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Air Quality in Selected Megacities

Luisa T. Molina, Mario J. Molina, and Robert S. Slott
Massachusetts Institute of Technology, USA

Charles E. Kolb
Aerodyne Research, Inc., USA

Philip K. Gbor, Fan Meng, Rakesh B. Singh, Oscar Galvez, and James J. Sloan
University of Waterloo, Canada

William P. Anderson
Boston University, USA

Xiaoyan Tang, Min Shao, Tong Zhu, Y.H. Zhang, and Min Hu
Peking University, China

Bhola Ram Gurjar
Max Planck Institute for Chemistry, Germany

Paulo E. Artaxo
Institute of Physics, University of São Paulo, Brazil

Pedro Oyola
Santiago, Chile

Ernesto Gramsch
Universidad de Santiago, Chile

Dario Hidalgo
Akiris S.A., Bogotá, Colombia

Alan W. Gertler
Desert Research Institute, USA

ABSTRACT

About half of the world's population now lives in urban areas because of the opportunity for a better quality of life. Many of these urban centers are expanding rapidly, leading to the growth of megacities, which are often defined as metropolitan areas with populations exceeding 10 million inhabitants. These concentrations of people and activity are exerting increasing stress on the natural environment, with impacts at urban, regional and global levels. In recent decades, air pollution has become one of the most important problems of megacities. Initially, the main air pollutants of concern were sulfur compounds, which were generated mostly by burning coal. Today, photochemical smog—induced primarily from traffic, but also from industrial activities, power generation, and solvents—has become the main source of concern for air quality, while sulfur is still a major problem in many cities of the developing world. Air pollution has serious impacts on public health, causes urban and regional haze, and has the potential to contribute significantly to climate change. Yet, with appropriate planning megacities can efficiently address their air quality problems through measures such as application of new emission control technologies and development of mass transit systems.

This review is focused on nine urban centers, chosen as case studies to assess air quality from distinct perspectives: from cities in the industrialized nations to cities in the developing world. This review involves megacities in a broader sense, and thus it also considers urban centers with somewhat smaller populations. While each city – its problems, resources and outlook – is unique, the need for a holistic approach to the complex environmental problems is the same. There is no single strategy in reducing air pollution in megacities; a mix of policy measures will be needed to improve air quality. Experience shows that strong political will coupled with public dialog is essential to effectively implement the regulations required to address air quality problems.

INTRODUCTION

Nearly half of the world's population (48%) in 2000 lived in urban areas, and the number of urban dwellers is expected to grow by 2% per year during the coming three decades.[1] Table 1 shows that world population is expected to increase from 6.1 billion in 2000 to 8.1 billion in 2030, with nearly all of this growth concentrated in urban areas (from 2.9 billion to 4.9 billion). Urban populations in less developed regions will double from 2.0 billion to 3.9 billion. These concentrations of people and their activities have consequences at urban, regional, continental, and global scales.[2] However, as centers of economic growth, education, technological advancement, and culture, large cities also offer opportunities to manage the growing population in a sustainable way.

The growth of urban environments presents a major challenge. This review addresses the effects of large urban areas on the Earth's atmosphere, in the cities themselves and beyond their borders. The topic is broad, and hence only a selection of the relevant issues is considered. Urban planning, industrial development, transportation, and other topics are discussed in the context of their interactions with air quality.

SCOPE OF REVIEW

This review is the complete on-line version of the 2004 Critical Review on Megacities and Atmospheric Pollution. A condensed, edited version appeared in the June issue of the Journal of Air & Waste Management.[3] This on-line review includes a detailed description of the air quality science and management strategies of the nine case study cities, as described below.

In this review, the driving forces behind the formation and growth of megacities and their consequences are described. The nature of megacities, their air quality problems, and the associated science are briefly addressed. Impacts of emissions and the ambient concentration of pollutants in megacities on the health of their populations, visibility (urban and regional haze), ecosystems (including acid and fixed nitrogen deposition, photochemical oxidant damage, and photosynthetically active radiation), climate change, and global pollutant transport are evaluated in the review. The air quality assessment tools available for large urban centers are discussed.

A megacity is often defined as a metropolitan area with more than ten million inhabitants; this review, however, involves megacities in a broader sense, and thus it also considers urban centers with somewhat smaller populations. The review is focused on nine urban centers, chosen as case studies to assess the air quality problem from the perspective of relatively clean urban areas in industrialized nations and some of the highly polluted cities in the developing world. The nine urban centers examined in this review as case studies are: 1) Los Angeles, USA; 2) Mexico City, Mexico; 3) Toronto, Canada; 4) Delhi, India; 5) Beijing, China; 6) Santiago, Chile; 7) São Paulo, Brazil; 8) Bogotá, Colombia; and 9) Cairo, Egypt. Table 2 summarizes selected statistics for the nine case study cities.

The review describes air quality in these nine urban centers and the management strategies to identify similarities and differences among the problems and strategies that are important to megacities throughout the world. Some strategies taken by other megacities, not included in the case studies, due to their innovation and potential for reducing air pollution will be presented also. Some of the barriers to implementing air quality management programs are discussed. The review concludes with an outlook of the air quality situation in coming years.

CAUSES AND CONSEQUENCES OF URBAN GROWTH

The number and size of megacities increased dramatically during the second half of the 20th century. In 1800, London was the only major city in the world, with a population of 1 million. Cities with a population of at least 1 million increased to three by the beginning of the 20th century; today, there are 281. The average population of the 100 largest cities was 200,000 in 1800; this increased to 2.1 million by 1950, 5 million by 1990, and 7.7 million by 2002.[32] In 1900, 9 of the 10 largest cities were in North America and Europe, whereas today only 3 (Los Angeles, New York, and Tokyo) are in the developed world. In 1950, New York and Tokyo were the only megacities. That number grew to 4 (Tokyo, New York, Shanghai, and Mexico City) by 1975 and to 20 by 2000, and is estimated to reach 22 by 2015.[1] Table 3 lists the 20 megacities of the world and Figure 1 shows their locations.[1]

Most of the world's urban population still lives in cities of fewer than 10 million inhabitants; many of these cities are growing faster than the megacities.[1] A metropolitan area - large population center that consists of several town or cities clustered together - usually combines a conurbation proper (the contiguous built-up area) with peripheral zones not themselves necessarily urban in character but closely bound to the conurbation by employment or commerce. For example, the Mexico City metropolitan area (MCMA), often simply called Mexico City, consists of 16 delegations of the Federal District and 37 contiguous municipalities from the State of Mexico and one municipality from the Statae of Hidalgo, some with population over 1 million, that make up the total population of about 20 million for this megacity.

Currently, there are 100 metropolitan areas with official populations exceeding 3 million. If several metropolitan areas are located in succession, they are sometimes grouped together as a megalopolis. A megalopolis consists of several large cities and their surrounding areas in sufficient proximity to be considered a single urban complex. The French geographer Jean Gottmann[33] coined the term "megalopolis" to describe the northeastern United States, a vast metropolitan area ("BosWash") more than 480 km long, stretching from Boston in the north to Washington, D.C., in the south.[34]

Megacity is a general term for cities together with their suburbs or recognized metropolitan area usually with a total population in excess of 10 million people. There is no exact definition of its boundaries, where it starts and where it ends. As a result, the term "megacity" is used loosely in this review, referring to large agglomerations of people with their consequent employment, housing, transportation, and security needs.

Levels of urbanization correlate with national income, and within a country, wealth is concentrated in urban areas. Developed countries are more urbanized, and urban areas may produce ~60% of a country's Gross National Product (GNP).[35] This higher income is a major cause of growth, as people from the countryside move to the city for the jobs, education, and services that an urbanized center provides. Conflict, land degradation, and the depletion of natural resources also motivate migration, especially in Africa, [36] and international migration is another factor. But the largest contributor to growth in urban settings is the increasing number of people in the world, especially in the developing world.

While economic growth is needed to increase the general welfare of the population, intense economic activity can create new stress on the environment as demand for resources increases and the damaging by-products of economic activity accumulate. However, economic growth can also create the means and the demand for an improved environment. Higher incomes improve the quality of life for the population by giving them access to more goods and services. However, increased production and consumption of goods generate more by-products, including pollution. One of the main hypotheses in environmental economics suggests that as the per capita income of a nation increases, the environmental quality deteriorates initially up to a point. After that point, environmental quality improves as incomes continue to rise. The relationship has an "inverted U" shape and is known as the Kuznets' curve.[37] The environmental deterioration related to increasing income at low-income levels is probably associated with increased industrialization. The association between improvement in environmental quality and higher income is less obvious. Wealthier nations can more easily prioritize environmental quality, implement more stringent control measures to reduce pollution, develop new technologies and enforce environmental regulations more strictly. However, they may also export pollution, e.g., by establishing factories in other nations or by simply purchasing goods that are produced in lower income, more environmentally compromised countries.[38]

Transportation is a major source of air pollution in many cities, especially in the developing countries. Yet transportation is also a critical enabler of economic activity and beneficial social interactions. The spiraling of demand for urban transport in these megacities represents a combination of several factors. In order to function as centers in the world production system, these cities must have accessibility to global flows of goods and people—implying the need for airport, rail, and road transport vehicles and facilities. Further, experience in many parts of the world suggests that the rising per capita incomes from economic growth leads to more than proportionate increases not only in vehicle ownership and even more sharply in the vehicle kilometer traveled (VKT).[39] The motorized vehicles in these low to moderate income megacities do not incorporate advanced fuel-efficient technology. The result is greater fuel use, and more urban air emissions for a given level of VKT. In addition to air pollution, the growing problems of congestion, accidents, noise pollution and lack of security are also very worrisome. The challenge facing the megacities is how to reduce the adverse environmental impacts and other negative effects of transportation without giving up the benefits of mobility. This dilemma becomes most pressing under conditions of rapid urban growth, which is likely to increase travel demand significantly.[40]

Growth in large cities is often accompanied by increases in urban poverty. The urban poor, who are often unskilled and unable to compete for scarce resources or protect themselves from harmful environmental conditions, are most affected by urbanization, especially in developing nations.[36] Land development processes tend to serve middle and higher income classes, forcing the poor to settle in high densities on marginal lands within cities or on the urban periphery. These urban area expansions often start as illegal settlements, sometimes in areas at risk from environmental hazards (such as floods and landslides), and without access to basic services (such as water and sanitation). Over half of the population of Mexico City lives in such settlements.[11] As the peripheries of cities enlarge, agricultural land, forests, and wetlands are consumed. Sand and gravel are excavated and removed for increased construction; woodlands are depleted for fuel; and rivers, lakes, streams, and coastal waters are polluted by untreated sewage and runoff.

Urbanization and industrialization have important consequences for the Earth's atmosphere.[41] Biomass and coal used for heating and cooking pollute indoor and outdoor air. Disturbed land, unpaved roads, and construction add to atmospheric dust levels. Transport is often accomplished with old city buses and poorly maintained two-stroke engines operating with adulterated fuels that are not conducive to passing "smog tests." Undesirable properties near polluting industries are often settled first by the economically disadvantaged, further adding to their atmospheric pollution exposure. The regional and global dispersion of pollutants generated locally causes acid deposition, and changes in the Earth's radiation balance. Concerns about tropospheric ozone (O_3) and particulate matter (PM) have heightened recently because the long-range transport of these pollutants influences air quality and its effects on climate are felt in regions far from their sources.

Cities create heat islands as green areas are converting into residential and commercial zones that can also aggravate pollution, alter regional meteorological conditions, and even global chemistry and climate.[42] Metropolitan areas like Tokyo, Los Angeles, and Mexico City are becoming warmer and warmer every day. For example, from 1990 to 2000, the average annual temperature in Mexico City increased from 14.8 ºC to 16.8 ºC.[43] Higher ambient temperatures enhance O_3 and some secondary PM formation. Warmer temperatures in the summer increase the demand for cooling and electric energy consumption, leading to yet higher temperatures in the city. Deterioration in urban environmental conditions can have serious effects on human health and welfare, particularly for the poor.[44] Air and water pollution cause chronic and infectious respiratory and water-borne diseases, and result in increased mortality rates.[45-49]. However, worldwide epidemiological and demographic information suggests that survival rates are better in cities than in rural areas because of better access to health services.[35] There are other less quantifiable but nonetheless important environmental impacts, such as loss of green space in urban areas, deterioration of local ecosystems, noise pollution, and unpleasant sights and smells, that reduce quality of life for the residents.

Although local environmental problems diminish as cities become wealthier, environmental problems arise on larger scales. Wealthier urban residents rely heavily on fossil fuels and electricity that create more gaseous, liquid, and solid wastes. Cities in industrialized countries are now facing the consequences of past environmentally damaging production techniques and inadequate waste disposal. This has resulted in many different forms of pollution and in particular the formation of brownfields.[50]

Cities are not self-contained entities. All of the resources that urban inhabitants use for their daily needs and activities come from somewhere, even if not from their immediate surroundings. Recently, Rees and Wackernagel developed the ecological footprint (EF) concept to highlight the impact of cities on the environment.[51] A city's ecological footprint (EF) is the biological productive area required to produce the resources used, and to assimilate the wastes generated, by a defined population at a specified standard of living.[36] EF is a measure of the biological capacity of the Earth to create new resources and absorb waste. The Earth has about 11.4 billion hectares of productive land and sea space; about one-fourth of the Earth's surface area is unproductive. Divided among the Earth's 6 billion people in 2000, this equates to an average of 1.9 hectares per person. In 1999, the EF was less than 1.4 hectares per capita for the average African and Asian, 5.0 hectares for the average western European, and 9.6 hectares for the average North American. The global average EF during 1999 was 2.3 hectares per person, 20% more than the 2000 estimate, and a substantial increase from the 1961 EF of ~1.3 hectares per person. The EF is likely to grow to 180% to 220% of the Earth's capacity by 2050,[52] a clearly unsustainable situation.

The world's richest countries, with 20% of the global population, account for 86% of total private consumption, whereas the poorest 20% of the world's population accounts for just 1.3% of consumption. A child born today in an industrialized country will add more to consumption and pollution over his or her lifetime than 30 to 50 children born in developing countries. The EF of wealthier consumers is a major cause for the exceedance of the Earth's carrying capacity.[53] **A** typical North American city with a population of 650,000 people would require 30,000 km^2, an area roughly the size of Vancouver Island in Canada, to meet its domestic needs—without including the environmental demands of industry. In contrast, a city of the same size in India would require only 2900 km^2.[36] However, when properly managed, EFs from urban areas can be smaller than those of a similar number of people in non-urban settings.

Cities can concentrate populations in a way that reduces land pressure and provides proximity to infrastructure and services.[54] Well-planned, densely populated settlements can reduce the need for land conversion and provide opportunities for energy savings. Sustainable development must include: 1) appropriate air quality management plans that include the development of an integrated policy for transport, land use, and air quality and the establishment of adequate monitoring capabilities for the surveillance of the environmental quality and health status of the populations; 2) adequate access to clean technologies, including the provision of training and development of extensive international information networks; and 3) improvement of data collection and assessment so that national and international decisions can be based on sound information.[55, 56]

Urban air pollution is not a new problem, and effective emission reduction strategies are available for most emission sources. The formulation and implementation of effective integrated air quality management strategies will be crucial to address this challenge and to protect human health and welfare, as well as ecosystems.

AIR POLLUTION IN MEGACITIES

Megacities consume a large fraction of the Earth's current fossil fuel budget to produce electrical energy, propel transportation, power industrial processes, prepare food, and provide heat and ventilation for homes, commercial enterprises, and public buildings. Exhaust emissions from these fossil fuel combustion sources and the processes they power emit large quantities of pollutant gases and fine particulate matter (PM) into the atmosphere.

The degraded atmospheres of megacities often contain high concentrations of PM; O_3; sulfur dioxide (SO_2); nitric oxide (NO) and nitrogen dioxide (NO_2), the sum of which is known as nitrogen oxides (NO_x); carbon monoxide (CO); volatile organic compounds (VOC), and hydrocarbons (HC, a VOC subset).[57] PM is often reported as mass concentration in the Total Suspended Particulates (TSP), PM_{10}, and $PM_{2.5}$ (particles with aerodynamic diameters of less than ~40, 10, and 2.5 µm, respectively). The major PM chemical components are sulfate ($SO_4^{=}$), nitrate (NO_3^{-}), ammonium (NH_4^{+}), organic carbon (OC), elemental carbon (EC), and soil (a weighted sum of mineral elements such as aluminum [Al], silicon [Si], calcium [Ca], titanium [Ti], and iron [Fe]). Long-lived greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbons (CFCs) are important on global scales.[58, 59]

In fact, it is now possible to monitor NO_2 levels in urban areas from the space. Measurements from the Global Ozone Monitoring Experiment (GOME) on board the ESA-satellite ERS-2 shows the weekly cycle of NO2, which came about from reduction in fossil fuel combustion during weekends.[60] Figure 2 shows the weekly cycle of mean tropospheric NO_2 vertical column densities for six urban centers. There is a clear Sunday minimum for Los Angeles, Milan and Mexico City; a shifted Saturday (Sabbath) minimum for Jerusalem; and a slight weekly effect on Friday for Cairo. There is no indication for a weekly cycle in Beijing, which indicates that the NOx emissions could be dominated by power plants and other industrial sources. In Los Angeles, Chinkin et al.[61] reported that Freeway traffic volume information showed that truck and bus activities decreased by as much as 80% on weekends. On the other hand, major point source NOx emissions on Friday, Saturday, and Sunday were 8-18% lower, on average, than on Monday-Thursday.

In an extensive compilation of urban air pollutant concentrations around the world conducted by Baldasano et al.,[62] the highest total suspended particulate matter (TSP) and SO_2 levels appear mostly in Asian cities, the highest PM_{10} levels in Latin American cities, and the highest ozone levels in Mexico City. However, these conclusions are limited to the cities that measure pollutants. In the developing world PM_{10} and ozone measurements are only conducted regularly in a handful of cities. A high priority action item should be to establish comprehensive monitoring in other cities in the developing world. More extensive atmospheric measurements and modeling are needed to define optimal emission control strategies for the particular urban center under consideration, taking into account the local economic, social and political circumstances. Policy makers should use this information to balance the economic and social benefits of health improvements against the costs of emission control. In practice, because of large uncertainties in air pollution and health effects science, measurements and air quality models are best used to help prioritize controls on different primary emitters in order to achieve various air quality improvement goals.

Some pollution control decisions are easy. Exposure to SO_2 and $SO_4^{=}$ from burning coal was identified during London's "killer smog" events in the 1940s and 50s, which were correlated with increased sickness and death.[4] Switching to low-sulfur fuels improved this situation. Nevertheless, areas with high sulfur levels remain in some regions of the developing world. Determining the causes of high PM and O_3 concentrations –the current more prevalent air pollutants of concern for human health -- is not as straightforward. NO_x and VOCs, much of which are emitted by the transportation sector, are transformed in the presence of sunlight to produce O_3, nitric acid (HNO_3), and other oxidants in a complex series of chemical reactions. These reactions also generate secondary PM organic compounds, NO_3^{-} and $SO_4^{=}$. The relationship between NO_x, VOCs, and O_3 is nonlinear: fresh emissions of NO destroy O_3. High levels of NO_2 scavenge hydroxyl (OH) radicals, the reactive species that initiate the breakdown of VOCs. Reductions of NO_x or VOC emissions may have little or no effect on, or may even increase, O_3 concentrations. The formation and the growth of suspended particulate matter also involve complex physical and chemical processes. The application and validation of air quality models requires spatially and temporarily resolved emissions data as well as knowledge of the meteorology (including solar radiation). In addition to commonly measured O_3, NO, NO_2, CO, and PM mass, individual VOCs and PM chemical compositions are needed. This detailed information is rarely available, however. Special studies are needed in megacities to better understand the causes of such emissions and to measure progress in limiting them. The following measurements from special studies in Mexico City demonstrate useful techniques that could be applied in other megacities:

- Routine hourly measurements of PM_{10}, O_3, NO, NO_2, and CO acquired from the Mexican Automatic Air Quality Monitoring Network (RAMA, *Red Automática de Monitoreo Atmosférico*) provide a long-term record to determine the temporal and spatial characteristics of air pollution.[4]
- Remote sensing of emissions from individual vehicles, obtained from absorption spectra of infrared (IR) and ultraviolet (UV) light projected through the exhaust plume, quantifies NO, CO, CO_2, and HC. These tests indicated that 4% of the automobiles contributed 30% of the tailpipe HC emissions, and 25% of the vehicles contributed 50% of the CO emissions in 1991.[63] Most vehicles emitted 3-6% CO, suggesting that they were deliberately tuned for power without regard for emission reductions. Similar measurements in 1994 showed a ~50% decrease in average CO and HC emissions, demonstrating the effectiveness of catalytic converters required on cars sold after 1991.[64] Remotely sensed emissions in 2000[65] found higher emissions in lower income areas of the city. Nevertheless, average vehicle emissions decreased by 70% for CO and 90% for HC relative to 1991 values. For all these species, the median emission is notably less than the average, which occurs because a fraction of vehicles have high emissions and thus disproportionately impact the average emissions. Past data shows that emissions of CO and HC decrease sharply after 1988, and NO_x emissions decrease sharply for cars manufactured after 1992.
- PAHs originate from emissions of motor vehicles, oil refineries, forest fires, and cooking. PAH concentrations along Mexico City roadways range from 60 to 910 ng/m^3.[66] These levels are approximately five times higher than concentrations measured in the United States and are among the highest measured ambient values reported. The large concentrations are likely due to a combination of old diesel-powered vehicles and the city's relatively dirty light-duty vehicle fleet, half of which lacked catalytic converters in 2003.
- In the spring of 2003, an MIT-lead multinational team of experts conducted an intensive, five-week field campaign in the MCMA. The overall goal was to contribute to the understanding of the air quality problem in megacities by conducting measurements and modeling studies of atmospheric pollutants in the MCMA and to provide a scientific base for devising emissions control strategies.[67]

EFFECTS OF DEGRADED AIR QUALITY IN MEGACITIES

Emissions and ambient concentrations of pollutants in megacities can have widespread effects on the health of their populations, urban and regional haze, and ecosystem degradation. Impacts on health, visibility, regional ecosystem (including acid and fixed nitrogen deposition, photochemical oxidant damage, photosynthetically active radiation), regional climate change, and global pollutant transport are evaluated.

Adverse Health Impacts

A variety of air pollutants have been found to have adverse effects on humans, plants and certain materials. Health effects on humans have been investigated with epidemiology, animal studies, and human exposure studies. The so-called "criteria pollutants" are those for which acceptable concentration limits have been set to protect public health and welfare. Table 4 lists recommended ambient air quality standards set by various countries and the World Health Organization (WHO) with the values usually expressed in terms of a given concentration of the pollutant over a specified period of time. The health effects of air pollution vary not only by the intensity and the duration of exposure, but also by the age and health status of the individual exposed. Populations at greater risk include children, the elderly, and those already suffering from diabetes or cardiovascular and respiratory disease.[68] Debates on what level of pollutant concentration is safe continue to take place in the US and other countries, especially in the case of fine particles.

WHO estimates that urban air pollution contributes each year to approximately 800,000 deaths and 4.6 million lost life-years worldwide, with approximately 65% of the deaths and lost life-years occur in the developing countries of Asia.[68] However, the estimated impacts are based largely on the results of research conducted in Europe and North America that have been extrapolated to developing countries; such extrapolation raises large uncertainties because of the differences in the nature of air pollution, the conditions and magnitude of exposures to that pollution, and the health status of the populations. The Health Effects Institute (HEI) has initiated the Public Health and Air Pollution in Asia (PAPA) program to evaluate epidemiologic studies of outdoor air pollution that have been studied in Asia and to identify gaps in knowledge that should be addressed in future research.[69] The PAPA program, conducted in cooperation with the Asian Development Bank's Clean Air Initiative, is designed to provide Asian decision makers with science on the magnitude of health effects related to air pollution in selected Asian cities over the next five years.

Recently, airborne particles have been of particular concern because a growing body of epidemiological findings is linking health effects such as lung cancer and cardiopulmonary mortality to fine particulate air pollution.[70] Particulate polycyclic aromatic hydrocarbons (PAHs)—combustion byproducts that are potent carcinogens and mutagens— bound to particles are a candidate group of chemicals that can react with DNA after metabolic activation.[71] New evidence shows that PAHs associated with inhaled particles also may cause changes in humans during development.[72] Studies in humans indicated that elevated air pollution may cause DNA damage in male germ cells.[73] A new study by Somers et al.[74] found that airborne particles can cause genetic damage in mice that can be passed along to offspring. This new finding, if confirmed, would extend the adverse health effects of air pollution to the health risks of future generations. The PAH concentrations in many large urban centers are very high, for example, they range from 60 to 910 ng/m^3 along Mexico City roadways,[66] which are approximately five times higher than concentrations measured in the United States. The large concentrations are likely due to a combination of old diesel-powered vehicles and the city's relatively dirty light-duty vehicle fleet. In some heavy industrial areas in Cairo, the concentrations have been reported to be as high as 24,000 ng/m^3.[75]

There are two types of studies that link air pollution with premature death: cohort and time-series. Cohort studies follow individuals for many years to evaluate whether long-term exposure to air pollutants is related to mortality, taking into account other variables such as age, gender, occupation, weather, smoking status, etc. Time-series studies track daily changes in air pollution levels and correlate them with the number of deaths in the exposed population that occur during the same or possibly within the next few days. Only a few cohort mortality studies have been carried out.[76-79] In contrast, many time-series mortality studies have been conducted around the world, mainly because they can be conducted more quickly and at lower cost. In general, both sets of studies conclude that premature mortality associated with air pollution is caused predominantly by PM rather than by O_3, which is linked to morbidity. However, studies in Asia often find a stronger association between mortality and SO_2, rather than PM. Relatively high levels of SO_2 are one reason; another is that TSP data is more readily available than data for PM_{10}. Other reasons could be differences in age structure, health status, etc.

Mexico City health studies[80-84] indicate a 1% change in daily mortality per 10-µg/m^3 increase in PM_{10} levels (the so-called risk coefficient). This compares with a 0.6% per 10 µg/m^3 increase derived from a meta-analysis of epidemiological studies conducted around the world.[85] A major question in the MCMA time-series studies is whether the $PM_{2.5}$, PM_{coarse} (PM_{10} minus $PM_{2.5}$), or both are causing the premature mortality effect. Another important question is whether the deaths involve infants and healthy young people, in addition to elderly individuals with pre-existing cardiopulmonary disease. Evans et al.[86] developed a simplified risk-benefit assessment for Mexico City by estimating the impact of a 10% reduction in air pollution exposures from baseline values prevailing in the late 1990s. They found that such a reduction could yield health benefits worth roughly $2 billion per year. The economic benefits of air pollution control are potentially quite large but highly uncertain. The health benefits of reducing ambient O_3 levels appear to be only about one-tenth of those obtained through similar fractional reductions in PM_{10}, and the benefits of reductions in air toxics are even smaller.

The Ontario Medical Association in Canada estimated that 1900 premature deaths, 9800 hospital admissions, 13,000 emergency room visits, and 46 million illnesses were caused by air pollution in the province during the year CY 2000[87] (the population of Ontario is about 12 million people). Approximately 5000 preventable premature deaths (~8% of the total) in 11 Canadian cities were attributable to the combined effects of O_3, SO_2, NO_2, and CO.[88] Other studies in 1995 estimated that pollution caused 1000 premature deaths and 5500 hospital admissions in the Greater Toronto Area, [89] and 298 premature deaths and 539 hospitalizations in Hamilton.[90] The number of deaths in the Greater Toronto Area believed to be caused by air pollution was comparable to that caused by lung cancer (1048) and stroke (1347). Sahsuvaroglu and Jerret[91] reported 374 deaths, 607 respiratory hospital admissions, and 2000 cardiac hospital admissions in Hamilton during 1997 due to air pollution.

In Delhi, India, Pande et al.[92] found increases of more than 20% in chronic obstructive pulmonary disease (COPD) and acute coronary events attributable to air pollution. Cropper et al.[93] found a significant relationship in Delhi between PM pollution and daily non-traumatic deaths, as well as deaths from certain causes (e.g., cardiovascular and respiratory diseases). On average, a 100 μg/m^3 increase in TSP was associated with a 2.3% increase in mortality. Although air pollution in Delhi appears to have less impact on mortality, the number of life-years saved per death avoided is greater in Delhi than in U.S. cities. In U.S. cities, PM has its greatest influence on daily deaths among people 65 and older, whereas in Delhi the largest impact occurs in the 15-to-44 age group. This implies that, on average, for each avoided death associated with air pollution, more life-years would be saved in Delhi than in U.S. cities.

In Beijing, China, Xu et al.[93] found a significant association between SO_2 levels and daily mortality throughout the year. The mortality risk was estimated to increase by 11% with each doubling in SO_2 concentrations (averages were 120 and 67 μg/m^3 in 1998 and 2002, respectively). A significant association was also found between TSP and mortality by Xu et al.[94] Dong et al.[95] found a statistically significant association between air pollution levels and daily mortality during 1990 and 1991. The influence of TSP on patients with cardiovascular disease (CVD) and of SO_2 on patients with respiratory disease was greater than that on other patients. The air pollutants were especially harmful to patients older than 65. Zhang et al.[96] observed statistically significant correlations between $SO_4^=$ concentrations and mortality from all causes, as well as on mortality due to CVD, malignant tumors, and lung cancer. Zhang et al.[97] showed a significant association of the air quality index with mortality, especially in the winter and among those 55 and older with COPD and other respiratory diseases. Similar findings, reported by Chang et al.,[98] showed an increase of ~20% in mortality from COPD for an SO_2 increase of 100 μg/m^3, and of ~3% in respiratory deaths for a TSP increase of 100 μg/m^3.

