Air Pollution Science for the 21st Century
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Chapter 1

Urban air quality

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Abstract

Since 1950 the world population has more than doubled, and the global number of cars has increased by a factor of 10. In the same period the fraction of people living in urban areas has increased by a factor of 4. In year 2000 this will amount to nearly half of the world population. About 20 urban regions will each have populations above 10 million people.

Seen over longer periods, pollution in major cities tends to increase during the built up phase, they pass through a maximum and are then again reduced, as abatement strategies are developed. In the industrialised western world urban air pollution is in some respects in the last stage with effectively reduced levels of sulphur dioxide and soot. In recent decades however, the increasing traffic has switched the attention to nitrogen oxides, organic compounds and small particles. In some cities photochemical air pollution is an important urban problem, but in the northern part of Europe it is a large-scale phenomenon, with ozone levels in urban streets being normally lower than in rural areas. Cities in Eastern Europe have been (and in many cases still are) heavily polluted. After the recent political upheaval, followed by a temporary recession and a subsequent introduction of new technologies, the situation appears to improve. However, the rising number of private cars is an emerging problem. In most developing countries the rapid urbanisation has so far resulted in uncontrolled growth and deteriorating environment. Air pollution levels are here still rising on many fronts.

Apart from being sources of local air pollution, urban activities are significant contributors to transboundary pollution and to the rising global concentrations of greenhouse gasses. Attempts to solve urban problems by introducing cleaner, more energy-efficient technologies will generally have a beneficial impact on these large-scale problems. Attempts based on city planning with a spreading of the activities, on the other hand, may generate more traffic and may thus have the opposite effect.

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1. Introduction

"Urban air quality" is a vast subject with different socio-economic aspects in different parts of the world – and even within a specific region. This is demonstrated for selected regions. The European Union representing the industrialised western countries is treated in most detail, the eastern part of Europe gives examples of economies in transition and East Asia – specifically China – represents the developing regions. Other regions: North America, Latin America, West Asia and Africa are only briefly discussed – not because their problems are less important, but because the general aspects of urban air pollution and air quality are already covered.

1.1. The historical perspective

Cities are by nature concentrations of humans, materials and activities. They therefore exhibit both the highest levels of pollution and the largest targets of impact. Air pollution is, however enacted on all geographical and temporal scales, ranging from strictly "here and now" problems related to human health and material damage, over regional phenomena like acidification and forest die back with a time horizon of decades, to global phenomena, which over the next centuries can change the conditions for man and nature over the entire globe. In this respect the cities act as sources.

Initially outdoor air pollution was by and large a purely urban phenomenon, and literature as well as historical records testify that the problems were extensive. They may even be underestimated, since generally people were less critical about their living conditions, and they had no means of evaluating long-term impacts of, e.g. carcinogens. Further, many of the records concern aesthetic impacts in the form of smell and soiling, which are not deleterious to health in themselves.

Finally it should be recognised that up to the Second World War many people had an ambivalent attitude towards pollution, which to some extent was perceived as a symbol of wealth and growth. Thus advertisements showed pictures of fuming chimney stacks and cars with visible exhaust – images hardly anyone would cultivate today!

Semi-quantitative evaluations of the early urban air pollution have been attempted in various ways, i.a. via records of material damage and impacts on human health and vegetation. Also simplified dispersion modelling is a possibility, when the consumption of fuels and raw materials within a confined area are reasonably well known (Brimblecombe, 1987).

Some direct measurements of air pollutants were carried out by scientists and amateur enthusiasts in the last century, but systematic and official investigations with continuous time series are of fairly recent date. In England the number of measuring sites was thus not increased substantially before the London smog disaster in 1952 was followed by the Clean Air Act in 1956 (Brimblecombe, 1998).

1.2. Present day records

In most of the industrialised world urban air pollution is now monitored routinely. Since 1974 WHO and UNEP have, within the "Global Environment Monitoring System", collaborated on a project to monitor urban air quality, the so-called GEMS/AIR (UNEP, 1991; WHO/UNEP, 1992; GEMS/AIR, 1996; and a series of related reports). Concentrations of air pollutants in selected countries are also reported yearly by the OECD (1997). A comprehensive presentation of urban air pollution in Europe, based on data from 79 cities in 32 countries (Richter and Williams, 1998) has recently been published by the European Environment Agency.

These data and similar ones give an indication of trends in ambient air quality at national level and in cities. However, one should be cautious when comparing absolute values from different regions. Often the data are based on one or a few monitoring stations, placed at critical sites and thus represent micro-environments. It should also be taken into account that the coverage of stations is different for different countries (Larssen and Hagen, 1997), and that average values can therefore be differently biased.

Information on air pollution in the developing countries and in some countries with economies in transition is limited and longer time-series are very rare. In some cases a general trend in air quality can only be estimated on the basis of uncertain emission inventories. Data presented in the open literature are seldom up to date and normally concern specific cities, which may not be fully representative. In recent years many governmental and private institutions from the industrialised countries (including Denmark) have acted as consultants in developing countries or performed investigations, but not all the efforts are reported in the open literature.

1.3. Air quality indicators

To date nearly 3000 different anthropogenic air pollutants have been identified, most of them organic (including organometals). Combustion sources, especially motor vehicles, emit about 500 different compounds. However, only for about 200 of the pollutants have the impacts been investigated, and the ambient concentrations are determined for an even smaller number.

This complex nature of air pollution, especially with respect to health impacts in cities, has prompted attempts to define the so-called indicators

(Wiederkehr and Yoon, 1998), which condense and simplify the available monitoring data to make them suitable for public reporting and decision makers. OECD (1998) has applied major pollutants measured in a specified way as indicators for the total mix of pollutants (an example is shown later as Fig. 17), but also weighed means of concentrations of several pollutants relative to guideline values has been used.

In another type of indicators OECD (1998) has aggregated monitoring data from various regions (Western Europe, USA, Japan) to demonstrate overall trends in pollution levels. The results of such an exercise should be treated with some caution, but yearly averages appear to represent the general developments reasonably well. Values for the period 1988–1993 and the pollutants SO_2, NO_2, CO and O_3 are shown in later sections.

1.4. Local emissions and global pollution

The growing global consumption of fossil fuels leads to energy-related emissions of carbon dioxide (e.g. Ellis and Tréanton, 1998) and may eventually, via the enhanced greenhouse effect result in climate changes with impacts on all human activities and natural ecosystems. One of the results of the UN-conference on environment and development in Rio de Janeiro in 1992 was an action plan for the attainment of a sustainable global development in the next century – the so-called *Agenda 21*. As a consequence many cities and administrative units in the industrialised world have embarked on local programs, and more than 290 European cities have signed the Aalborg Charter of European Cities and Towns towards Sustainability. Noteworthy in this connection is The International Council for Local Environmental Initiatives (ICLEI, 1998) with the purpose to achieve and monitor improvements in global environmental conditions through cumulative local actions. Although the political attention emphasises climate protection and thus reduction of emission of the ultimate product of combustion – CO_2, the attempts to save energy may also improve the urban air quality (e.g. Pichl, 1998).

2. Global growth and increasing urbanisation

2.1. Population and urbanisation

Just after the Second World War the world population was about 2.5 billion, and in mid-1998 it had more than doubled to 5.9 billion. The more developed countries account now for 1.2 billion and the less developed for 4.7 billion, among these China alone accounts for 1.2 billion. In the same 50 year period the global urbanisation, defined as the fraction of people living in settlements above 2000 inhabitants, has risen from below 30 to 44%. In the more developed countries it is now on the average 73% and in the less developed 36% (Population Reference Bureau, 1998).

There is no indication that these global trends will change in the next decades (Fig. 1). Around year 2000 nearly half of the world population will live in urban areas, and various projections estimate a total population in the order of 10 billion in the middle of the next century with the sharpest rise in the (now) developing regions – and among them most in Africa.

Especially in the developing countries there is a significant migration of people from the countryside to the towns – both because of a mechanisation of farming and opportunities in new industries and public services. This may here lead to a further growth in urbanisation with a factor in the order of 1.5 in the next 50 years (UNEP, 1997). In China alone more than 100 million people are reported to move around in search for work, and, e.g. Beijing appears actively to prevent their permanent settlement.

In Asia, Latin America and Africa this urbanisation has been accompanied by the proliferation of slums and squatter settlements (United Nations, 1997a). In some cases the situation has been aggravated by polluting industries, which have been transferred from industrialised countries with stricter environmental legislation and higher wages.

Regions with high birth rates and immigration are therefore faced with environmental problems due to unplanned urban growth and emerging megacities. In 1950 there were only eight cities with inhabitant numbers above 5 million,

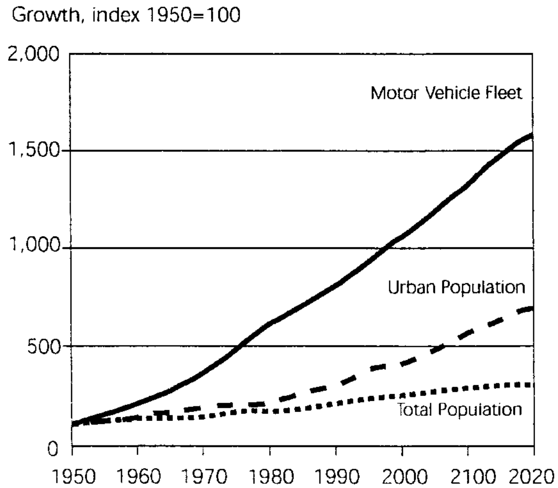

Figure 1. The increase since 1950 of the total world population, the urban population and the number of motor vehicles – excluding motorbikes and three wheelers (UNEP/WHO, 1992).

in 1990 there were about 35, and in year 2000 there will probably be more than 40. About half of them will be situated in East Asia (WHO/UNEP, 1992). Probably more than 20 of the cities will have more than 10 million inhabitants.

On the other hand there has been a tendency in the industrialised world that relatively fewer people live in the inner areas of the cities (OECD, 1995b). This leads to increasing urban travel and expanding road systems.

2.2. Global energy consumption, production and emissions

The global number of motor vehicles – excluding 2- and 3-wheelers has increased by a factor of 10 since 1950 (Fig. 1) and is now above 600 million. In addition to this there is now an estimated 80 million motorcycles (OECD, 1995a). In the same period the industrial production has increased by a factor 10 and the global energy consumption by nearly a factor 5 (United Nations, 1997b and earlier reports). Since the major part of the energy has been produced by fossil fuels, and to a minor extent by biofuels, initially without flue gas cleaning, the global emissions of air pollutants have increased correspondingly. Since 1950 the global emission of sulphur oxides has more than doubled, and the emission of nitrogen oxides increased by a factor of 4.

2.3. Pollution development

In general the environmental quality in a given country depends upon the average income of the inhabitants (The World Bank, 1992). The availability of safe water and adequate sanitation increases with the income, and so does the amount of municipal waste per capita. The air pollution however, appears initially to increase with the income up to a point and then to decrease (Fig. 2).

Based on more recent data Grossman and Krueger (1995) estimate that the turning point for different pollutants vary, but in most cases comes before a country reaches a per capita income of USD 8000. Although this suggests that global emissions will decrease in the very long run, a continued rapid growth over the next several decades is forecasted (Selden and Song, 1994).

Seen in a time perspective the air pollution in a developing urban area initially increases, goes through a maximum and is then again reduced, when pollution abatement becomes effective (Fig. 3). As it will be demonstrated in later sections, cities in the industrialised western world are in some respects in the last stage of this development, in economies in transition many cities are in the stabilisation stage, whereas in the developing countries the pollution levels are still rising. In the developing countries indoor pollution from biomass combustion for heating and cooking may, however be an even more serious problem with concentrations of particles orders of magnitude higher than the safe levels in WHO guidelines (Smith, 1988).

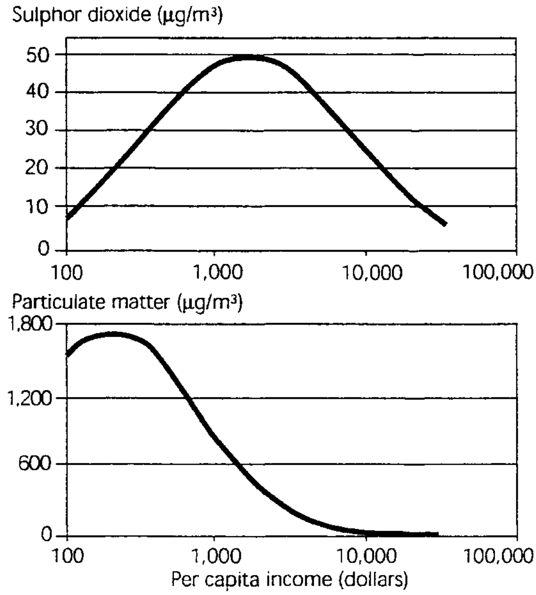

Figure 2. Urban concentrations of SO_2 and particulate matter as a function of national per capita income (based on data from the 1980s. The World Bank, 1992). The curves only show general tendencies, there are marked deviations. Thus in the early 1980s Kuwait had both some of the highest incomes and highest pollution levels (Smith, 1988).

