessarily mean that it has the same effect, even for the same pollutant. As technology progresses, it might be realistic to adopt targets that vary locally and with time. Hence, technological infrastructures and algorithms that allow such variations might be useful.

The verification with actual air-quality measurements in the target year shows that the scenarios used until now have achieved maximum results with reasonable emission reductions. It is likely that further emission reductions might not lower the concentrations further but these might shift the problem in another source category. Without new vehicles technologies and fuels, scenarios of further reducing emissions in one sector might shift the problem in another sector or simply another geographical area.

The integrated use of urban and regional models in this study has already forecasted some reductions and some deterioration in ozone concentrations. However, these were more significant outside the urban areas where the mechanism of ozone formation is more closely related to the background concentrations and to the improvement due to the climatological conditions.

New technologies for monitoring can further enhance all steps of regulatory simulations and introduce significant advancement in the actual verification of abatement strategies. Conventional air quality monitoring systems are expensive and consist of a limited number of stations installed in fixed locations, with consequently coarse spatial resolution. In order to increase the areal coverage and usefulness of air quality data it is necessary to acquire real-time information and provide this in a dynamic way to both regulatory authorities and the general public.

References

1 H.R. Olesen and T. Mikkelsen (editors) *Proc. of the workshop on the Objectives for Next Generation of Practical Short-Range Atmospheric Dispersion Models*, Risø, Denmark. National Environmental Research Institute, P.O. Box 358, DK-4000 Roskilde, Denmark, 1992.
2 A. N. Skouloudis, *Issues in Environmental Science and Technology*, Royal Society of Chemistry, 1997, Issue **8**, 67-93.
3 A. N. Skouloudis, *EUR Report No EUR19725EN*, European Commission, EU Bookshop ISSN: 1018-5593, 2000 1-264.
4 AutoOil-I, Sub Group-2, *DG-XI/D3 Report on 'Air quality report of the AutoOil programme'*, European Commission, Belgium, 1996.
5 D. Simpson D., *Atmos. Environ.*, 1992, No. **9**, 1609-1634.
6 C. Dore and S. Vidič S., *EMEP Centres*, Note **3,** 2012, www.unece.org/fileadmin/DAM/env/documents/2012/air/EMEP_36th/n_3_EMEP_note_on_grid_scale__projection_and_reporting.pdf.
7 P. Völgyesi, A. Nádas, X. Koutsoukos, and A. Lédeczi, *Proc. of the 7th International Conference on Information Processing in Sensor Networks*, IEEE Computer Society Washington, DC., 2008, pp. 529-530.
8 S. C. Hu, Y.-C. Wang, C.-Y. Huang, and Y. C. Tseng, *the Journal of Systems and Software*, 2011, **84**, 2005-2012.
9 S. Devarakonda, P. Sevusu, H. Liu, R. Liu, L. Iftode and B. Nath, *Proc. of the 2nd ACM SIGKDD International Workshop on Urban Computing*, ACM, New York, 2013 1-22.
10 M. Miura, *Novel Carbon Resource Sciences Newsletter*, 2010, **2**, 10-16.
11 A. de Nazelle, E. Seto, D. Donaire-Gonzalez, M. Mendez, J. Matamala, M. J. Nieuwenhuijsen, and M. Jerrett, *Environmental Pollution*, 2013, **176**, 92-99.