Xu et al.[99] collected 1990 data from a community-based hospital in Beijing to assess the association of air quality with daily non-surgery outpatient visits, and found significant associations with both SO_2 and TSP levels. Chang et al.[100] also found significant associations between air pollutant concentrations and outpatient visits for colds, pneumonia, and bronchitis for children in Beijing from 1998 to 2000. Wang et al.[101] found a significant association with SO_2 and NO_2. Zhang et al.[102] attributed a decrease in the levels of vital capacity and maximum voluntary ventilation to high TSP and NO_x levels. Xu et al.[103] reported that long-term exposure to high levels of TSP and SO_2 in Beijing was correlated with significantly reduced pulmonary function in adults; the associations were stronger among smokers than non-smokers. Exposure to TSP and SO_2, or to a more complex pollution mixture, appears to contribute to excess risk of preterm delivery in Beijing. In a prospective cohort study,[104] all pregnant women living in four residential areas of Beijing were registered and followed from early pregnancy until delivery. Xu et al.[104] found a significant dose-dependent association of gestational age with TSP and SO_2 concentrations.

In Santiago, Chile, Sanhueza et al.[105] found that PM_{10} has the strongest association with premature mortality, with lower associations for O_3 and SO_2. Using daily counts of non-accidental deaths in Santiago from 1988 to 1996, Cifuentes et al.[106] found a significant association between mortality and PM levels, with finer particles being more important than coarse particles. The concentration of PAHs and the mutagenicity of airborne particles in Santiago have been investigated and compared to those in Tokyo.[107] Ochoa and Roberts[108] reported the estimated cancer risks posed by exposure to suspended PM in Santiago. Ilabaca et al.[109] investigated the association between $PM_{2.5}$ and hospital visits for pneumonia and other respiratory illnesses among children. These studies demonstrate the adverse effect of pollution on human health.

Cifuentes and Bravo[110] assess whether the impacts of particulate air pollution on daily mortality are affected by place of residence and by educational attainment status in Santiago, Chile using daily mortality data and PM10 data from eight monitors within the city, from 1997 to 1999. They found that for adults the risk is higher in those municipalities with lower educations status, with an increase in risk of 1.53%; for the elderly, the highest risk is for the higher educational status municipalities, with an increase of 1.67%. There is a very different dependence of risk on age for the two different groups of municipalities. In the higher education municipalities, elders are at significant risk, while for the lower educational status municipalities, adults (including ages 20 to 40) are at higher risk.

In São Paulo, Brazil, Saldiva et al.[111] found significant effects of PM on respiratory functions in children. An increase in the mortality of elderly people in São Paulo associated with high PM_{10} levels has also been documented.[112, 113] Experiments with exposure of rats in downtown São Paulo and a control clean area revealed important changes in the respiratory function.[114] Studies in elderly people[115] reveal significant changes in mortality. Braga et al.[116, 117] studied children and adolescents respiratory function with different levels of air pollution in São Paulo.

In a time-series study conducted in the two largest cities in Brazil, São Paulo and Rio de Janeiro, Gouveia et al.[118] found statistically significant associations between air pollution (mostly for PM_{10}, CO and SO_2) and mortality and hospital admissions for respiratory and cardiovascular illnesses for children and the elderly after adjustment for long-term trends, seasonality, temperature and humidity. The relationship between birth weight and maternal exposure to air pollution was also examined in São Paulo.[119] For a 1-ppm increase in mean exposure to CO during the first trimester of pregnancy, a reduction of 23 g in birth weight was estimated.

Visibility Impairment

The connection between air pollutants and visibility impairment is related mostly to $PM_{2.5}$ concentrations, but it is often accompanied by high levels of other pollutants.[120] Urban haze is the most commonly perceived effect of excessive concentrations. In Beijing, China, visibility is often low, in part because of the relatively high frequency of foggy days. Nevertheless, the sky overhead is almost always gray, even in the absence of fog or clouds. Bergin et al.[121] concluded that during June 1999, combustion-related particles rather than wind-blown dust were mainly responsible for visibility degradation. It is well documented that Asian sand storms and dust cause poor visibility during the spring.[122] Song et al.[123] developed regression equations to estimate visual range as a function of $PM_{2.5}$ mass concentration.

In Ontario, Canada, the visual range without the effect of anthropogenic PM is estimated to be between 86 and 120 km; visual range decreases to between 35 and 50 km in the presence of PM. These calculations were based on average 24-hr $PM_{2.5}$ or PM_{10} levels; the results vary with season, changing PM concentrations, and relative humidity levels.[124]

In Santiago, Chile, the study of air pollution started around 1980, when researchers noticed unusually hazy days during winter. These studies were related to TSP and its chemical characterization.[125-129] Truer and Silva[130] measured the optical properties of PM in Santiago and found high extinction and absorption coefficients. Trier and Horvath[131] found high daily variability in the extinction coefficient, from 0.018 km^{-1} in the morning to 0.15 km^{-1} in the afternoon, attributing this result mainly to a change in the mixing height and finding a high correlation with TSP levels. Trier and Firingueti[132] performed a time-series investigation of visibility. Horvath et al.[133] found high variability in optical absorption coefficient on a time scale of a few hours due to changes in meteorological conditions. Concentrations between 1.3 and 25 $\mu g/m^3$ of black carbon (BC) were estimated on the basis of observed light absorption. Gramsch et al.[134] reported a strong correlation between optical absorption coefficients and traffic patterns in Santiago. Maximum absorption coefficient often occurs during the morning rush hour (7 to 8 a.m.), with the lowest value found either early in the morning (3 to 5 a.m.) or in the afternoon (2 to 5 p.m.). The absorption coefficient also shows a strong seasonal dependence, with values 10-20 times higher in winter than in summer. Most of the absorption is attributed to BC, mainly from vehicle exhaust. Using a low-cost optical instrument, Gramsch et al.[135] compared the absorption coefficient with PM and carbon concentrations.

A "black cloud" has often appeared above the Nile Delta and Cairo, Egypt, during October.[136, 137] After the rice harvest, farmers burn rice straw to clear fields for the next crop. There is a prevalent upper-air high pressure system over the Nile Delta during such episodes. Nighttime cloudless skies also contribute to a decrease in surface temperature, leading to a steep thermal inversion.[138] Aerial photoreconnaissance identified the locations and intensities of the emissions.[139] Straw building has been encouraged as an alternative use for rice straw that minimizes vegetative combustion.[140]

Regional Ecosystem Impacts

Acid and Fixed Nitrogen Deposition. The detrimental impacts of acids that form from SO_2 and NO_x emissions on sensitive lakes, streams, forests, and farmlands have been well documented.[141] A related issue involves fertilization effects caused by the deposition of airborne fixed nitrogen species (PM NH_4^+ and $NO_3^=$ and their gas phase precursors) to buffered soils and surface waters that are not susceptible to acidification. Combined with fixed nitrogen and phosphorous from fertilizer, animal waste, and human sewage sources, atmospheric deposition of fixed nitrogen can over-fertilize soils, lakes, streams, and estuaries, leading to changes in primary productivity and, potentially, to eutrophication.[142] Atmospheric nitrogen deposition can even affect the ocean by stimulating phytoplankton blooms.[143-145] High levels of fixed nitrogen deposition can have significant effects on ecosystem diversity, even when deposition receptor areas are not heavily acidified. For instance, Stevens et al.[146] report that British grasslands subject to long-term chronic levels of nitrogen deposition have significantly lower levels of species diversity than those exposed to lower deposition rates; at average deposition rates of 17 kg N ha^{-1} per year for central Europe, and a 23% reduction in plant species was found.[146] As the number of motor vehicles in developing world megacities increases, NO_x emissions will increase dramatically;[147-150] consequently, the impact of fixed nitrogen deposition on downwind ecosystems can be expected to rise rapidly.

Photochemical Oxidant Damage. Photochemically produced oxidants and their precursors frequently produce high levels of O_3 and other oxidants that transport from one major city to the next, subjecting the intervening suburbs, forests, and agricultural areas to high oxidant exposures.[150, 151] Exposure to O_3 and related photochemical oxidants is known to damage both native and agricultural vegetation.[151] O_3 damage may affect crop yields in agricultural areas impacted by emissions from major cities in China.[152-154] Model calculations predict semi-continental to continental-scale plumes of high summer O_3 associated with urban and industrial emissions from the urban complexes in the midwestern and eastern United States, western and central Europe, and East Asia.[155]

Gregg et al.[156] report greater plant growth in New York City compared with a rural environment and attribute the effect to the higher O_3 levels in the rural area. Fenn et al.[157] document the significant damage to forests surrounding the Mexico City air basin caused by exposure to high levels of photochemical oxidants, mainly O_3.

Photosynthetically Active Radiation. Recent model analyses demonstrate the impact of Asian megacity SO_2 emissions on regional pollution. High SO_2 and other gaseous precursors can result in high levels of fine PM, with absorption and scattering properties that significantly influence both the direct and diffuse components of photosynthetically active radiation (PAR).[158] In fact, the resulting haze over eastern China has decreased solar radiation reaching the surface since 1954.[159] Attenuation of PAR by both atmospheric PM and by PM deposited on plant leaves may significantly impact the solar radiation available for photosynthesis in agricultural regions in China.[153, 160]

Regional Climate Change

Emissions from megacities may also play a role in regional climate impacts. High levels of GHG associated with major cities[58] have a direct impact on infrared radiative forcing globally.[161] Furthermore, the powerful but shorter-lived tropospheric O_3 will have a more pronounced regional effect.[155]

Fine PM can have a direct effect on short wavelength radiative forcing by scattering and/or absorbing solar radiation. Satellite observations show an albedo reduction due to absorbing aerosols and their impact on cloud absorbance over urbanized regions in China.[162]

Surface temperature records in urbanized regions of China[159, 163, 164] and India[165] show a measurable cooling since the 1950s. Analyses of meteorological data in heavily urbanized regions of China demonstrate significant downward trends in both sunshine duration (1% to 3% per decade) and maximum daily temperatures (0.2 to 0.6 °C per decade).[159, 163] The observed cooling trends are consistent with the predicted effects of elevated soot levels in fine PM,[164] and are achieved despite a general warming observed for most of the globe over the same time period.

High PM loadings that increase the number of effective cloud condensation nuclei (CCN) can also influence precipitation levels by lengthening cloud lifetimes and suppressing rain and snow as a result of nucleating more, but smaller, cloud droplets. Satellite observations show significant rainfall suppression downwind of major cities.[165] High PM loadings with a large fraction of absorbing soot particles are predicted to reduce cloudiness by absorptive heating of cloud particles,[166] although the impact on cloud cover may also be affected by the increased atmospheric circulation.[164]

Yet another consequence of long-range transport involves impacts on urban populations of sand, dust or smoke that originate beyond the urban centers, giving rise to episodic pollution events. For example, dust and sand storms that originate in the dry regions of northern China and Mongolia and blow across parts of China, the Korean peninsula, and Japan are now taking place nearly five times as often as in the 1950s. These dust storms are also growing in intensity, and occur during the spring months as cold air masses from Siberia whip deserts and soils eastward after the dry continental winter.[167] In April 2002, dust levels in Seoul—1200 km from their source—reached 2070 $\mu g/m^3$. The effects in Beijing are also striking.[168, 169] Between 1994 and 1999, the Gobi Desert in China expanded by 52,400 km^2, moving closer to Beijing. Up to 400 million people are threatened by the fast-advancing deserts. Nearly 30% of China's land area is affected by desertification caused by over-farming, grazing, and deforestation. The annual direct economic losses are estimated to be around $6 billion. China, Mongolia, Japan, and South Korea are pooling their efforts to reduce the impact. Backed by the U.N. Environmental Program (UNEP), the Global Environment Facility, the Asian Development Bank, the U.N. Economic and Social Commission for Asia and the Pacific, and the U.N. Convention to Combat Desertification, they are setting up a monitoring and early warning system for dust and sand storms, which is aimed at standardizing data collection and sharing information throughout the region.

Global Pollutant Transport

Satellite, aircraft, and ground-based observations throughout the global atmosphere are confirming model simulations that air pollution can be transported over long distances, e.g., from eastern Asia to the western United States, from North America to Europe, and from mid-latitudes to the Arctic.[170-174] Tropospheric oxidants, changes in precipitation chemistry, and reduced visibility are already significant environmental issues in much of the industrial Northern Hemisphere.[152, 175, 176] Globally, current levels of pollution-related tropospheric PM and O_3 are significant contributors to the atmospheric "greenhouse" radiation budget.[177-180] Long-term changes in global OH concentrations, and therefore in the atmospheric residence times of many gases, are a matter of great interest but remain highly uncertain.[181, 182]

Recent field campaigns have studied pollutants in the remote troposphere,[183-186] the outflow from East Asia,[187-196] the Indian subcontinent,[196] and North America.[197-201] Several regional-scale studies have been carried out in the United States[202-206] and Europe[207-210] that demonstrated the enormous pollutant potential of major cites and "megalopolis" regions, as well as the fact that significant quantities of gaseous pollutants and fine particles can be transported and detected over intercontinental scales. These insights have erased the distinction between air quality (long thought to be a local- to regional-scale issue) and global atmospheric chemistry (focused on concerns about GHG-induced climate change, stratospheric O_3 depletion, and tropospheric oxidative capacity). It is now clear that the gaseous pollutants and fine particles dispersed from heavily polluted regions may have significant impacts on continental to global scales.[59, 171]

However, to date, relatively few measurements have been carried out on the polluted outflow from megacities in tropical and subtropical latitudes. Given the high growth rates and rapid industrialization and motorization of these megacities of the developing world,[58] it is likely that regional and even intercontinental transport of pollutants at low latitudes will grow rapidly, posing an even greater challenge.

AIR QUALITY ASSESSMENT TOOLS FOR MEGACITIES

Air quality management in megacities takes place in four stages.[211] The initial stage of *problem identification* recognizes that existing air quality is unacceptable and determines the causes of excessive levels. Having determined the type and severity of the problem, *policy is formulated* to solve it. *Implementation of poli*cy follows, in which the strategies to reduce emissions are enacted and enforced. Assuming that the problem was correctly identified and that appropriate policy has been formulated and successfully implemented, the *control situation* is achieved. Although the initial problem might have been resolved, management capabilities are required to ensure that the control situation persists. Changes in emissions affecting the urban area and a more precise definition of the problem may identify new air quality issues to be resolved, and the management cycle is initiated again. Continued monitoring is needed for problem definition and maintaining the control situation. Throughout each cycle it is essential to ensure that the public remains informed of the status of their air quality.

The design of emission controls requires detailed information on the status of the air quality (provided by monitoring networks) and the principal sources of pollution and their location, as characterized by the emission inventory. Combining the information from monitoring and emission estimates with knowledge of dispersion characteristics for the city and chemical transformations of pollutants enables air quality models to be developed. Such models are powerful tools for air quality managers, but there is no perfect model that can be applied to formulate an effective air quality management strategy. It is important to consider an overall view of urban air quality rather than to focus on single-pollutant or isolated problems.

Air Quality Monitoring Networks

Ambient monitoring at representative exposure locations is carried out to represent the effects from the aggregate of all emissions. Monitoring is conducted to examine excessive pollutant levels, determine compliance with standards, identify and quantify source contributions, determine exposures, evaluate the effectiveness of emission reductions, and perform air quality modeling.[212] Data quality objectives, network design and management structures, monitoring locations, instrumentation, operation and maintenance of systems, quality assurance and control procedures, data review, data validation, and data usage vary depending on the monitoring objectives.

Many monitoring systems are based on recommendations for U.S. EPA compliance monitoring.[213] These include the U.S.-regulated criteria pollutants of PM (TSP, PM_{10}, and $PM_{2.5}$ mass), O_3, SO_2, NO_2, and CO. Meteorological data should also be monitored concurrently at air quality monitoring sites. In some areas, visibility and acid deposition may be important. Several different methods can be applied for these measurements that vary in the complexity, reliability, and detail of data. These range from simple passive sampling techniques to highly sophisticated continuous analyzers and remote sensors. Assessing which measurement technique is the most appropriate depends on the objective for which the measurements are to be conducted, as well as the resources available to achieve this objective. Current state-of-the art continuous analyzers and remote sensors are able to provide highly time-resolved data that can be used to understand pollution evolution and distribution. However, most of these instruments are expensive to purchase and maintain, and they require considerable technical support, which often is not available in developing countries.

The selection of monitoring locations also depends on network objectives. One primary reason for monitoring ambient air pollutants is to provide information for estimating their likely effects, particularly on environmental and human health; therefore, monitoring stations are often established in population centers. They can be next to busy roads, in city center locations, or at a location of particular concern, such as a school or hospital. Background and boundary monitoring stations are also established to determine pollutants transported into and out of megacities.

In many urban areas, individuals spend a considerable amount of time indoors, where concentrations of pollutants are often quite different from those experienced outdoors. Indoor air pollution can be generated by the penetration of outdoor air. It can also be generated by indoor sources, such as combustion processes for heating and cooking, and other daily activities, such as cleaning. Therefore, an integrated assessment of indoor and outdoor exposure will allow the most appropriate, effective, and equitable controls on exposure to be imposed.

Once air quality data have been generated, quality assurance and control procedures should be developed and followed to ensure that the measurements obtained meet the specified level of accuracy and precision, and that those which do not are removed through data validation.

Emission Inventories

The most direct way to confirm that specific emission-control technologies are working effectively is to measure changes in the rate at which pollutants are released from relevant sources. Continuous emission monitors (CEMs) for PM, SO_2, and NO_x have been used for on-site stack sampling of large stationary sources, but these are not practical for the millions of smaller and mobile sources in a typical megacity. Temporally and spatially averaged emission inventories are constructed for this purpose.

Emission inventories tabulate emission rates from individual sources and source categories for the pollutants of interest. Although emission inventories are an essential tool for managing and regulating pollution, large uncertainties in emission rates, temporal cycles, spatial distribution, and source identification often confound the development of cost-effective control strategies. Emission inventories apply an emission factor that represents the mass of emissions per unit of activity (e.g., grams of $PM_{2.5}$ per kg of fuel consumed) times an activity factor (e.g., kg of fuel sold over a time period). Emission factors and activity levels are highly uncertain for vehicle exhaust, one of the largest source categories in megacity inventories. It is essential to reduce these uncertainties in order to manage air quality more effectively.

The U.S. EPA publishes national emission inventories for criteria pollutants and hazardous air pollutants (HAPs). The Emission Factors and Inventory Group (EFIG) of the EPA maintains a national emission inventory (NEI) that characterizes emissions of criteria and hazardous air pollutants. Although these contain data for U.S. megacities, similar products are not easily obtainable from other countries.

To estimate the accuracy of the emission inventory it is useful to have an independent check with an alternative method that may be based on receptor modeling source apportionment[214, 215] using emission ratios, multivariate methods, inverse air quality modeling, and equilibrium models. Receptor models relate speciated emissions to speciated source profiles. To the degree that a source profile is not unique (and many are not) or some emission species may be disproportionately removed by chemical reaction, deposition, or adsorption, source/receptor analysis will have uncertainties. Receptor model source apportionment shows the importance of sources to the emission problem directly, even if the results are somewhat uncertain. Frequently, source/receptor analysis can point to a source that may have been overlooked. The benefit of an unequivocal and easily communicated “top down” approach has value beyond confirming a “bottom up” emission inventory. Receptor model source apportionment has found large discrepancies between ambient measurements and emission inventories for transportation-related vehicle exhaust and road dust.[215, 216]

Mobile Source Emissions. Mobile source emission models[217, 218] include the time and emission factors for vehicles while parked and at idle, for the frequency of cold and warm starts, and for vehicles at various speeds in congested and non-congested driving. Emission factors are derived from laboratory measurements of evaporative and tailpipe emissions for simulated driving on a dynamometer. Vehicles selected for measurements come from different vehicle types, technologies, and ages. However, on-road vehicle emissions may vary by orders of magnitude from vehicle to vehicle even within the same type, technology, and age due to deterioration and breakage of the fuel delivery and emission control system. A limited number of vehicles can be tested in the laboratory, and the most poorly maintained are rarely volunteered to be tested; high-emitting vehicles are often underrepresented in the vehicle samples that have been tested in the laboratory.[219]

Remote sensing has been used to estimate on-road vehicle emissions, usually while vehicles are in light-acceleration driving. An advantage of this technique is its ability to measure large numbers of vehicles, although the emission measurements represent less than 1 second of driving for each vehicle. The technique has been used to: 1) verify the reduction of emissions from installing catalysts on vehicles in Mexico City,[220] 2) evaluate the reduced emission deterioration in newer vehicles,[221] 3) serve as the basis for estimating fuel-based emission inventories,[222] and 4) estimate the distribution of on-road high-emitting vehicles in various vehicle fleets.[223] Lidar-based remote sensors can detect low levels of PM emissions.[224] Remote sensing cannot measure evaporative emissions, and high evaporative emitters have not been identified by this technique.

On-board diagnostic (OBD) systems automatically monitor and document problems that lead to increased emissions from individual vehicles in an on-board computer. OBD systems alert the motorist by turning on the malfunction indicator light (MIL) to indicate that repair is needed. Motorist response to the “MIL ON” is being studied, especially for vehicles that are no longer under warranty, in which case the motorist would have to pay for diagnosis and repair. Newer OBDII systems,[225] installed on U.S. vehicles from 1996 onward, monitor evaporative emission control systems better than current vehicle emission inspection tests, and EPA is recommending that OBDII be used to inspect vehicles. The newest OBDIII systems link on-board diagnostics with wireless communication so that emission systems can be monitored at a central facility. OBDIII is currently being evaluated on high-mileage vehicle fleets, especially taxis, in Los Angeles and the San Francisco Bay Area.[226, 227]

In roadway tunnel studies,[228] air quality monitors are deployed inside tunnels and along roadways to characterize integrated emissions from vehicle fleets with minimal interference from other sources and atmospheric transformation. Tunnel measurements have led to revisions of emission models,[229] determined the effect of reformulated gasoline on HC species emitted by vehicles,[230] and quantified carbonyl and PAH emissions.

Mobile laboratories are designed to measure multiple pollutants while following vehicles on the road.[231-233] These systems draw a portion or all of the exhaust plume through a series of instruments for characterization. They are often used as chase vehicles to sample individual plumes from preceding vehicles. Measurements made in the laboratory dilute the exhaust before analysis and the excess air and time delay change particle size depending on sampling conditions.

Portable emission measurement systems (PEMS) are used on a vehicle to measure real-time emissions.[234] These operate on battery power and can be located in the trunk or back seat of a vehicle, with sampling from the exhaust pipe or the diluted plume beyond the exhaust pipe. A cooperative research program to examine commercially available PEMS devices is being organized.[235]

Aircraft and Satellite Observations. In addition to ground-based measurement, aircraft and satellite observations are useful for verifying elements of emission inventories and the location and extent of air pollution. Advanced multispectral satellite sensors can quantify trace gas concentrations and sometimes relate them to sources. The Global Ozone Monitoring Experiment (GOME) onboard the European Space Agency's (ESA) Second European Remote Sensing Satellite (ERS-2) provides continuous spectral measurements of nadir backscattered earth radiances and solar irradiances in the UV/visible wavelength range. GOME measures integrated column concentrations of SO_2, NO_2, and HCHO that are often emitted by fossil fuel combustion.[60, 236-237] Satellite plume detection can track long-range transport of gases and particles[238-241] and help researchers understand how meteorological situations influence air pollution on local, regional, and global scales.[242, 243]

The SCanning ImAging spectroMeter for Atmospheric CHartographY (SCIAMACHY) on the ESA Envisat satellite detects tropospheric gases and particles from lower earth orbit. The smaller ground pixel size of SCIAMACHY (30 km x 60 km) is comparable to the size of megacities, offering the possibility of estimating total emissions from these large urban expanses to create and verify inventories. SCIAMACHY's high spatial resolution also creates a higher probability of finding cloud-free ground pixels. SCIAMACHY extends the spectroscopic range into the infrared to provide column-concentrations measurements for O_2, O_3, SO_2, NO_2, N_2O, bromine oxide (BrO), H_2O, HCHO, CO, CO_2, methane (CH_4), other gases, clouds, and PM.[244]

Validation from aircraft measurements and model intercomparisons, together with new spectral interpretation algorithms,[239] will make satellite data a quantitative tool for air quality research and management.

Air Quality Standards

Ambient air quality standards define pollutant levels that should not be exceeded if public health is to be protected. These standards require definition and justification for acceptable levels, averaging times, allowable number of exceedances, sampling frequency, measurement method, and sampling locations. All of these components of an air quality standard affect the extent of emission control required for their attainment. Most air quality standards are established to prevent adverse human health effects for a particular pollutant. Since pollutant to health effect relationships are uncertain,[245] the form and level of ambient standards vary from country to country, and this variability will affect the levels of control applied in different megacities. Ambient standards should provide a management tool that can be used progressively to improve air quality while at the same time remaining a realistically attainable target. Standards are effective only when compliance is measured and enforced.

Air Quality Forecasting

Air quality forecasting[246-249] uses source and receptor models to estimate the severity of future pollution events. These forecasts are communicated to the public via mass media so they can make decisions about their daily activities. Most forecasts produce one- to three-day advance estimates of pollutant concentrations. In phenomenological forecasts, an expert familiar with past air quality and meteorological information recognizes patterns that are conducive to high pollution levels. This information is used subjectively, relying on past experience. Empirical models use artificial intelligence computer programs to recognize patterns and project them into the future. Chemical transport models coupled to detailed meteorological forecasts are also being employed for forecasting.

Air Quality Simulation Models

Air quality simulation models[250] combine and systematize knowledge of emissions, meteorology, and atmospheric chemistry to estimate ambient concentrations. These models can be used to explain past episodes, to evaluate the potential effects of different emission reduction strategies, or to make air quality forecasts. Air quality models in common use include:

- California/Carnegie Institute of Technology (CIT) Model,[251] which was developed and applied in the SoCab[252] and the MCMA.[253] This model uses the SAPRC99 photochemical transformation mechanism[254] or the CalTech Atmospheric Mechanism.[255]
- MODELS-3/CMAQ Model,[256] the U.S. EPA model, which has been widely adopted within the modeling community in the United States. It is able to run the CB-IV,[257] RADM2,[258] and SAPRC99 chemical mechanisms, and uses a known-local vertical diffusion scheme that has the ability to handle convective cells.[259]

- CAMx Model,[260] based on the earlier Urban Airshed Model (UAM)[261-263] which has also been widely used in California and more recently in Houston, TX.
- Multiscale Coupled MM5/Chemistry Model/Weather Research and Forecast with Chemistry Model (MCCM, WRF-Chem),[264] which links the Fifth-Generation NCAR/Penn State Mesoscale (MM5) meteorological model[265] and atmospheric chemistry models. This work is being continued with the development of WRF-Chem, placing the RADM2 chemical mechanism in-line with the WRF model.

Advanced air quality models contain modules for inorganic and organic aerosols using modal and sectional representations for particle size. For inorganic aerosols, the ISORROPIA equilibrium module[266] is used by CMAQ and CAMx models. The CIT model includes the SCAPE2 models[267] and WRF-Chem uses the MADE equilibrium module.[268] Secondary organic aerosol models also differ for the CIT[255] and CAMx[269] models, while CMAQ and WRF-Chem models use the formulation of Schell et al.[270]

A Master Chemical Mechanism (MCM) is being constructed using a large set of kinetics and product data for the elementary reaction steps of the VOC oxidation process.[271, 272] The process of aromatic HC oxidation is becoming better understood,[273-278] leading to MCM updates that have been evaluated against simulation chamber measurements.[279-281]

The MM5[282, 283] and CALMET[284] meteorological models generate three-dimensional wind fields from basic physics and from observations. CALMET is best suited to areas without complex terrain and with dense meteorological measurement networks. For complex flows, e.g., in mountainous terrain or coastal areas, CALMET can be used as a filter to merge the results of prognostic models such as MM5 or RAMS[285] with available observations or as an interface between prognostic and air quality models. Martilli et al.[286] proposed an improved parameterization for urban surfaces, which is especially important in megacities, to take into account radiation trapping and shadowing along with turbulence effects based on simplified building geometries. MM5 is now in its last major release and will be replaced by WRF-Chem.[287] In this model, photolysis rates are calculated on the basis of the UV radiation scheme of Madronich,[288] which accounts for effects of albedo, haze, total column ozone, and aerosol optical depth.[289]

EMISSION CONTROL STRATEGIES

In the higher income cities and megacities of North America, Europe and Japan (with a high demand for good air quality), there has been a three to four-decade long experimentation and development of air pollution abatement experience. On the other hand in the lower income megacities of Asia and other developing nations, the demand for pollution abatement is emerging and accompanied by more limited resources.[290-292] Therefore, the design of air quality management strategies must be preceded by a careful analysis of the social, economic and institutional circumstances in these cities and what policy challenges and opportunities this context offers.

As mentioned above, transportation is a major source of air pollution in many cities. Technical factors pertaining to engine characteristics, vehicle age, fuel type used, and maintenance patterns of transport vehicles contribute to the level of emissions for a given level of transport demand.

The major challenge for air pollution control policy is the exploding demand for private automobile ownership and VKT in the megacities with rising incomes. The combination of increasing VKT, limited road space and consequent congestion leads to a vicious cycle of ever worsening air pollution. Policies of transportation and pollution control typically developed in this context emphasize road expansion, parking and other auto friendly initiatives, which frequently induce further traffic growth and pollution, defeating such policies in short order.[293]

The growth in private automobile ownerships decreases the level of resources available and works against the development of adequate urban public transportation systems that are crucial to the mobility of the low- and moderate-income residents in these cities. In some cases, public transportation systems are weakened further by policies instituting fare subsidy that prevent the recovery of operating and capital costs of transit service, which in turn leads to deteriorating public transit, worsening service and safety, decreasing public transit patronage, and further downward spiraling service. For example, the metro fare is heavily subsidized in Mexico City and covers less than 50% of the operating cost.[40]

A second major challenge is the excessive age of some of the vehicle fleet, especially the diesel-powered freight transport and urban buses, many lack even basic pollution controls. Another challenge is the quality of fuel used. Improvements in fuel to lower sulfur content and other changes can have an important effect on air quality, even with no reduction in vehicle miles traveled. The final challenge for the industrializing megacities is the limited availability of the technical and analytical skills necessary for developing effective pollution reduction policies, and the institutional capacity to implement such policies.