Fully in line with this typical development The World Commission on Environment and Development in its report "Our common future" (The World Commission on Environment and Development, 1987) conceives technological development and rising standard of living as a prerequisite for environmental improvement. Or as Bertholt Brecht has put it: "Erst kommt das Fressen, dann kommt die Moral" – in modern form: "First development and only later pollution control".

3. Pollutants, sources and emissions

The air pollutants can be divided into two groups (Wiederkehr and Yoon, 1998): The traditional *Major Air Pollutants* (MAP, comprising sulphur dioxide, nitrogen dioxide, carbon monoxide, particles, lead and the secondary pollutant ozone) and the *Hazardous Air Pollutants* (HAP, comprising chemical, physical and biological agents of different types). The HAP are generally present in the atmosphere in much smaller concentrations than the MAP, and they appear often more localised, but they are – due to their high specific activity –

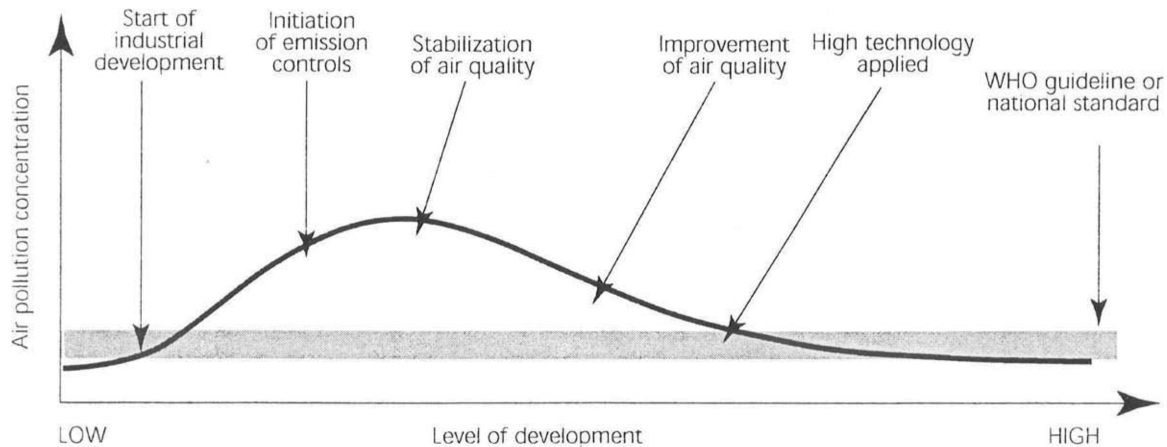

Figure 3. Schematic presentation of a typical development of urban air pollution levels. Depending upon the time of initiation of emission control the stabilisation and subsequent improvement of the air quality may occur sooner or later in the development. (Based on WHO/UNEP, 1992; Mage et al., 1996).

nevertheless toxic or hazardous. Both in scientific investigations and in abatement strategies HAP's are difficult to manage, not only because of their low concentrations, but also because they are in many cases not identified.

3.1. The major pollutants

Sulphur dioxide (SO_2) is the classical air pollutant associated with sulphur in fossil fuels. The emission can be successfully reduced using fuels with low sulphur content e.g. natural gas or oil instead of coal. On large plants in industrialised countries desulphurisation of the flue gas is an established technique.

Nitrogen oxides (NO_x) are formed by oxidation of atmospheric nitrogen during combustion. The main part, especially from cars, is emitted in the form of the nontoxic nitric oxide (NO), which is subsequently oxidised in the atmosphere to the secondary "real" pollutant NO_2. The emissions can be reduced by optimisation of the combustion process (low NO_x burners in power plants and lean burn motors in motor vehicles) or by means of catalytic converters in the exhaust.

Carbon monoxide (CO) is the result of incomplete combustion with motor vehicles as the absolutely dominant source. The emissions can be reduced by increasing the air/fuel ratio, but with the risk of increasing the formation of nitrogen oxides. Most effective reductions are carried out with catalytic converters.

Particulate matter (PM) is not a well-defined entity as, e.g. carbon monoxide. Originally it was determined as soot or "black smoke" for which there is an EC air quality limit value (Edwards, 1998). Later the concept of total suspended particulate matter (TSP) was introduced, but since 1990 size fractionating has been attempted by measurements of PM_{10} (particles with diameter less than 10 µm). Unfortunately the major part of PM_{10} may have a natural origin (e.g., sea spray or desert and soil dust), and it is therefore important also to measure $PM_{2.5}$ or even, when the appropriate technology has been developed, PM_1.

The applications of different concepts and measuring techniques complicate evaluations of the development in pollution levels. To some extent it is possible to establish relationships between the concentrations of fine and coarse particles relevant to epidemiological studies (Wilson and Sue, 1997), but only under well-defined conditions. Measurements from Erfurt in the former DDR thus show that the level of $PM_{2,5}$ has been reduced substantially after the reunification and the subsequent introduction of updated technology. Nevertheless the amount of even smaller particles has increased and so has the total number of particles indicating a change in major sources (Tuch et al., 1997).

A further complication is that the chemical composition of particles is not well known, and that the health impacts may be due to other pollutants adsorbed on them – typically heavy metals or less volatile organic compounds.

The emissions of particles of antropogenic origin can be reduced by use of cleaner fuels, better combustion techniques and a series of filtration or impaction technologies.

Lead (Pb) as an additive to petrol has been phased out in the major part of the industrial world, but is still used in many developing countries and economies in transition, where also emissions from industrial activities play a role.

3.2. The hazardous pollutants

Volatile organic compounds (VOC) as air pollutants are the result of incomplete combustion of fuels or are formed during the combustion – typically in cars, where also evaporation may play a role. Also some industrial processes and the use of solvents result in the emission of VOC. In urban air the most important compounds are benzene and the series of polyaromatic hydrocarbons (PAH) among which some have until recently been unnoticed (Enya et al., 1997), but also, i.a. 1,3-butadiene, ethene, propene and a series of aldehydes have received attention (Larsen and Larsen, 1998).

It is a formal question whether biogenic VOC e.g. from vegetation constitute a pollution, but they must be taken into account in relation to photochemical air pollution.

The removal of lead as an additive has not been completely without side effects. Changes in the mixing of the petrol to increase the octane number may increase the emission of aromatic hydrocarbons i.a. benzene. Benzene concentrations have increased in many urban atmospheres with the introduction of catalytic converters (Richter and Williams, 1998). An alternative additive MTBE (methyl-tert-butyl ether) not only increases the octane number, but also improves the combustion and thus reduces the emissions of carbon monoxide and hydrocarbons. It is however an air pollutant causing both immediate eye and respiratory irritation and long-term risk of cancer. More important may be the contamination of soil and groundwater, especially around petrol filling stations (trans-media pollution). In Denmark MTBE is only used for 98 octane petrol.

Other heavy metals than lead of interest as air pollutants include cadmium, nickel and mercury, all with industrial sources.

3.3. Urban sources of air pollution

Since combustion is the dominant cause of urban air pollution, the various sources emit to a large extent the same pollutants – only in varying proportions. Table 1 indicates the typical relative importance of source categories for emission of the main pollutants. The distribution of course varies, thus e.g. in Eastern Europe SO_2 from space heating play a relatively more important role compared to Western and Southern Europe, and in Southern Europe the contribution from SO_2 from traffic is relatively high due to the use of diesel oil with a high sulphur content.

3.4. Emission inventories

National or regional inventories of emissions as they are carried out e.g. in the form of the European Corinair database (CORINAIR, 1996) are used in international negotiations. They may also for lack of better information suggest general trends in air pollution levels, but dispersion modelling in urban areas requires time and space resolutions relevant to the applied scale. Proxy data for larger areas can be generated on the basis of information on i.a. traffic pattern (Friedrich and Schwarz, 1998), but detailed investigations of individual streets (Berkowicz, 1998) are based on actual traffic counts.

4. From emissions to impacts

In the design of cost effective abatement strategies (e.g., Krupnick and Portney, 1991) it must be realised that the relations between emissions and resulting concentrations are by no means simple. Measurements are still the foundation of our understanding, but application of mathematical modelling, and also

Table 1. Main emission sources and pollutants in air pollution in commercial non industrial cities. The table indicates the relative importance of *urban sources* for the main *urban pollutants*. x: 5–25%; xx: 25–50%; xxx: More than 50%. (Based on Stanners and Bourdeau, 1995)

Source category		Pollutant						
		SO_2	NO_2	CO	TSP	Organic	Pb	Heavy metals[a]
Power generation (Fossil fuel)		xx	x	x				x/xx
Space heating	- coal	xx	x	xx	xx	xx/x		x/xx
	- oil	xx	x					
	- wood				xx	xx/x		
Traffic	- gasoline		xx	xxx		xx	xxx	
	- diesel	x	xx		xx	xx		
Solvents						x		
Industry		x		x	x	x	x	xx/xxx

[a]With the exception of lead (Pb).

of physical modelling in wind tunnels, is of increasing importance in urban air pollution management. As a consequence numerous techniques have been developed for different spatial scales ranging from entire regions down to individual streets. Some models only describe dispersion or have simple reaction schemes; more sophisticated models comprise a large number of interacting reactions. Such models can be further developed to form full decision support systems (e.g., Dennis et al., 1996).

4.1. Dispersion in the urban area

The importance of dispersion was recognised already with the invention of chimneys, and the meteorological conditions played a crucial role in a series of pollution disasters (Brimblecombe, 1987). The dispersion mechanisms have received special interest with the increasing urban traffic in built up areas. Fig. 4 demonstrates the significance of wind speed for the resulting air pollution in a street canyon, where a fairly strong wind ($8\,\mathrm{m\,s^{-1}}$) is seen to nearly halve the concentration of NO_2 at rush hours.

Measurements and dispersion calculations (e.g. Berkowicz, 1998) have shown that also the wind direction is important; therefore in areas with a dominant wind direction – thus in Denmark from the west – the orientation of the individual streets counts. The overall significance of the climatological conditions is clearly demonstrated in a comparison between the air quality in Copenhagen and Milan. Since the frequency of low wind speeds is considerably higher in Milan than in Copenhagen, Milan has much higher pollution levels for comparable emissions (Vignati et al., 1996).

In more open spaces (parks, squares, residential areas) the pollution levels take the form of an urban background, with increasing impact of more distant sources. Recent applications of mesoscale computer models have demonstrated that also the regional component is important, especially in areas with a complex landscape such as coastal regions; thus studies in the Mediterranean Region and Southern Europe have indicated that in certain periods the urban areas may be significantly affected by sources located hundreds of kilometres away (Kallos, 1998).

4.2. Chemical reactions

During dispersion the pollutants interact chemically (e.g. Finlayson-Pitts and Pitts, 1997) and for the urban atmosphere reactions between nitrogen oxides, organic compounds and ozone are the most important. Photochemical smog with formation of ozone and other oxidants was first recognised in Los Angeles in the mid-1940s as an urban phenomenon related to car exhaust in a subtropical topographically confined region.

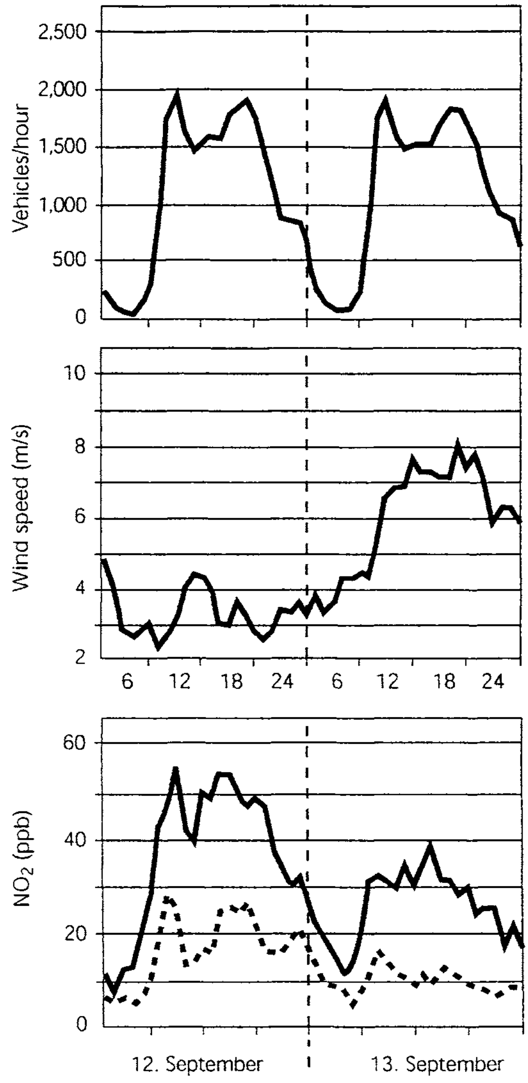

Figure 4. Relations between traffic intensity, wind velocity and NO_2-concentrations on two consecutive weekdays in 1997, measured at Jagtvej, a busy street surrounded with buildings in Copenhagen. The concentrations are measured both at the roadside (upper curve) and at a nearby rooftop (lower curve). (Based on material from Kemp et al., 1998 and related reports.)

It is now observed in most parts of the world, but with distinctly different patterns. In the south of Europe cities like Athens and Rome may experience a "summer smog" of the Los Angeles type, but in many cases it is a large scale phenomenon (Guicherit and van Dop, 1977). In cities in the northern part of Europe the predominant reaction is a reduction of ozone by nitric oxide in car exhaust to form oxygen and nitrogen dioxide. As a result ozone levels are generally lower at ground level in the streets than at roof level or in the surrounding countryside. Urban ozone levels are further higher during weekends with low traffic and may be practically nil during some pollution episodes (Fig. 5). Note also in Fig. 5 that the concentration of NO follows the traffic with rush hours and weekends much more closely than NO_2, the concentration of which is largely determined by the available O_3, supplied from outside the city.

These mechanisms often lead to formation of elevated ozone concentrations downstream from the city (city or urban plume). As a similar phenomenon on a larger-scale elevated ozone concentration in Central Europe due to extended high pressure events can, via long-range transport, also be detected in Northern Europe, where concentrations normally built up over several days – often in parallel with rising temperatures.

Since ozone is a secondary pollutant it can only be regulated via the primary pollutants. Long-range models can demonstrate the effects of ozone levels of changes in the emissions, and they indicate that a concerted international effort is necessary. In computer experiments it has thus been shown that in the hypothetical situation, where all Danish emissions were reduced to zero, the average ozone levels in Denmark would go slightly *up* (Zlatev et al., 1996).

Generally reductions in emissions of hydrocarbons are more effective than reductions of nitrogen oxides, but even with simultaneous reductions of 95% the European vegetation will not be fully protected against damages.

4.3. Formation of particles

Usually particles are grouped in the three so-called modes: ultrafine, fine and coarse (Fig. 6). The ultrafine particles are chemically formed or condensed from hot vapour e.g. from diesel exhaust and coagulate into fine particles (Whitby and Sverdrup, 1980). Defined as having an aerodynamic diameter less than 2.5 μm (UNEP/WHO, 1994), the ultrafine and fine particles, which are predominantly of antropogenic origin are deposited with high probability in the lower parts of the human respiratory system and thus have the largest impact. Coarse particles, on the other hand, are often of natural origin (dust, seaspray, pollen or even insects). Their health impacts are modest, both because they are deposited in the upper airways, and because they may be less toxic. Still, in determinations of total suspended particulate matter (TSP) the coarse particles dominate with their high weight.

In the atmosphere the actual size spectra show quantitative differences with e.g. more pronounced mass peaks for fine particles in urban and suburban sites and larger peaks for coarse particles near sea coasts.

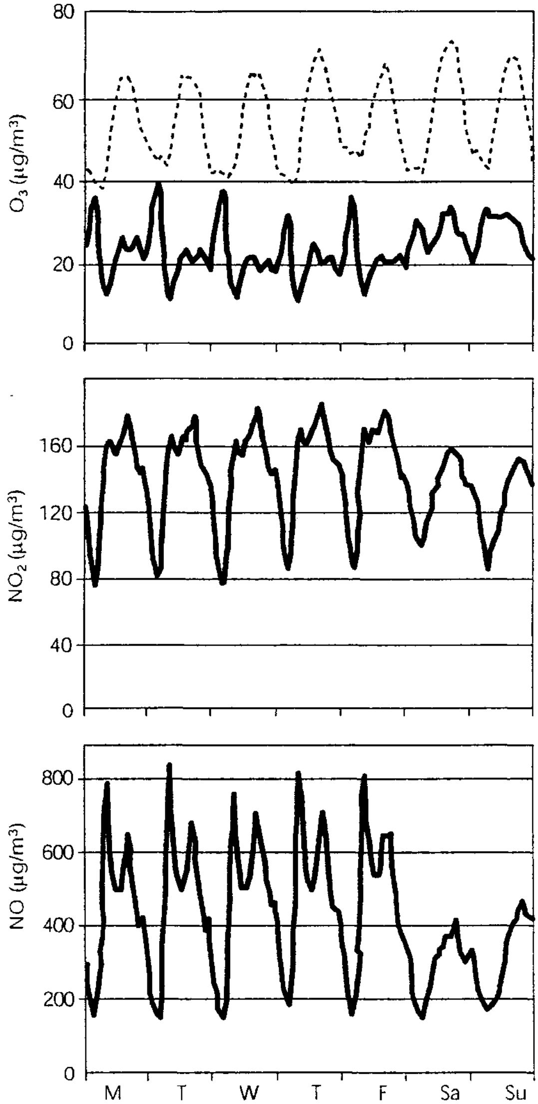

Figure 5. Average weekly variations for ozone and nitrogen oxides at H.C. Andersens Boulevard in Copenhagen with a daily traffic of 60,000 cars. For comparison is shown (dotted) a typical O_3-variation at a rural site. (Based on HLU, 1994.)

4.4. Exposure

Human health is the main concern in the regulation of urban air quality, and it is therefore an important question to which extent people are actually exposed

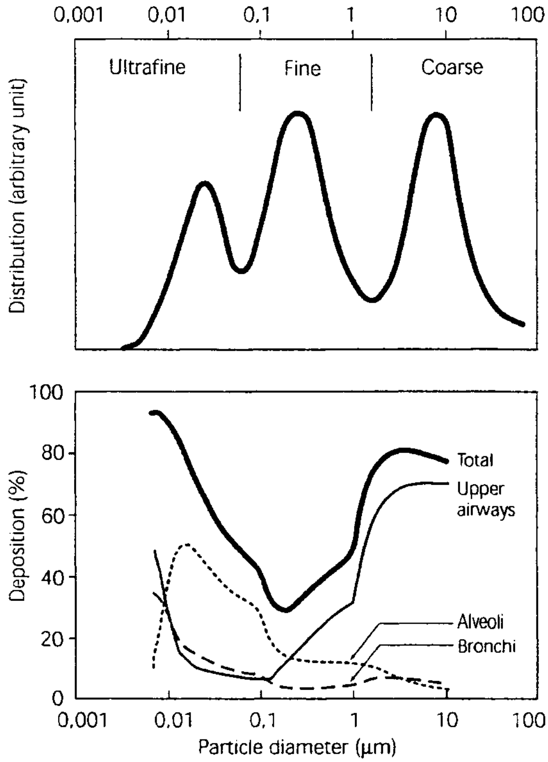

Figure 6. Schematic size distribution of particulate matter in the atmosphere and the corresponding deposition in the human respiratory system. (Based partly on Whitby and Sverdrup, 1980.)

to the measured or calculated pollution levels. In most cases so far the pollution exposure of the population has been assessed through crude assumptions, e.g. that levels observed at a single or a few street monitoring stations are representative for the exposure of the entire population in an urban area. Results of such an evaluation (WHO, 1995) are summarised in Section 6 (Table 2).

Direct monitoring (Fig. 7) demonstrates that the levels a person is exposed to vary drastically during the day, and that the ambient, outdoor air quality, regulated by various limit values do not describe the overall load, even in industrialised countries. Similar plots for, e.g., particles give slightly different patterns, but lead to the same general conclusion.

Still however, a realistic evaluation of population exposures requires more statistical information, where the time and activity pattern of the entire population must be taken into account. In reasonable agreement with Fig. 7 earlier Danish studies (Andersen, 1988) indicate that on the average the population

Table 2. Population exposure to various pollutants in Europe before and after 1985. The table shows how large a fraction (%) of a registered city population is exposed to (living in) concentrations above WHO guidelines for yearly averages (SO_2 and black smoke) or to the lowest level at which long-term exposure is reported to cause respiratory effects (SPM and NO_2); unit: $\mu g\,m^{-3}$ (Based on WHO, 1995)

Pollutant	"Limit value"	Western countries	CCEE countries	USSR	Total Europe
SO_2	50	58.2/14.3	37.3/11.1	77.9/48.1	63.1/20.5
Black smoke	50	25.5/19.1	65.7/58.2	100/25.5	33.4/22.9
SPM	60	91.6/51.8	—/100	—/100	—/61.0
NO_2	60	20.3/23.9	38.5/24.1	19.2/3.7	20.8/19.1

spend only 1 h per day outdoors, 1 h commuting and the remaining 22 h indoors. Ongoing Danish studies (Jensen, 1998) apply a geographic information system (GIS) to combine air pollution data calculated with the OSPM model (Berkowicz, 1998) with population data available from administrative databases. In view of the large fraction of time spend indoors in cities with a cold climate, also the relations between outdoor pollution and related indoor levels (typically about the half), must be taken into account. And then nothing has been said about active and passive smoking, which have large regional and cultural variabilities, but in general appear to have health impacts an order of magnitude above general air pollution!

In the so-called "EXPOLIS" study (Jantunen et al., 1998) personal exposure is determined by monitors and diary records in six European cities (Helsinki, Bilthoven, Prague, Basel, Grenoble and Milan), but detailed results are not yet available.

4.5. Impacts

Urban air pollution has a series of impacts on materials, vegetation (including urban agriculture) and visibility. These impacts depend of course on the relevant levels, but also on other factors, for material damage (Tidblad and Kucera, 1998) thus on temperature and humidity and the possibility of interaction between different components. The main concern, however – and the one which by and large determines the abatement strategies – is its impact on human health and well-being, although the health of urban populations is determined by many factors (Phillips, 1993), which may blur the picture.

Various types of health impacts of the major air pollutants are well established (WHO, 1987/1999), but a series of, notably organic, compounds are not sufficiently investigated. In recent years numerous epidemiological studies of short- and long-term effects of air pollution have shown that fine particles at the present levels are responsible for significant impacts, especially on people

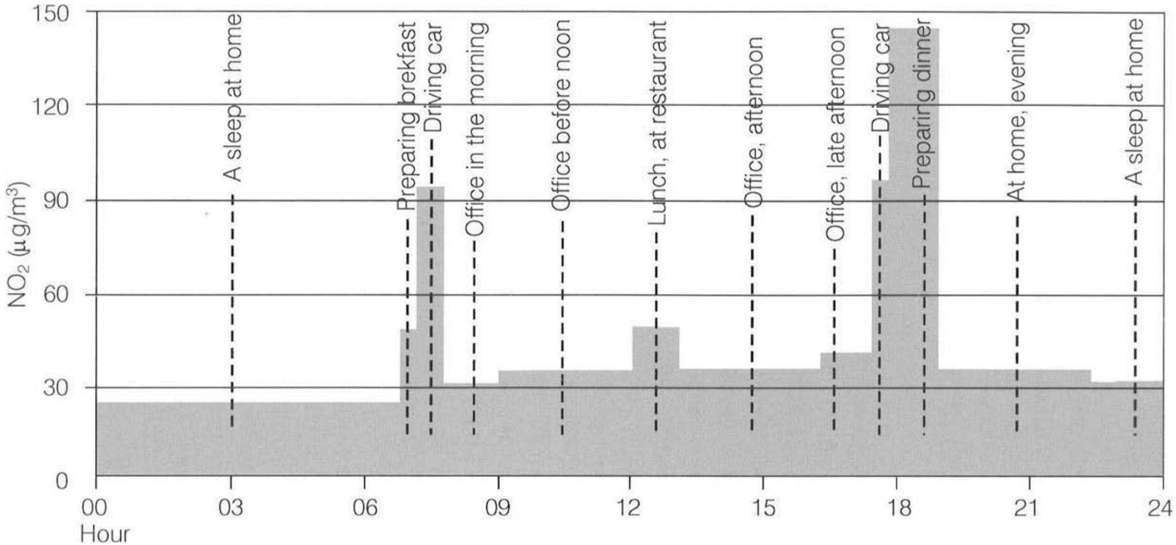

Figure 7. An example of personal exposure with NO_2 during a working day in The United States. Note the peak during preparation of dinner; it of course depends on the means of heating (Sexton and Ryan, 1988).

suffering from respiratory and cardio-pulmonary diseases (Pope et al., 1995). Thus Schwartz et al. (1997) have reported that a $10\,\mu g\,m^{-3}$ increase in $PM_{2,5}$ 2 day mean was associated with a 1.5% increase in total daily mortality, although the actual mechanisms are still not known. For coarse particles (above $10\,\mu m$) no impacts were observed.