If the policy challenges noted above are typical of the early stages of development and use of pollution abatement policy in developing megacities, a number of policy opportunities also exist in this situation. First, while private automobile ownership and usage are growing rapidly in these cities, the levels of penetration of car use are still relatively low compared to the levels in megacities in rich countries. There are still opportunities for designing and implementing effective pricing mechanisms in these megacities to reduce the demand for motorized trips.[40]

To create a sustainable system encompassing the requirements for transportation, mobility, and a healthy environment for the megacities would require a combination of policies that ‘get the right prices’ for vehicles and, complementary land use and transport policies can help these megacities to develop effective pollution reduction strategies.

There is a wide range of ways in which the same strategies can be implemented, but they can be classified into three major categories: 1) technology-based regulatory mandates on processes, fuels, and emission treatment; 2) economic instruments such as incentives, emission taxes, road pricing, and emission trading; and 3) policy adaptation such as land-use planning, infrastructure development, and transport management.

Regulatory controls include emission limits imposed on industry and vehicles. These usually are based on technological limitations such as Maximum Available Control Technology

(MACT) for new emitters or Best Available Retrofit Technology (BART) for existing sources. Lloyd and Cackette[294] note that regulated emission limits often spur technological development, especially with respect to vehicle emissions. Economic instruments apply the power of the market to encourage use of cleaner technology and fuels, and are often based on the "polluter pays" concept.

Infrastructure modification can be applied to mobile and stationary sources. Road works and land use planning can reduce emissions from mobile sources, such as the building of ring-roads around heavily congested and polluted areas and the development of public transport to reduce vehicle usage. Large stationary emission sources can be moved out of the urban area, as has been done in Los Angeles and Mexico City.[4] Policy instruments can be used to reduce exposure to pollutants, e.g., by encouraging investment in industries or their relocation away from residential areas.

The most effective air quality management strategies use a combination of these approaches together with public outreach programs, and enforcement through persuasion and incentives, to produce an equitable and appropriate reduction in emissions.

Technology-Based Regulations

Administrative and legislative frameworks are needed to ensure adherence to regulatory emission controls. Monitoring, reporting and auditing programs for effective control of sources often require considerable technical, human, and financial resources. Legislation enabling effective penalties to discourage violation of emission limits is essential. Cost analysis ensures that appropriate measures are taken so that the costs of establishing, carrying out, and enforcing the regulations are not disproportionate to their benefit. Cost analysis can also help to choose among alternative emission reduction strategies or to determine when making a strategy more stringent is no longer beneficial.

A U.S. National Research Council (NRC)[295] panel recommended that regulatory agencies target groups of pollutants coming from the same sources rather than focus on single pollutants. Since air pollutants are transported from state to state and across international borders without regard for political boundaries, the study recommends that future regulations need to reach beyond individual cities, counties, and states. For megacities, this should apply as well to sovereign nations. The NRC panel noted that regulations for new cars and light trucks have greatly reduced vehicle emissions, but less progress has been made in the United States in reducing emissions from older heavy-duty diesel trucks, non-road vehicles, and faulty automobiles. Although regulations governing new power plants and large factories have led to substantial reductions in emissions, many older "grandfathered" plants remain large sources of pollution. The study recommended that more emphasis be placed on measurable results than on the process of creating implementation plans. Improved tracking of emissions is needed to accurately assess which populations are at the highest risk of health problems from pollution and also to better measure the success of pollution-control strategies.

Over the last 30 years there have been radical improvements to fuels and technologies, which have contributed to a reduction in air pollution. However, there are significant constraints on what improvements to fuels and technologies alone can deliver. In many megacities, reductions in per-vehicle emission levels have been offset by increases in the numbers of vehicles and greater use of the same vehicle. For this reason, motor vehicle emissions must be a major focus of regulation in every megacity. Fortunately, transportation technology is rapidly advancing, and megacities in developing countries may be in a position to leapfrog older technologies.

Hybrid Vehicles. California required that 2% of vehicle sales had to be zero-emission vehicles (ZEVs) by 1998. It was believed that battery-powered electric vehicles would meet the need, but available batteries limited their range to barely 100 km and the vehicles did not sell. However, electric vehicle research created the technology for using smaller batteries that could be continuously recharged by a small gasoline-powered generator. These hybrid gasoline-electric vehicles have been shown to be near-ZEV, efficient, and popular. At low speeds, where internal combustion engines are least efficient and most polluting, the hybrid drives the wheels with an electric motor. At higher speeds, where an electric motor lacks sufficient power, a small internal combustion gasoline engine provides an assist. The engine can directly spin the wheels or spin a generator to provide electricity. The Toyota Prius, which uses both a gasoline engine and an electric motor for propulsion, averages 23.2 km per liter (88 miles per gallon)—about double the mileage of a comparable gasoline car. Within a decade, the gas-electric combination could be offered in every category of vehicle the automaker sells, from subcompacts to heavy-duty pickup trucks.[296] Although hybrid vehicle purchase costs are higher than a comparable non-hybrid, the additional cost is recovered over time from fuel-cost savings. However, an additional expense may occur, possibly when the hybrid is owned by the second or third owner, when the battery needs replacement. Currently batteries are warranteed for 100,000 miles, and the replacement cost should be on the order of replacing a transmission.

Toyota is marketing its hybrid vehicles to the Mexican government and is testing the Prius to learn how to adapt its performance to Mexico City's driving conditions.[297] The Chinese government is also imposing strict emission and fuel economy standards to encourage automakers to introduce hybrid vehicles in its urban areas.

Fuel Cell Vehicles. Fuel cells are generating excitement as clean alternatives for powering automobiles, but the environmental benefits of shifting to a hydrogen-based economy are uncertain at present.[298] Hydrogen (H_2)-powered fuel cell vehicles reduce transportation pollution because the combustion of O_2 and H_2 creates only water vapor as an emission product. Although the H_2 may have been produced from a fossil fuel, the fossil fuel conversion process would most likely be at a central facility where emission controls are more easily applied, and at a lower cost than that of individual vehicle controls. H_2 can also be produced by electrolysis of water with energy from solar- or wind-powered generators, and this would provide substantial global CO_2 emission reductions in addition to the NO_x, VOC, and $PM_{2.5}$ reductions that affect urban and regional environments. One out of 14 vehicles in Japan may use fuel cells by 2020. In the United States, the President's Hydrogen Fuel Initiative forecasts H_2 fuel cell vehicles will enter the commercial mass market in 2020.[299] However, DeCicco et al.[300] believe current market or regulatory forces are not sufficient to result in fuel cells supplanting conventional vehicles in the United States and that other technologies will be needed to address transportation energy and pollution problems over the next two decades. In addition to developing the vehicle itself, H_2-powered vehicles will need a new fuel infrastructure.

A fuel cell can convert H_2 into electric energy much more efficiently than internal combustion engines can convert gasoline into mechanical energy. However, a fossil fuel well-to-wheels analysis of the energy efficiency of fuel generation to energy delivered does not see H_2 fuel cell vehicles as a way to reduce CO_2 emissions in the next 20 years, especially compared to more technologically demonstrated options. Improving mainstream gasoline and diesel engines and transmissions, and expanding the use of hybrids, will better reduce CO_2 emissions until non-fossil means for generating H_2 become cost effective.[301]

Hydrogen-Powered Internal-Combustion Engine (ICE) and Hybrid Vehicles. While automakers are advancing fuel cell vehicle technologies, the SCAQMD is developing H_2 refueling technologies. This is viewed as a bridging technology that will provide an incentive to develop H_2 storage and fueling technologies. The H_2 internal combustion engine vehicle project will convert 35 Toyota Prius hybrids to run on H_2 instead of gasoline, as well as compare different fueling strategies and H_2 production methods. The SCAQMD is co-sharing the project cost with a number of industries. The Toyota Prius was selected for this demonstration project due to its advanced hybrid technology. H_2 will be provided for these vehicles through a variety of methods, but mostly through electrolysis, which uses electricity and water. If the electricity were from nuclear power, no CO_2 emissions would be created. If the electricity were generated from renewable power sources, e.g., wind and solar, then there are no pollutant emissions. Whether this can ultimately be done cost-effectively is not yet known. Although use of renewables is currently an expensive strategy, the SCAQMD intends to demonstrate various electrolysis processes to advance the technology, improve competition, gain experience, and, therefore, reduce the costs to accelerate commercialization.[302]

Ultra-Low Sulfur Fuels. Ultra-low sulfur fuels (S <10 to 15 ppmw) enable much better emission control technology and result in less pollution from existing vehicles. Ultra-low sulfur diesel fuel allows the use of diesel particulate filters and NO_x traps.[294, 303] Greater benefits and cost-effectiveness are achieved by one major decrease in sulfur content than are obtained by incremental reductions over a period of years.[304] Human health and environmental benefits due to sulfur reduction exceed costs by a factor of 10.[305] However, the natural tendency of governments is to proceed in several steps because financing the required oil refinery upgrades is costly.

Alternative Fuels. LPG (a mixture of propane and butane) and CNG (methane) are replacing gasoline and diesel fuel in some megacities. Hong Kong converted its entire taxi fleet from diesel to CNG. São Paulo, Brazil, uses ethanol that has a higher O_2 content than gasoline. LPG and CNG reduce emissions when they replace low-grade liquid fuels in unsophisticated vehicles. The International Association for Natural Gas Vehicles shows that Euro III buses using low-sulfur diesel fuel with continuously regenerating particulate traps emit low PM, but emissions are still higher than those from CNG-fueled buses, even when the CNG buses have oxidation or three-way catalysts. Emissions of aldehydes and mutagenicity were less for the buses using CNG. Carcinogenic PAHs in CNG emissions were not detected.[306]

CNG fueling also mitigates against adulteration with a cheaper fuel. This was a factor in the replacement of diesel with CNG buses in Delhi, since the diesel fuel was frequently blended with less expensive, and much more polluting, kerosene sold for home cooking. Brazil uses more ethanol as automotive fuel than other countries due to a subsidy for ethanol produced from sugar cane. Although ethanol has no sulfur and low PM and PAH emissions, it results in higher ambient concentrations of alcohols and aldehydes.[307]

Economic Instruments

Regulations take a "command-and-control" approach to emission reductions. Market-based programs are an alternative to command-and-control regulations[308, 309] that allow a broad mix of emission reduction options to be exercised among a group of emitters. These include emission trading and congestion pricing.

Emission Trading. Emission trading has been most widely applied to reducing U.S. utility SO_2 emissions and is gaining favor for global CO_2 trading. A group of sources emitting into an airshed may be able to reduce overall emissions more cost-effectively by applying stringent controls to a few facilities, and less stringent controls to others. This is best accomplished by setting an emission cap for a region and allocating allowances to the sources within that region. The allowances can be sold by sources that emit less than their allowances to those that emit more. The price of each allowance will depend on the cost of control and the overall emission cap. A source that installs high-efficiency pollution controls has excess credits to sell that can offset the cost of control. In some cases, emission reduction targets may be best met by changing the process or by fuel switching. Successful emission trading includes the following requirements: 1) emissions are not a local health risk, 2) tradable emissions are measured accurately and measurements can be audited, and 3) administrative costs of operating the trading program are not excessive (in comparison to the cost of administering a command-and-control program).

There are two basic kinds of international markets for GHG emission trading. In a "formal" emission trading market (sometimes called "cap and trade"), an international agreement sets a cap on aggregate emissions for a period of time and allocates GHG emission allowances among the participating countries for that period. The national governments then allocate these allowances to businesses within their countries. Emitters must hold allowances to cover every unit they emit; they can control emissions, buy additional allowances if their abatement costs are high, or sell allowances if their abatement costs are low.

In an "informal" market, an international agreement sets aggregate and national caps on emissions but does not allocate formal allowances. Each country may meet its cap through contracts for "abatement services" obtained both within and outside its territory. Emitters seeking to invest in abatement services may do so in their home country, and they may also purchase "credits" for emission reductions generated in other countries, including those not subject to an overall emission cap.[310]

The SoCAB has established SO_2 and NO_x credits under its REgional CLean Air Incentives Market (RECLAIM) program, which replaces certain command-and-control regulations with market incentives for facilities that meet the inclusion criteria. RECLAIM included 335 facilities at the end of the 2000 compliance year. More than U.S. $650 million in RECLAIM Trading Credits (RTC) have been traded since the adoption of RECLAIM, of which more than $48 million occurred in 2002. The annual average prices for SO_2 and NO_x RTCs during 2002 were below the backstop price of $15,000 per ton.[311]

Emission reduction credits may be pegged at less than one-to-one; the emissions traded are required to be more than the credit received. This further reduces emissions with every trade. Emission caps may decrease over time to take advantage of (or even force) improvements in emission reduction technology. Allowances may also be purchased by environmental advocates and permanently retired, thereby effectively limiting the upper limit on overall emissions.

Congestion Pricing. As of February 2003, London has implemented a program that charges drivers each time they enter the central city, similar to the toll charged at major bridge crossings. A 22 km^2 area, 1.2% of greater London, is subject to the charge. This congestion zone was always crowded with traffic and is also surrounded by perimeter roads that serve as its boundaries. Charges for individual vehicle registrations can be paid weekly, monthly, or annually. The charge is enforced by fixed and mobile cameras that are linked to automatic license plate number recognition technology. If no record of the £5 charge is paid by midnight, an £80 penalty is assessed against the vehicle owner. Persistent evaders are booted or towed. Exemptions and discounts (average 6,000 per day) are provided for military vehicles, emergency services, taxis and licensed minicabs, disabled persons, buses, some alternative-fuel vehicles, and some health service workers. There is also a 90% discount for residents of the congestion zone.

For the first six-months, passenger vehicle traffic decreased by 20% while bus usage increased by 14% during the peak traffic hours. Bus delays due to traffic congestion decreased, and bus speeds increased, as did bus reliability measured in waiting time. There is a concern about negative financial impact on the local retail sector and on wider economic activity.[312]

For congestion pricing to be successful, the public needs to support the program. Extended studies and communications between city officials and the public were made to achieve this in London. Revenues are used only to reduce congestion and to improve public roads and transportation. Payments can be adjusted if congestion levels change, since the purpose of the congestion charge is to elicit a behavioral response from the motoring public.

The cost of congestion is estimated as the cost of the fuel wasted by driving in a less efficient way, and by the time lost, compared to free-flowing traffic. It is estimated that drivers wasted 21.6 billion liters of fuel, or ~60 liters per person per year, in the 75 areas studied by the Texas Transportation Institute.[313] Annually, 3.5 billion hours of extra travel time are caused by traffic congestion. The total cost of congestion has risen to nearly U.S. $70 billion a year, which is $4.5 billion more than for the previous year. Santos[314] provides a different approach that gives lower estimates of marginal congestion costs for different types of roads in the United Kingdom.

Policy Implementation

Urban policy making is a complicated process that is influenced more by political and sociological factors than by scientific knowledge. Good urban planning is needed to improve megacity air quality by encouraging people to live closer to where they work, developing cost-effective and convenient mass transit networks, creating economic activities outside of megacities to reduce migration incentives, and strategically locating industries. Owing to the limited terms of many politicians and the lack of public awareness of the benefits, much of this policy is left to chance rather than to careful planning.

AIR QUALITY AND MANAGEMENT PROGRAMS OF THE NINE CASE STUDY CITIES

The air pollution problems of megacities differ greatly and are influenced by a number of factors, including topographical and meteorological conditions, mobility and transportation patterns, fuel quality and usage, and the level and rate of industrialization, the political attitude towards emission control and the financial resources available. The concentration and composition of pollution within cities and between cities therefore varies considerably.

The nature of air pollution depends on the source profile of the cities; however, unfavorable topographical and meteorological conditions result in poor dispersion of pollutants and exacerbate their adverse impacts. Some metropolitan areas such as Mexico City, Los Angeles and Santiago are located in basins where air pollutants tend to get trapped because of poor ventilation. In addition, low altitute thermal inversions often contribute to the accumulation of pollutants. In the normal troposphere, temperature decreases with altitude; warm air close to the Earth's surface rises and is replaced by cooler air from a higher elevation. This results in efficient vertical mixing within this lowest layer. However, in certain geographical areas and at certain times the temperature of the air may start to rise with increasing altitude before reversing itself again, giving rise to an "inversion layer"—a layer of warmer air above colder, denser air. The formation of low altitude thermal inversions limits vertical mixing by trapping the pollutants below the inversion layer, resulting in high ground-level concentrations of pollutants emitted at the surface.

In the 1990s, as a result of stringent regulations and the availability of new technologies, some of the cities have cleaned up the air significantly. However, in some of the cities, especially in the newly industrialized nations, the air pollution problems have worsened due to population growth, uncontrolled urban expansion, unsustained economic growth, increased energy consumption and increased motorization.

Increased concern about the effects of air pollution has resulted in a greater emphasis being placed on air quality management by many local and national governments and international agencies such as the United Nations Environment Program (UNEP) and the World Health Organization (WHO).

The following sections describe the air quality problems, the associated science, the air quality management capabilities and strategies of the nine case study megacities, with major emphasis on the metropolitan areas of Los Angeles and Mexico City. Due to the large scope, only a few selected measures and the consequences are discussed. Some strategies taken by other megacities not included in the case studies are also presented, due to their innovation and potential for reducing air pollution. Finally some of the barriers in implementing air quality management programs are discussed.

LOS ANGELES METROPOLITAN AREA, USA

Population, Topography, and Meteorology

The Los Angeles metropolitan area—which includes the City of Los Angeles and consists of five counties: Los Angeles, San Bernardino, Riverside, Ventura and Orange counties—is the second most populated urban area in the United States, after the New York Metropolitan Area. The multi-county South Coast Air Basin (SoCAB) is bordered by mountains on the east and north, and by the Pacific Ocean on the west and south. The area of the basin is ~17,500 km^2 with a population of 16 million [see Figure 3]. During summer, the SoCAB is often under the influence of a large-scale subsidence inversion that traps a layer of cool marine air. Pollutants emitted from various sources are pushed inland during the day by an on-shore breeze. Approximately 10 million gasoline vehicles and 250,000 diesel vehicles travel in the SoCAB, which (in conjunction with other emitters) results in poor air quality.[302]

Air Quality in the Los Angeles Metropolitan Area

The air quality in the Los Angeles Air Basin has improved over the last 50 years, despite the very large increase in population and motor vehicles. Figures 4 and 5 show the peak ozone and particulate trends for the past two decades.[315]

The peak ozone level has decreased from 500 ppb in 1980 to less than 200 ppb in 2000 and the number of days above O_3 standard has declined since 1975 (see Figure 6). However, O_3 concentrations have recently leveled and may even be increasing as a result of population growth, additional vehicle kilometers traveled, and increased sales of low-economy sport utility vehicles.[302] PM_{10} has also decreased significantly over the last decade. Similarly, CO concentrations have been reduced. Nevertheless, federal and/or state standards were exceeded during 2002 at one or more monitors for PM_{10}, $PM_{2.5}$, O_3, NO_2, and CO, particularly in the spring and summer.[7]

Table 5 shows the emission inventory for the South Coast Air Quality Management District.[7] As other emissions are controlled, non-road emissions of $PM_{2.5}$ are exceeding on-road emissions. Dust from paved and unpaved roads is also a large emission source. On-road motor vehicles are the largest source of reactive organic gases, while solvent evaporation, an area-wide source, accounts for 20% of the total. NOx emissions are dominated by mobile source emissions because Los Angeles has moved some large stationary sources out of the Basin and requires stringent controls on those that remain.

Air Quality Management Programs in the South Coast Air Basin

Since smog was first detected in Los Angeles in 1943, California air quality management authorities, together with air pollution scientists, have pioneered ways to fight air pollution. California’s regulations have often forced technological innovation resulting in improved emission reductions. In most cases, from cleaner fuel to catalytic converters, the U.S. has followed California's lead. In this section, we discuss air quality management in California and how the state reduced air pollution in the Los Angeles metropolitan area over the past 30 years.

The way the Los Angeles metropolitan area has coped with the problem is a remarkable success story with useful information for the megacities of the 21st century.

The program and regulations adopted by the Los Angeles City government were driven by public concern for the deterioration in air quality. From the beginning, social factors as well as science and technology played major roles in regulatory efforts.

The California Air Resources Board (CARB), created in 1967, oversees all air pollution control efforts in the state to attain and maintain health-based air quality standards, and it is responsible for the control of air pollution from motor vehicle and consumer products, including the identification and control of toxic air contaminants. In 1969, the First California Ambient Air Quality Standards were established. California is the only state that has the power to set standards for vehicles different from those set by the U.S. EPA, as long as the standards set by California are at least as strict as the federal standards.

The South Coast Air Quality Management District (SCAQMD) is the regulatory agency in charge of the South Coast Air Basin, which consists of the majority of Los Angeles, Orange, San Bernardino, and Riverside counties, covering more than 11,000 square miles, many municipal governments, and serving about 16 million people. The Board was authorized to develop stationary source regulations and to set fines for violators. Thus, the biggest polluters pay the most toward funding the air pollution control effort. Also, businesses must pay annual fees for their operating permits.

However, since motor vehicles account for more than half of this region's pollution problem, beginning in 1991, a surcharge was added to the vehicle registration fee. Part of the surcharge goes to the SCAQMD to be used for air quality improvements involving mobile sources such as those promoting ridesharing, developing clean fuels, and as grants for programs intended to reduce vehicle emissions.

Air Quality Management Programs in the South Coast Air Basin Prior to 1970

During the 1940s and 1950s, air pollution control focused on obvious sources such as backyard burning and incinerators, open burning at garbage dumps, and smoke emissions from factories.[316] In 1953, the Los Angeles County Air Pollution Control District started requiring controls to reduce hydrocarbon emissions from industrial gasoline storage tanks, gasoline tank trucks, and underground storage tanks at service stations.

During the 1950s and 1960s, Southern California air quality officials implemented the use of vapor recovery equipment for the bulk transfer of gasoline, regulated petroleum-based solvents, and required permits for rendering plants that process animal waste. Air quality regulations significantly reduced those emissions, but the Los Angeles Air Basin's peak ozone levels remained extremely high, more than four times the current health standard. The rapid growth in automobiles as a result of increased urbanization and the design of the Los Angeles urban area was a major cause of the continuing smog problem.

Control Strategies for the South Coast Air Basin (1970-present)

Passage of the 1990 Amendments to the Federal Clean Air Act initiated a planning cycle for a new State Implementation Plan (SIP), which was submitted by CARB in 1994 and approved by EPA in 1996. From 1970 to 1990, the SIP planning activity and commitments led to the development by California state and local agencies for a wide variety of programs to reduce emissions. The following are some key control programs and measures developed and implemented by the Air Resources Board. The information was obtained from the CARB and SCAQMD websites:[317, 318]

Motor Vehicle Pollution Control.

In 1959, the California Legislation established the California Motor Vehicle Pollution Control Board to test emissions and certify emission control devices. In 1961, the first automotive emissions control technology in the US, Positive Crankcase Ventilation (PCV), was mandated by California to control hydrocarbon crankcase emissions. In 1966, California imposed initial regulations for automobile tailpipe emissions for hydrocarbons and carbon monoxide the first of their kind in the US. The California Highway Patrol began random roadside inspections of vehicle smog control devices.

In 1975, the first oxidizing catalytic converters to reduce carbon monoxide and hydrocarbon tailpipe emissions came into use as part of CARB's Motor Vehicle Emission Control Program. This is the state's first example of "technology-forcing" regulations, compelling industry to develop a new pollution control capability by a set deadline. In 1977, the first three-way catalytic converter to control hydrocarbons, nitrogen oxides, and carbon monoxide was introduced. During the late 1970s, Los Angeles and later the entire state required vehicle inspections for measuring emissions and inspecting emission control equipment which in 1984 evolved into California SmogCheck Program administered by the state Bureau of Automotive Repair (BAR).

In 1988, CARB adopted regulations effective on 1994 model cars requiring that they be equipped with on-board diagnostic (OBD) computer systems to monitor emission performance and emission control equipment. Owners are alerted when there is a problem. All 1996 and newer vehicles less than 14,000 lbs. (e.g., passenger cars, pickup trucks, sport utility vehicles) throughout the United States are equipped with OBD II systems, the second generation of OBD requirements.

In 1990, CARB approved standards for Cleaner Burning Fuels resulting in gasoline composition changes that reduced vehicle emissions and enabled advances in catalytic converter technology. In 1999, the Board amended and adopted Low-Emission Vehicle regulations, known as LEVII, which set stringent emission standards for most mini vans, pickup trucks, and sport utility vehicles (SUVs) to reduce emissions of these vehicles to the level of emissions from passenger cars by 2007.

In 1998, CARB identified diesel particulate emissions as a toxic air contaminant. This led to the development of the Diesel Risk Reduction Plan in 2000. One of the key elements is to retrofit existing diesel engines in California to reduce diesel particulate emissions to near zero in the shortest time possible. The program focuses on several control options such as low sulfur diesel fuel together with catalyst-based diesel particulate filters or traps and other viable alternative technologies and fuels.

Fuel Control.

In the 1960s, regulators took the first step to clean up motor vehicle fuels by reducing the amount of highly photochemically reactive olefins in gasoline. Starting in 1970, the federal government phased out lead in gasoline.

CARB has pioneered a motor fuels specification enforcement program since 1977 in response to adoption of a state Reid Vapor Pressure (RVP) standard. Other regulations were adapted to further control the chemical properties of gasoline by limiting the lead, sulfur, phosphorus, manganese, as well as the sulfur content of vehicular diesel fuel in Southern California.

In 1991, California Phase I Reformulated Gasoline regulations were adopted; this was followed by the introduction of Phase II Reformulated Gasoline (also known as Cleaner Burning Gasoline, CBG) in 1996. The emission reductions are accomplished by lowering previously regulated components (RVP and sulfur); requiring the use of oxygenates year round; and regulating additional components (benzene, total aromatics, olefins). In addition to reducing smog, the use of CBG also reduces the cancer risk from certain pollutants in vehicle emissions by more than one third.

Clean Fuels and Vehicles.

In 1990, CARB adopted a landmark regulation targeting both motor vehicles and fuels. The agency launched its Low Emission/Zero Emission Vehicle program, requiring auto makers to develop much cleaner cars, culminating with the mandate for an electric, zero-emission vehicle by 1998. However, the mandate was delayed until 2003 to allow automakers sufficient time to improve battery technology. In this case, the technology-forcing regulation could not drive battery technology to improve so that battery powered ZEVs could have sufficient range to be marketable in California. What the regulation did was to cause technology to be generated which enabled the gasoline-electric hybrid vehicle. In 2003, as a result of complaints from automakers, California regulators altered the ZEV mandate to include hybrids vehicles as well as hydrogen vehicles of the future.

Consumer Products.

In 1998, CARB amended off-road engine regulations for lawn mowers, weed trimmers, and other small engine power tools and in 1999, adopted a new regulation that reduces by over 70% the smog-forming emissions from portable gas cans. Consumer products rules were adopted to cut smog-forming emissions and volatile organic compounds (VOC) from an estimated 2,500 common household products ranging from nail polish removers to glass cleaners.

As mentioned above, the SCAQMD regulates the emissions from stationary sources; however, since about 80% of smog-forming emissions come from mobile sources, the SCAQMD is also using three main tools to reduce vehicle emissions to achieve the emissions reductions needed to bring the region into compliance with federal air quality standards by 2010:

(1) Regulation: The SCAQMD has been authorized by the state to require fleets to purchase the cleanest available technology when replacing a vehicle. Since the rules rely on fleet turnover, the reductions realized are mid-term to long-term as vehicles are replaced. Despite their effectiveness, engine manufacturers and the oil industry challenged these SCAQMD "Fleet Rules" and the US Supreme Court ruled in favor of the Engine Manufacturers Association in April 2004.

(2) Technology advancement: In 1988, the SCAQMD established its Technology Advancement Office to help private industry speed up the development of low- and zero-emission technologies. These include: fuel cells, electric vehicles, zero-VOC paints and solvents, remote sensing, and alternative fuel heavy-duty vehicles and locomotives.

The SCAQMD's technology advancement projects focus on real-world demonstrations of clean air technologies with the potential for commercialization. The agency has funded several clean air technology research, development, and demonstration (RD&D) projects over the years, including advanced engine development, engine after-control, electric hybrid vehicles, fuel cell vehicles and hydrogen infrastructure, VOC and toxic emission reduction, stationary power combustion processes, and clean fuel alternatives. These RD&D projects helped drive the market by improving and optimizing the technology, increasing manufacturer competition, and reducing costs of the eventual commercial product.

One of the current projects involved developing hydrogen-fueled vehicles. These could either be fuel cell vehicles or internal combustion vehicles powered by hydrogen. Hydrogen powered vehicles would only produce water "tailpipe" emissions. The emissions produced while producing hydrogen would depend on the method of hydrogen formation. However, these emissions could be produced outside of the Los Angeles Basin, just as much of the electric power consumed in Los Angeles is imported from outside the Basin.

(3) Incentive: The SCAQMD is providing funding to offset the typically higher prices associated with alternative vehicles and fuels. A good example of this type of mechanism is the Carl Moyer Incentive Program. For the past several years, the state of California has provided funding administered by the SCAQMD to pay the differential amount for the purchase and operation of cleaner heavy-duty vehicles and off-road equipment. To date, the SCAQMD has used $55 million in state funding to replace 2,600 vehicles and engines, this result in the reduction of NOx emissions by over 2,400 tons per year. The SCAQMD is working closely with businesses and environmental interests to establish a long-term funding mechanism for the Carl Moyer Program through state legislation.

Another incentive program funded solely by the SCAQMD has helped local school districts purchase 300 clean fuel or low emission school buses and install particulate traps on 1,300 school buses. This program, however, is dependent on available funds through the SCAQMD's enforcement activities and so is subject to annual budget priorities.

In 1993, the SCAQMD adopted the Regional Clean Air Incentives Market (RECLAIM) Program, which imposes an overall emissions limit on each of the region's larger emission producing facilities. The limit declines each year, so that by 2003, these facilities will have reduced their emissions by 35 tons/day of nitrogen oxides emissions and 8 tons/day of sulfur oxides. Businesses are free to reduce emissions any way they wish, giving them the flexibility to choose the most cost-effective method. If a facility reduces its emissions below its limit in a given year, it earns RECLAIM trading credits that can be sold to a facility unable or unwilling to meet its target that year. As of early 1997, more than $30 million in credits had been sold and the emission reduction targets were being met.