4.6. City planning

The impacts of urban air pollution can be mitigated by constructive city planning. The complete separation of industry and habitation, originally envisaged as an environmental improvement and a reasonable solution in a society with heavily polluting industries, is now outdated and only leads to increased commuting traffic and congestion. Attempts to reduce urban driving by various types of economic incentives (green taxes, road pricing, km taxes), parking restrictions and pedestrian streets have had some success, but has often been opposed by trade. It must also be considered that driving restrictions *in* cities may increase recent years growth of big shopping centres, hotels and office buildings *outside* the cities, where they can offer free parking space and other facilities as e.g. child minding, thus often resulting in an increase in total traffic (OECD, 1995b).

The goal now is integrated land use, which minimises transport and thus total urban emissions. Open spaces and parks can here be used to improve the environmental quality especially in residential areas (Fig. 8).

In existing cities the possibilities of restructuring are limited, but the construction of ring-roads, which lead part of the traffic round the city-centre is one of the options (OECD, 1995).

In the industrialised world few cities and urban areas can be constructed from scratch, but when possible new concepts of integrating urban planning, building design and supply of renewable energy should be applied. Also the climate of the city is important, and the influence of buildings and street canyons on solar radiation, shade and wind pattern should be taken into account (Bitan, 1992).

In this planning, which to a large extent is planning of traffic, it must be realised that air pollution is not its only environmental impact, and probably not even its most important. It is estimated (European Commission, 1995) that on the average the external costs of air pollution (not including greenhouse effect) from transport in the EU amount to 0.4% of the GNP, compared to 0.2% from noise, 1.5% from accidents and 2.0% from congestion.

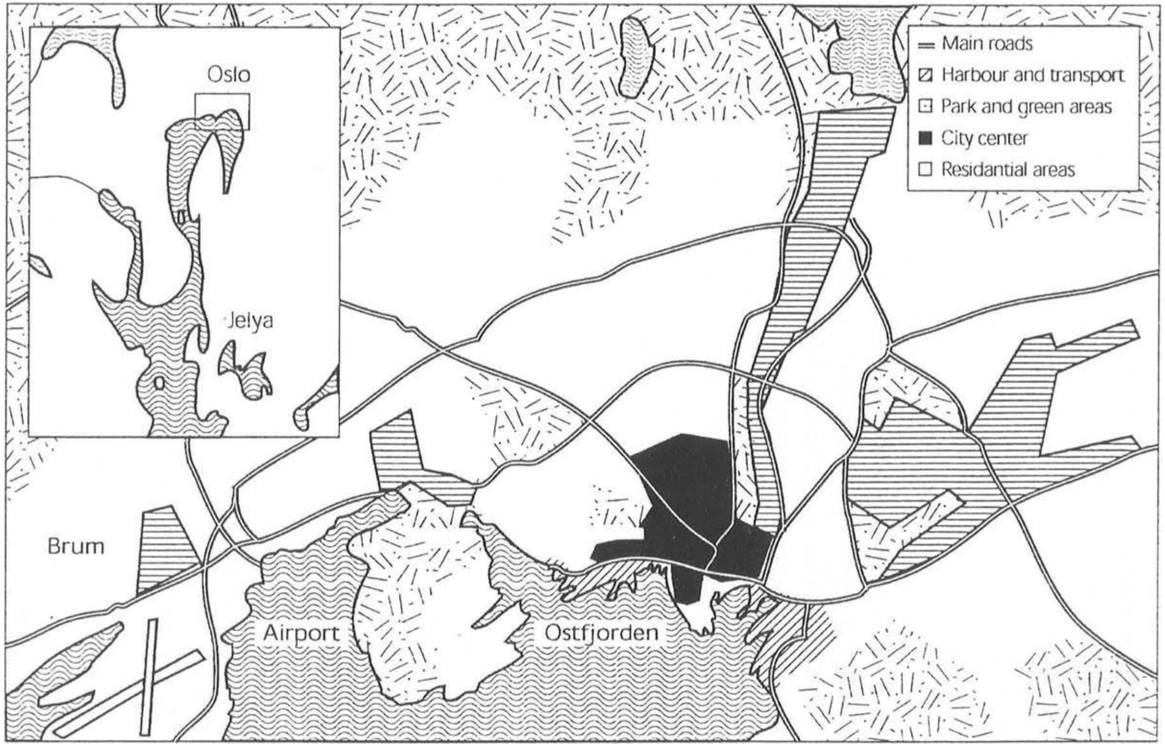

Figure 8. Oslo, the capital of Norway. The map shows a city plan aimed at mixing polluting activities and green areas to improve environment (Grønskei, 1998).

5. National and international legislation

Past experiences have with depressing clarity shown that existing technical possibilities and recommended management practices will not be used unless legally or economically enforced. Air quality is controlled by limit values. Their scientific foundation is experiments on humans or animals and epidemiological investigations. The results are evaluated by the World Health Organization (WHO) and expressed in the form of guidelines (WHO, 1987/1999), which are subsequently used as a main part of the basis for legally binding limit values.

Most countries have established such limit values for the major air pollutants and they use in addition guideline values for a series of other compounds. Most important are the legislation in the European Community and in The United States, which in many cases have served as models for other regions. Also US emission standards, especially for motor vehicles (Faiz et al., 1996) have been used in this way.

5.1. Air quality in the European Union

In the European Union the setting of limit values is a multistep process (Edwards, 1998) with a system of EC directives, the first being adapted in 1980. Since 1996 a framework directive provides a basic structure, and daughter directives, lay down limit values and proscribe dates for attainment, methods for measurements, etc., which are mandatory throughout the territory. These directives will be ratified in the individual memberstates in the form of national legislation. The first directive comprises sulphur dioxide, particulate matter, nitrogen dioxide and lead. Threshold values for ozone for information and warning to the public are also regulated by EU-directives. Other pollutants for which daughter directives are planned include: Benzene, carbon monoxide, polyaromatic hydrocarbons, cadmium, arsenic, nickel and mercury (Edwards, 1998).

5.2. Vehicle emissions

The most direct mean of regulating air quality is of course through regulation of emissions. The EC legislation on vehicle emissions and fuel quality standards has evolved greatly since the first directive in 1970. The early legislation had the dual purpose of reducing pollution and avoiding barriers to trade due to different standards in different member states. It is now giving place for designs aimed at meeting air quality targets. Thus the "Auto Oil I Programme" carried out by the European Commission in conjunction with industry (EU Commission, 1996a) has set up targets for a series of traffic related pollutants and assessed different technologies and fuel quality standards. Thus the target for nitrogen dioxide was a full compliance with the new WHO guideline of $200\,\mu g\,m^{-3}$ as a maximum 1 h average.

By means of models with simplified chemical reactions, the impacts, compared to 1990, on the air quality in seven representative European cities (Athens, Cologne, London, Lyon, Madrid, Milan and The Hague) have been estimated (EC Commission, 1996b). Already agreed measures (i.a. introduction of 3-way catalytic converters) were expected to reduce pollution from vehicles by 40–50% in 2010 compared to 1990. The auto oil programme will increase this reduction to 70% – even for the expected higher traffic.

It appeared that the objectives for carbon monoxide ($10\,mg\,m^{-3}$, 1 h max.), benzene ($10\,\mu g\,m^{-3}$ annual mean) and particulate matter ($50\,\mu g\,m^{-3}$ 24 h average) would be met by year 2010, and also the NO_2 objective should be met in most of the Union in 2010. In some cities like Athens, however further action would be needed. A more stringent target value for benzene of $2.5\,\mu g\,m^{-3}$, preferred by several member states, would be exceeded in all investigated cities except The Hague.

In an ongoing second programme also nontechnical measures will be evaluated. Possibilities for local use in areas with high pollution levels include road pricing, traffic management and scrapping schemes. Further the resulting reductions in pollution levels will be calculated in more detail.

5.3. Stationary sources

EC legislation on industrial air pollution has always taken air quality limit values into account and required the operators to use "Best available technology" not entailing excessive costs. In a Council Directive from 1996 on integrated pollution prevention and control (IPPC) the purpose is to reduce pollution to the environment as a whole, avoiding transfer from one medium to the other (Edwards, 1998).

5.4. The United States Clean Air Act

In the United States the first federal air pollution legislation was enacted in 1955, and in 1970 the administration was transferred to the new US Environmental Protection Agency (EPA). The Clean Air Act was first passed by Congress in 1967 as the Air Quality Act and has later been followed up by amendments in 1990. Under the act the EPA set national air quality standards (NAAQS) for six pollutants: Sulphur dioxide, nitrogen dioxide, carbon monoxide, particulate matter and lead.

The standards are reviewed regularly, and new proposals were put forward in 1997. For ozone the new EPA standard allows no more than 0.08 ppm

($160\ \mu g\, m^{-3}$) as an 8 h average. For particles a separate standard will be set for $PM_{2.5}$ (Brown, 1997).

5.5. Long-range transport and urban air pollution

The United Nations Economic Commission for Europe (UN-ECE), comprising all European countries and Canada and the US has been an important forum for east–west discussions of air pollution. It was therefore also in the ECE that the so-called Geneva Convention on long range, transboundary air pollution was established and undersigned in 1979. In 1983 it had been ratified by a sufficient number of member states and went into force. A series of related protocols set targets for reductions of national emissions of sulphur dioxide, nitrogen dioxide and volatile organic compounds.

These protocols are all aimed at protecting natural systems, and a new multipollutant-multieffect protocol will comprehensively address acidification, eutrofication and photochemical air pollution. Since however, the main part of the relevant emissions take place in urban areas, the necessary reductions have a direct impact on urban air quality. Thus the later decreases in levels of sulphur dioxide in the 1980s are related to the use of natural gas, low sulphur fuel oil and desulphurisation (or alternative sources of energy), necessary to comply with the international agreements. Also attempts to reduce ecological impacts of large scale photochemical air pollution will directly influence urban ozone levels – especially in the North of Europe.

In other parts of the world, notably in East Asia, unregulated local air pollution emissions have increasing regional and transboundary impacts.

6. Europe

6.1. The characteristics of Europe

Europe is a highly urbanised continent with more than 70% of the population living in cities. The population changes in many countries however, are modest and partly due to refugees and migration from east to west. The most extensive comprehensive treatment of Europe's environment up to 1992 was given in the so-called Dobris Assessment (Stanners and Bourdeau, 1995) from the European Environment Agency. It is now updated in a second assessment (EEA, 1998). The general air quality in European cities has improved in recent decades – often in spite of an increase in population density and standard of living – but air pollution is still considered a top priority environmental problem with both urban and large scale impacts. Its special aspects are treated in more detail in several reports from the agency (i.a. Jol and Kielland, 1997; Richter and Williams, 1998).

The European cities differ in various ways, which influence the relations between emissions and resulting pollution levels. Thus infrastructure and town planning determine the emission pattern, and meteorology and topography determine the possibilities of dispersion and transformation (Grønskei, 1998). *Western Europe* is influenced by the predominant westerly wind bringing moist air from the sea, a climate which also favours long-range transport. In the *northern part of Europe* the small amount of sunlight favours persistent inversions with poor dispersion conditions. In *Central and Eastern Europe* high pressures with air stagnation and accumulation of local pollution are frequent. During the summer the climate in the *Mediterranean Region* likewise favours accumulation of local emissions, whereas during the winter large-scale wind systems are more frequent. Formation of photochemical oxidants depends upon sunlight, which in combination with poor dispersion conditions result in frequent episodes during summer.

6.2. The political and economic development

The large resources of coal in England, Central Europe and Eastern Europe have been the primary source of energy during the industrial revolution, but in recent decades oil and gas have been found in the North Sea and in Russia and has been transported through pipelines to centralised regions. In western urban areas the consumption of coal in small units, e.g. used for domestic heating, has therefore been substituted with less polluting fuels resulting in reduced emissions of sulphur dioxide and particles.

In Eastern Europe however, solid fuels are still used in private houses and industries. Many buildings are badly insulated with large potential savings, but combined heat and power production is limited partly due to problems with financing and management. As a consequence in 1990 the energy intensity of economies in Central and Eastern Europe (CEE) was about 3 times higher than in the Western Europe; per unit of GDP emissions of NO_x and SO_2 were more than 4 times higher; and emissions of particles and volatile organic compounds (VOC) considerably higher (Bollen et al., 1996; UNEP, 1997). SO_2-emissions were highest in the northern part of the region (Poland), which depends heavily on indigenous coal and lignite (Adamson et al., 1996), and lower in the southern CEE, where oil and gas are available.

In general it is fair to say that industrial "hot spots" have shifted from Western Europe to the east and southeast, where heavy industry, use of low-quality fuels and outdated production technologies have resulted in high emission levels.

When, nevertheless, emissions have been reduced, it is partly a result of the German reunification in 1990 and the collapse of the Soviet Union in 1991. Already in 1990/1991 distribution problems, ethnic conflicts and mafia-crime in combination with an outdated technology resulted in a drop in the Soviet Russian GDP of 10–15%. And in the period 1990–1996 NO_x-emissions dropped with 1/3 and SO_2 with 1/4.

A typical Polish example is Katowice (GEMS/AIR, 1996), where since the late 1980s many older more polluting industrial plants have been closed down. In the period 1988–1992 this has – in combination with introduction of better emission controls – resulted in a fall in emissions of nitrogen oxides and particulate matter of 22 and 41%, respectively. In the same period the air quality was improved with reductions in overall long-term averages of 30 and 44% for SO_2 and NO_x, respectively.

Further substantial reductions in emissions are possible, even when only current Western European practices are applied (Bollen et al., 1996), but it is a serious problem for Central and Eastern Europe to raise funds for economic and technological growth in connection with a transition to market economy. For some cities e.g. Krakow the most effective strategy to improve air quality would be a ban on use of coal – possibly limited to the town centre (Adamson et al., 1996).

The southeastern urban areas have a partly outdated car fleet and are decades behind in the organisation of road traffic. Only recently have efforts been put into the construction of ring highways (i.a. in Budapest and Prague) to reduce unnecessary crossings of the city centres.

6.3. Total emissions

In Europe the total emission of sulphur dioxide steadily increased from about 5 million metric ton in 1880 to a maximum of nearly 60 million in the 1970s only interrupted by the Second World War. It peaked in the mid-1970s, but has now been reduced to less than half. For the traffic-related pollutants nitrogen oxides, carbon monoxide and volatile organic compounds an increase has only recently been reversed (10–15%) by the introduction of three way catalytic converters (TWC)(EMEP/MSC-W, 1998 and related reports).

European road traffic currently accounts for the main part of the total CO-emissions, more than half of the NO_x-emissions and a third of the emissions of volatile organic compounds. The emission of sulphur dioxide from traffic is of minor importance; in western and northern cities it accounts for only about 5%; in southern cities, where diesel oil have a higher sulphur content, it accounts for 14%.

It is estimated that in 2010 the pollution from traffic with CO, VOC and NO_x within the EU-region will be reduced drastically in spite of the expected growth

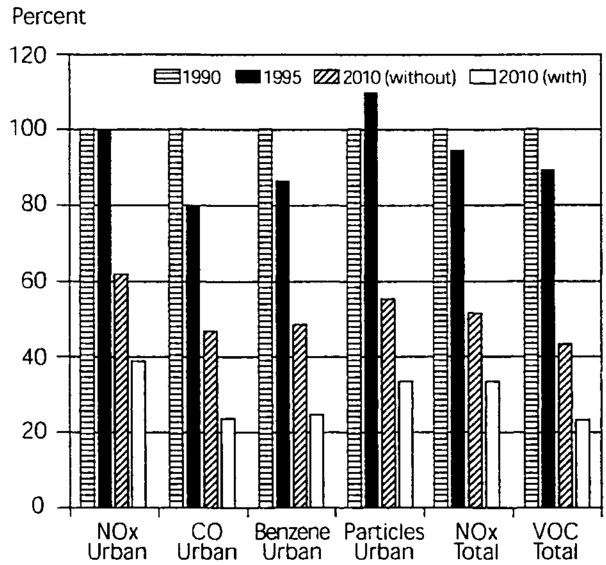

Figure 9. Expected impacts of the European auto oil programme on emission of air pollutants in the European Union and specifically in urban areas. The diagram shows calculated emissions in 1990, 1995 and projected emissions in 2010 without and with the programme in force. (Based on EC Commission, 1996a.)

in traffic (Fig. 9). On the other hand, total emissions within the European area covered by the European Monitoring and Evaluation Programme, comprising a series of eastern countries (EMEP/MSC-W, 1998) are not expected to be reduced much in 2010 compared to 1980: VOC and NO_x only about 10% and CO about 18%. In comparison SO_2 will be reduced by 53%.

6.4. Smoke

The most visible air pollutant is black smoke, which acts as a precursor for fogs (an important ingredient in early English detective novels). The drastic improvements in urban air quality in the 1960–1970s, partly brought about by a change from coal to less polluting fuels for domestic heating partly by the closing down of polluting industry, has also resulted in a marked reduction in incidence of fogs, shown in Fig. 10 for Lincoln in UK.

Most other West European cities show similar downward trends in particulate matter, but the lack of chemical analysis and size fractionation preclude more than a qualitative evaluation of the health impacts.

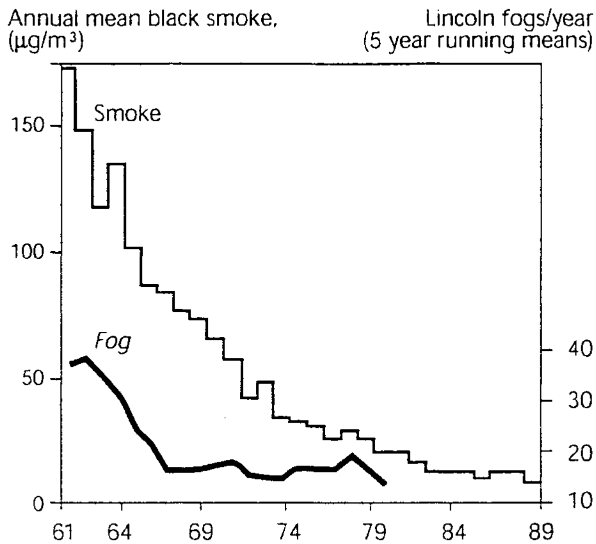

Figure 10. The reduction of annual mean black-smoke concentrations and the number of fogs per year (5 yr running means) in Lincoln, UK (Eggleston et al., 1992).

6.5. Sulphur

In many West European cities also the severe pollution with sulphur dioxide is a thing of the past. Thus in Copenhagen the yearly average of the SO_2 concentration was around 1970 about 80 $\mu g\, m^{-3}$ and during the winter about 120 $\mu g\, m^{-3}$. Today it is reduced to a fraction, well below the WHO guideline of 50 $\mu g\, m^{-3}$. In provincial towns it is even lower (Fig. 11).

It appears though that the reduction is most evident for medium and average values, which are determined by the contributions from local sources, whereas there still are significant peak values (95- and 98-percentiles), identified as being due to long-range transport from Central and Eastern Europe. Consistent with this the reduction of the levels of particulate sulphur (sulphate) show only a slight downward trend up to 1996. In 1997 levels for all types of sulphur pollution were very low, but so far it has not been established, whether it has been due to reduced emissions or special meteorological conditions.

This development has had several causes. An important aspect is the Geneva Convention on transboundary air pollution, which resulted in reduction of total emissions, but also a widespread transition from individual to district space heating produced on large units with high stacks (often as combined heat and power production) has played a role. A further factor is that the oil crisis in the beginning of the 1970s resulted in better insulation of buildings. Thus in

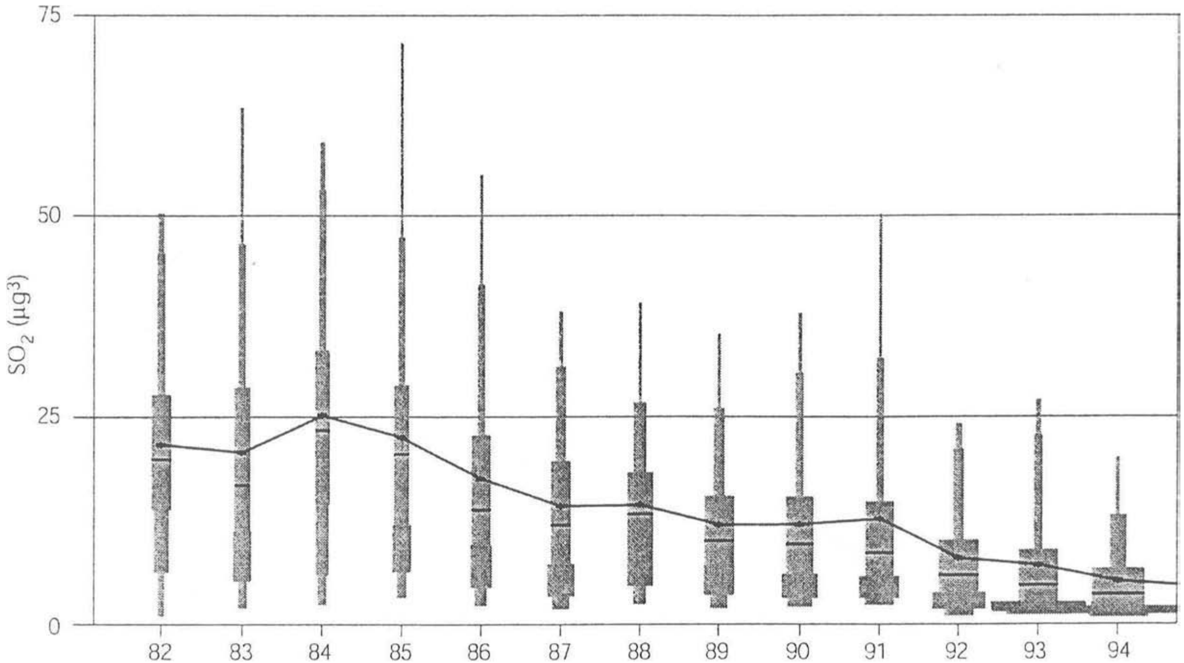

Figure 11. Trends for annual 98-, 95-, 75-, 50-, 25- and 5-percentiles, average and minimum value based on hourly average concentrations of SO_2 measured in Aalborg, a major provincial town in Denmark. The widths of the bars indicate the number of observations of a given concentration (Kemp et al., 1998).

Denmark the consumption of energy used for space heating was reduced by about 30% in the period 1972–1982 – in spite of a simultaneous increase in area of about 20% (ENS, 1997).

In 1990, 10 European cities observed exceedances of the long-term WHO-AQG for SO_2 of 50 µg m^{-3}; in 1995 it was only in Katowice and Istanbul. The short-term guideline of 125 µg m^{-3} daily average is, however, still exceeded for a few days per year in many countries.

6.6. Nitrogen oxides

In recent years urban air pollution with nitrogen dioxide has shown a downward trend in most European cities, although the short-term WHO guideline (corresponding to 200 µg m^{-3} as maximum hourly value) is exceeded in cities (EEA, 1998).

The situation is complicated by chemical reactions in the urban atmosphere. Thus since the introduction of catalytic converters on all Danish petrol cars registered after 1990 there has been a marked reduction in the levels of NO in Danish cities. The levels of NO_2, however are reduced much less, the median in Copenhagen about 20%, reflecting that the emissions of NO is not the limiting factor, but rather the available O_3 (Kemp et al., 1998).

6.7. Carbon monoxide

Urban concentrations of carbon monoxide have likewise been reduced since 1990, although exceedances of the 8-h WHO guideline have been reported from many cities (EEA, 1998).

6.8. Lead

In countries that have reduced or eliminated lead in petrol the lead levels have substantially declined (EEA, 1998), especially in countries with few or no lead-emitting industries. Since car exhaust is emitted at low height, and often in street canyons, there has been a close correspondence with the lead concentrations in urban air. In Denmark, where lead from petrol in 1977 accounted for 90% of the national lead emissions, the problem has virtually disappeared. Remaining low lead concentrations of about 20 ng m^{-3} are essentially due to long-range transport (Fig. 12).

In the early 1980s, 5% of Europe's urban population in cities with reported lead levels were exposed to more than the WHO guideline of 0.5 µg m^{-3}. At the end of the decade levels above the guideline value were no longer reported from the western countries, but were still found in Eastern Europe, notably in Romania and Bulgaria near large uncontrolled metal industries (WHO, 1995).