The SCAQMD is expanding its market incentive programs to include area-wide pollution sources, such as home hot water heaters. It is also developing a broader trading program that will further enhance the efficiency and cost-effectiveness of emissions trading. CARB has incentive plans to introduce cleaner heavy-duty diesel vehicles and to accelerate automobile fleet turnover to increase the population of low emission vehicles sooner. In 2000 California introduced programs to subsidize scrapping certain light-duty vehicles and repair certain vehicles that failed the emissions inspection program.

MEXICO CITY METROPOLITAN AREA, MEXICO

Population, Topography, and Meteorology

The MCMA lies in an elevated basin at an altitude of 2240 m above the mean sea level (MSL). The nearly flat basin covers about 5000 km^2 of the Mexican Plateau and is confined on three sides (east, south, and west) by mountain ridges, with a broad opening to the north and a narrower gap to the south-southwest. The surrounding ridges vary in elevation, with several peaks reaching nearly 4000 m, but the air basin is between 800–1000 m deep. Two major volcanoes, Popocatépetl (5452 m) and Ixtaccíhuatl (5284 m), are on the mountain ridge southeast of the basin. The metropolitan area is on the southwest side of the basin and covers about 1500 km^2.[319]

During the twentieth century, the urban area and demographics of the MCMA have undergone massive transformations. The MCMA attracted migrants from other parts of the country due to fast economic growth as the nation began to industrialize. The population grew rapidly, from 3 million in 1950 to 18 million in 2000, and occupying land increasingly far from the historic center. In the last half-century alone, the urbanized area of the region has increased by 13 times, from just 118 km^2 in 1940 to almost 1500 km^2 in 1995. The expansion pushed the city beyond the Federal District and into other municipalities of the State of Mexico, as well as into some parts of the State of Hidalgo.[4] Current and projected population growth stresses the urban environmental balance.[320-322] The MCMA population density of 12,200 inhabitants/km^2 in 2000 is among the largest in the world, but it is exceeded, for example, by the Asian cities of Mumbai, Kolcata, and Hong Kong.[323] Densities have also fluctuated in response to the sporadic efforts of the State of Mexico to control irregular settlement expansion.[323] Population growth has generated extraordinary demand for transportation, health services, and housing.[319]

Currently, the MCMA includes four geographic elements. First, the historical "inner city" or downtown area known as the *Ciudad de México* or the "City of Mexico" includes four delegations. Second, the Federal District (*Distrito Federal* or DF) includes the four "City of Mexico" delegations and twelve others. The DF is the site of the national government and is the financial, commercial, and service center of the region. Third, the MCMA is comprised of the 16 delegations of the DF and 37 major urbanized municipalities from the State of Mexico and one from the State of Hidalgo. Finally, there is the so-called "Megalopolis" which extends beyond the MCMA to include the surrounding "corona" or "crown" of cities including Puebla, Tlaxcala, Cuernavaca, Cuautla, Pachuca, and Toluca and extending 75-150 km from the city center. Figure 7 is the topographical map of the MCMA, showing the urban expansion between 1910 – 2000.

The MCMA's 20 million inhabitants, 35,000 industries, 3.5 million vehicles, complex topography, and meteorology cause high pollution levels. The mountains, together with frequent thermal inversions, trap pollutants within the basin. The high elevation and intense sunlight also contribute to photochemical processes that create O_3 and other secondary pollutants. More than 40 million liters of fuel consumed per day produce thousands of tons of pollutants per day. Air pollution is generally worst in the winter, when rain is less common and inversions more frequent.

Owing to the high altitude, MCMA air contains ~23% less mass of oxygen (O_2) than at sea level. Consequently, internal combustion engines need to be carefully tuned to the proper O_2/fuel ratio to minimize inefficient combustion and increased emissions.[324, 325]. People at higher altitudes are more susceptible to respiratory ailments than those at sea level. More air must be inhaled for an equivalent amount of O_2 at high altitudes, which causes exposure to a higher dose of air pollutants.[326]

Air Quality in the Mexico City Metropolitan Area

High O_3 is measured throughout the year because the subtropical latitude and high altitude are conducive to photochemistry. Anticyclone high-pressure systems appear during winter, resulting in light winds above the basin and nearly cloudless skies. This leads to the formation of strong surface-based inversions at night that persist for several hours after sunrise. Strong solar heating of the ground generates turbulent mixing that erodes these inversions in the morning, producing deep boundary layers by the afternoon. Pollutants trapped below the inversion layer are then mixed within the convective boundary layer, which can reach altitudes of 4 km. There is sufficient time for O_3 formation in the morning before the development of the deep convective boundary layer because of high emission rates and intense solar radiation.

During the wet summer months (June to September), clouds inhibit photochemistry and rainfall removes many trace gases and PM; high O_3 episodes are less frequent. Near-surface northerly winds during the day may transport pollutants to the southwest, where O_3 concentrations are highest.[327] The relationship between meteorology and O_3 differs for different episodes.[328-330]

Air quality measurements for criteria pollutants are reported as IMECA units (*Indice Metropolitano de Calidad del Aire*, or Metropolitan Index of Air Quality), which are the ratio of a measured concentration to the air quality standard for each pollutant multiply by 100, therefore 100 IMECA units is equal to the air quality standard. A contingency program is triggered when the IMECA value exceeds a certain threshold, currently 240 IMECA (~280 ppb of O_3). During a contingency, the activity of polluting industries is reduced, vehicle circulation is restricted, and outdoor activities of children in primary schools are reduced.[331]

The most dramatic improvement in MCMA air quality resulted from the removal of lead from gasoline, which led to lower ambient and human blood levels. SO_2 concentrations decreased after the reduction of sulfur content in diesel and heavy oil and a legislated move away from this latter fuel. The closing of a large oil refinery also improved air quality. CO concentrations have also decreased because 3-way catalytic converters are required on all new automobiles since 1993. Inspection and maintenance of automobiles has also had an effect, although it is difficult to document.[40] Figure 8 shows downward trends for most pollutants, but PM_{10}, O_3, and NO_2 are not decreasing as rapidly as desired. The PM_{10} and O_3 standards are the ones most often exceeded in the MCMA. In the case of ozone, the standard has been violated on about 70-80% of days every year since 1988 (see Figure 6).

Emission inventories have been developed in the MCMA since 1986.[332-334] VOC to NO_x molar ratios are ~3:1 ppbC/ppbNO in the inventory, but they are 15:1 or higher in ambient air.[174] This inaccuracy is consistent with emission models that were developed in California in the early 1990s.[255, 335-337] More recent emission inventories[338-342] have been developed. Table 6 shows the emissions inventory for the year 2000 and Figure 9 shows the percentage of emissions for various species by source category. There are substantial differences in the emissions inventory reported in the different years. These can be explained partly by changes in emissions over time, but they are more likely the result of differences in emission inventory estimation methodology.[331]

Air Quality Management Programs in the MCMA

Air Quality Management in the MCMA: 1960s to mid-1980s

In the following sections, we summarize the air quality management plans developed and implemented by the Mexican authorities to illustrate how a megacity with limited resources tries to cope with severe air pollution problems. A detailed analysis of the air quality management programs and recommendations were conducted by the Integrated Program on Urban, Regional and Global Air Pollution at the request of the Mexican authority, which provided the foundation for the new 2001-2010 air quality management program.[4]

The first research paper addressing the air pollution problem in the Mexico City Metropolitan Area and its potential effects on the health of the inhabitants was published forty years ago.[343] Despite the low priority given to environmental protection in the sixties, the first air pollution measurement stations were installed, the first emissions inventories were conducted, and an attempt to start a systematic data collection of SO_2 and total suspended particles concentrations began.[344, 345]

Efforts to deal with the air pollution problems in the MCMA began in 1971 with the passage of the Federal Law for the Prevention and Control of Environmental Pollution. Air pollution was then defined solely in terms of smoke and dust. The second environmental legislation was the Federal Law of Environmental Protection introduced in 1982. The law was amended in 1984 to include an air quality monitoring system. In 1985, the National Commission on Ecology was established to define priorities in environmental matters and to coordinate the different institutions dealing with environmental actions. However, actions to prevent pollution were limited by the financial crises of the early 1980s; the 1985 earthquake in Mexico City also diverted attention and resources.

As the MCMA dealt with financial limitation and the demands to provide basic living conditions for its citizens, information about air pollution and its consequences were scarce during this period. In addition to a lack of systematic data collection, institutional factors also limited information collection and inhibited the development of control measures. The first emissions inventory was put together in the 1970s, but suffered from spotty data and little follow-up. The first MCMA air quality management program, the Coordinated Program to Improve Air Quality in the Valley of Mexico announced in 1979 to reduce vehicular and industrial emissions, was not successfully implemented.

Air Quality Management in the MCMA: Mid-1980s to 1990s

By the mid-1980s, the public became alarmed about poor air quality as pollution got worse. The new air quality monitoring network RAMA revealed high concentrations of all criteria pollutants. The ozone levels in the MCMA were dramatically increasing, reaching peaks close to 400 ppb, and had become among the worst in the world. Responding to increased public pressure, the government announced the "21 measures to control air pollution in the MCMA" in 1986, this was followed with "100 actions needed to reduce pollution" in 1987.

In 1988, the legal framework was strengthened with the new General Law of Ecological Equilibrium and Environmental Protection (*Ley General del Equilibrio Ecológico y la Protección al Ambiente* or *LGEEPA*) that defined responsibilities at federal, state, and local government levels. The Federal District (DF) and the State of Mexico (EM) were each responsible for emissions from commercial enterprises, private autos, and public transportation services in their jurisdictions, but the Federal Government retained its responsibility over industry and assisted in coordinating efforts within the fuel and energy sectors. Several important air pollution reduction measures were introduced during this period:

- The conversion of about 2000 state-owned buses to use new, lower emission engines with basic pollution control devices;
- The extension of the nonpolluting urban electric transport network (both metro and trolleys);
- The implementation of "No Driving Day" (Hoy No Circula or HNC) by the government of the Federal District in 1989 in which 20% of all private vehicles were forbidden from circulating one day a week according to their license plates numbers;
- Mandating of the vehicle inspection and maintenance in 1988;
- Development and enforcement of the first contingency plan which included vehicle circulation restriction and reduction in industrial activities on high pollution days;
- Gradual substitution of fuel oil with natural gas in the *Valle de México* power plant;

- Move some high-polluting and water-intensive industries out of the city within three years.

Air Quality Management in the MCMA: 1990-2000

By 1988, Mexico had begun to emerge from the economic crisis and again began to address the growing environmental crisis facing the MCMA. Mexico also received technical and financial support from major international agencies. The Comprehensive Program against Air Pollution in the MCMA (*Progama Integral contra la Contaminación del Aire* or PICCA). PICCA was implemented in October 1990 and lasted until 1995.[346] Major government agencies were involved in the preparation of the program. The main objectives of PICCA included eliminating lead, reducing SO_2, particulate matter, hydrocarbons, and NO_x emissions. Without the benefit of accurate emissions inventories or modeling capabilities, most strategies were based on technology modernization and fuel improvement that had been successfully implemented in other countries. These included: i) improving fuel quality used in the MCMA; ii) decreasing vehicular emissions by lowering the level of lead in gasoline, the mandatory use of catalytic converters, and enhanced inspection and maintenance programs; iii) increasing the use of natural gas by industry and power plants in the MCMA; and iv) restoring natural resources to control soil erosion. Many responsibilities that were previously held by the federal government were delegated to state and municipal governments. However, the decentralized enforcement across jurisdictional lines resulted in confusion and inefficiency. To address the lack of coordination among the responsible institutions in the MCMA for the implementation of PICCA, the Metropolitan Commission for Pollution Prevention and Control was created in 1992.

In 1996, the Program to Improve the Air Quality in the Valley of Mexico (*Programa Para Mejorar la Calidad del Aire en el Valle de México 1995-2000* or PROAIRE) was initiated to replace PICCA.[347] The objectives of PROAIRE included reducing hydrocarbons, nitrogen oxides and particle emissions, as well as modifying the overall distribution of ozone concentrations, to reduce ozone peaks and averages and increase number of days in compliance. The program also addressed the need for integration of environmental policies with those for urban development and transport. It was the first program to address health studies and epidemiological surveillance and relating particulate matters and mortality.

Policy Measures and Control Strategies in the 1990s – Present

In the decade of the nineties, important control measures were proposed and some were implemented in the MCMA. The following list the six key areas of policy measures and emissions reduction strategies:

1) Vehicle emission reduction/fuel improvement and substitution measures included:

- Tightening of emission standards for both new and in-use gasoline vehicles and new diesel vehicles (including 100% compliance with Tier I standards for model-year 1999);
- Introduction of two-way catalytic converters in new gasoline vehicles starting with model-year 1991 and three-way catalytic converters starting with model-year 1993;
- Introduction of unleaded gasoline in 1990 and complete phase-out of leaded gasoline in 1997;

- Reduction of Reid Vapor Pressure, and limits on olefins, aromatics, and benzene content in gasoline;
- Gradual reduction of sulfur content in diesel;
- Centralize and strengthen the inspection and maintenance program;
- Introduction of alternative fuels for vehicles (LPG and CNG); and
- Use “No Driving Day” as an incentive to promote fleet modernization.

2) Measures to reduce emissions from industrial and commercial sectors included:

- Shut down major refinery (“18 de Marzo” in Azcapotzalco) in 1990;
- Relocation of some large industrial plants outside the Valley;
- Substitution of heavy fuel oil with natural gas in power plants and major industrial facilities;
- Installation of emission controls in fuel storage tanks and vapor recovery systems in the gasoline distribution network;
- Establish inspection and Environmental Audit Programs;
- Promote cleaner technologies by providing fiscal incentives and tax exemptions.

3) Integration of metropolitan policies in the areas of transport and land use with air quality.

4) Ecological restoration, including rural and urban reforestation, restoration of eroded areas, control human settlement in rural areas; and fire prevention programs.

5) Initiation of environmental education and research programs.

6) Strengthening institutions with mandates for environmental protection.

Assessment of Air Quality Management Programs in the MCMA

As a result of the implementation of some of the measures described above, both ambient and blood lead levels have been substantially reduced. Similarly, levels of CO and SO_2 have dropped significantly and both are now typically below the standard. The most significant reductions in air pollution are attributable to the introduction of catalytic converters and the improvement in fuel quality, and to some extent, the implementation of stricter industrial standards and the conversion of power plants to natural gas. However, the results of some of these measures were mixed in part because not all measures were enforced. Ozone peaks have decreased substantially, but are leveling off at a point still significantly above the standard. PM_{10} also tends to exceed the standard. In 2003, the ozone standard was exceeded on about 75% of the days of the year, reaching twice the standard on a couple of days. The 24-hour PM10 standard was also violated on 32 days.

Clean fuels and vehicles. In 2000, the environmental authorities reached an agreement with the automobile industry for Mexico to reach vehicle emissions standards equivalent to the US federal regulations with a delay of no more than two years as compared with the US time frame. The automobile industry, in turn, asked the authorities and the Mexican National Petroleum Company (PEMEX) to coordinate the emission-limiting program with improvement in the quality of fuels, in particular to decrease sulfur to low levels in gasoline and diesel fuels, to enable the use of more sophisticated emission control equipment in trucks and automobiles. In recent years, the gasoline and diesel that is distributed in the MCMA met standards that are comparable with low emissions urban quality fuels in the United States and Europe. However, sulfur levels in fuels in the United States and Europe will become much lower in the next few years. Because Mexico's heavy high sulfur crude oil averages 770 ppm, achieving lower sulfur levels will be costly. It will require a significant capital investment in refining processes as well as additional production costs. Because PEMEX is a national company, investment in refining capability directly affects government income, therefore any investment plans must be approved by the Federal Finance Ministry.

In August 2003, the Mexican Ministry of the Environment (SEMARNAT), the Ministry of Energy (SENER) and PEMEX drafted an agreement Mexican Official Norm (NOM-086) to introduce Ultra Low Sulfur Fuel (ULSF). Sulfur levels for Premium gasoline are planned to be brought down to an average of 30 ppm by 2006, with 250 ppm by 2004-2005. This goal was accomplished in May 2004. For Magna (regular) gasoline in the metropolitan areas, 30 ppm are planned to be introduced starting in 2008. Reduction of sulfur in diesel is also planned nationwide to a maximum of 300 ppm in January of 2006 and 15 ppm by September of 2008. Introduction of ULSF will require 3.3 billion dollars of investment. SENER and SEMARNAT are looking for the approval from the Finance Ministry to make this investment; otherwise, ULSF will not be introduced according to the proposed schedule.[348]

Alternative fuels. In the 1990s the conversion of intensively-used vehicles to liquefied petroleum gas (LPG) with certified equipment was encouraged for both environmental and safety reasons. This measure should have had important environmental benefits in different segments of the fleet, which are appropriately organized to ensure optimal maintenance of the equipment. However, according to estimates of the Energy Ministry, 90,000 of the vehicles using LPG were not properly regulated. These vehicles are often greater polluters than gasoline vehicles, in addition to having an increased risk of accident.[65]

Environmental authorities in the State of Mexico and the DF have promoted the use of compressed natural gas (CNG). They have introduced vehicles built to run on natural gas, and converted others to do so; these vehicles are used, for example, as police patrols and trash collection trucks. The private sector participates in the installation and operation of refilling stations and the conversion to CNG of government vehicles and passenger vehicles. However, by 2000, there were only around 1200 CNG vehicles and two refilling stations in the MCMA—a very small number, with modest environmental impact. To promote the use of natural gas, investigators are developing a policy review of the relative pricing of CNG, gasoline, LPG, and diesel. Recently, the French Global Environmental Fund has authorized 1.5 million euros to support the State of Mexico in the conversion of 3,000 public transport vehicles to natural gas. Conversions are slated to begin in March of 2004.

Inspection and maintenance. Vehicle inspection lies at the core of emissions control policy for the MCMA. The previous vehicle inspection system, in which hundreds of small shops were responsible for inspection and repair, had many problems. There were about 500 test & Repair centers in the DF and another 500 in the State of México. By converting to a limited number of larger centers designated exclusively for inspection the authorities have been able to gain better control of the program. However, administrative and technical problems that limit the efficiency of the program persist. Test-only inspection station owners are competing with one another. There is an incentive to pass vehicles that should not pass in order to increase the number of clients.

The controversial "No Driving Day" program has been mandatory since November 1989. This program was designed to reduce daily traffic and was also used to reduce emissions in critical pollution episodes such as days with ozone concentration above the contingency limits. The true effectiveness of the program is still under debate. The original program restricted travel a certain day of the week based on the license plates. Some vehicle owners purchased additional older vehicles with different license plates to ensure their ability to drive on all days of the week. Since few families previously had more than one vehicle, these extra vehicles were driven on more than one day by other members of the household. The net effect of the program may have been to increase pollution and congestion.

A number of changes have been made over the years to gain benefit from the program. These include the extension of the program for public transport vehicles, the creation of the "Double No Driving Day" and the exemption of new vehicles with emission control technology. These refinements have changed "No Driving Day" from a program designed to reduce the numbers of vehicles on the streets into a system that enhances vehicle fleet turnover and modernization.

Diesel trucks are among the most polluting modes of transportation. Official 1999 figures show about 5% to be older than 30 years. Fleet renovation in this sector has been traditionally particularly slow. Many heavy-duty diesel trucks have registered with federal plates instead of local places, in order to avoid the stricter emissions verifications in place in the MCMA. During 2004, a scrappage program for Trucks, Highway Tractors Buses and Coaches will offer fiscal incentives of up to 15% of the price of a new unit per scrapped vehicle and the US EPA will be working with the government of Mexico to implement a diesel retrofit pilot project, which will investigate the costs and in-use effectiveness of diesel particulate filters, diesel oxidation catalysts, and ultra low sulfur diesel fuel under Mexican operating conditions.

Reduction of emissions in industries and services. The substitution of fuel oil by natural gas in the operation of the two power plants Valle de México and Jorge Luque began in 1986 and concluded in 1992. In 2000 the industrial fuel oil supply was completely replaced with diesel having a sulfur content of 0.05 %. These measures not only reduced SO_2 concentrations in the MCMA, but also emissions of particles and their precursors. Evaporative emission controls have contributed significantly to the reduction of VOCs emissions from the fuel distribution system.

Air pollution impacts are relatively well controlled for large industries, but not for the medium, small, and micro industries. The processes and equipment of small and micro industries are often obsolete and some of these enterprises are using fuel oil illegally because of its relatively low cost. Many of the micro industries are in the informal industry sector which is not effectively regulated.

The establishment of the *Licencia Ambiental Unica and the Cédula de Operación Anual* for businesses under federal jurisdiction has been an important step in establishing unified criteria for registration and operation and has improved the environmental management of industry. The inspection results now show some reduction, compared to the early 1990s, in the irregularities detected in industry. On the other hand, there is a need to continue improving emissions inventory as a tool to assess progress on emissions reduction and to identify pending issues.

Improvement of the transportation system. In recent years, in addition to the growing motorization rate, many commuters have shifted from high-occupancy modes of transport (e.g., buses and rail transit) to medium- and low-occupancy mass transit vehicles (microbuses or colectivos) and private autos. To a substantial degree, these changes have occurred because the existing transportation system has not adequately adapted to the changing population distribution, economic changes, and resulting new travel patterns. Also microbuses and ‘colectivos’ offering competing service on the same routes as the high-occupancy buses gained passenger acceptance due to shorter journey times. Because of weak land-use planning and controls, low-income housing has been constructed in locations that lack adequate road capacity and mass transportation options, and new commercial development occurs with inadequate roadway construction and transit access. Current housing projects led by the Secretariat of Urban Development are attempting to increase housing density in central sections of the DF where the Metro operates.

A number of steps to improve public transport in the near and long term are proceeding in Mexico City. Plans are underway to establish a bus rapid transit (BRT) system along two of the main commuting routes in Mexico City. This would involve development of 200 km of BRT corridors. The application of Smart Card technology is being considered for several public transport modes within the DF. This technology would be used in the Metro, RTP, light rail, and trolley buses, as well as the proposed BRT lines. There do not appear to be efforts to extend this intermodal transit card into the State of Mexico at this time.

CENTRAL ONTARIO REGION, CANADA

Population, Topography and Meteorology

Ontario is Canada’s most populated region and its third-largest province, covering about 1 million km^2.[349] The Central Ontario Region (COR) extends from Long Point in the south, through the Niagara, Hamilton, and Waterloo regions, to the east of the Greater Toronto Area (GTA). The area is bounded by lakes Ontario and Erie to the south.

In 2003, the total population of Canada was 31.6 million, with 12.1 million in Ontario, 7.3 million in the COR, and 5.4 million in the GTA.[350, 351] The population growth rate of the COR is estimated to be ~1.5% from 2000 to 2010, with a population density of ~400 inhabitants/km^2. The Toronto City has an average population density of 3000–4000 inhabitants/km^2 with a maximum of 6700 inhabitants/km^2.[352] Figure 10 is a map of Ontario showing the Central Ontario Region.

The climate in the COR is one of the mildest of any region of Canada, which has contributed to the area's industrialization and habitation.[353] The region lies across a major storm track; high and low pressure systems passing over the area produce wide variations in meteorology. Moisture from the Great Lakes in fall and winter increases precipitation, while the latent heat of the Great Lakes protects the region from winter cold. In spring and summer, the cooler waters of the Great Lakes moderate the heat of the tropical air that approaches the area.[354]

Air Quality in Central Ontario Region

The Air Quality Index (AQI) is based on hourly pollutant measurements of some or all of the six most common air pollutants: SO_2, ground-level O_3, NO_2, total reduced sulfur (TRS), CO and $PM_{2.5}$.[355] At the end of every hour, the concentration of each pollutant that the stations monitor is converted into a number that ranges from zero upwards using a common scale or index. The calculated number for each pollutant is called a sub-index. At a given site, the highest sub-index for any given hour becomes the AQI. AQI less than 16 implies "very good", 16 to 31 "good", 32 to 49 "moderate", 50 to 99 "poor" and 100+ "very poor". The air quality is described as poor if the concentration exceeds 30 ppm for CO, 254 ppb for NO_2, 80 ppb for O_3, 340 ppb for SO_2.[356] On August 23, 2002, the Ontario Ministry of the Environment (OMOE) incorporated $PM_{2.5}$ into Ontario's AQI. If poor AQI is predicted to be sustained over a period of time and over a wide area, then a smog alert is issued. The number of Smog Advisory Days (without including $PM_{2.5}$) for which OMOE issued Air Quality Advisories in the GTA between 1993 and 2003 is shown in Figure 6. O_3 was responsible for most of the smog advisories.

Inclusion of $PM_{2.5}$ into the AQI caused the number of days with moderate/poor air quality to increase substantially. For example, between January and November of 2003, there were 53 days with AQI >31 in Toronto, and 14 of them (26%) were caused by $PM_{2.5}$. There were 77 such days in Hamilton, 46 of which (60%) were caused by $PM_{2.5}$.[357] Elevated O_3 concentrations are generally recorded on hot, sunny days from May to September, between noon and early evening, with much of the O_3 originating from cross-boundary transport. For the same land use, O_3 levels in southern Ontario decrease from southwest to northeast due to the combination of trans-boundary sources and synoptic meteorology.

Since 1971, SO_2 and CO concentrations in Ontario have decreased by more than 80%. NO_x concentrations have decreased by ~50% over the past 26 years. Current concentrations of SO_2, NO_x, and CO do not exceed provincial and federal air quality criteria, but $PM_{2.5}$, PM_{10}, and O_3 are above the air quality standards. Though the average O_3 concentration varies over time, it shows a general increase from 1982 to 2001. The COR contributes over 49% of the NO_x, VOC, and CO emissions in Ontario, while the remainder originate elsewhere. Over 58% of NO_x and CO emissions in the COR are from mobile sources while ~50% of PM and VOC emissions are attributable to area sources. The COR's proximity to the border makes it vulnerable to the long-range transport of pollutants from the United States.

Figure 11 shows the ozone annual mean for selected sites within the COR for 2001; higher values were recorded in rural sites. Besides being rural, Simcoe is also more southern and receives more ozone from transboundary transport. Figure 11 also shows the annual means for $PM_{2.5}$ in similar selected sites for 2001. In contrast to ozone, the highest concentration for $PM_{2.5}$ was recorded at an urban site in Hamilton while the lowest was recorded in Simcoe. Similar trends were observed for PM_{10} data but the concentration values were approximately twice those of $PM_{2.5}$.

In 2001, transportation and fuel combustion accounted for more than 50% of $PM_{2.5}$ emissions in Ontario. More than half of the elevated $PM_{2.5}$ in Ontario and as much as 90% of the $PM_{2.5}$ in the border cities may be transported from the United States.[358] NO_x concentrations did not change significantly from 1991 to 2001, but there has been a general decrease from 1970.

The Ontario transportation sector emitted ~63% of the NO_x[358] and 85% of the CO, with the highest NO_2 level of 27.1 ppb recorded in Toronto, based on estimates in 2001. The maximum annual average of CO was found in Toronto, while the maximum 1-hr average was recorded in Hamilton. Between 1992 and 2001, the annual average CO concentration (based on nine sites in Ontario) did not show a trend (0.6–0.9 ppm) but the composite average of the 1-hr maxima decreased by 29%. These CO reductions occurred despite a 17% increase in vehicle-kilometers traveled over the same 10-year period. The transportation sector accounted for approximately 29% of anthropogenic VOC emissions in Ontario in 2001, while general solvent use accounted for 24%.[358] Benzene, toluene, and o-xylene decreased by about 50% from 1993 to 2001.

Table 7 shows the 1995 emissions of some pollutants in the Central Ontario Region. The major SO_2 emission sources in the COR and across Ontario are metallurgical industries such as copper smelters, and iron and steel mills.[359] Other major sources include utilities, petroleum refineries, and pulp and paper mills. Lesser sources include residential, commercial, and industrial heating. In 1995, point sources contributed ~71% and 86% of SO_2 emission in the COR and Ontario, respectively. Similarly, in 2001 about 83% of the SO_2 emissions in Ontario were from smelters, utilities, refineries, and the primary metal sectors. Historically, the highest SO_2 concentrations in the COR have been recorded in the vicinity of large local industrial sources. Lee et al.[360] found that long-range transport contributes to the $SO_4^{=}$ pollution within the COR. The implementation of regulations on smelting operations and the Ontario government's "Countdown Acid Rain" program resulted in a significant decrease of SO_2 emissions from 1991 to 1994, and has remained constant.

Air Quality Management Programs in Central Ontario Region

Government Initiatives

In view of the negative effects of air pollutants on human health and ecosystems, the federal and provincial governments in Canada have begun to take steps to reduce air pollution. Regulation 346 (formerly Regulation 308) is the cornerstone of the Ontario provincial Ministry of Environment (MOE) air protection efforts.

Institutional structure in Canada. The regulation of pollutants in Canada occurs at the federal, provincial and municipal levels. The Golden Horseshoe urbanized region at the western tip of Lake Ontario, which includes the cities of Toronto, Oshawa and Hamilton, is made up of a quilt work of seven regional municipalities within which there are a total of over 30 cities and towns. These local governments have responsibility for public transport, land use planning, education, law enforcement, fire protection and a variety of other public services. While their mandate for air quality is unclear, they have been highly active and many have devised their own air quality plans. In order to coordinate policy at the three levels of government the Greater Toronto Area Clean Air Council was established at the first annual "Smog Summit" in 2000. The Council includes representatives of the federal and provincial governments as well as 29 municipal members. For the most part its activities are limited to the coordination of policies and the sharing of best practice information.

Emissions Standard and National Pollution Release Inventory. The Canadian federal government has responsibility for setting new equipment emissions standards, however, provinces are free to set there own more stringent standards. Until fairly recently Canadian standards were more lax than US standards, but in the past few years there has been a gradual adoption of the US standards.