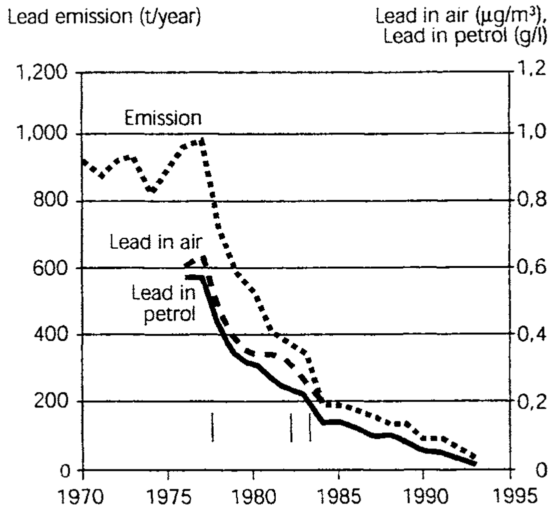

Figure 12. Annual average values for the total Danish lead emissions 1969–1993, the lead pollution in Copenhagen since 1976, and the average lead content in petrol sold in Denmark (Jensen and Fenger, 1994). The dates of tightening the restrictions on lead content are indicated with bars. Lead concentrations for the recent years can be found in Kemp et al. (1998). In 1997 they were below 20 ng m^{-3}.

6.9. Volatile organic compounds

Recently published (EEA, 1998) levels of benzene range from a few to more than 50 μg m^{-3} with the highest values normally found near streets with high traffic. Of the reporting cities only Antwerp did not observe exceedances of the WHO-AQG corresponding to 2.5 μg m^{-3} as yearly average.

In the 1960s the annual average concentrations of BaP was above 100 ng m^{-3} in several European cities (WHO, 1987/1999). In most developed countries improved combustion technology, change of fuels and catalytic converters on motor vehicles have reduced the urban levels to 1–10 ng m^{-3}. Still, however, the urban air pollution with potentially carcinogenic species is not satisfactorily understood.

6.10. Ozone

European ozone levels appear to have increased from about 20 μg m^{-3} around 1900 to now about the double with the most rapid rise between 1950 and 1970 concurrent with the rise in emissions of primary precursors (Volz and Kley, 1988). In the outskirts of Paris the early ozone levels were about 20 μg m^{-3}, but in the centre only 3–4 μg m^{-3}. Since at that time there were no nitric oxide from motor vehicles it is assumed, that O_3 was reduced by SO_2 or NH_3 (Anfossi and Sandroni, 1997).

Generally the present European ozone concentrations increase from northwest towards southeast, and summer smog with high ozone concentrations occurs in many European countries. As an urban phenomenon it is most serious in Athens and Barcelona with concentrations up to 400 $\mu g\, m^{-3}$, but also Frankfurt, Krakow, Milan, Prague and Stuttgart are affected.

An EU ozone directive contains a threshold value for information to the population of 180 $\mu g\, m^{-3}$ and for warning of 360 $\mu g\, m^{-3}$. In the Nordic countries the level for information is seldom exceeded – and the level for warning never.

Implementation of the VOC-protocol is expected to result in a 40–60% reduction in high peak values and 1–4% in annual average O_3-concentrations (EEA, 1995).

6.11. OECD trend indicators

The OECD (1998) uses average values for typical sites and major air pollutants as indicators for the development of air quality. In Western European cities in the period 1988–1993 the trends were (with approximate average values in 1993 in parentheses):

SO_2, annual average		
Traffic sites	(18 $\mu g\, m^{-3}$)	37% decrease
Residential areas	(22 $\mu g\, m^{-3}$)	22% decrease
NO_2, annual average		
Traffic sites	(48 $\mu g\, m^{-3}$)	10% decrease
Residential areas	(35 $\mu g\, m^{-3}$)	12% decrease
CO, annual max. 8 h average		
Traffic sites	(8.3 $mg\, m^{-3}$)	unchanged
Residential areas	(5.7 $mg\, m^{-3}$)	unchanged

6.12. Overview of population exposure in Europe

It is not only the pollution levels as such, which determine the potential health impacts, but also the extent to which people are exposed to them. Table 2 summarises the results of a WHO (1995) study, where a series of data for the period 1976 to 1990 from European urban areas with populations above 50,000 were pooled in two groups: up to and after 1985. Notwithstanding the limited and not fully representative data it appears that there has – taken as a whole – been a substantial general improvement for SO_2 and a somewhat smaller, and varying, improvement for particles. Concerning nitrogen dioxide there is an increase in the western countries and decreases in the eastern – probably reflecting an increasing traffic and an economic recession, respectively.

Also the number of peak values has decreased, thus the total population experiencing episodes exceeding 250 $\mu g\,m^{-3}$ SO_2 decreased during the 1980s from 71 to 33% in the western countries and from 74–51% in Russia (WHO, 1995). In spite of the general improvement of European air quality however, the WHO short-term air quality guidelines for SO_2 and TSP are often violated during winter-type smog, where the highest exceedances are observed in Central European cities (Fig. 13).

7. North America

The two countries in North America: The United States and Canada are among the wealthiest in the world both with respect to natural resources and production. This has formerly, especially in the US, lead to serious urban pollution.

7.1. United States

Many cities in the early industrialised United States were like in Europe characterised by heavy smoke and have subsequently gone through the typical development shown in Fig. 3. As an example (Davidson, 1979) Pittsburgh had pollution problems already in 1804, and they by and large increased until the first effective smoke control in the late 1940s after the city experienced severe pollution due to the Second World War steel production.

As a general measure of the development in the period 1970–1993 in air pollution the overall emissions of carbon monoxide, volatile organic compounds and particulate matter have been reduced by 24, 24 and 78%, respectively. A decline in emissions of nitrogen oxides from vehicles has been offset by increased electricity generation to a resulting increase of 14%, but since the emissions are generally not in urban areas, it has not prevented a reduction of NO_2 levels in cities. Lead as an air pollutant has virtually disappeared, but toxic chemicals are still a problem.

Los Angeles still has the largest ozone problem in the US. In 1990 the highest 1 h average was 660 $\mu g\,m^{-3}$. In the US as such ozone concentrations showed a significant decrease of 30% from 1988–1993 in urban residential areas both as an average and in the most polluted cities. With the new ozone standard of 0.08 ppm (Brown, 1997) many counties will find it hard to comply (Fig. 14).

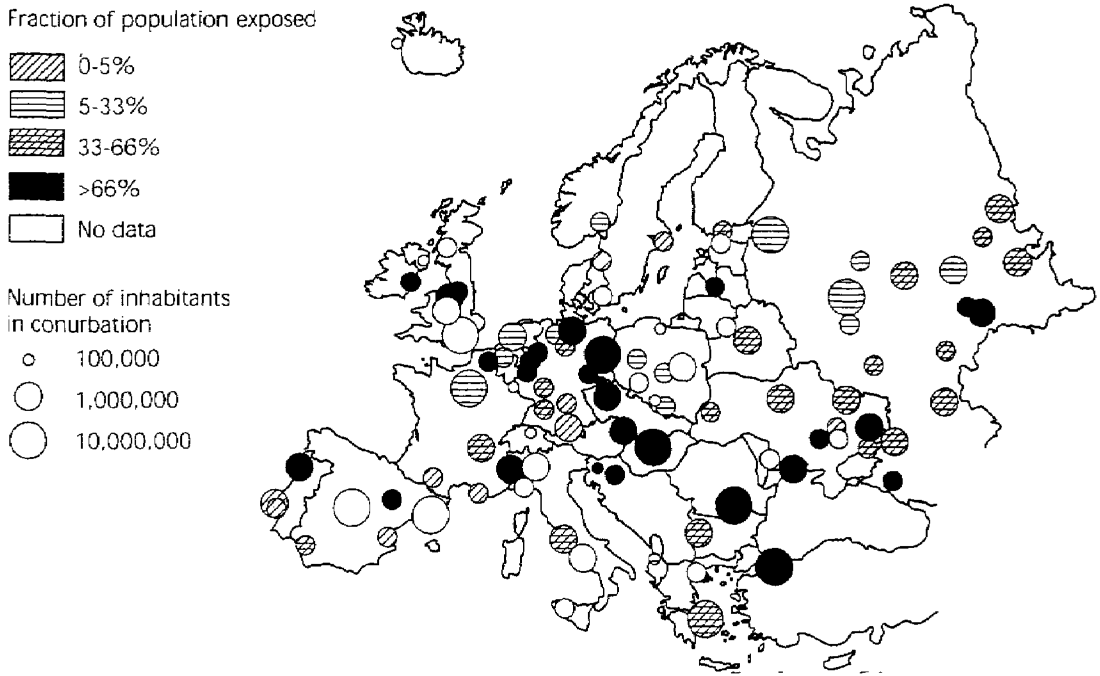

Figure 13. The present exposure of inhabitants in larger European conurbation's to exceedances of short-term WHO air quality guidelines for SO_2 and/or particulate matter (EEA, 1998).

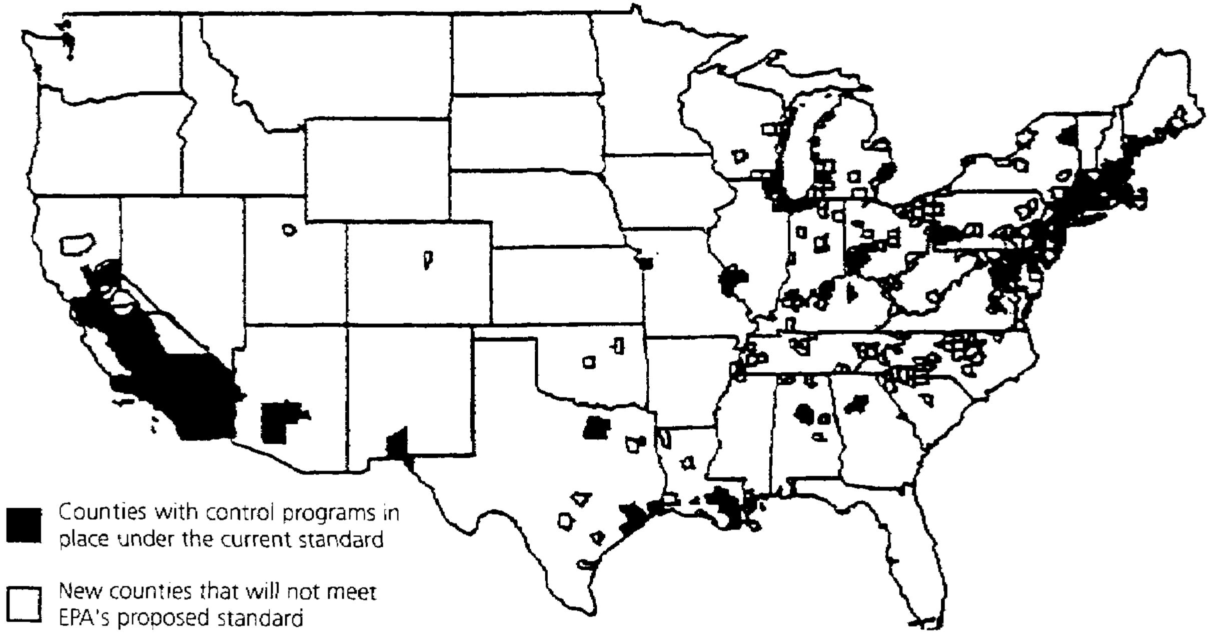

Figure 14. Counties not meeting EPA's ozone proposal standard, 8 h average 3rd maximum, 0.08 ppm. Based on 1993–1995 data (EPA Office of Air and Radiation World Wide Web site at http:ttnwww.rtpnc.epa.gov/naaqspro/).

7.2. OECD trend indicators for urban air quality in the US

According to the OECD (1998) the trends for air quality in cities in the US in the period 1988–1993 were (with approximate average values in 1993 in parentheses):

SO_2, annual average		
Traffic sites	(20 $\mu g\,m^{-3}$)	23% decrease
Residential areas	(20 $\mu g\,m^{-3}$)	23% decrease
NO_2, annual average		
Traffic sites	(42 $\mu g\,m^{-3}$)	11% decrease
Residential areas	(40 $\mu g\,m^{-3}$)	16% decrease
CO, annual max. 8 h average		
Traffic sites	(6.8 $mg\,m^{-3}$)	22% decrease
Residential areas	(6.4 $mg\,m^{-3}$)	25% decrease

7.3. Canada

In Canada (UNEP, 1997) emissions of sulphur dioxide and particulate matter have been reduced significantly since the early 1970s, and lead has virtually disappeared. Still however, some central Canadian cities experience unacceptable air quality with high levels of ozone and particulate matter, especially during the summer.

8. East Asia

This region contains three of the worlds largest countries (China, India and Indonesia), several minor landlocked states and a series of archipelagic states (including the highly industrialised Japan). The region is 35% urbanised and contains about half of the largest cities in the world. They therefore also represent all stages of pollution development. Urbanisation is not restricted to the continent and the major archipelagic states, but is also seen as in-migration to the main island on small island states as the Maldives. Urban congestion and air pollution is seen as a high-priority problem in many countries such as China, India, Pakistan, Indonesia, Philippines and Thailand (UNEP, 1997).