The federal government is required under the Canada Environmental Protection Act to maintain a National Pollution Release Inventory. Major inputs to the inventory are mandatory reports of seven criteria pollutants from larger facilities. The number of facilities reporting is expected to rise from just over 2000 to 7000 by 2005. A nationwide road network and traffic volume database is also used to create the inventory.[361]

Ambient Air Quality Standards. The Canadian federal government, in consultation with provincial ministers of the environment, recently developed a set of ambient air quality standards known as Canada-wide standards (CWS). Provincial governments are responsible for implementing air quality standards, but are free to design their own implementation plans (note 1, CCME, 2000). Ontario's Anti-Smog Action Plan is a commitment to achieve 45% reduction in NOx and VOCs by 2015. A recent report claims that by 2002, NOx and VOCs had been reduced by 17 and 20% respectively while SO_2 had been reduced by 50% under the program, although there is some dispute whether the government way of calculating reductions produces an overestimate (OME, 2002b; Wellner, 2000). Air quality monitoring is a joint federal-provincial activity. The province also maintains an air quality index (AQI) and issues smog alerts when it reaches critical levels.

Canada-US Air Quality Strategy. As mentioned above, the proximity of the COR to the US-Canada border makes it vulnerable to long-range transport of pollutants from the US. It has been estimated that about 50% (or more for cities close to the US-Canada boarder) of atmospheric pollutants in the COR stem from the US, therefore it is essential for the two countries to work together in the development and implementation of cost-effective emission control strategies. The Canadian and United States Governments signed agreements in 1991 on the reduction of SO_2 and NO_X emissions to address transboundary pollution. These were later extended to include ground-level ozone and PM. The two countries also set up a number of pilot projects, including an attempt to establish a joint airshed management framework for the Great Lakes Basin.

Fuel Quality and Standard. The Canadian federal government recently defined lower sulfur limits for gasoline and diesel fuels. New federal regulations have been established to reduce evaporative emissions at fuel pumps.

In 1999, Ontario had some of the highest sulfur gasoline in the developed world, averaging about 460 ppm. Overall, Canada's gasoline contained a relatively high 330 ppm.[362] Since then, Environment Canada has instituted a limit of 150 ppm that went into effect in 2002. A new limit of 30 ppm is required by 2005. The current limit on diesel fuels is a high 500 mg/kg, but this will be reduced drastically to 15 mg/kg in 2006.[363] In order to accelerate the benefits of low sulfur fuels, a number of municipal governments, including the City of Toronto, the Region of Waterloo and the City of Brampton, have adopted policies of purchasing only low sulfur fuels for public vehicles.[364] Many municipalities have also adopted strict anti-idling policies for their vehicles.

The federal government has also instituted a limit on the flow rate of gasoline pumps to 38 liters per minute in order to limit emissions of benzene and other VOCs. There is also a tax break of 10% for ethanol gasoline, which makes its price comparable to conventional gasoline, although the air quality benefits of ethanol are controversial.

Inspection and Maintenance. Ontario's Drive Clean program of vehicle testing was established in 1999 but initially only applied to the Toronto and Hamilton metropolitan areas. In 2002 the program was expanded to cover a Southern Ontario "Smog Belt" extending from Windsor in the southwest to the Quebec border in the east. Light duty vehicles are tested every two years and heavy-duty trucks and buses are tested annually. The test takes place in certified private establishment. For light vehicles that fail the test there is a repair expenditure limit of $450. However, vehicles that still fail after $450 in repairs are given a one-year, non-renewable permit.

"Drive Clean" program is supplemented by the Smog Patrol program, which conducts random tests of on-road vehicles. The province estimates that the Drive Clean program reduced emissions of ozone precursors by 15.2% in the Hamilton and Toronto areas over the period 1999-2001 by taking high emissions vehicles off the road.[365] The on-road vehicle emissions limits have been periodically tightened. For example, new heavy-duty truck and bus standards for particulates that come into force in 2004 will be the most stringent of any jurisdiction in North America.[366]

Transit and land Use. The Ontario Anti-Smog Action Plan, which includes the measures described above, has been criticized for its lack of emphasis on land planning and land use – transportation coordination as a means to reduce emissions.[367] "Smart Growth" measures such as increasing the density of residential development, focusing urbanization along transit corridors and rehabilitating urban "brownfield" sites could reduce the rate of urban sprawl, which is associated with longer trips and an ever more automobile dependent lifestyle.

Emissions Trading. The Ontario provincial government has established, and is planning to expand, an emissions trading program for utility and industrial polluters. An emissions trading program for SO_2 and NO was established in 2001. It applies only to electricity generation facilities of over 25 MW. All of the covered facilities were owned and operated by Ontario Power Generation at the time, but they are in the process of being sold off to individual firms that can eventually trade permits among themselves. The overall cap of 35kt/yr will be reduced to 17kt/yr by 2007. The program also permits firms to cover 33% of their required NO_x reductions and 10% of their required SO_2 reductions by purchasing emissions credits from facilities not covered by the program. Emissions can be purchased from facilities in Ontario or from a number of nearby US states whose emissions contribute to Ontario's air quality problems.[368]

Electricity generation accounts for only 27% of Ontario's SO_2 emissions. This is a much lower share than in most US jurisdictions for two reasons: first, much of Ontario's electricity is generated in hydro and nuclear facilities and second, Ontario has a large nonferrous smelting industry that accounts for 41% of emissions. Thus, the emissions trading program covers a relatively small proportion of point source emissions. The Ontario Ministry of Environment has proposed to extend the program to a range of other industrial point sources in 2004,[369] but there appears to have been no official notification as yet.

Public outreach: The Canadian federal government conducts information campaigns, such as a vehicle anti-idling campaign and household energy conservation campaign, to encourage emissions reductions.

Industrial Initiatives

Various industrial sectors in the COR have taken steps to reduce air emissions. Most of these are signatories to Ontario's Anti-Smog-Action Plan.[370] The major point source emitters are the automobile, cement, electricity, steel and chemical manufacturing industries. These industries have taken a number of steps including increasing energy efficiency; replacing and rebuilding furnaces with combustion technologies that lead to low NO_x emission; implementing leak detection and repair programs to measure and control fugitive VOC emissions; use of low sulfur fuels; improving SO_x and NO_x removal technologies; use of green belting (planting vegetation), paving and other programs to reduce PM emissions from roads and open sources. These measures have led to the reduction of emissions.

Public Initiatives

A number of Non-Governmental Organizations (NGOs) are actively involved in promoting cleaner air for the COR as well as the rest of Canada. Some of the important local NGOs include Pollution Probe, Toronto Environmental Alliance (TEA) and the Clean Air Foundation (CAF). These work with other organizations like the David Suzuki Foundation and the Sierra Club of Canada that focus on climate change and general ecosystem concerns. These organizations spend considerable amounts of time on campaigns to raise awareness of environmental issues and public participation in pollution reduction. They also lobby governments and industries to adopt policies aimed at improving air quality. For example, in 1993, Pollution Probe initiated the "Clean Air Commute" Program, according to which workers in the Greater Toronto Area are encouraged to choose a cleaner way to commute to work for one week of the year. In 2002, 150 workplaces and 6,000 employees participated in this program, thereby preventing the release of over 245 tonnes of pollutants.[371] Pollution Probe has also introduced the "Save Money and the Air by Reducing Trips (SMART)," a trip-reduction program designed to guide individual workplaces in reducing employee drive-alone car trips. The CAF through its "Car Heaven" program uses incentives (charitable receipt, bicycles, transit passes etc) to encourage Canadians to get their older, high-polluting cars off the road permanently. Since the program launch in July 2000, "Car Heaven" and its partners have retired and recycled over 8,000 vehicles, leading to a reduction of 63 tons of NOx, 42 tonnes of VOCs and 823 tonnes of CO.[372]

DELHI, INDIA

Population, Topography and Meteorology

Delhi, the capital city of India, is located in the northern part of the country at an elevation of 216 m above MSL, with an area of 1483 km^2.[373, 374] The Yamuna River and the terminus of the forested Aravali hill range are the two main geographical features of the city. Figure 12 shows a map of Delhi. The average annual rainfall in Delhi is 700 mm, three-fourths of which falls in July, August, and September.[375]

In 1901, Delhi was a small town with a population of only 0.4 million. Its population started to increase after it became the capital of British India in 1911. As India achieved independence in 1947, a large number of people migrated from Pakistan and settled in Delhi. The population growth rate was 90% in the decade 1941-51. Delhi's population increased from 4 million in 1971 to ~14 million in 2001.[375] In 1965, Delhi had a cloudless, bright blue sky; by the 1990s, haze was common and pollutant levels were high, especially during winter.[376] During the same period, the number of vehicles increased more than 19-fold, from 0.18 million to 3.5 million.[377] About two-thirds of the registered motor vehicles are two-wheelers (half scooters, half motorcycles) and of these 60% have two-stroke engines. The number of small-scale industrial units grew from 8200 in 1951 to 126,200 in 1996.[375] Delhi ranks among the top three States/Union Territories in terms of per capita income (38,864 Rs. in 2000-2001). More than 80% of the state income is from the tertiary sector that is basically the service-sector comprising trade, transport, storage, communications, financing, insurance, real estate, hotels, restaurants, business services, and community/social and personal services, which contributed 70% to state economy during 1993-94 and increased its share to 78 % during 2000-01.[375]

Delhi's climate is semi-arid, with an extremely hot summer, average rainfall, and cold winters. The annual average temperature is 25.3 °C, while average monthly temperatures range from 14.3 °C in January to 34.5 °C in June.[378] During winter, frequent ground-based temperature inversions restrict atmospheric mixing; coupled with traffic emissions, this leads to high pollution events in Delhi.[378] During summer, large amounts of wind-blown dust carried by strong westerly winds from the Thar desert result in elevated PM.[374] These dust storms are followed by the monsoon season (July to mid-September), which is the least polluted because frequent rains wash out pollutants. The prevailing wind in Delhi is northwesterly, except during the monsoon season, when it is southeasterly,[379] causing spatial and seasonal variations in the pollution profile.

Air Quality in Delhi

Nine ambient air quality monitors operate in Delhi,[380] including five industrial and four residential sites.[381] Most of the monitoring stations measure TSP, SO_2, and NO_2. PM, lead, benzo-(a)-pyrene, and O_3 are also measured regularly at a major traffic intersection.[380, 382]

Figure 13 shows averaged annual ambient concentrations of SO_2 and NO_2 and SPM (i.e., TSP) for the last 10-year period (1994-2003). With reference to the national ambient air quality standards for industrial and residential areas, averaged annual concentrations of SO2 and NO2 in Delhi have never crossed the prescribed limits. However, TERI [383] reports that in 1997, the mean 24-hr NO_2 levels exceeded the national standard at 8 out of 18 locations. Further, averaged annual TSP levels (Figure 13) as well as monthly mean concentrations have always exceeded the national standards.[380] Furthermore, if we see the observed concentrations of SO_2 and NO_2 in the light of national air quality standards for sensitive areas, we note that annual averages of SO_2 and NO_2 often exceeded national standards of 15 $\mu g/m^3$ from 1994 to 2003.

While ambient SO_2 levels show a decreasing trend in Delhi (as expected after the introduction of low-sulfur fuel) NO_2 concentrations are increasing since 2001. The ambient CO concentrations in Delhi have consistently violated the CO standard of 2000 $\mu g/m^3$ for residential areas. During 1997, O_3 levels were 150–200 $\mu g/m^3$ for 1-hr and 100-200 $\mu g/m^3$ for 8-hr averages.[381] Varshney and Aggarwal[373] and Singh et al.[374] observed 1-hr average O_3 concentrations exceeding the prescribed WHO standard of 100 $\mu g/m^3$ at various locations in Delhi. Compared to other large Indian cities such as Mumbai, Chennai, and Kolkata, the accumulation of air pollutants in Delhi during winter is more critical.[374]

Several emission inventories have been developed for Delhi.[377, 384-392] Table 8 shows vehicular emissions in Delhi and their increases relative to base year 1990-91. Within the past decade, emissions have doubled for SO_2, and increased about 6-fold for NO_x, CO, and HC, and nearly 12-fold for TSP.

Air Quality Management Programs in Delhi

In response to increasing public awareness, extensive media coverage on the seriousness of the state of air pollution in Delhi and subsequent directions issued by the Supreme Court of India, the Government of Delhi has implemented various air quality improvement measures in industry and the transport sector in Delhi.[393, 394]

Some of the emissions reduction measures taken by the government are described below. In particular, a compendium on the CNG conversion program in Delhi is presented as an example of a court-mandated regulation that has tremendous impact. The entire city bus fleet in Delhi became diesel free, perhaps representing the largest city CNG bus fleet in the world. The compendium is based on the various newsletter accounts from the Center for Science and Environment (Anumita Roychowdry and John Rogers, private communication).

The government of Delhi, with the directions of the Supreme Court, has taken a series of steps to reduce the pollution in Delhi, especially from the mobile sources (Transport Department, 2004). The following list some of the key measures:

1) Improvement in fuel quality:
   - Gradual reduction of sulfur in diesel from 1% in 1996 to 500 ppm in 2001.
   - Phase-out of leaded gasoline in 1998.
   - Reduction of benzene in gasoline from 5% in 1996 to 1% by 2000.
   - Introduction of pre-mixed 2T oil in retail outlets in 1998 and low smoke 2T oil in 2000.

2) Phasing out of:
   - over 15-year old commercial/transport vehicles in 1998.
   - diesel fuelled taxis
   - diesel fuelled city buses

   The government is providing fiscal incentives by way of sales tax exemption and interest subsidy on loans for purchase of new replacement vehicles.

3) Tightening emission standards for new vehicles:
   - Require Euro-I equivalent standards for all types of vehicles in 2000 except passenger Vehicles, which are Euro-II equivalent
   - Replace pre-1990 three-wheelers/taxis with clean fuel vehicles in 2000.
   - All taxis, three-wheelers and buses to run on compressed natural gas in 2001.

4) Inspection and Maintenance:
   - Pilot Center with automated inspection and maintenance facilities to be set up for commercial vehicles in 2004.

5) Mass rapid transport system

   In addition to increasing the buses from 6600 to 10000, the government is constructing a non-polluting, efficient and affordable rail-based mass rapid transit system for Delhi, which will be integrated with other modes of transport.

6) Power plants: Installed electrostatic precipitators (ESPs) in all the units of the three (Indraprastha, Rajghat and Badarpur) thermal power plants to control particulate emissions.

CNG Conversion Program in Delhi: An Example of Court-Mandated Regulation

On July 28, 1998 the Supreme Court of India ruled, in an ongoing public interest litigation on air pollution in Delhi, that the public transport bus fleet of Delhi should be increased from approximately 3000 to 10,000 by April 1, 2001, and the entire bus fleet along with three wheelers and taxis be converted to CNG. The objective was to immediately reduce the alarmingly high levels of particulate concentrations in Delhi. All the buses were prior to Euro I and the proposed technology change was to Euro II new-vehicle emissions standards in 2005.

The Supreme Court's decision to use CNG fueled buses rather than clean diesel fueled buses was made because of the common practice in India of adulterating diesel fuel with kerosene or naphtha to reduce its cost. The existing fuel specification standards and the tests specified were inadequate for detecting adulteration. There was a lack of enforcement of environmental law.[395]

This CNG conversion program was not easy to implement in Delhi. Resistance from entrenched diesel businesses and lack of policy support held up its progress. The Indian Supreme Court finally ruled on April 5, 2002 that orders and directions of the Court on CNG could not be altered by any administrative decision of the government and dismissed all objections to the program.

The expansion of the CNG program has been impressive. There are now more than 77,000 CNG vehicles in the city: 10,000 buses, 5,000 minibuses, 47,000 three-wheelers, 5,000 taxis and 10,350 cars. On December 1, 2002, the entire city bus fleet in Delhi became diesel free, perhaps representing the largest city CNG bus fleet in the world. An extensive network of 119 CNG refuelling stations is in place with total compression capacity of more than 1500 tons/day.

Main Challenges

Some of the main challenges that were faced initially included:

- *Inadequate planning:* The city was unprepared to design appropriate regulations for the new program: During the initial phase of implementation weak emissions and safety regulations, inadequate inspection system for safety and emissions, poor planning of refueling infrastructure, and no planned procedures for conversion of old buses to CNG, afflicted the program.
- *Lack of institutional capacity to address new operational problems:* The government did not have the ability to take immediate corrective action or continuously monitor of the performance of the program involving new technology. About 12 CNG bus fires that were reported during 2001-2002 served to expose the weaknesses in the regulatory capacity.
- *Independent technical evaluation and monitoring for corrective action*: In the face of weak institutional responses, the burden shifted to the civil society groups and the Judiciary to look into the matter closely. Delhi based Center for Science and Environment (CSE) organized two independent technical evaluations of the program in May 2001 and June 2002. The key recommendations of these evaluations became the basis of the reports on safety and emissions standards for CNG buses submitted by the Environment Pollution Prevention and Control Authority (EPCA), the statutory committee that advises the Supreme Court of India in pollution control matters in Delhi; this led to the revision and notification of rules for emissions, and safety for CNG vehicles in November 2001 and setting up of new safety inspection system in August 2002.

Although the basic prerequisites for the CNG bus program were in place, the program still required a supportive institutional framework to be able to make constant improvements in emissions and safety standards, compliance and training to address the new safety concerns.

• *Standards:* Initially the in-force emission standards were weak particularly for converted vehicles which only had to meet, after conversion, the corresponding standards in force during the year of manufacture. Thus the CNG buses only had to meet pre-Euro I standards and this could be accomplished with very basic, poorly developed conversion systems with no closed loop mixture control or catalytic converters. After complaint from CSE, the regulations for emissions, safety and inspection were modified in November 2001. Euro II emissions standards were made mandatory for new CNG buses and Euro I emissions standards mandatory for diesel buses converted to CNG.

• *Safety*: The 12 CNG bus fires caused by sub-standard installation during 2001-2002 in Delhi further exposed the weaknesses in the regulatory capacity. The regulations were not keeping pace with the expansion of CNG fleet in Delhi. The rules for emissions, safety and inspection systems for CNG vehicles that were revised in November 19, 2001, were deferred to November 2002, by which time most of the mandated fleet would be on the roads (and meeting old standards). The Supreme Court intervened again and ruled that no retrofitted or converted CNG bus will be allowed on the road unless and until they pass independent safety checks. However this was not easy to implement as the existing institutions were not equipped with the adequate skills and technique to do safety inspection of gaseous fuel buses. The government was forced to handpick technicians from the All India State Road Transport Union, train them and empower them to inspect all buses.

Inspection and Maintenance

The in-use emissions standards called for a maximum of 3.0 % CO at idle conditions from CNG buses while the CNG buses equipped with catalytic converters and close loop mixture control were expected to emit no more than 0.5 % CO, however, 18 % of the CNG buses tested at the inspection center were found to exceed the 3.00 % limit. It was recommended that CO and NO be measured under loaded test on a chassis dynamometer but this has not yet been implemented. Idle CO standards have been revised and lowered to 0.5 percent; however the equipment used has a greater measurement uncertainty.

Recently, EPCA has directed the bus manufacturers and other concerned agencies to come back with a plan to monitor efficiency of catalytic converters and their replacement as and when needed.

Conversions. The quality of the conversion of old diesel buses and the state of the conversion workshop were often in question. According to the government notification, the kit installation on in-use vehicles could only be carried out by authorized kit manufacturers/suppliers. But neither legal nor technical requirements for conversion workshops have been defined.

CNG filling stations. CNG is a court mandated market in Delhi and the entire program had to be implemented within a short time frame. The Supreme Court had simultaneously directed setting up of the 80 CNG stations to begin to cater to the anticipated demand in the city. But the refueling activities could not keep pace with the expected increase in demand leading to transitional problems of delayed filling and long queues.

Delhi has overcome these infrastructure problems today. At present there are 119 CNG stations. The commissioning of the 23-km Natural Gas Pipeline from Dhaula Kuan to GT Karnal Road has enabled the city to connect about 20 CNG stations along the pipeline and also helped in creating stations in west Delhi.

CNG pricing. The issue of CNG pricing was highlighted when Indraprastha Gas Ltd (IGL) raised CNG prices in March 2002. Simultaneously, the central government increased the excise taxes on CNG. This was a serious setback to the program. The Supreme Court on May 09, 2002 directed EPCA to investigate the pricing issue. EPCA recommended to the Court that the Indian government frame a fiscal policy to allow better price competitiveness to environmentally-friendly fuels.

Ambient concentrations. The reason to legislate CNG was due to the high ambient air concentrations of PM in Delhi. The World Bank is currently analyzing the historic PM data from the monitoring network. The final report has yet to be issued but preliminary findings have raised doubts that the change to CNG as a vehicle fuel can be correlated to any drop in ambient PM concentrations (John Rogers, Private Communication, 2004).

In Summary, the CNG program in Delhi is widely acclaimed to be highly successful and is being repeated across the region. All 3-wheelers and urban buses are now on CNG, the Supreme Court of India is planning to ban complete access to the city for long-haul diesel buses and trucks (trucks are currently allowed in at night) and to force the conversion of all pick-up and delivery trucks to CNG. Nevertheless, additional measurements and studies seem to be required to substantiate the value of this fuel shift in improving the air quality.

BEIJING, CHINA

Population, Topography and Meteorology

Beijing lies in the North Plain of China. Another large city, the Tianjin Municipality, is located to the east of Beijing. Beijing covers 16,810 km^2, and slopes from the northwest to the southeast. Mountains form the north, west, and northeast boundaries of Beijing, while to the southeast is a plain that inclines gently toward the coast of the Bohai Sea. Thus, the region behaves like a dustpan that accumulates air pollutants. Figure 14 shows a topographical map of Beijing. Located in a warm temperate zone, Beijing has a semi-humid climate with four distinctive seasons: short springs and autumns, and long summers and winters. Average temperatures range from -6.4 °C in January to 29.6 °C in July, with an annual precipitation of 371 mm.

Beijing's population in 1970 was 8.3 million;[55] at the end of 2000, it had a registered population of 11 million, in addition to about 3 million temporary residents. The city is considering restrictions to its future growth. The urban district area will be limited in size to 300 km^2, and more than 20 towns will be built to relocate industries and population. At the same time, roads will be paved, green belts will be built along the second and the third ring roads, and several gardens will be set up on the outskirts of the city.

Beijing has benefited from fast economic development since the state policy of reform and opening to the outside world became official in late 1978. A rapid rise of high-tech industry has also contributed to its economic development. Over the past 10 years, urban construction has flourished, with tall buildings now standing shoulder to shoulder around the second ring road, thus slowing the dispersion of air pollutants.

Air Quality in Beijing, China

The main air pollutants in Beijing are TSP/PM_{10}, O_3, SO_2, NO_x, and CO.[19] Figure 15 shows the trends for SO_2, NO_X, CO, TSP and O_3 from 1984 to 2002. The pollutant levels have generally decreased from 1998 to 2002, except for NO_x, as expected due to fuel switching from coal to oil.

Beijing is the city with the largest motor vehicle population in China, the vehicle fleet is1.6 million in 2000.[396] In the warm months, 55% of the NO_x emissions and 61% of the CO emissions come from vehicle exhaust. In 1997, O_3 concentrations exceeded the national standard of 160 μg/m^3 for 71 days between April and October. Maximum O_3 concentration was 346 μg/m^3, more than double the standard. As the motor vehicle population reached 1.35 million in 1998, O_3 concentration exceeded the standard on 101 days, 82% of which occurred between June and September, with a maximum of 384 μg/m^3.

Elevated PM concentrations have been found in Beijing. Shi et al.[397] reported some PM_{10} levels over 400 μg/m^3 (weekly average), 655 μg/m^3 (12-hr average), and 230 μg/m^3 (annual average). The annual average $PM_{2.5}$ concentration was 106 μg/m^3, which is approximately seven times larger than the U.S. annual National Ambient Air Quality Standard (NAAQS) of 15 μg/m^3. He et al.[398, 399] measured an annual average $PM_{2.5}$ concentration of ~120 μg/m^3, with a weekly $PM_{2.5}$ concentration ranging from 37 to 357 μg/m^3. Bergin et al.[121] reported a daily average value for $PM_{2.5}$ of 136 ± 48 μg/m^3, which is twice the 24-hr U.S. NAAQS of 65 μg/m^3. Daily averages were 513 ± 212 μg/m^3 for TSP and 192 ± 47 μg/m^3 for PM_{10}, respectively.

Major anthropogenic SO_2 sources are fossil fuel and coal combustion, the metallurgical industry, and the manufacturing of sulfuric acid. Between 1994 and 2002, SO_2 emissions decreased from 360 to 190 million tonnes. The main VOC sources are fossil fuel combustion (mainly in stationary stoves and motor vehicles), solvent use, paint applications, degreasing operations, dry cleaning, chemical production, and asphalt.[400] Ispoprene and monoterpenes were the main biogenic emissions, accounting for 48% and 22% of biogenic VOC emissions, respectively.[401] Measurements of VOCs between 1995 and 1999 indicate that benzene, toluene, ethylbenzene, and xylene (BTEX) were the main constituents of ambient VOCs in Beijing. The BTEX concentrations have increased considerably in recent years as a consequence of the rapid growth in the transportation and industrial sectors: in 1999 ethylbenzene increased by 220%, xylenes by 133%, and toluene by 91%.[402]

Table 9 shows the contribution of different sources to the emissions and ambient concentration of PM_{10}, SO_2, and NO_x in Beijing. PM_{10} is largely contributed by fugitive dust and industries; major sources of SO_2 are heating and industries, while traffic and industrial activities were the most important sources of NO_x.[403, 404]

Air Quality Management Programs in Beijing

After 20 years of uncontrolled economic development, Beijing faces serious air pollution problems. In Beijing, the air quality reporting system has raised public awareness and consequently generated the pressure to bring in the political will to act. The Chinese government has been making great efforts to improve the air quality since the late 1990. As the host city of 2008 Olympics, it is now surging ahead with an aggressive schedule of stringent emission standards and alternative fuel program for its vehicles to clean up the air of the capital and other urban areas.[405]

In March 1998, the State Environmental Protection Administration (SEPA) was officially upgraded to a ministry-level agency, reflecting the growing importance that the Chinese Government places on environmental protection. In recent years, the Chinese government has strengthened its environmental legislation and made some progress in stemming environmental deterioration. In 1999, the government invested more than one percent of GDP in environmental protection, a proportion that will likely increase in coming years. During the 10th 5-Year Plan, the PRC plans to reduce total emissions by 10%. Beijing in particular is investing heavily in pollution control as part of its master plan to host a successful Olympic in 2008. Some cities have seen improvement in air quality in recent years.

Control Pollution from Coal Combustion

China’s national dependence on coal—still the source of almost three-quarters of its energy—is seen as a key cause of the country’s environmental problems. The smoke from coal stoves at low elevation contributes to serious problem of SO_2 and particulate matter during the winter. According to the State Environmental Protection Administration, coal-fire power stations in China emitted more than 6.6 million tons of SO_2 in 2002, more than 30% of China’s SO_2 emissions.[406]

The Chinese government is taking steps to control pollution from coal burning. In October 2003, the Chinese government announced the ban of coal-fire power plants in the capital Beijing and other major cities. Desulfurization projects are being carried out in over 100 coal-fire power plants across the country, which are scheduled to be completed by 2005.[407]

Control Pollution from Vehicles

In an effort to reduce air pollution in Beijing, the municipal government is ordering city vehicles to convert to liquefied petroleum gas and natural gas. In early 1999, officials stated that by 2000, the capital's 3,600 buses and 14,000 taxis would run on these alternate fuels and about 50 gas stations would offer these two kinds of clean vehicle fuels.[407]

In general, the People's Republic of China has adopted Euro 1 equivalent standards. However, Beijing has adopted stricter standards (Euro 2), taking advantage of the Chinese Clean Air Act, which allows more stringent local regulations than the national law. Now it plans to implement Euro III for gasoline vehicles from 2005 and Euro IV for light-duty diesel vehicles at the same time. The entire country plans to move to Euro III in 2008.[408]

In addition, major financial incentives are provided to vehicles meeting advanced standards ahead of their scheduled requirement: there was a 30 per cent tax reduction for cars meeting Euro II when they were required to meet Euro I only. As a result of the incentive, almost all new cars started meeting Euro II norms within one year.[405]

Vehicle technology advancement: The Chinese government is taking a series of steps to regulate its rapidly growing auto industry. It plans to impose minimum fuel economy standards on new cars that will be significantly more stringent than those in United States. The new standards will require new cars, vans and sport utility vehicles to get two miles a gallon of fuel more in 2005 than average required in US, and five miles more in 2008. These proposed regulations are intended to save energy and to force automakers to introduce latest hybrid engines and other technology in China.[409]

Traffic management: The Italian Ministry for the Environment and Territory (IMET) is working with the Chinese authority to apply ITS to address traffic-related air pollution problem in Beijing during the 2008 Olympic Games. This will involve reducing pollution levels by limiting vehicle access when high levels of ambient pollution are observed.[410]

SANTIAGO, CHILE

Population, Topography and Meteorology

Santiago, the capital of Chile, occupies 235 km^2 and has a population of 5.3 million, which represents ~40% of the Chilean population.[411] It is located in central Chile at an elevation of 520 m above MSL in the middle of a valley and is surrounded by two mountain ranges: the Andes Mountains and the Cordillera de la Costa. Figure 16 is a topographical map of Santiago. The climate in Santiago is mediterranean: summers are hot and dry with temperatures reaching 35 °C while winters are more humid, with temperatures ranging from a few degrees above freezing to 15 °C. The unique topographic and meteorological patterns restrict the ventilation and dispersion of air pollutants within the valley, making Santiago particularly susceptible to poor air quality, especially during the winter (April to September).

Air pollution in Santiago results from a fast growing economy, rapid urban expansion, industrial sources, and an increasing rate of automobile use. Although the city has an extensive state-run underground metro system, cars and trucks are becoming increasingly popular as the number of private automobiles in Santiago has increased to nearly 1 million. The city also has a large fleet of diesel buses that are poorly maintained and contribute substantially to air pollution, particularly through soot emissions.

Air Quality in Santiago

Santiago ranked as one of the most polluted cities in the world and frequently confronts air-quality alerts and pollution emergencies. Since the early 1990s, the Chilean government has taken numerous steps to mitigate air pollution levels. These steps include an air pollution alert system based on the maximum PM concentration in the city's air, and a rotating schedule that restricts the number of cars allowed on the streets on given days. One of the commitments undertaken by the current administration is to modernize the Metropolitan Region's Public Transportation System. Santiago has also partnered with U.S. Department of Energy Clean Cities International program to increase the use of alternative fuels in Santiago's public transportation sector.[412]

One of the first studies of air quality in Chile was a comparison of the pollutant levels in Caracas, Venezuela, and Santiago, and the relationship of those levels to meteorological conditions.[128] Subsequent studies measured daily gaseous pollution levels,[413] the suspended particles,[129] and their size distribution.[127] Contaminants in rain water[125] and elemental composition of TSP[414] were also reported. Trier and Silva[130] found high extinction and absorption coefficients in Santiago, whereas Horvath et al.[415] compared outdoor and indoor soot concentration. Figure 17 shows the trends of the annual averaged PM concentration between 1988-2002.

In the 1990s, the number of studies and publications related to air quality increased considerably. Romero et al.[416] discussed changes in land use, seasonal and daily weather cycles, and geographical and cultural factors that contribute to pollution. Rappengluck et al.[417] discussed the evolution of photochemical smog, which included O_3, NO_x, and CO, peroxyacetyl nitrate (PAN), and non-methane HCs, and estimated that over 50% of the maximum daytime O_3 and almost all PAN are formed within the urban plume. Kavouras et al.[418] reported a PM source apportionment study in Santiago. Based on the loadings of PAHs and n-alkanes, four factors (sources) were identified: high-temperature combustion, fugitive emissions from oil residues, biogenic sources, and unburned fuels. The results of this study are in good agreement with the estimates made by Chen et al.[419] Further study by Kavouras et al.[420] reported source contributions of PAHs in several cities in Chile and compared the results with Santiago. Tsapakis et al.[421] and Gramsch et al.[422] reported on-road and non-road engine emissions as the main sources of carbonaceous aerosols in fine particle samples in Santiago.

Since 1990, aerosol source apportionment studies in Santiago de Chile have pointed out the impact of the vehicular emissions, as well as road dust.[423] Source apportionment studies in the late 90´s indicate a change in the source structure, with small air quality impact of sulfates.[424]

Air Quality Management Programs in Santiago

Because of the air circulation patterns and the emissions structure in the central valley, smog pollution in Santiago during the winter months is particularly strong. Movement of pollutants from downtown to the western part of the metropolitan area occurs, with significant production of secondary organic aerosol, with larger particles being formed. The main sources of $PM_{2.5}$ organic aerosol were road and non-road engine emissions.[421]

The Government has been trying to reduce the air pollution problem in two ways: by reducing the impact of mobile sources through the ambitious 2000-2010 Urban Transport Plan for Santiago (Transantiago Program)[425] and by providing incentives to heavy industry to move out of the central valley. The latter approach has not been successful so far even though financial incentives have been offered. Mobile source emissions have been influenced by the shift of trips from mass transport to private vehicles. Since 1991, bus ridership has fallen from

59.1% to 40.8%. Metro ridership has also declined from 8.5% to 7.15% while car usage has increased.

Atmospheric Decontamination and Prevention Program

In 1997 the Santiago Metropolitan Region had very high levels of TSP, PM10, CO, and O_3, and increasing concentrations of NO2. An Atmospheric Decontamination and Prevention Program for the Metropolitan Region was initiated by the National Commission for Environment (Comisión Nacional del Medio Ambiente or CONAMA) to reduce air and noise pollution from mobile and fixed sources of emissions. Important collaboration between CONAMA and the universities was initiated to improve capacity building.[426]

The following are some key measures taken by the government:

- Renovation of buses: retirement of 2,700 pre-EPA buses; incorporation of low emission's buses and post treatment systems starting year 2004.
- Renovation of trucks: EURO III and EPA98 Standards; incorporation of post combustion treatment systems.
- New standards for light vehicles. Tier1 and EURO III Standards.
- Dust Control: street dust control; street pavement programs, street cleaning program with removal of road dust.
- Fuel Improvemet: diesel Quality, with reduced sulfur content from 300 to 50 ppm by 2004.
- New industry standards: reduction program of SO_x in major industrial processes.
- Integrated System of Compensations and Tradable Emission Permits: emission shares of NO_X and PM_{10} in the industry; 150% emissions compensation for all new activities (industry and transport).

As a result of these measurements, there have been substantial reductions in some contaminants in Santiago. As shown in Figure 17, the total particle fraction PM_{10} has decreased from a yearly average of ~ 100 $\mu g/m^3$ in 1989 to about 70 $\mu g/m^3$ in 2002. The fine particle fraction $PM_{2.5}$ has decreased from about 70 in 1989 to 35 $\mu g/m^3$ in 2002. This decrease is noteworthy, because it has occurred when the economic activity of the city has almost doubled during the same period.

Transantiago Program

The Transantiago Program[425] seeks to radically transform the Metropolitan Region's Public Transportation System. Santiago has an extensive, but chaotic, privately-run bus system. There are three metro lines that function excellently though their coverage is somewhat limited. The Plan involves building and maintaining critical road infrastructure and transfer stations. This initiative – which involves environmental, social and economic aspects – aims to achieve an integrated, efficient, safe and sustainable system for more than 6 million users who travel in Santiago every day. This would be achieved through better traffic flows, improved access to public transport, improved mobility, and improved air quality from reduced emissions of air pollutants. The road infrastructure concession program includes the development of two public transportation corridors and the implementation of two strategic highway links for Santiago.[427]

Transantiago is created to coordinate and integrate the transit control system in the city of Santiago. The Santiago metropolitan area consists of 34 different municipalities. The mayors are willing to work together in Transantiago. Transantiago so far set up the following plans:

- To increase the metro. The current metro has 3 lines and is 40 km long. The idea is to create peripheral lines. The metro will be doubled to 4 lines, 80 km.
- Build urban freeways from the North to South and East to West of the city. A beltway around the city is being built with an investment of 1,500 million dollars. However, this project has been the subject of environmental conflicts since it could increase vehicle traffic.
- To develop a transit network with different services that feed into the trunks. The city will be divided into 10 different zones serviced by exclusive bus lines. A smart card will integrate the different forms of transportation. This will influence the current operation of the Santiago transit system. By 2010 the network will have 300 km of trunk lines.
- To regulate emission standards for buses. There has been a reduction of sulfur in the diesel fuel that is used.
- To create an Urban Development Zone where housing projects can be developed. One of the problems has been that within city limits the price of land has increased so much that it is not possible to build social housing. Transantiago is helping to make room for urban expansion which will reduce the travel time for many people.

Alternative Fuel Program

Santiago is also cooperating with the United States' Department of Energy's (US DOE) Clean Cities International Program to increase the use of alternative fuels in Santiago's public transportation sector. In 2000, the program began converting diesel buses to run on compressed natural gas (CNG), and in May 2001, a prototype hybrid (diesel-electric) bus was introduced. So far, 500 taxis have been converted from gasoline to natural gas, and 12 of the city's diesel buses have been converted to CNG. Ultimately, Santiago and the US DOE hope to generate a critical mass of vehicles that would allow for the installation of CNG service stations in the capital city.[412]

Emission reduction efforts have already shown reductions in PM between 1997 and 2003. PM10, as measured by the ICAF index, declined in many regions of Santiago. For example, in Pudahuel it went down 43%, in Cerrillos it declined by 35% and in La Paz it declined by 44%. Anthropogenic PM10 emissions sources are follows: 48% mobile sources, 33% fixed sources, and 19% area sources. Mobile sources consisted of buses (21%), trucks (13%), and light vehicles (14%). Fixed sources included combustion (12%), processed (14%), and homes (7%). Area sources included firewood, farmland and sewage.

The costs of pollution abatement are substantial but the benefits greatly outweigh these costs. According to CONAMA, emissions reductions of 2.8 thousand tons per year of PM and 15 thousand tones of NO_x cost about US$127 million. But the benefits have been estimated at $260 million dollars per year. The avoided costs are mainly due to improved health by reducing pollution from diesel-powered vehicles.[426, 427]

SÃO PAULO, BRAZIL

Population, Topography and Meteorology

São Paulo is ~60 km from the south-east coast of Brazil, at an elevation of 800 m above MSL. The Greater São Paulo area has in 2004 approximately 18 million inhabitants in 39 municipalities covering ~8000 km^2, two-thirds of which are urbanized. Figure 18 shows a satellite image and a city map of São Paulo.

The metropolitan area is home to a strong industrial base, which is responsible for ~16% of Brazil's GNP. In addition, vehicle population has doubled in the last decade, reaching 3.5 million; mass transport is not efficient and covers only a small area of the city. A significant fraction of the bus and automobile fleet is more than 10 years old, with high emission factors. The fuel used in Brazil is mostly gasohol (gasoline with 23% ethanol), and a small fraction of the automobile fleet runs on pure ethanol. As a consequence, the atmosphere is heavily loaded with aldehydes, in particular acetaldehyde and formaldehyde (HCHO).[428, 429] Concentrations of HCHO in downtown São Paulo range from 4 to 8 ppb, while acetaldehyde concentrations range from 6 to 11 ppb.[428, 430] O_3 formation rates are significantly affected by these high aldehyde concentrations. Evaporative emissions from gas stations and vehicles are also significant. Additionally, most of the new automobiles have small 1-liter motors that are quite economical and have low emissions factors. Recently, a new technology was introduced that allows cars to be fueled with any mixture of gasoline and ethanol (called FlexFuel), which provides flexibility to the user, and the engine adapts itself to the fuel being used at each particular moment.

Air Quality in São Paulo

São Paulo suffers from severe air pollution from PM_{10}, O_3, and aldehydes. During wintertime, shallow inversion layers trap pollutants within the 200–400 meter range for several days, resulting in elevated pollutant concentrations.[431] Ambient SO_2 concentrations are low, and most of it comes from the sulfur content in diesel fuel. The average CO concentrations are in the 2–4 ppm range, but in some heavy traffic areas the 8-hr averages exceed the air quality standard of 9 ppm. As measured at the 33 monitoring stations within the city, the range of NO_2 values is from 25 to 75 $\mu g/m^3$, well below the air quality standard of 100 $\mu g/m^3$.[430]

Figures 19 shows the number of days with concentrations of PM_{10}, CO and ozone above the air quality standard in São Paulo for the period 1997-2002. The 24-hr PM_{10} standard of 150 $\mu g/m^3$ is frequently exceeded, mostly during wintertime; average annual PM_{10} concentrations reached 75 $\mu g/m^3$ at some stations. Vehicular emissions are responsible for ~35% of PM_{10}, while industrial emissions account for ~25%, re-suspended dust ~20%, secondary sulfates ~10%; other small sources such as wood combustion, garbage incineration, metallurgical emissions, marine aerosol, etc., account for the remaining PM_{10}.[432-434] Secondary organic aerosol is an important fraction of $PM_{2.5}$, as is BC, which accounts for about 11% $PM_{2.5}$. In winter, high concentrations of aerosols could affects the actinic flux, reducing UV radiation, and high ozone levels are not reached within the city. However, airborne studies indicate the presence of high ozone levels 50-200 km downwind from São Paulo.

Air Quality Management Programs in São Paulo

São Paulo, Brazil, with a population of 18 million people and 3.6 million vehicles, is one of the most congested metropolitan areas in Latin America. The vehicle estimates may not be accurate because many vehicles that are in circulation are not on the registration records or are registered in other municipalities.[435] The local people spend an average of two hours every day stuck in a traffic jam, fighting their way through a network of streets that resemble a gigantic parking lot. Those who can afford it get around by helicopter; in fact, São Paulo has the second largest fleet of private helicopters in the world. As is the case in other Latin American cities, air pollution is more than just a matter of the huge numbers of vehicles on the road. The average age of the vehicles is also a problem. In São Paulo the average car is ten years old, the average bus seven, and the average truck has been around for twelve years.

The problems with the region's transport system are known, but the solutions are not. Every ten years an origin destination survey is conducted in order to assess the situation. The results of the last survey (done in 2002) showed that 38.6 million trips are made per day, of which 24.5 million trips are motorized -- 53% are made by private cars and 47% by public transportation. The number of trips by individual vehicles has increased over the years; it is not likely that this will change in the future.

According to some estimates, the average time traveled by bus is 43 minutes, including trip time, waiting time, and walking time. By comparison, the average trip in a car is 20 minutes and 16 minutes by motorcycles. The direct costs are 1.2 R$ for buses, 1.8 R$ for cars, and 0.6 R$ for motorcycles; these figures help explain the attractiveness of cars and the increasing number of motorcycles in the city. Unfortunately, motorcycles pollute a lot. Simulations for various mode share shifts show that if 20% of the bus trips were shifted to autos, 32% more gasoline would be used and 17% more pollutants emitted. With a shift of 20% to motorcycles, pollutants increase by 54%. However, if 20% of trips are shifted back to buses, gasoline, pollution, energy, transport costs, and road space are all improved.[436]

São Paulo has a complicated organizational structure with a municipal transportation system and a metropolitan system that manages trips between different municipalities. The new Brazilian constitution of 1988 has reinforced the power of mayors and municipalities, while there is no clear legal definition of the metropolitan area. [435]

Another problem was resistance from the informal sector, comprising minibus operators. The informal buses do not operate on new routes but on routes that already exist. They do not pay taxes, are not concerned about the safety of the passengers, and they do not worry about schedules.

The government of São Paulo had begun working on ways to manage the chaotic traffic and dangerous emissions levels.

Traffic Management

Since 1996, a system has been in place that requires cars to take turns staying off the roads. This program, known as Rodizio, is similar to the "Hoy no Circula" in México, but it is enforced only within the central area and during peak hours. The cars rotate based on the last number on the license plate; the police impose heavy fines on offenders. The system removes from circulation two plate numbers per day in the morning and afternoon rush hours.

In São Paulo, road charging has been discussed for a long time, and the London experience has been encouraging. However, transport engineers in Brazil remain divided on this. There are equity and control problems that need to be considered.

Public Transportation

Metro. From 1995 to 2001, the municipal bus system lost about 30% of its demand, while the railway and inter-municipal buses also lost mode share, but not as much. Since 1995 to 2002, there have been large investments in the subway system. The metro had 3 extensions and construction of a new line has started while another is being extended. Large investments in 1994 were made on the metropolitan train system when 267 people died from accidents in 1996, particularly “surfer” passengers (those who are standing and not holding on to anything). The government invested in modernizing services, buying new cars and safety measures, and in 1998 the death toll had been reduced to zero. Demand went from 400,000 passengers per day in 1995 to over one million in 2002.

Cleaner bus fleet. Buses have also improved: 3,000 new buses were purchased over a period of 7 years. This reduced the average age of the fleet. São Paulo is also aiming to introduce Euro 3 engines. From mid-2003 onward, all new buses must comply with European emissions standards.

*Clean vehicles***.** Two new technology programs were implemented: hybrid diesel-electric buses to be used in the new bus corridors and hydrogen fuel-celled demonstration buses. Three hybrid buses are currently being tested through funding from the private sector.

Inspection and maintenance. The government planned to introduce a vehicle inspection program for cars at the end of 2004 and inspection program for cars at the end of 2003; however, it has not been implemented.

BOGOTA, COLOMBIA

Population, Topography and Meteorology

Bogotá is the capital of Colombia and also its administrative and political center. In 2003, the population was 6.5 million, with a growth rate of 2.4% per year. The population density is ~3700 inhabitants/km^2.[437] The city’s elevation is 2640 meters above MSL on the highest plateau in the Colombian Andes, and occupies an area of 1732 km^2. The city is bordered by mountains on the east and south; most of the urban area is flat, but there is some development in hilly areas in the southern part of the city. A map of Bogotá is shown in Figure 20.

Bogotá has a high-mountain tropical climate, with an average temperature of 14 °C. The dry season is December to March, and the rainy seasons are April to May and September to November. During August, there are usually heavy winds from the north. The weather is strongly influenced by El Niño.[437] Bogotá has about 900,000 private vehicles,[438] and a large number of highly polluting small industries (e.g., brick and quicklime manufacturing).

Air Quality in Bogota

Bogotá has an air quality monitoring network (DAMA, Departamento Técnico Administrativo del Medio Ambiente) composed of nine stations. The network monitors TSP, PM_{10}, O_3, SO_2, NO_2, and CO and meteorological parameters. Between 1998 and 2002, the air quality network showed reductions in average annual concentrations of CO (-28%), NO_2 (-13%), and O_3 (-6%).[439] However, there was a 12% increase in PM_{10} and a 15% increase in SO_2 during the same period, with both pollutants showing non-compliance with local standards in 2002.[439] Figure 21 shows the trends for these pollutants.

There are about 1 million private vehicles with an annual grow rate of 2.5% between 1998-2000, and 5.5 % since 2001. There are about 20,000 public transport vehicles with about the same number of vehicle owners and 67 public transport companies. Most of the public vehicles are old (average age over 14 years) and between 4000-10,000 are illegal.[440] There are about 70,000 taxis of which some 15,000 are illegal.[441]

It is estimated that there are around 14 million trips per workday with the following modal share: 73% transit, 11% private vehicle, 13% non-motorized, 3% other for year 2002.[442] TransMilenio Phase I (41 Km) served 750,000 passengers per workday in 2003. A recent extension of 12 Km increased the figure to 880,000 passengers per workday.[443]

Air Quality Management Programs in Bogotá

Bogotá's demand management policies include the "Pico y Placa" program, which restricts vehicles operation based on the number of the vehicle license plate. For private transport, 40% is restricted daily, Monday through Friday, from 7-9 AM and 5-7 PM. For public transport (taxis included), 20% is restricted daily, Monday through Saturday, throughout the day. There are now more than 200 km of bicycle paths.

Finally, there is TransMilenio, which has achieved a major change in the way the public perceives the transit system. Bogotá started bus priority measures in the 1980s. By 1989 the most important corridor –Avenida Caracas- was segregated, giving two lanes per direction to buses and building bus stops with 8 docking berths every 400 meters on average, at a cost of US$ 1 million per kilometer. The project was successful in carrying more than 30,000 passenger per hour at an average speed of 18 Km/h.[444] Nevertheless operations were chaotic, and pollution, safety and urban environment levels declined sharply over a decade. This was completely changed with the implementation of the TransMilenio BRT System between 1998-2002 (Phase 1), which not only upgraded the infrastructure –bus and general traffic lanes, median stations, terminals, depots, public space, and safe pedestrian access-, at a cost of US$5 million per kilometer, but changed the operation scheme and introduced several other elements under a systems approach.

In spite of the success of the TransMilenio, there is still a challenge with respect to public transportation. Ongoing policy decrees should focus on a few problem areas. First, bus companies must lease vehicles from owners. Second, companies must operate their fleet, collect fares, contract drivers, and maintain vehicles. Electronic vehicle licensing allows on-road detection and retention of illegal vehicles. Part of the fare goes to a fund to purchase old vehicles and destroy them.

In the following we describe the BRT system in Bogotá as an example of sustainable transportation system. Due to its success, many urban centers around the world, including Mexico City, are copying it, however, as discussed below, there are several key principles that contribute to its success. It is important to include a comprehensive system approach, adapting the Bogotá experience to local conditions, just as Bogotá used the experience of Brazilian cities and Quito, Ecuador. México City, Santiago de Chile and Delhi, India, are introducing BRT systems using TransMilenio concepts, as well as 7 Colombian cities, and places as diverse as Jakarta, Indonesia; Cape Town, South Africa; and Dar es Salaam, Tanzania.

Bus Rapid Transit: An Example of Sustainable Transportation System

Eight years ago, Bogotá was overwhelmed with a chaotic urban transportation system without a clear long-term sustainable policy. Fast population increase, very rapid growth in automobile ownership and use, and lack of resources, resulted in extensive congestion, air and noise pollution and many traffic accidents.[445] The prevailing policy during the 1980s and early 1990s was to allocate the scarce city funds for road expansions and construction of overpasses in a few critical intersections. Road maintenance was generally neglected because of insufficient resources.

Metro construction and elevated highways were proposed,[446, 447] but there were no resources to finance these projects. This could be regarded as a blessing, since the city was forced to find innovative and low-cost alternatives while preserving the urban landscape. In 1998, Mayor Enrique Peñalosa redirected transportation policy away from road construction and launched a long-term mobility strategy based on bus transit improvements, automobile restrictions, and non-motorized transportation,[448] which has been continued in succeeding local administrations.[449]

Today, Bogotá is an example of a successfule implementation of sustainable transportion.[450-454] Travel time has been reduced by 12%, traffic deaths by 21%, and the city consumes less energy, is less polluted, and is less segregated, both socially and in its use of public space and transit. In spite of anticipated changes in political authority, these priorities for mobility are still in place.

Rather than focusing only on vehicle technology, the city adopted measures to increase the share of walking, biking, and transit, and reducing the use of private automobile. Some important elements of the strategy are:[455]

- Generation of institutional capacity, transforming and providing technical resources to existing agencies to be able to focus on non motorized transportation and transit improvements, and creation of a Bus Rapid Transit (BRT) authority.

- Completion of detailed planning studies, aimed at implementing change;[456-459]
- Redirection of existing budgets and obtaining dedicated funds (local gasoline tax 16%, created in 1996, raised to 20% 1998, raised to 25% in 2002), as well as obtaining long-term national grants (1998-2016) to ensure funding for BRT.
- Inclusion of traditional service providers through incentives to join in well organized companies and continue providing public transportation service under adequate regulatory framework for BRT.
- Promotion of cultural changes towards favorable perception of non-motorized transportation and transit use (e.g., days without car, media campaigns, guides, etc.)

Although there were major debates about these policies, they were not rejected; only 16% of the population uses private automobiles. As a result, the strategy was continued under the administration of Mayor Antanas Mockus (2001-2003). Since, due to term limits in Bogotá, the mayor is not re-elected, each administration must deliver results within 3 years.

The strategy includes very extensive construction and recovery of pedestrian areas (sidewalks, plazas, walk-ways); the construction of separate facilities for bicycles (200 km+ network already built), restriction of 40% of the private vehicles during the peak periods using the plate numbers, and the introduction and expansion of a full-scale BRT System. There are indications that these measures have resulted in increases in non-motorized and transit commuting (4% and 1% difference between 2002 and 1998, respectively), and reductions of the use of private automobiles (minus 5% difference between 2002 and 1998) as shown in Table 10.

Average travel time has declined 12% over the last 4 years; nevertheless, it is still much higher than an average of 35 minutes estimated for 17 global cities.[460] Public perception of the transportation system has improved significantly (from a 2.78 rating to 3.47, in a scale of 1 to 5) and it is no longer one of the most important concerns of the population.

The most visible element of the mobility strategy is the TransMilenio BRT system,[454, 461, 462] but it is not isolated from the whole vision. It is a fully scaled BRT, with stations, exclusive busways in the median on arterial roads, large articulated buses, level boarding, prepayment, ITS and branding. TransMilenio was based upon successful experiences in Brazilian cities and Quito, Ecuador. With the advantage of hindsight, however, TransMilenio was able to improve on these earlier examples. It comprises specialized infrastructure, efficient operations, advanced fare collection systems and a new institutional arrangement, organized under the principles of respect for life, diversity, and travel time, with high quality but also affordable for government, the users and the operators. The BRT system capacity is comparable with heavy rail transit (metro and regional rail) at a fraction of their capital cost and without operational subsidies.

The initial phase, implemented between 1998 and 2002, consists of 41 km exclusive busways, 61 stations, 470 articulated buses and 241 feeder buses, providing service to 750,000 passengers daily. The system is currently under expansion with 40 km of additional exclusive bus ways; 335 articulated buses and 170 feeder buses would be gradually introduced between 2003 and 2005. The long-term goal for the total system is to have 85% of the city area within 500 meters of the trunk system by 2020.

One of the most important features of the TransMilenio BRT System is the innovative institutional scheme of public and private involvement based on binding performance contracts. The public sector is in charged of planning, developing and maintaining its infrastructure, and controlling service delivery. Private companies, through concession contracts, acquire equipment and provide the operations of trunk line and feeder bus services and fare collection. It is important that these contracts are based on open bidding, and that they include ways to fire the contractor if they fail to perform. Competition for the individual passenger is being replaced by competition for the market.

This system has improved quality of life in many ways. Impacts of the BRT system implementation include reduction in travel time, operational cost, accident and emissions; furthermore, there is a positive sentiment of pride and belonging among the residents.[463] Although air quality was not at the top of the agenda for the system, it has been positively impacted by the program. Emission reductions come from replacement of obsolete transit fleet, more efficient bus transit operations, and modal shift from less efficient modes. A rough estimate of these reductions is presented in Table 11. The estimate assumes the replacement of 1500 obsolete buses by 709 new buses, and a 26% reduction in auto trips. The modal shift has been more important in reducing CO, while TransMilenio's cleaner and more efficient bus fleet has had greater impacts on NO_X and VOCs.

The success of the Bus Rapid Transit System in Bogotá shows that sustainable transportation measures can have important impacts in improving quality of life, including air quality. Nevertheless, there is still a long way to go. The Bogotá experience is transferable to other cities. One needs a strong political will in order both to generate a continuous process, with clear ideas and vision from the beginning, and to allocate the required financial and technical resources for project preparation and execution. To finance the project, the gasoline tax was raised 20% and the national government provided a 16-year grant. It is also necessary to have a long-term vision, but with specific, practical actions that are able to show short-term results and assure financial sustainability. Measures employed must reinforce these principles, even if they are not popular (like taxes and traffic demand management).

The main principle behind this success story is the straightforward application of a simple, but powerful, principle "Common welfare prevails over special interests."

CAIRO, EGYPT

Population, Topography and Meteorology

Cairo, the capital of Egypt, is the largest city in Africa and the Middle East. It is located on the banks and islands of the Nile in the north of Egypt. A map of Cairo is shown in Figure 22. The population of the Cairo urban agglomeration is 10.8 million, and is projected to reach 13.1 million by the 2015.[1] Greater Cairo consists of Cario, Giza, and Kalubia, and has a population of more than 20 million.

Cairo has a hot, dry desert climate. The monthly average temperature ranges from 14 °C in January to 29 °C in July. The maximum daily temperature can reach 43 °C in the summer.

The average annual rainfall is only 22 mm, and the monthly maximum of about 7 mm occurs in December.

Although Cairo itself is only about 1000 years old, parts of the metropolis date back to the time of the Pharaohs. The first Muslim settlement of Egypt was Al-Fustat, now a part of old Cairo. Cairo was conquered and controlled by a host of invaders, including the Mamluks, the Turks, and Napoleon Bonaparte of France. In the 19th century, one of the city's rulers, Khedive Ismail (1863-1879), sought to transform Cairo into a European-style city. This, along with the British occupation of Cairo in 1891, led to the development of new suburbs for affluent Egyptians and foreigners. By the turn of the century, most commercial activity was also moving into modern Cairo. The urbanization of the Greater Cairo area has been facilitated by an extensive flood control program and improved transport facilities developed over the past 30 years. Cairo is the only city in Africa with a metro system.

Although the conservation of agricultural land has long been a priority of Egyptian development policy, much of the critically needed arable land in Cairo is being lost to urban development, half of which is illegal; the remainder is planned developments in the desert. Cairo has about one-third of Egypt's population and 60% of that nation's industry. It is one of the world's most densely populated cities, with one of the lowest provisions of road space per capita and a dramatic growth in the number of private vehicles. The government has exacerbated this situation by spending on bridges and overpasses, and by heavily subsidizing fuel, all of which promotes the use of private vehicles.

Air Quality in Cairo

Emissions from industry and motor vehicles cause high ambient concentrations of PM, SO_2, O_3, NO_x, and CO in Cairo.[464] However, continuous measurements of these pollutants need to be conducted to establish the extent of the air quality problem.

Lead levels in Cairo are among the highest in the world, and are estimated to cause from 15,000 to 20,000 deaths a year, according to a 1996 report by the Egyptian Environmental Affairs Agency. PM lead concentrations ranged from 0.5 µg/m3 in a residential area to 3.0 µg/m3 at the city center, and the high lead levels were mainly attributable to motor vehicle emissions.[464] Sturchio et al.[465] measured lead and TSP at 11 sites; the concentrations ranged from 0.08 µg/m3 and 25 µg/m3, respectively, at one site to over 3 µg/m3 and 1100 µg/m3, respectively, at the city center. Because Cairo began to phase-out leaded gasoline in 1996, Sturchio et al.[465] concluded that the majority of atmospheric lead was emitted by local lead smelters. Rodes et al.[466] measured $PM_{2.5}$ and PMcoarse concentrations during a source apportionment study in Cairo from 1994 to 1995. The annual average PM_{10} concentrations exceeded the 24-hr U.S. NAAQS of 150 µg/m3 at almost all sampled sites. Figure 23 shows the PM_{10} and $PM_{2.5}$ source apportionment results for Shobra, an industrial and residential area in Cairo.

In order to develop and implement a pollution control strategy in Cairo and to reduce the health impact of air pollution, the Cairo Air Improvement Project (CAIP) was established.[466] Source attribution studies were performed as part of this project to assess the impact of various sources (e.g., lead smelters, motor vehicles, oil combustion, vegetative burning, geological material, etc.) on ambient pollutant levels.[467]

The design of the CAIP network, and ambient PM and lead measurement results, have been reported by Labib et al.[468] For the period 2000 to 2001, high levels of PM were reported for all sites, with annual average PM_{10} and $PM_{2.5}$ levels generally exceeding 150 µg/m^3 and 75 µg/m^3, respectively. Maximum PM levels were observed in the highly industrialized areas of the city. In spite of the introduction of unleaded fuel, ambient lead remains a major problem. For 2000, the annual average PM_{10} and $PM_{2.5}$ lead levels in most contaminated sites exceeded 20 µg/m^3. Observed levels were reduced by approximately 40% in 2001 through CAIP-initiated efforts.

In order to determine the sources of pollution episodes, intensive PM_{10}, $PM_{2.5}$, and VOC monitoring was carried out at six to eight sites in the greater Cairo area during a fall and winter period in 1999, and during a summer period in 2002.[467] Crustal components Si, Ca, Fe, and Al were significant at all sites. The majority of crustal material was in the PM_{coarse} fraction. OC and EC were major components of PM at all sites. The likely sources include mobile emissions, open burning, and fossil fuel combustion. The highest average VOC concentrations were found at a mobile-source dominated site: 2037 ± 1369 ppb during the fall and 1849 ± 298 ppb during the winter.[467] The temporal variations of VOCs were consistent among the six sites during winter.