8.1. The general pollution with sulphur and particles

Taken as a whole the rapid growth of energy use, combined with extensive use of coal in most of Asia has resulted in a drastic increase in emissions of sulphur dioxide. Attempts to solve *local* problems by installing taller stacks only transformed them into an extensive *regional* pollution. The acidification phenomena, known from North America and Europe are now emerging. A network comprising 45 locations throughout Asia (Carmichael et al., 1995) has demonstrated annual average levels of SO_2 above $20\,\mu g\,m^{-3}$, especially in China, with the highest concentrations (about $60\,\mu g\,m^{-3}$) in the industrial area in Luchongguan, Guiyang.

In China coal is the main source of energy, in 1995 accounting for 76% and resulting in a sulphur dioxide emission of 21,000 kt. On the basis of projected energy consumption and available desulfurisation investment it is estimated (Wang and Wang, 1996) that the emission in 2020 will reach 31,780 kt or an 80% increase from the 1990 level. This will increase the emerging acidification in the southern part of China, and will undoubtedly also influence the urban air quality.

In the important agricultural and industrial region of the Jiangsu Province and Shanghai Municipality the SO_2 emissions are already high and are projected to double by the year 2010 (Chang et al., 1998). Model calculations demonstrate that in large regions the WHO-guideline for long-term exposure ($40–60\,\mu g\,m^{-3}$) is exceeded and in some regions even the 1 h guideline ($350\,\mu g\,m^{-3}$). Without drastic measures the short-term guideline will by 2010 be exceeded in large part of the province for more than 5% of the time. In line with this the new version of Atmospheric Pollution Control Law passed by the National People's Congress in 1995 calls for emission reductions on power plants and other large coal users based on a permit system and emission taxes (Chang et al., 1998).

Aerosol analysis 1987–1992 by a privately established network comprising five cities in China (Beijing, Chengdu, Bautou, Lanzhou, Urimuqi), one in Korea (Seoul) and one in Japan (Tokyo) (Hashimoto et al., 1994) demonstrated TSP-levels for Chinese cities up to averages above $500\,\mu g\,m^{-3}$ (Lanzhou) or seven times higher than in Tokyo to be compared with a tentative WHO-guideline of $120\,\mu g\,m^{-3}$ as a 1 h average. Lower values in Seoul (around $70\,\mu g\,m^{-3}$) showed a gradual increase.

Some of the highest reported levels of TSP, compared to what is seen in e.g. European cities, should however be evaluated critically, since not all is of human origin; thus high concentrations observed in Beijing in the December–April period are partly due to sand storms from the northern desert.

A further complication, with a different relation to abatement strategies, is forest fires, which are generally blamed for causing smog over major cities in the ASEAN region (Hassan et al., 1997). In Malaysia it has been confirmed that the high concentration of SPM during haze episodes are largely caused by transboundary impacts from intense biomass burning, not by build-up of local pollution (NERI, 1998).

8.2. Traffic

Urban transport is an increasing problem, which has been treated in a series of reports from The World Bank (Walsh, 1996; Walsh and Shah, 1997). A special aspect is that Asia is responsible for the main part (about 90%) of the worlds motorbike production, and China alone accounts for about 40% (Fig. 15).

Asia is also responsible for most of the motorbike use – partly because motorbikes constitute the cheapest mean of individual motorised transportation for the expanding working class, partly because many Asian cities are too crowded to allow a drastic expansion of the car fleet. In Beijing motorcycles accounted for 27% of the vehicle fleet in 1992 and in Guangzhou for 65%. This results in comparatively large emissions in relation to the fuel consumption, since most motorcycles have two stroke engines with poor pollution characteristics.

8.3. Examples of Asian cities

Taiwan is characterised by limited land and rapid economic growth, consequently the environmental stress is serious. In the early 1990s the monthly SO_2 averages in *Taipei City* were reported to be about 30 ppb (80 $\mu g\,m^{-3}$), but a gradual decrease is expected concurrent with a reduction of permissible sulphur contents in fuels. Thus the limit for diesel fuel is scheduled to be reduced to 0.05% in 1999. Also lead in petrol is being phased out (Fang and Chen, 1996).

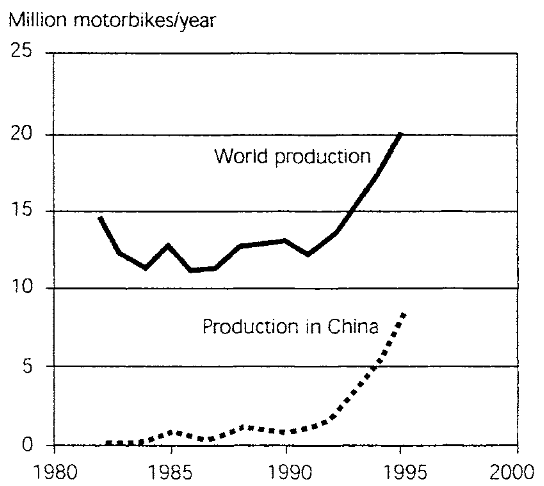

Figure 15. Annual motorbike production 1992–1995 in the World (upper curve) and in China (lower curve). (Based on material compiled by G. Gardner in Brown et al., 1998b.)

In *Beijing* the air quality is in a transition from coal burning caused problems to traffic exhaust related pollution (Zhang et al., 1997), and vehicle emissions are projected to double within the next two decades unless drastic strategies both to lower actual driving and emissions per km are employed (Fig. 16).

The SO_2 levels have been fairly constant around 100 μg m^{-3} as annual average since the early 1980s with a slight recent decrease, and TSP has been reduced from about 500 to 400 μg m^{-3}, but the NO_x levels have increased drastically from about 70 to 170 μg m^{-3}. Also general O_3 levels and frequency of exceedance of the 80 μg m^{-3} national standard have been increasing (Zhang et al., 1997) with maximum concentrations above 300 μg m^{-3} (Zhang and Xie, 1998). Similar values have been observed in the Guangzhou area (Zhang et al., 1998).

Shanghai is the commercial centre of China with an extensive industry. Data from the late 1980s (WHO/UNEP, 1992) demonstrate levels of both SO_2 and TSP well above WHO guidelines. Shanghai has the highest cancer mortality in China and the mortality for male lung cancer doubled from 1963 to 1985.

In *Ho Chi Minh City* in Vietnam the air quality has been deteriorating i.a. due to the increasing vehicular traffic. Although the fuel consumption per capita is still low, a series of factors as narrow overcrowded streets and outdated cars result in high pollution levels. Daily average values of NO_2 are between 50 and 250 μg m^{-3} with hourly peaks, which can exceed 700 μg m^{-3} (Duc, 1998). The average lead concentration measured on top of an eight-storey building in a residential area was found to about 180 ng m^{-3} for the period 1993–1994 (Hien et

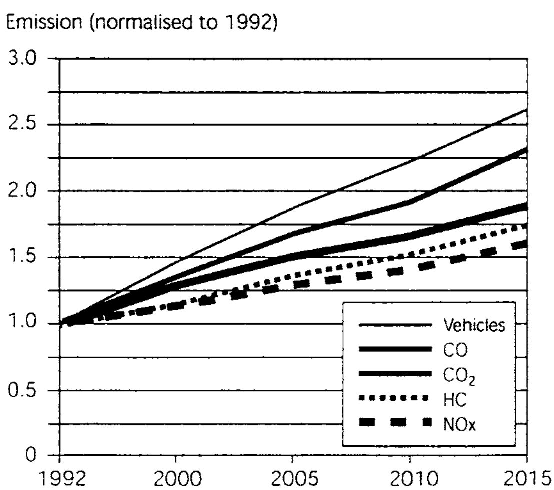

Figure 16. Official Beijing motor vehicle emission projections. Summer conditions. More likely projections result in about the double increase (Walsh, 1996).

al., 1997). Some contributions from open burning of refuse and firecracker discharges (sic!) can not be excluded, but lead from traffic is considered the main source. From 1995 the maximum permitted lead content in petrol is $0.4\,g\,l^{-1}$. Typical concentrations of TSP were $100\,\mu g\,m^{-3}$.

In a series of major cities, where energy production is based on gas or low sulphur coal (e.g. *Bombay, Calcutta, Bangkok*) SO_2 with average levels about $30\,\mu g\,m^{-3}$ is not a serious problem. In many cases, however TSP levels are above WHO guidelines (WHO/UNEP, 1992).

The capital of Japan, *Tokyo*, is an encouraging example of an industrial megacity, where air pollution is controlled. In the 1960s it was heavily polluted due to coal combustion and insufficient emission control. Concentrations peaked in the late 1960s with annual mean values for SO_2 and TSP up to 200 and $400\,\mu g\,m^{-3}$ respectively (Komeiji et al., 1990). By switching the major fuel consumption from coal to oil and installation of dust collectors the annual mean values of SO_2 and TSP were brought well below WHO guidelines already in the 1980s (WHO/UNEP, 1992), and as a spectacular example the reduction of particulate emissions in the 1970s (Kurashige and Miyashita, 1998) has resulted in a corresponding increase in visibility.

As in the western world stricter control of vehicle emissions has been counteracted by a growth in traffic and the levels of traffic related pollution have merely been stabilised. However the ozone levels have generally been halved since 1970, when the yearly average was about $80\,\mu g\,m^{-3}$.

8.4. OECD trend indicators for urban air quality in Japan

Japan is in many respects not typical for East Asia, but more like the western countries. According to the OECD (1998) the trends for air quality in Japanese cities in the period 1988–1993 were (with approximate average values in 1993 in parentheses):

SO_2, annual average		
Traffic sites	($18\,\mu g\,m^{-3}$)	20% decrease
Residential areas	($22\,\mu g\,m^{-3}$)	17% decrease
NO_2, annual average		
Traffic sites	($50\,\mu g\,m^{-3}$)	unchanged
Residential areas	($35\,\mu g\,m^{-3}$)	unchanged
CO, annual max. 8 h average		
Traffic sites	($5.5\,mg\,m^{-3}$)	26% decrease
Residential areas	($4.3\,mg\,m^{-3}$)	25% decrease

In urban residential areas the average concentrations of oxidants increased by about 5% from 1988 to 1993, while the 95-percentile decreased.

9. Other developing regions

9.1. Latin America

As demonstrated in a series of case studies (Onursal and Gautam, 1997) Latin America and the Caribbean is the most urbanised region in the developing world with a rapidly increasing vehicle fleet, which is the dominant source of air pollution. In Mexico City e.g. it accounts for 99% of the CO, 54% of the hydrocarbons and 70% of NO_x. Leaded gasoline is still permitted in most countries and even in 1995 constituted the entire sale in Venezuela. In other countries it is being phased out; thus in Mexico City the lead concentrations decreased 80% in the period 1990–1994.

Most of the air pollution occurs in major urban centres. In 1994, 43 of them had more than 1 million inhabitants. Often the situation is aggravated by the cities (e.g. Mexico City and Santiago de Chile) being situated in valleys surrounded by mountains.

Not surprisingly, the most critical air pollutants in Mexico City are ozone, NO_2, VOC and PM. The ambient ozone concentrations have concistently exceeded the Mexican 1 h standard of $220\,\mu g\,m^{-3}$. The highest value ever recorded (in 1992) was $955\,\mu g\,m^{-3}$.

In Santiago the most critical air pollutant is particulates, especially in the colder period (Apr.–Sep.). The principal source being a large number of poorly maintained diesel busses (GEMS/AIR, 1996). The concentration of TSP is among the highest in any urban area in the world. In 1995 it reached a 1 h mean of $621\,\mu g\,m^{-3}$ to be compared with the Chilean standard of $260\,\mu g\,m^{-3}$.

Sao Paulo in Brazil is the third of the three most polluted cities in the study. There has been some success in attempts to control emissions from the rapidly growing industry, and the SO_2 concentrations have been reduced substantially during the 1980s (WHO/UNEP, 1992), but ambient air quality standards for all traffic relevant pollutants are exceeded.

9.2. West Asia

In the recent two decades West Asia has been radically transformed with an urban growth rate above 4%. Although the most pressing urban problem seems to be waste management, also air pollution is emerging (UNEP, 1997). In many cases protective trade regimes and lack of environmental regulations have prevented adequate substitution of outdated polluting industries. Fuels with high sulphur content and old inefficient cars using leaded petrol have exacerbated urban air pollution. Recently however, the situation has been improving, thus in Oman new industries will be regulated with environmental standards.