The most abundant VOCs were isopentane and n-pentane, which are associated with evaporative emissions from motor vehicles; C2 compounds (e.g., ethane, ethene); propane; isobutene; and n-butane, which comes from compressed natural gas (CNG) and liquefied petroleum gas (LPG). Methyl tertiary-butyl ether (MTBE)—a gasoline additive—toluene and benzene were also abundant.

Air Quality Management Programs in Cairo

In order to develop and implement a pollution-control strategy and to reduce the health impact of air pollution in Cairo the Cairo Air Improvement Project (CAIP) was established.[469] The air quality measurements conducted in Cairo highlight the severe air pollution problems associated with the greater Cairo area. Specific objectives of CAIP included:

- Improving fuel efficiency and reducing exhaust emissions from gasoline fueled vehicles.
- Reducing total suspended particulate (TSP) emissions from diesel buses.
- Reducing airborne lead and PM emissions from lead smelters.
- Instituting an air quality monitoring and analysis program to assess changes in ambient pollutant levels.
- Initiating a public awareness and communications program.
- Identifying and implementing additional initiatives to support air pollution reductions in Cairo.

According to a report published by the Ministry of State for Environmental Affairs (MSEA) and the Egyptian Environmental Affairs Agency (EEAA), the protection of the environment from air pollution is a long-term commitment, as expressed by the five-year action plan. Air quality is one of the principal issues addressed in Law 4/1994 for the Environment, which has been designated as the highest coordinating body in the field of the environment that will formulate the general policy and prepare the necessary plans for the protection and promotion of the environment.[470]

Initiatives and activities are carried out on both the strategic and operational levels. On a strategic level, the preparation of an Air Quality Management Strategy is currently underway, to address air pollution resulting from the solid waste and mobile sources. Moreover, an emissions inventory, including all industrial and non-industrial sources in Greater Cairo, will be carried out with support from the United States EPA.

On an operational level, a number of activities and initiatives were carried out during 2000/2001 with a particular focus on the Greater Cairo area, where the highest levels of air pollution occur. A comprehensive national air quality monitoring system has been established over the past years as part of Environmental Information and Monitoring Program of EEAA, implemented with support from the Danish Government. The 42 monitoring system located throughout the country has been operational for the past two years, measuring concentrations of common air pollution parameters such as SO_2, NO_2, CO, O_3 and PM_{10}. The monitoring data collected are continuously used to evaluate the effectiveness of various efforts to reduce lead and particulate emissions.

Reduction of Vehicle Emissions in Greater Cairo

Mobile emissions are one of the major sources of air pollution in Greater Cairo. The MSEA is currently working towards a tighter control over emissions from more than one million on-road vehicles. During 2000/2001, on-road testing of vehicles with mobile emission analyzers has continued in partnership with the Ministry of Interior. Moreover, a network of stationary facilities for emissions testing, operated through the Traffic Department has been identified as the most feasible option for systematic long-term testing of vehicles.

As part of the feasibility study to replace diesel-fuelled city public transport buses with compressed natural gas (CNG) in Greater Cairo, In 2000/2001, twenty CNG buses were introduced on the road in 2000/2001. Most of Cairo's taxi fleet operates on CNG. In addition, an inspection program has been established to identify, tuned up or replace the worst polluters among the fleet of more than 4500 diesel-fuelled public buses.[470]

Reduction of Emissions from Lead Smelters in Greater Cairo

The 1999-2000 inventories of stationary lead emission sources in Greater Cairo clearly shows that secondary lead smelters, and in particular rotary furnaces at these facilities, are the most significant sources of lead emissions in the city.

The Government of Egypt's Lead Smelter Action Plan addresses the high emissions from the smelters by promoting the use of more environment-friendly technology in the smelting industry, and by supporting the relocation of all lead smelting activities away from densely populated areas. For example, the relocation of a major lead smelter plant away from the Shoubra El Kheima area during the past year has resulted in a decrease in ambient lead concentrations.[470]

Natural Gas Conversion:

The conversion of the power plants in the Greater Cairo region from the use of fossil fuels to that of natural gas was successfully carried out as a cooperative activity between MSEA, EEAA, and the Ministries of Electricity and Petroleum to improve the air quality. Also, following the implementation of three demonstration projects for the environmental upgrading of brick factories and their conversion to natural gas use for their combustion processes, the Egyptian Environmental Initiatives Fund will provide technical and financial assistance for the further upgrading of another 50 factories in the area of Arab Abu Saed. This initiative, started in 2001/2002, was supported by the Climate Change Secretariat of Canada.[470]

In addition, as part of the CAIP, source attribution studies are performed to assess the impact of various sources (e.g., lead smelters, motor vehicles, oil combustion, vegetative burning, geological material, etc.) to ambient pollutant levels.[471]

Effectiveness of Reduction Strategies

Effectiveness of the reduction strategies can be assessed by evaluating the ambient data[472] and source attribution results.[471] The major success has been the reduction of ambient lead by approximately 40%. The VET and CNG bus programs have only recently been instituted so it is too early to determine their impact. PM_{10} and $PM_{2.5}$ levels have decreased during the period 2000 to 2001; however, this is likely due to favorable meteorological conditions. In summary, aside from the improvement in the observed lead levels, it is too early to determine the effectiveness of the reduction strategies.

AIR QUALITY MANAGEMENT STRATEGIES IN OTHER MEGACITIES

Confronting Two- and Three-Wheel Vehicles in Asian Cities

One of the big challenges confronting Asian cities is the two- and three-wheeler vehicular technology and the vehicle inspection and maintenance (I&M). More than 70% of vehicular fleets in Asian cities – including New Delhi – consist of smoke-belching two- and three-wheelers.[473] Some of Asia's most vibrant megacities are taking proactive steps to control emissions from the burgeoning numbers of their two- and three-wheeler vehicles.

In Bangkok, the capital city of Thailand with a population of 8 million, motorcycles constitute 42% of the vehicle fleet, and contribute to 48 % of particulate and 32 % of hydrocarbon emissions from vehicles. Until 2000, 90% of these motorcycles were two-stroke. The government of Thailand took a three-pronged approach to control harmful emissions from motorcycles: introduction of technology to reduce white smoke emissions, setting up of stringent emission standards and establishment of a credible I&M program. The measures had a tremendous impact: the share of sales of two-stroke motorcycles dropped from 54% in 1999 to about 2% in 2003. The on-road share of two-stroke motorcycles went down from about 96% in 1999 to 40% in March 2004. The contribution of motorcycles to fleet PM emissions decreased from 48% in 1994 to 14% in 1997.

In Bangladesh, the government has successfully implemented a ban on two-stroke three wheelers in Dhaka (one of the megacities with 12 million people and the industrial, commercial, and administrative center of Bangladesh). Prior to September 2002, between 30,000 and 65,000 old, 2-stroke Baby Taxis used to ply in Dhaka, these were replaced with a max of 10,000 new 4-stroke units leading to significant reductions in PM2.5, CO and hydrocarbon emission.[473]

In Lahore, Pakistan, the government announced on March 2004 that two-stroke engine rickshaws will be banned in 2005 and only four-stroke engine rickshaws that work on compressed natural gas will be allowed to operate in the city. The owners of motorcycle rickshaws would be given three years to convert to four-stroke engines and no new motorcycle rickshaws would be registered during this period. The two-stroke engine rickshaws would be sent to smaller cities.[474]

Emissions Reduction Strategies in Hong Kong

Hong Kong became the first city in Asia to introduce ultra low-sulfur fuel with the help of fiscal incentives and tightening of the emission standards. When the air pollution levels in Hong Kong reached the highest ever levels in March 2000, a huge public outcry followed, demanding government action to bring down the pollution levels. The Hong Kong government responded swiftly by instituting a task force to implement measures to control vehicular emissions, to monitor effectiveness of control measures and to take further actions based on the impact. The task force set a target of reducing PM emissions by 80% and NO_x by 30% by the end of 2005. In order to meet the target, the government went ahead with tough measures in a very short time.[306] Two of the measures are described below:

In 2000, Hong Kong introduced ultra low sulfur diesel (ULSD), with a sulfur content of 50 ppm. In addition, new gasoline private cars were asked to meet Euro III standards starting 2001 and diesel cars were asked to meet the most stringent California emission standards at the same time. Moreover, Hong Kong established the most stringent smoke density standards for heavy-duty diesel vehicles at 35 Hartridge Smoke Unit (HSU). Officials found that diesel vehicle owners temporarily adjusted the fuel injection pump, enabling high smokers to pass the snap acceleration smoke test. When the so-called lug-down dynamometer test (test conducted at full throttle, with the dynamometer load gradually increased to slow down the engine speed so that the engine is laboring, or “lugging”), was introduced, they found that the number of vehicles that were repeatedly found to be high smokers drastically fell. As a consequence, the number of smoky vehicles spotted per hour reduced from 11 in December 1998 to about 4 in September 2003. These regulatory measures were supplemented by economic incentives also. When the city introduced unleaded gasoline in 1991, it was sold at a lower price by 1 Hong Kong Dollar for the first year. Similarly, the ULSD was also sold at a concession of 0.11 US Dollar. As a result ULSD gained 100 % market share by August 2000[306] shortly after it was introduced.

The government of Hong Kong has taken up a program to replace diesel vehicles by alternative fuels, in addition to tightening new vehicle emission standards similar to Europe and introducing ultra low sulfur diesel (50 ppm sulfur).[306]

The following are the strategies to replace diesel vehicles by alternative fuel:

(1) Phase-out diesel light buses and taxis and replace them with vehicles using LPG. After a one-year trial involving 30 taxis ended in 1998, the government obtained the full cooperation of industry for implementation of the program.

(2) Devise fiscal instruments (for car owners, LPG station owners, taxi and bus owners) to facilitate the introduction of LPG as an automotive fuel.

- Fuel tax was waived for auto LPG
- Free land lease to existing stations to set up LPG infrastructure.
- Zero land premium facility was provided for setting up new LPG stations.
- From 2003, the government offered grants worth about US$5,000 to each taxi owner and US$7,700 to each light bus owner to switch over to LPG.

As a result of this program, almost all taxis on the roads of Hong Kong now run on LPG and there were 310 LPG light buses on road by the end of 2003. The government is now targeting the introduction of more LPG and electric buses in both public and private bus segment. The alternative gaseous fuel program is expected to reduce particulate emissions by 29 % and that of NO_x by 8 %.

CNG Strategy in Lahore, Pakistan

In July 2003, the Lahore High Court instituted the Lahore Clean Air Commission in response to a public-interest litigation. The commission was given the responsibility of preparing a report on practical solutions for monitoring, controlling and improving vehicular air pollution in Lahore. At present the government policies promote the use of CNG for taxicabs and private vehicles only. Out of more than 350,000 CNG vehicles in Pakistan, 100,000 vehicles are in Lahore alone. However, LPG is used at a much wider scale in the three-wheeler segment. Of the total fleet of 40,000 rickshaws, 70% run on LPG. This is primarily due to the price advantage of LPG kits that cost Rs. 12,000 compare to CNG kits that cost Rs. 20,000.[306]

The government is going ahead with a plan of introducing 100 CNG buses between 2004 and 2005 and another 300 buses between 2006 and 2009. There is also a plan to allow only CNG taxis between 2004 and 05 and for the replacement of diesel vans/buses with CNG vans/buses by 2008. The government also plans to replace all its vehicles to run on CNG.

AIR QUALITY MANAGEMENT INSTITUTIONS IN THE CASE STUDY CITIES

There are several important differences between the different cities on their capabilities to address air pollution problems. These differences affect mainly the policy process, influencing the effectiveness of control strategies that appear otherwise similar. The main differences can be summarized as financial capacity, institutional capacity, political pressure, and human resources.

In the following sections we discuss the barriers to effective air quality management, focusing on the institutional issues, which are both the most difficult and most important problems, particularly in metropolitan areas where there are many institutions with overlapping responsibilities and jurisdictions. We will discuss the air quality management institutions in the metropolitan areas of Los Angeles and Mexico City to contrast the different barriers encountered by two megacities with vastly different management capabilities.[4]

Air Quality Management Institutions in the South Coast Air Basin

In the early 1970s, residents and air quality officials in San Bernardino and Riverside counties became dissatisfied with the air pollution control efforts of their neighbors to the west, Los Angeles and Orange counties. Most air pollution originated from vehicles and industries in Los Angeles and Orange counties. However, as air pollution knows no county boundary, the region's westerly ocean breezes blow most of that pollution into San Bernardino and Riverside counties each afternoon, leaving residents of the inland valleys to suffer most of the effects of smog. In 1977, after years of complaints, the California state legislature finally created the South Coast Air Quality Management District (SCAQMD) by merging programs from the four counties, Los Angeles and Orange counties and parts of Riverside and San Bernardino counties, that make up the Los Angeles metropolitan area to develop consistent set of regulations for the four counties in the air basin.

The SCAQMD consists of an independent board of 12 members appointed by the Governor, Senate, and Assembly as well as representatives from cities and counties. It raises its own revenues through permitting operations as well as government funding. The Board was authorized to develop stationary source regulations and to set fines for violators; thus, the biggest polluters pay the most toward funding the air pollution control effort. In addition, the SCAQMD also receives part of the surcharge from motor vehicle registration fees to be used for air quality improvement programs involving mobile sources.

In California, the local agencies have primary authority to control emissions from stationary sources while the state agency, California Air Resources Board (CARB), is responsible for the control of air pollution from motor vehicle and consumer products, including the identification and control of toxic air contaminants. The US EPA has jurisdiction over emissions from interstate commerce: trains, planes, ships, and interstate trucking. CARB is responsible for meeting this federal mandate in all areas within the state, and can assume authority at the local level if local authorities do not develop or implement their air quality plan.

The Governor of California, with the consent of the Senate, appoints the 11 members of the Air Resources Board, five of which are from local air quality management districts. It is an independent Board when making regulatory decisions. The Board oversees a $150 million budget and a staff of nearly 1,100 employees located in northern and Southern California. In addition, the Board provides financial and technical support to 35 local districts establishing controls on industrial emissions.

Although everyone would like clean air and the process is a bipartisan effort, the economic implication of environmental regulation separated stakeholders into four groups: the legislature (both state and federal); the executive branch (the governor and his executive agencies); the regional air quality management districts; and the special interest groups (including both business, utilities, and the environmental/public health lobby).[475]

The California legislature has played a major role in forming air pollution policies over the years; this reflects the high level of interest of their constituents in air pollution issues. Most of the debate in California on air quality issues has revolved around how to trade off air pollution against other political interests. Federal representatives and senators from California take these interests to the US Congress where national air quality policy has long reflected the experience in California.

The governor and the executive branch agencies are key players in the California political system. The CARB is considered as one of the most powerful executive branch agencies with an independent source of revenue and political power. It has traditionally seen itself as a technology-forcing agency that achieves its goals through a balanced consensus-building approach that resonates with public opinion. The actual implementation and enforcement of the state implementation plan (SIP) is the responsibility of the local air pollution control districts. The SCAQMD is the responsible district in the South Coast Air Basin.

Due to the bipartisan nature of the air pollution issue, lobbying groups become increasingly important in air pollution politics. The three main factions lobbying on air pollution are: business (especially the vehicle manufacture and repair shops, and oil industries); the utility companies; and public interest groups (both environmental and public health-based). Businesses will lobby based on their concerns about the effects of environmental regulations on their competitiveness. Much of the utility lobbying has occurred along the same lines, with competitiveness and equity as primary concerns. The public interest lobby has benefited from a surge in interest in environmental and health-based issues among concerned citizens; this has been the driving force behind much of the regulatory efforts to date in California.

In summary, regulatory efforts in the South Coast Air Basin to combat air pollution have created powerful and independently funded institutions to promote significant and sometimes unpopular policies to reduce pollution in Los Angeles. Both CARB and AQMD are professionally staffed organizations that have leveraged widespread public support into institutional power to confront the air pollution problems. The most significant reduction in emissions over the years has come from technological improvement in the automotive sector, largely due to regulatory pressure and incentives placed on the auto industry. In addition, larger industrial sources have been very well controlled or have moved out of the area, and now contribute to a relatively small percent of the overall emissions in the Los Angeles area.

Air Quality Management Institutions in Mexico City Metropolitan Area

The population of the MCMA is split about equally between two different local constituencies: the Federal District (DF) and the State of Mexico (EM). It is also the nation's capital and the site of the federal government. These jurisdictions must develop a metropolitan approach to key elements of environmental management: air, water, solid waste, transportation, and land use plans. One of the major obstacles to the implementation of anti-pollution measures in the MCMA is the lack of a powerful metropolitan institutional structure.[4]

The Metropolitan Environmental Commission (*Comisión Ambiental Metropolitana*, or CAM) was created in 1996 to coordinate the policies and programs that are implemented in the metropolitan area. Permanent members of CAM consist of the federal Secretariat of

Environment and Natural Resources, the federal Secretariat of Health, the Chief of Government of the Federal District, and the Governor of the State of Mexico. The Plenary Committee includes the above and several federal cabinet secretaries and top government officials.

Every two years, the responsibility to preside over CAM changes between the DF and the EM governments. Any decision on how to organize the Commission as well as the responsibility for operating costs would go to the jurisdiction in office at the time. Frequently, the side presiding over CAM has to use its own financial resources to manage the commission; its own environmental officials also serve as CAM officials. The local government not presiding over CAM at a given moment, as well as the federal government, contribute human resources and other support to CAM operations, mainly for the specific tasks of its working groups.

The Technical Secretariat is responsible for coordinating and presenting project proposals and reports to the Plenary Committee with the support of no more than ten staff members. Staff members also have other full-time responsibilities and thus cannot devote much of their time to CAM-related activities. The operation of CAM is overseen by a Consulting Council, formed by representatives from the scientific community, specialists in environmental disciplines, members of the social and entrepreneurial sectors, and members of the Federal Congress, the DF Chamber of Representatives, and the State of Mexico Congress. However, they have met no more than twice per year recently.

The Environmental Trust Fund for the Valley of Mexico (*Fideicomiso Ambiental del Valle de México*) was created exclusively to support CAM projects. Between 1995 and 1997, the Trust Fund received money collected from the application of a surcharge on gasoline sold in the MCMA. The annual renewal of the surcharged required the approval by the Finance Ministry, which did not happen in 1998. Since then, the surcharge has not been reactivated. The Trust Fund has its own organization and rules of operation, and it is managed through an Executive Committee headed by the Finance Ministry. One representative each from CAM, governments of the DF and the State of Mexico and SEMARNAT are included. However, without income, the Trust Fund has been depleted. Other sources of funding for CAM projects include international environmental agencies, national and international financial institutions, international and national academic institutions, and foreign governments.

There are serious concerns over its current operation: one of the most important issues is that CAM does not have a specific budget for its own operation, it does not have a defined operative organizational structure as well as lack of continuity. The Technical Secretariat is appointed by the presiding government, which rotates every two years; in addition, local and federal representatives change in response to political events. These deficiencies in institutional memory cloud an integrated long-term vision of the policy requirements.

The Metropolitan Commission for Transport and Roadways (*Comisión Metropolitana de Transporte y Vialidad*, or COMETRAVI) has a mandate similar to that of CAM, but it also lacks financial resources and has no executive or regulatory powers. In 1999, COMETRAVI developed a proposal for the adoption of comprehensive integrated strategies for transportation and air quality in the MCMA. This strategy has not been incorporated into the official programs.

The lack of integration of environmental policies with transportation, urban development and land use planning is one of the most important barriers preventing sustainable environmental improvements. Another important barrier is the incomplete harmonization of environmental policies among the Federal Government, the State of Mexico and the Federal District, which results in unfair practices and inefficiency. Also, at present neither local nor federal environmental agencies have sufficient human and financial resources to efficiently carry out their environmental management activities.

Furthermore, the continuing dispersion and growth in the size of the MCMA drive the need for vehicle-miles traveled still higher. The almost totally unregulated establishment of communities on the periphery creates both mobility and environmental problems. The development of a regional planning commission with strong enforcement capability is fundamental to creating a sustainable transportation/environmental system in the MCMA.[4]

As mentioned in the Los Angeles case, air pollution knows no boundary. As a large source of emissions, the MCMA has the potential to influence air quality over a much wider region than the Valley of Mexico thus exposing larger populations in nearby cities and also affecting forests and crops. Pollutants emitted outside of the MCMA likewise may influence air quality within the Valley of Mexico. Therefore in addition to metropolitan coordination, there is an urgent need for regional coordination and planning.

To ensure continuity in the implementation of long-term strategies, it is essential that the CAM be significantly restructured and be empowered to carry out the planning, integration and implementation of metropolitan environmental policies.[4]

Other Air Quality Management Institutions

In the following section, we describe briefly the institutional structures that contribute to the success or barriers to air quality/transportation management in the other case study cities.

The regulation of pollutants in Canada occurs at the federal, provincial and municipal levels. Provincial governments are responsible for implementing air quality standards, but are free to design their own implementation plans. In order to coordinate policy at the three levels of government the Greater Toronto Area Clean Air Council was established in 2000. The Council includes representatives of the federal and provincial governments as well as 29 municipal members. For the most part its activities are limited to the coordination of policies and the sharing of best practice information. The proximity of the COR to the border makes it vulnerable to long-range transport of pollutants from the US; this entails the collaboration between the two countries in the development and implementation of cost-effective emission control strategies. The Canadian government, industries and non-governmental organizations are all taking positive steps to help reduce the level of pollution in Canada. The government has instituted emission caps, emission trading, a “drive clean” program and other initiatives aimed at reducing pollutant emissions. Many industries are also taking voluntary steps to reduce emissions, while the non-governmental organizations continue to lobby government, industry, and the public to adopt practices that will reduce the emission levels.

There are also critical institutional issues in the São Paulo metropolitan area, which has 39 municipalities, as well as three other metropolitan areas within a 100-km radius. In the future there will be five major metropolitan areas in the same radius. São Paulo is not the federal capital, as is the case with Mexico City and Santiago. It is far away from the federal government, there are problems with obtaining funds. The Brazilian Constitution of 1998 gave significant power to the municipalities, and the fragmentation makes it difficult to implement new policies for metropolitan areas. Authorities and society must overcome the institutional issue. This involves 39 mayors meeting and agreeing on the metropolitan scale planning of issues affecting transportation, land-use and the environment.

As demonstrated in the case of Bogotá, it is necessary to have a strong political will, a long-term vision, but with specific, practical actions that are able to show short-term results and assure financial sustainability. The innovative institutional scheme of public-private collaboration, the transparency in the bidding process and performance evaluation all contributed to the success of the TransMilenio Program and acceptance by the public in Bogotá.

In the case of Santiago, the ambitious Transantiago project was created to coordinate and integrate the transit control systems in the city, which consists of 34 different municipalities. The success of the program will also depend on the coordination among the different municipalities, whose mayors have pledged to work together.

In Delhi, there are 12 federal, state and local agencies responsible for transportation services with overlapping authority. There is a need for institutional reform and integration. Information needs to be disseminated to all agencies concerned and stakeholder analyses should be conducted.

In Cairo, there is frequent turnover of upper-levels administrators in government, which makes it difficult to develop and implement measures. They also need to address the lack of enforcement of current regulations, and convince the government that there is a problem.

BARRIERS TO AIR QUALITY MANAGEMENT CAPABILITIES

Financial Capacity

The most obvious differences between cities in developed nations and cities in the developing nations or countries with economies in transition are the income level and the extent of industrial development.[4] Many cities have to borrow from international lenders to finance industrial development and domestic infrastructure; environmental agenda is usually the least of their concerns.

Institutional Capacity

The success of pollution control policies depends critically on the institutional context in which the policies are implemented. Currently, there is too much fragmentation and overlapping of authority among transport and environmental agencies, as is the case in Mexico

City and Delhi. Institutional reform and the creation of integrated land use and transportation agencies—with further integration of transport and environmental agencies is necessary.

Institutional capacity is closely linked to financial capacity. Frequently, agencies find themselves with budgets inadequate to address their statutory mandate. Furthermore, there are conflicting interests among the different government institutions; interagency conflicts often need to be resolved through political means. In some countries, because of the relatively weak political standing given to environmental issues, it is difficult to address the air pollution problem in the face of other needs that are viewed as more pressing. In some countries, especially in the developing nations, since economic development is the primary priority, when programs conflict, the one more directly linked to economic development has more influence. As demonstrated in the case of Los Angeles, independently funded metropolitan institutions are essential to implement significant and sometimes unpopular policies to manage air quality.

Political Pressure for Environmental Programs

In many countries, the problem of air pollution has been addressed when the public opinion became strong enough. For example, in the United States, especially in California, the citizens have been very vocal about their desire for clean air. Much of the progress made in cleaning up the air can be attributed to public pressure to reduce the atmospheric pollutants. Similarly, Hong Kong government responded promptly to the outrage from its citizen when the air quality was deemed unacceptable. In Bogotá and Santiago, stakeholder participation provided support for radical measures adopted in the public interest. Public opinion can guarantee accountability from public officials and institutions and facilitate long-term continuity in spite of personnel changes in government agencies.

On the other hand, in some urban centers such as Mexico City, citizens tend to have a fatalistic attitude towards the pollution problem and in the past have been more reluctant to pressure the government for action. While the transport sector and other interest groups almost always have a strong lobby, consumers may not be well organized in demanding an efficient, safe, and clean transportation service and reduced air pollution. However, in Mexico City, this situation has been changing recently and NGOs are becoming more active.

In many urban centers in the developing nations, there is a correlation between the wealth of the population and their interest in the environmental issues. Mobilizing the wealthy residents was important in addressing air pollution, but it may take a long time. In Cairo, most of the population is struggling to survive; pollution is the least of their concerns. It seems that the wealthier people are aware of the magnitude of the issue in Cairo, but they may also be concerned that the infrastructure might not be able to handle this problem.

Human Resources

Many countries have come up with ideas for controlling air pollution, but a critical question is their level of technical capacity. For example, knowledgebase requirements: when trying to establish emissions standards, monitoring networks and revising emissions inventories, often there is insufficient information about the levels of emissions, etc. In many cities, especially in the developing nations, the modeling and monitoring capacity is weak and there is no research on health effects. These are essential tools for effective air quality management.

Although many international organizations are providing technical assistance to help clean up the environment, it is better if a local group tries to convince government that there is a problem, rather than a group from outside. For this reason, in the long-term, capacity building is probably more effective than short-term technical help.

Many megacities of industrializing Asia and Latin America, while experiencing rapidly rising pollution levels, are in the early stages of development of pollution abatement policies. The key requirement at this stage for these cities is building capacity for formulation, assessment, selection and implementation of pollution control policies as quickly as possible.

SUMMARY AND FUTURE OUTLOOK

Although megacities are defined as those with more than 10 million inhabitants, there are more than 100 cities worldwide that contain the same types of problems, and could even be classified as megacities. These are contiguous urban areas that are magnets to growth owing to the concentration of economic activity, services, and opportunity. Urban areas are growing faster than non-urban areas, and higher levels of pollution accompany this growth. However, owing to their dense populations, increasing wealth, and central governments, megacities can implement policies that can minimize environmental degradation, including air pollution.

Air pollution adversely affects human health through the cardiovascular and respiratory systems. Health studies throughout the world have reached similar conclusions: PM, O_3 and other air pollutants attack the cardiovascular and respiratory systems and are associated with premature mortality as well as sickness. SO_2 and NO_x are the main precursors of acid rain pollution that can harm forests, lakes, and river ecosystems, and also have been blamed for damaging buildings and statues in cities. SO_2 and NO_x can be generated hundreds of kilometers away from the areas affected by acid rain. Agricultural practices such as “slash and burn” generate smoke and precursors of photochemical smog. These emissions, added to the outflow from urban centers lead to the degradation of air quality on regional scales and also potentially affect climate.

Reducing sulfur in fuel and after-combustion exhaust treatments are strategies that have minimized sulfur air pollution in practically all cities of the developed world, as well as in many urban centers of the developing world. Much has also been learned about reducing emissions of photochemical smog precursors –NOx and VOCs—from motor vehicles and industrial activities. Efficient clean technologies have led to new car emissions of smog precursors fifty to a hundred times smaller than those from older cars without emission controls. However, appropriate maintenance of cars with emission controls, even the newest cars, is an important issue because when controls fail emissions increase. Vehicle maintenance is expensive and establishing regulations and enforcing them for large numbers of vehicles is difficult, particularly in places where the population has limited economic resources. Fine particulate matter and hazardous VOCs are emitted from diesel vehicles, especially those that are old and not well maintained. New emission control technologies have recently been developed to reduce particulate matter from diesel vehicles, although these technologies require ultra-low sulfur diesel fuel, which is more expensive to produce. New urban buses designed to use natural gas have low PM emissions, but may emit high levels of unburned or partially burned fuel. Conversions of existing vehicles to use natural gas or LPG must be done correctly if low emissions are to be achieved.

A variety of measures have been applied to reduce motor vehicle emissions besides engine improvement and exhaust controls. Some of these measures are also aimed at reducing traffic congestion, which in turn exacerbates emissions. Further, people using congested roads or living nearby have increased exposure to air pollutants. One way to reduce congestion is by limiting the circulation of vehicles. London has started doing this by charging vehicles to enter part of the city. Another example is the "no drive day" program, which, however, may have unintended consequences if not properly designed. In the Mexico City area, it appears to have induced the purchase of a second vehicle, often older and more polluting. A more effective strategy, restricting the circulation of the vehicles only during peak hours, is being implemented in Bogotá, Santiago and São Paulo.

Given the expected scale of urban population growth in the coming decades, continued growth in the number of vehicles will pose an enormous challenge in managing megacities, especially in the developing nations. Effective strategies to control vehicle growth and traffic intensity in some cities can be adopted in others facing similar challenges.

Scientific Knowledge

Air pollution science has progressed steadily in the past decades due to improvements in the ability to measure pollutants, precursors, and reactive intermediates. This information has facilitated the development of improved computer models of the complex photochemistry that cause the formation of ozone, other oxidants and secondary particulate matter. These scientific advances motivate further research to gain a better understanding of how air pollution is formed in megacities and how best to control it.