9.3. Africa

For the larger African cities Cairo, Alexandria, Nairobi and Johannesburg air pollution has been monitored for some years and there is an increasing awareness of the need for air quality management (WHO/UNEP, 1992; GEMS/AIR, 1996).

Urbanisation is however increasing rapidly all over Africa and especially in the least developed countries with up to 5% per year, the driving force being a mixture of population growth, natural disasters, and armed ethnic conflicts. Most African cities have been unable to keep pace with this development and lack adequate industrial and vehicle pollution control.

Much of the urban population growth is in coastal cities i.a. in the Mediterranean area. So far the general air pollution appears to be modest, but urban problems are emerging. In most countries however, emission inventories are nearly non-existent, pollution is neither monitored nor controlled, and there are no long-term records of pollution levels and impacts (UNEP, 1997).

10. Conclusion

Urban air pollution and its impact on urban air quality is a world-wide problem. It manifest itself differently in different regions depending upon the economical, political and technological development, upon the climate and topography, and last – but not least – upon the nature and quality of the available energy sources. Nevertheless a series of general characteristics emerges.

10.1. From space heating to traffic

Originally urban air pollution was a strictly local problem mainly connected with space-heating and early industry – and not far from being considered unavoidable or even a symbol of growth and prosperity. The situation in the industrialised western world has in some respects proved this viewpoint outdated. Emissions from industry and space heating are by and large controllable, but the urban atmosphere is now in most cities dominated by traffic emissions with documented impacts on human health. Thereby the attention has been shifted from sulphur dioxide and soot to nitrogen oxides, the whole spectrum of organic compounds and particles of various sizes and composition, which are reported to be carcinogenic and/or cause a significant reduction of life through respiratory and cardiovascular diseases. These pollutants require much more detailed investigations both in the form of chemical analysis and computer modelling.

In principle the control of sulphur emission is relatively straightforward, when it is related to power production on large plants, which can be compelled to use clean fuels and equipped with proper cleaning technology. Traffic emissions are more difficult to control, since they, in the nature of things, arise from small units. Meeting the increasing stringent air pollution targets is therefore not an easy task. According to the conclusion of the "auto oil programme" even with the maximum technical package introduced in the EU not all cities will be able to comply.

The situation in developing countries is mixed. In some major cities in Asia the sulphur emissions have been brought under control, i.a. via a transition from coal to natural gas, but especially in China a rapid growth in energy production based on coal has resulted in increasing sulphur pollution both on an urban and a regional scale. Also in the developing countries, however and in some economies in transition (including Eastern Europe) traffic is becoming *the* problem. The expectation of private cars in these countries is understandable, but regrettable. This will in the future be a challenge in town planning.

As a demonstration that the traffic-related nitrogen dioxide in many cities exceed the WHO air quality guideline is shown (Fig. 17) a bar chart for peak statistics comprising more than 60 cities all over the world. In fact very few never experience exceedenses.

10.2. Regional impacts on urban air pollution

The interactions between the cities and their surroundings are becoming increasingly important. With the expanding and often merging urban areas and the diminishing sulphur emissions in the cities proper, the pollution levels can to a large extent be determined by long-range transport. The same applies to lead pollution in countries, where lead has been removed from petrol. Another example is photochemical air pollution, which in many cases is a large-scale phenomenon, where emissions and atmospheric chemical reactions in one country may influence urban air quality in another.

10.3. The cities as sources of pollution

A more far reaching problem is the city as a source of pollution. In the past, local problems were attacked by dispersing pollutants from high stacks, but this only resulted in a transfer to a larger geographical scale in the form of acidification and other transboundary phenomena. Now long-lived greenhouse gases, and especially carbon dioxide, threatens the global climate – irrespective

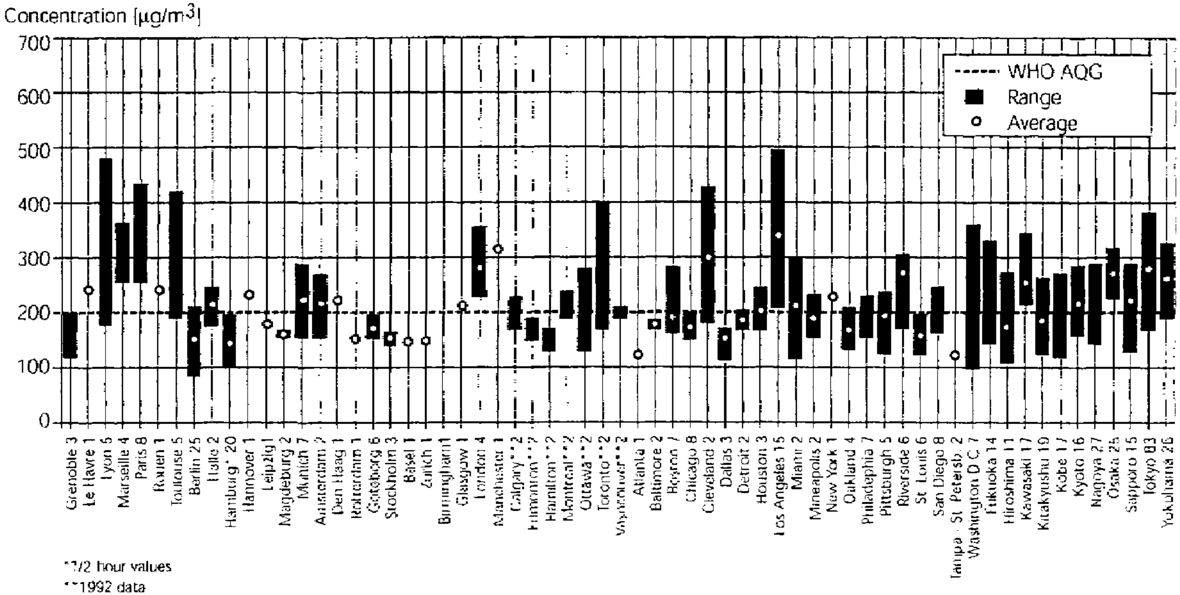

Figure 17. Urban peak statistics for nitrogen dioxide with averages and ranges of 1-h values in 1993. The numbers after the city name indicate the number of monitoring stations (Wiederkehr and Yoon, 1998).

of the origin. This problem can only be solved by a general reduction in the net emissions (Brown et al., 1998a).

In the industrialised countries the development in technology and legislation to protect air and water quality in many cases resulted in improved energy efficiency and emission reductions, although some means of improving urban air quality, such as catalytic converters, which consume energy and emit nitrous oxide (another greenhouse gas) are contrary to this goal. On a global basis, the growing population and its demand for higher material standard of living have so far counteracted any reductions in total emissions. Therefore the responsibility for the future is both national and global with many actors comprising national environmental agencies, international organisations, The World Bank, etc.

Long-term abatement however, has been intensified in recent years. An example is the ICLEI initiative with the purpose to achieve and monitor improvements in global environmental conditions through cumulative local actions.

10.4. A comprehensive approach

The realisation that traffic is rapidly becoming *the* urban air quality problem both in industrialised and developing countries calls for comprehensive solutions, where traffic-related air pollution is seen in connection with other impacts of traffic as noise, accidents, congestion and general mental stress. As a consequence technological improvements in the form of less polluting vehicles are not sufficient. Also support of infrastructures, where the need of transport is minimised, and where use of public means of transport dominate over individual private cars and motorbikes should be encouraged. Unfortunately most attempts of control will be perceived as a restriction of the individual freedom, and they are frequently met with outspoken opposition. Obviously a change in attitude is called for.

11. Note to references

The literature relevant to urban air quality is vast, and the references in this paper are only given as typical examples. The present review however, contains material from a recently published textbook (Fenger, Hertel and Palmgren, 1998), where further references on specific subjects can be found. Some of the presented data have been used by different authors and are compiled from various sources. Not all references are therefore primary, but they are a key to a full documentation.

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Appendix

Neither environmental science nor management progresses as fast as some journalists and politicians seem to believe. And the global situation of urban air quality has not changed significantly since the publication in 1999 of the Millennium Review on Urban Air Quality.

In the industrialised world, the classical pollutants (soot and sulphur dioxide) from heating systems are by and large under control and – in spite of widespread use of catalytic converters and other measures – traffic emissions are now the main problem. This applies especially to particulate matter, which for a foreseeable future will remain a significant urban air quality problem (European Commission 2000). A similar development is appearing in economies in transition, and it can be anticipated in major cities in the developing countries.

Some aspects will, however, in the coming years receive increasing attention, partly as a result of the development of better analytical techniques, partly due to a growing awareness of the importance of comprehensive studies and abatement policies.

1. New pollutants

In general the *concentration* of major pollutants in the environment are decreasing, but the *number* of pollutants being detected is increasing. Today some hundred thousand chemical compounds must be evaluated internationally. Many of them, mostly volatile organic compounds (VOC), may be present in the urban atmosphere due to vehicle exhaust or industrial emissions, but so far only a few indicator compounds have been studied in detail.

A new EU (European Union) directive (1999/30EC; 22 April 1999) includes limit values for particulate matter (PM_{10}) and obligations for the member states to collect data on $PM_{2.5}$. So far however, WHO (World Health Organisation) has not recommended a limit value for particulate matter.

Studies of fine and ultrafine particles from traffic are therefore intensified. Not only because of their health impacts, but also because their emission has been reported to *increase*, even if the total mass of particles emitted from vehicles *decreases*. A new technique based on measurements with a Differential Mobility Analyser (DMA) followed by factor analysis and constrained linear receptor modelling has been developed (Wåhlin et al., 2000). It allows field identification of particle spectre from diesel and petrol fuelled vehicles. It appears that although diesel cars are the main source of very fine particles, petrol driven cars also contribute with generally larger particles.

2. Population exposure and health impacts

Air quality management has so far mainly been carried out on the basis of measurements and model results of ambient concentrations of pollutants.

However, direct personal monitoring demonstrates that the levels *an individual* is exposed to can vary drastically during the day (e.g. Zhiqiang et al., 2000), and that the ambient, outdoor air quality does not adequately describe the actual exposure in sufficient detail. Many tools are available (Hertel et al., 2000) including GPS (Global Positioning System) to trace the movements of test persons, but still some mechanisms are poorly understood. Thus, for example, people appear to stir up "personal clouds" of particle-laden dust from their surroundings. They may therefore experience exposure to fine particles about 60% greater than classical monitoring may suggest (Renner, 2000).

In view of the large fraction of time spent indoors, especially in cities with a cold climate, the relations between outdoor pollution and related indoor levels of pollutants from outdoor sources must also be taken into account. That is not always simple. Typically indoor levels are only about half the outdoor levels, but for benzene this was not reflected convincingly in the *personal exposure* in a series of European Cities (Cocheo et al., 2000). In some cases the population exposures were found to exceed the average ambient urban concentration. It is speculated that the reason may be that people are generally outdoors, when the ambient levels are high, and indoors, when they are low, and that the indoor environment may store pollution with an outdoor origin (a sort of "flywheel effect").

Notwithstanding an extensive documentation (see e.g. Künzli et al., 2000 for a European assessment) some important problems concerning relations between exposure and impacts remain to be satisfactorily elucidated. First of all the statistical procedures are debated. Thus it is a question how to relate daily mortality with longer term mortality effects (McMichael et al., 1998) and especially how to filter out a possible "harvesting effect" (Zeger et al., 1999). Secondly the assessment of human exposure is still being developed (Mage et al., 1999). In addition, it must be admitted that epidemiological studies provide little (or no) information on the underlying impact mechanisms, which are still poorly understood (Brunekreef, 1999). For example, it is not obvious to what extent the particulate matter *per se* is important and what is the role of the chemical composition (e.g. PAH). This may influence the future design and application of exhaust cleaning devices. For an extensive critical review see Lightly et al. (2000).

3. Cities in a global context

In its 3rd assessment report The Intergovernmental Panel on Climate Change (IPCC, 2001) applies a more holistic approach to human induced climate change than in its previous reports. It is now explicitly acknowledged that some changes can not be avoided and various means of adaptation are discussed.

In this context the interplay of various environmental loads should be considered. In the long run climate changes may influence urban air quality via changes in temperature, precipitation, wind pattern and solar radiation. Thus for example, formation and dispersion of photochemical pollution may be enhanced and allergens and irritants may have larger impacts. On the other hand the mix of pollutants may change with less need for space heating. More important is undoubtedly the attempt of general phasing out of fossil fuels. To the extent that this is successful many problems with urban air quality may be solved.

4. Conclusion

The conclusion can not be better expressed than in a report on the recently concluded Auto-Oil II project (European Commission 2000):

- There is a need for improved knowledge on the links between emission targets and air quality requirements.
- A really cost-effective policy package will require an integrated approach across sources, pollutants and measures.

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