The MCMA 2003 field measurement campaign demonstrated that it is now possible to measure in real time, that is, on a time scale of seconds, the gas-phase concentrations of a variety of key intermediates in the formation of photochemical smog, as well as the size-resolved composition of suspended particles. Such highly time-resolved data allowed close correlation of photochemical pollutant precursors, intermediates and products and will lead to a better understanding of closely coupled photochemical processes. On the other hand, much remains to be learned about the complex chemical processes that characterize the atmospheric oxidation of all but the simplest hydrocarbons. Laboratory research and quantum chemical calculations need to be conducted to further elucidate these gas-phase oxidation mechanisms at a molecular level.

In addition, there is a need to better elucidate the processes that lead to the formation, chemical evolution, growth and removal of atmospheric particles –in particular those containing organic species, because of their importance for human health and climate change. Although it is well established that atmospheric particulate matter—PM_{10} and $PM_{2.5}$—have strong impacts on human health, an important gap exists in our knowledge of the chemical identity of the particles that actually do the damage. Organic chemicals such as polycyclic aromatic hydrocarbons (PAHs) adsorbed on soot, as well as some heavy metals contained in fine particles are possible culprits, although it is likely that a variety of compounds are hazardous. Further developments in laboratory and field instruments for real-time particle characterization will pay large scientific dividends. It is also not known what role physical parameters, including particle size, surface area, or particle mass play in degrading human health. Advances in health studies will require a close collaboration between epidemiologists, physiologists and atmospheric scientists.

However, we should stress that enough is known already to amply justify emission control measures aimed at reducing ambient levels of criteria air pollutants that exceed current standards. In many cities of the developing world the concentrations of many criteria pollutants are not routinely measured, even when the concentrations are known or suspected to be high. Thus, there is a pressing need to start monitoring air pollutant levels routinely in such cities.

Field measurement campaigns focused on the characterization of the outflow of air pollutants from megacities need to be carried out to assess their regional and global impacts. There is also a clear need to establish long-term measurement programs to characterize air quality on a regional to global scale. Such measurements are challenging: the relatively short atmospheric residence times of species such as ozone, NOx and aerosols (days to months) require frequent measurements and good spatial coverage, in contrast to long-lived species such as CO_2 and CFCs, whose global concentration can be characterized with less than a dozen properly located monitoring stations. A better understanding of the potential climate effects of atmospheric particles, particularly those containing black carbon or soot is also required.

Interdisciplinary Research

To address the pressing environmental problems confronting megacities, it is essential to bring together world-class national and international experts in science, engineering, economics, and other social and political sciences to engage in collaborative research that leads to both holistic assessments of the complex environmental problems and the development of practical solutions. This will necessarily involve face to-face interactions among all relevant stakeholders, including the civic leaders responsible for protecting the health of megacity populations. Cost-effective solutions to such complex problems can only be developed through consensus building.

The methodology adopted must be multidisciplinary, taking into account political, scientific, technical, social and economic aspects. The social, economic and political barriers characteristic of the megacity problem will need to be recognized and analyzed. A strategy to overcome these barriers —which might include advocacy, public pressure, education, etc.— will have to be developed jointly with the relevant stakeholders. Furthermore, various research activities, financial analysis, coordination and communication among government officials, stakeholders, and experts in the academic and industrial sectors will all be required to successfully develop and implement air quality improvement plans.

Institutional Improvement

Most urban environmental problems can only be successfully solved by establishing a strong regional authority committed to reducing pollution. Furthermore, substantial progress requires good communication with the public. Successful examples of this approach are found in Los Angeles and Bogotá. On the other hand, deficiencies in air quality management result when there is a lapse in integrating relevant metropolitan policies for transportation, land use and air quality, and a lack of connection with policies affecting population, energy supply, and other key urban factors. Strong political will is essential to develop institutional capacity, ensure that funding is available and properly allocated, and to increase local, state, and federal coordination.

Air pollution is transported from state to state and across international borders. Therefore, air quality management agencies should be given greater statutory responsibility and authority to deal with these problems in a regional context, and international coordination and collaboration should be strongly encouraged.

Regulation and Enforcement

An important outcome of the megacity case studies is the importance of enforcement of emission control strategies. Enabling legislation is important, but enforcement is also necessary. If reducing air pollution is not a priority for a megacity, it will almost surely become a worsening problem. Many developing countries have extensive regulations on pollution, which, however, all too often are not applied effectively because of the lack of proper institutions, legal systems, political will and competent governance. Unfortunately, established political and administrative institutions are usually obsolete for dealing with the problems that occur with the expansion of megacities, particularly where economic and social change is rapid. Political leadership is needed to cut through overlapping and conflicting jurisdictions and short-time horizons. Experiences in some cities (like Bogotá and Santiago) show that radical and integrated packages of transport measures, based upon management of road space and an enhanced role for high quality bus and rapid transport systems can deliver efficiency and equity and be economically, environmentally and socially sustainable. But this is not possible without strong political leadership.

Stakeholder Involvement

Over the past few decades, there have seen significant political changes with profound implications for urban areas and for the urban and global environment. There is increased pressure from the citizens for participation, accountability and transparency in government. Efforts to improve urban governance involve activities such as promoting participatory processes; developing effective partnerships with and among all stakeholders of civil society, particularly the private and community sectors. Public participation adds legitimacy to these policies and helps to bring about their success. Many policies will not work unless stakeholders have ownership and share responsibility for their implementation. Stakeholder participation can also provide support for unpopular but cost-effective measures adopted in the public interest, especially if these measures are transparent to the public. In this way the accountability of public officials and institutions can be greatly improved, and furthermore long-term continuity is facilitated in spite of frequent personnel changes in government agencies.

Capacity Building

Some of the common obstacles in the air quality management in many megacities, especially of the developing nations, include insufficient understanding of the connection between the underlying scientific, economic, and social issues, and difficulty in comprehensively addressing the problem with limited personnel, resources, and infrastructure. There is a clear need to increase the number of professionals—in government, industry, and academic institutions—with a basic understanding of the different aspects of environmental problems.

Sustainable Transportation

There is a strong linkage between air quality and the transportation sector. First, transportation emissions are the major cause of air quality problems in many large urban centers, and the trend in the megacities of the developing world is for these emissions to become the dominant source of air pollutants. Second, economic growth is closely linked to personal and freight transportation and efficient mobility, so restrictions to transportation activities, while perhaps improving air quality, could hinder economic growth. On the other hand, without any traffic control or infrastructure improvement the increasing number of vehicles will cause congestion resulting in both poor air quality, decreased mobility, and hindered economic growth.

The challenge is thus to improve air quality while ensuring personal and freight mobility. It is clear that no single strategy will suffice to achieve this difficult goal. Rather, what is required is a set of integrated strategic options involving cleaner fuels, advanced vehicle technologies, institutional change, infrastructure investment, operations improvements, and active stakeholder participation. Quantitative analysis of transportation strategies involving multi- and inter-modal networks need to be carried out, taking into account both personal mobility and freight transportation needs.

Reduction in per-vehicle emission levels resulting from new, clean technologies is often largely offset by increases in the numbers of vehicles in many large urban centers. This growth in the size of the vehicle fleet has in turn generated serious congestion and air quality problems. Growth in vehicle ownership needs to be decoupled from daily vehicle usage, an approach that requires the availability of very efficient public transportation. Historically, rapid urban public transport systems were built underground or on dedicated rail lines. A much less expensive alternative is to use surface streets and BRT systems, such as the one developed in Bogotá, where prime road space was allocated to low emission buses, resulting in reduced travel duration, improved air quality, and increased pedestrian space and bike use, while decreasing private vehicle use. Santiago de Chile has also initiated a BRT and integrated bus-metro system, reversible street directions, and land-use planning structure to significantly reduce trip duration. A BRT system is also under development in the Mexico City metropolitan area, which already has an extensive metro system.

Clean Vehicle and Fuel Technology

In terms of mobile source emissions, new vehicle technology has been responsible for enormous improvements in new vehicle emissions performance. In California, 40 years of such improvements have resulted in a slow but consistent reduction in air pollution despite the huge increase in the numbers of vehicles and vehicle miles traveled. The use of clean vehicle technologies in developing countries is occurring because vehicle emissions controls are being applied world-wide, as gasoline fuel quality has been improved through removal of lead. The next generation of new gasoline vehicle emissions control technology will depend on reducing sulfur to very low levels. Emissions from diesel trucks, motorcycles, and two-stroke engines have not progressed as rapidly. Issues such as fuel contamination and limited financial resources make dealing with pollution from these vehicles difficult. Progress is being made in some countries by fuel switching to CNG and removing two-stroke engines.

Improved Inspection and Maintenance Program

Fitting vehicles with advanced emission control technologies is not sufficient; appropriate maintenance is essential. Further, old vehicles remain in the fleet because the cost of replacement is often perceived as being too high for populations in the developing world, because the consequent public health costs are not taken into account. In fact, these countries frequently use the cast off vehicles that people in the developing world no longer want, often because the vehicle is polluting too much. This problem is particularly difficult to solve with heavy-duty vehicles, because the existing fleet is likely to remain functional for decades and cannot be ignored. Heavy-duty vehicle emissions standards are evolving, and one of the technologies of growing interest is the retrofit of oxidation catalysts with particulate traps for diesel engines. In Hong Kong, for example, 40,000 diesel vehicles were successfully retrofit with oxidation catalysts.

Appropriate maintenance and a good emissions inspection and maintenance (I/M) program may be difficult to implement, and yet the alternative is more expensive. There are several requirements for a successful I/M program: very strict enforcement, public awareness, good inspector training, and separation of testing and repair. Government enforcement and auditing is also very important.

CONCLUSION

Megacities present a major challenge for the global environment. However, as the centers of economic growth, technological advances, social dynamics, and cultural production, these urban areas also offer opportunities to manage a growing population in a sustainable way. Well-planned, densely populated settlements can reduce the need for land conversion and provide proximity to infrastructure and services. Sustainable development must include: 1) appropriate air quality management plans that include adequate monitoring capabilities for the surveillance of the environmental quality and health status of the populations; 2) adequate access to clean technologies, including the provision of training and development of extensive international information networks; and 3) improvement of data collection and assessment so that national and international decisions can be based on sound information.

Much progress has been made in combating air pollution problems in developed and some developing world megacities. However, there continue to be many areas where comprehensive solutions appear to be elusive. By learning from the experiences in other regions, government officials may be able to overcome problems that appear insurmountable. There is no single strategy for addressing air pollution problems in megacities. A mix of policy measures best suited for each cities challenges and customs will be needed to improve air quality. An important lesson learned throughout the world is that addressing air quality issues effectively requires a holistic approach: one that takes into account scientific, technical, existing infrastructure, economic, social, and political factors. A successful result will be to arrive at integrated control strategies that are effectively implemented and embraced by the public.

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REFERENCES

1. UNPD (United Nations Population Division). *World urbanization prospects, the 2003 revision*; 2004. http://www.un.org/esa/population/publications/wup2003/2003WUPHighlights.pdf.

2. Chow, J.C.; Engelbrecht, J.P.; Watson, J.G.; Wilson, W.E.; Frank, N.H.; Zhu, T. Designing monitoring networks to represent outdoor human exposure; *Chemosphere* **2002**, *49*(9), 961-978. ISI:000179483700007.

3. Molina, M.J.; Molina, L.T. 2004 *Critical Review: Megacities and Atmospheric Pollution.* J. Air Waste Manage. Assoc. (volume, page??)

4. Molina, L.T.; Molina, M.J. *Air Quality in the Mexico Megacity: An Integrated Assessment,* Molina, L.T., Molina, M.J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002.

5. The World Fact Book, CIA website < http://www.cia.gov/>

6. Nicolas Rodriquez, PEMEX Refinacion (private communication, 2004).

7. CARB (California Air Resources Board) *The 2003 California Almanac of Emissions and Air Quality*; 2003. http://www.arb.ca.gov/aqd/almanac/almanac03/almanac03.htm.

8. Statistics Canada. http://www.statcan.ca/ (accessed November 2003).

9. Ontario Ministry of Environment. *Air Quality in Ontario, 2001 Report*; Toronto, 2001.

10. ESD (Economic Survey of Delhi). *Economic Survey of Delhi 2001-02*; Planning Department, Government of National Capital Territory of Delhi, Delhi Secretariat: New Delhi, 2002.

11. Kandlikar, M.; Ramachandran, G. The causes and consequences of particulate air pollution in urban India: A synthesis of the science. *Annu. Rev. Energy Environ.* 2000, *25*, 629-84.

12. ESD (Economic Survey of Delhi). *Economic Survey of Delhi 1999–2000*; Planning Department, Government of National Capital Territory of Delhi, Delhi Secretariat: New Delhi, 2000.

13. Singh, A.; Sarin, S.M.; Shanmugam, P.; Sharma, N.; Attri, A.K.; Jain, V.K. Ozone distribution in the urban environment of Delhi during winter months; *Atmospheric Environment*, 1997, *31* (20), 3421–3427.

14. CPCB (Central Pollution Control Board). *Air quality of Delhi*. http://cpcb.delhi.nic.in/bulletin/bul.htm (accessed 2004).

15. Balachandran, S.; Meena, B.R.; Khillare, P.S. Particle size distribution and its elemental composition in the ambient air of Delhi; *Environment International* 2000, *26*, 49-54.

16. The Environmental Annual Report of 2002, China. http://www.bjepb.gov.cn/newhb/index.asp

17. Statistics Beijing. http://www.bjstats.gov.cn/english/sqsl/sqsl.htm

18. Beijing Statistical Bulletin of National Economy and Social Development in Beijing in 2003. http://www.bjstats.gov.cn/english/tjyl/tjgb/200402090012

19. Beijing Environmental Protection Bureau. http://www.bjepb.gov.cn

20. UITP Millenium Database of Towns and Regions. http://www.uitp.com/publications/index4.cfm#statistics

21. CNE (Comisión Nacional de Energía, Gobierno de Chile). http://www.cne.cl

22. Comisión Nacional del Medio Ambiente, Summary of the Air Pollution Quality of Santiago, 1997 - 2003, Santiago, Chile, (2003). http://www.conamarm.cl/propertyvalue-12242.html

23. CETESB. *Relatorio de qualidade do ar no estado de São Paulo – 2002*; CETESB: Companhia de tecnologia de saneamento ambiental de São Paulo, 2002.

24. Agência Nacional do Petróleo (ANP, Brazil). http://www.anp.gov.br/

25. Bogota Distrito Capital *Bogotá en cifras*. http://www.bogota.gov.co/bogota/decide.php?patron=1.08

26. Behrentz, E., 2003. Research Project Concept Note, *Analysis of greenhouse gas emissions in Bogotá city*, Prepared for Advance Institute on Urbanization, Emissions, and the Global Carbon Cycle, Universidad de Los Andes, Bogotá, Colombia, Environmental Science and Engineering Program, School of Public Health, University of California, Los Angeles, California, January 23, 2003. http://www.bol.ucla.edu/~ebehrent/bogota.pdf

27. DAMA, 2004. http://200.110.105.66/php/reqair.php?patron=1.02

28. Elgendy, H. *Cairo: Megacity MegaProblems*. http://www.isl.uni-karlsruhe.de/vrl/ResEng/2000/global_trends/cairo/cairo.htm

29. Bakr, M. Al-Ahram Weekly On-Line, 29th May- June 4th 2003, Issue 640. http://weekly.ahram.org.eg/2003/640/fel.htm

30. INE (Instituto Nacional de Ecología). Almanaque de Datos y Tendencias de la Calidad del Aire en Ciudades Mexicanas; JICA, INE, CENICA: Mexico, 2004.

31. Metropolitan Air Quality Network (Metropolitan Ambient Health Service) data for 2003. http://www.sesma.cl.

32. United Nations CyberSchoolBus. *Cities of today, cities of tomorrow!*; 2004. http://un.org/cyberschoolbus/habitat/projdesc.asp.

33. Gottmann, J. *Megalopolis: The Urbanized Northeastern Seaboard of the United States*; The Twentieth Century Fund: New York, 1961.

34. Birdsall, S.S.; Florin, J. *An Outline of American Geography*; 1998. http://usinfo.state.gov/products/pubs/geography/geog04.htm.

35. UNCH (United Nations Centre for Human Settlements). *State of the world's cities 2001*; United Nations Centre for Human Settlements (Habitat): Nairobi, 2001.

36. UNEP (United Nations Environmental Program). *Global Environmental Outlook 3*; Earthscan Publications, Ltd.: London, 2003.

37. Kuznets, S. Economic growth and income inequality; *Am. Econ. Rev.* **1955**, *45*(1), 1-28.

38. Levin, S. *Fragile Dominion, Complexity and the Commons*; Helix Books, Perseus Publishing, 1999.

39. World Bank. *Sustainable Transport: Priorities for Policy Reform (Development in Practice Series)*. World Bank, Washington D.C., 1998

40. Gakenheimer, R.; Molina, L.T.; Sussman, J.; Zegras, C.; Howitt, A.; Makler, J.; Lacy, R.; Slott, R.S.; Villegas, A.; Molina, M.J.; Sanchez, S. The MCMA transportation system: Mobility and air pollution, in *Air Quality in the Mexico Megacity: An Integrated Assessment*, Molina, L.T., Molina, M.J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002, pp. 213-284.

41. NRC (National Research Council). *Global Air Quality: An Imperative for Long-Term Observational Strategies*; National Academy Press: Washington, DC, 2001.

42. Crutzen, P.J. The growing urban heat and pollution island effect: Impact on chemistry and climate; *Atmos. Environ.* **2004**, *38*, 3539-3540.

43. Thundiyil, K. *Rising temperatures and expanding magacities: Improving air quality in Mexico City through urban heat island mitigation*; Master Thesis MIT, Cambridge, MA, 2003.

44. Hardoy, J.E.; Mitlin, D.; Satterthwaite, D. *Environmental Problems in Third World Cities*; Earthscan: London, 1992.

45. Hardoy, J.E.; Cairncross, S.; Satterthwaite, D. *The Poor Die Young: Housing and Health in Third World Cities*, Hardoy, J.E., Cairncross, S., Satterthwaite, D., Eds.; Earthscan: London, 1990.

46. McGranahan, G. Household environmental problems in low-income cities: An overview of problems and prospects for improvement; *Habitat International* **1993**, *17*(2), 105-121.

47. Satterthwaite, D. Sustainable cities or cities that contribute to sustainable development?; *Urban Studies* **1997**, *34*(10), 1667-1691.

48. Listorti, J.A. Is environmental health really a part of economic development - or only an afterthought? *Environ. Urbanization* **1999**, *11*, 89-100.

49. OECD-DAC. *Shaping the Urban Environment in the 21st Century: From Understanding to Action. A DAC Reference Manual on Urban Environmental Policy*; Organization for Economic Cooperation and Development: Paris, 2000.

50. Butler, B.E. Consultation with national experts: Managing contaminated land; *UNEP Industry and Environment* **1996**, *19*, 2.

51. Rees, W.E.; Wackernagel, M. *Our Ecological Footprint: Reducing Human Impact on the Earth*; New Society Publishers: Gabriola, BC, Canada, 1995.

52. WWF (World Wildlife Fund). *Living planet report*; 2002. http://www.panda.org/news_facts/publications/general/livingplanet/index.cfm.

53. UNFPA. *The state of the world population*; 2001. http://www.unfpa.org/swp/2001/english.

54. Hardoy, J.E.; Mitlin, D.; Satterthwaite, D. *Environmental Problems in an Urbanizing World*; Earthscan: London, 2001.

55. UNEP/WHO (United Nations Environmental Program/World Health Organization). *Urban Air Pollution in Megacities of the World*; Blackwell Publisher: Oxford, 1992.

56. GEMS/AIR. *Air quality management and assessment capabilities in 20 major cities*; The Monitoring and Assessment Research Center: London, 1996.

57. Carmichael, G.R.; Ferm, M.; Thongboonchoo, N.; Woo, J.H.; Chan, L.Y.; Murano, K.; Viet, P.H.; Mossberg, C.; Bala, R.; Boonjawat, J.; Upatum, P.; Mohan, M.; Adhikary, S.P.; Shrestha, A.B.; Pienaar, J.J.; Brunke, E.B.; Chen, T.; Jie, T.; Guoan, D.; Peng, L.C.; Dhiharto, S.; Harjanto, H.; Jose, A.M.; Kimani, W.; Kirouane, A.; Lacaux, J.; Richard, S.; Barturen, O.; Cerda, J.C.; Athayde, A.; Tavares, T.; Cotrina, J.S.; Bilici, E. Measurements of sulfur dioxide, ozone and ammonia concentrations in Asia, Africa, and South America using passive samplers; *Atmos. Environ.* **2003**, *37*(9-10), 1293-1308.

58. Decker, E.H.; Elliot, S.; Smith, F.A.; Blake, D.R.; Rowland, F.S. Energy and material flow through the urban environment; *Ann. Rev. Energy Environ.* **2000**, *25*, 685-740.

59. Mayer, M.; Wang, C.; Webster, M.; Prinn, R.G. Linking local air pollution to global chemistry and climate; *J. Geophys. Res.* **2000**, *105*, 22869-22896.

60. Beirle, S.; Platt, U.; Wenig, M.; Wagner, T. Weekly cycle of NO_2 by GOME measurements: a signature of anthropogenic sources; *Atmospheric Chemistry and Physics* **2003**, *3*, 2225-2232.

61. Chinkin, L.R.; Coe, D.L.; Funk, T.H.; Hafner, H.H.; Roberts, P.T.; Ryan, P.A.; Lawson, D.R. Weekday versus Weekend Activity Patterns for Ozone Precursor Emissions in California's South Coast Air Basin; *JAWMA* **2003**, 53 (7), 829-843.

62. Baldasano, J.M.; Valera, E.; Jimenez, P. Air quality data from large cities; *The Science of the Total Environment* **2003**, *307*, 141-165.

63. Beaton, S.P.; Bishop, G.A.; Stedman, D.H. Emission characteristics of Mexico City vehicles; *JAWMA* **1992**, *42*(11), 1424-1429.

64. Bishop, G.A.; Stedman, D.H.; de la Garza Castro, J.; Dávalos, F.J. On-road remote sensing of vehicle emissions in Mexico; *Enivron. Sci. Technol.* **1997**, *31*(12), 3505-3510.

65. CAM/IMP (Comisión Ambiental Metropolitana / Instituto Mexicano del Petróleo) *Auditoría Integral al Programa de Verificación Vehicular*; Report published by Comisión Ambiental Metropolitana and Instituto Mexicano del Petróleo: Mexico City, November 2000.

66. Marr, L.C.; Grogan, L.A.; Wöhrnschimmel, H.; Molina, L.T.; Molina, M.J. Vehicle traffic as a source of particulate polycyclic aromatic hydrocarbon exposure in the Mexico City Metropolitan Area; *Environ. Sci. Technol.* **2004**, *38*, 2584-2492.

67. Guizzo, E. Smog Patrol. *Technology Review*, October, 2003.

68. WHO (World Health Organization). *The World Health Report 2003: Reducing Risks, Promoting Healthy Life.* WHO, Geneva, Switzerland, 2002.

69. HEI (Health Effects Institute). *Health Effects of Outdoor Air Pollution in Developing Countries of Asia*. HEI Special Report 15, April 2004.

70. Pope, C. A.; Burnett, R. T.; Thun, M. J.; Calle, E. E.; Krewski, D.; Ito, K.; Thurston, G. D. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, *J. Am. Med. Assoc.* **2002**, *287*, 1132-1141

71. Samet, J.M.; DeMarini, D.M.; Malling., H.V. Do Airborne Particles Induce Heritable Mutations? *Science* **2004**, 304, 971-972.

72. Perera, F.P.; Rauh V,; Tsai, W.Y.; Kinney, P.; Camann, D.; Barr, D.; Bernert, T.; Garfinkel, R.; Tu, Y.H.; Diaz, D.; Dietrich, J.; Whyatt, R.M. Effects of transplacental exposure to environmental pollutants on birth outcomes in a multiethnic population; *Environ. Health Perspect.* **2003.** *111*, 201-205.

73. Selevan, S.G.; Borkovec, L.; Slott, V.L.; Zudova, Z.; Rubes, J.; Evenson, D.P.; Perreault, S.D. Semen quality and reproductive health of young Czech men exposed to seasonal air pollution; *Environ. Health Perspect.* **2000**. *108.* 887-894.

74. Somers, C.M.; McCarry, B.E.; Malek, F.; Quinn, J.S. Reduction of Particulate Air Pollution Lowers the Risk of Heritable Mutations in Mice; *Science*. **2004.** *304*, 1008-1010.

75. Lowenthal, D.H., Gertler, A.W.; Abu-Allaban, M. *Cairo Air Improvement Project: 1999 Source Attribution Study*. Final Report prepared for Chemonics International, Inc., Washington, DC, May 2001.

76. Dockery, D.W.; Pope, C.A., III; Xu, X.; Spengler, J.D.; Ware, J.H.; Fay, M.E.; Ferris, B.G.; Speizer, F.E. An association between air pollution and mortality in six U.S. cities; *N. Engl. J. Med.* **1993**, *329*(24), 1753-1759.

77. Pope, C.A.; Thun, M.J.; Namboodiri, M.M.; Dockery, D.W.; Evans, J.S.; Speizer, F.E.; Heath, C.W. Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults; *Am. J. Respir. Crit. Care Med.* **1995**, *151*(3.1), 669-674.

78. Abbey, D.E.; Nishino, N.; McDonnell, W.F.; Burchette, R.J.; Knutsen, S.F.; Beeson, W.L.; Yang, J.X. Long-term inhalable particles and other air pollutants related to mortality in nonsmokers; *Am. J. Respir. Crit Care Med.* **1999**, *159*, 373-382.

79. Krewski, D.; Burnett, R.T.; Goldberg, M.S.; Hoover, K.; Siemiatycki, J.; Jarrett, M.; Abrahamowicz, M.; White, W.H. *Particle epidemiology reanalysis project Part II: Sensitivity analysis*; Health Effects Institute: Cambridge, MA, 2000.

80. Borja-Aburto, V.H.; Loomis, D.P.; Bangdiwala, S.I.; Shy, C.M.; Rascon-Pacheco, R.A. Ozone, suspended particulates, and daily mortality in Mexico City; *Am. J. Epidemiol.* **1997**, *145*(3), 258-268.

81. Borja-Aburto, V.H.; Castillejos, M.; Gold, D.R.; Bierzwinski, S.; Loomis, D.P. Mortality and ambient fine particles in Southwest Mexico City, 1993-1995; *Environ. Health Perspect.* **1998**, *106*(12), 849-855.

82. Loomis, D.; Castillejos, M.; Gold, D.R.; McDonnell, W.; Borja-Aburto, V.H. Air pollution and infant mortality in Mexico City; *Epidemiology* **1999**, *10*(2), 118-123.

83. Castillejos, M.; Borja-Aburto, V.H.; Dockery, D.W.; Gold, D.R.; Loomis, D. Airborne coarse particles and mortality in Mexico City; *Inhal. Toxicol.* **2000**, *12*(Suppl 1), 61-72.

84. Téllez-Rojo, M.M.; Romieu, I.; Ruíz-Velasco, S.; Lezana, M.A.; Hernández-Avila, M. Daily respiratory mortality and air pollution in Mexico City: Importance of considering place of death; *Eur. Respir. J.* **2000**, *16*, 391-396.

85. Levy, J.I.; Hammitt, J.K.; Spengler, J.D. Estimating the mortality impacts of particulate matter: What can be learned from between-study variability?; *Environ. Health Perspect.* **2000**, *108*, 109-117.

86. Evans, J.; Levy, J.; Hammitt, J.; Santos-Burgoa, C.; Castillejos, M.; Caballero-Ramirez, M.; Hernandez-Avila, M.; Riojas-Rodriguez, H.; Rojas-Bracho, L.; Serrano-Trespalacios, P.; Spengler, J.D.; Suh, H. Health benefits of air pollution control, in *Air Quality in the Mexico Megacity: An Integrated Assessment*, Molina, L.T., Molina, M.J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002, pp. 105-136.

87. Ontario Medical Association. *The illness cost of air pollution in Ontario: A summary of findings*; 2000.

88. Burnett, R.T.; Cakmak, S.; Brook, J.R. The effect of the urban ambient air pollution mix on daily mortality rates in 11 Canadian cities; *Canadian J. Public Health* **1998**, *89*(3), 152-156.

89. Toronto Public Health. *Toronto air quality index: Health link analysis*; Toronto, 2001.

90. Pengley, D.; Szakolcai, A.; Birmingham, B.; Cole, D.; Muller, P.; Bailey, S.; Bell, R.; Socha, A. *Human Health Risk Assessment for Priority Air Pollutants*; McMaster Institute of Environment Health, McMaster University: Hamilton, 1997.

91. Sahsuvaroglu, T.; Jerret, M.A. *A public health assessment of mortality and hospital admissions attributed to air pollution in Hamilton*; McMaster Institute of Environment Health, McMaster University: Hamilton, 2003.

92. Pande, J.N.; Bhatta, N.; Biswas, D.; Pandey, R.M.; Ahluwalia, G.; Siddaramaiah, N.H.; Khilnani, G.C. Outdoor air pollution and emergency room visits at a hospital in Delhi; *Ind J Chest Diseases & Allied Sci* **2002**, *44*(1), 13-19.

93. Cropper, M.L.; Simon, N.B.; Alberini, A.; Sharma, P.K. *The health effects of air pollution in Delhi, India*; PRD Working Paper #1860; Policy research working paper by The World Bank, 1997.

94. Xu, X.; Gao, J.; Dockery, D.W.; Chen, Y. Air pollution and daily mortality in residential areas of Beijing, China; *Arch. Environ. Health* **1994**, *49*(4), 216-222.

95. Dong, J.; Xu, X.; Chen, Y.; Dorkery, D.W.; Jiang, J. Research on the relationship between air pollution and daily mortality in Beijing urban resident in 1990~1991; *J. Hygiene Research* **1995**, *24*(4), 212-214.

96. Zhang, J.; Song, H.; Tong, S.; Li, L.; Liu, B.; Wang, L. Ambient sulfate concentration and chronic disease mortality in Beijing; *Sci. Total Environ.* **2000**, *262*(1-2), 63-71.

97. Zhang, J.; Zhou, Q.; Xie, S.; Xie, X. Study on the association between ambient air quality and daily death in Beijing; *J. Environ. Health* **2003**, *20*(2), 75-78.

98. Chang, G.; Pan, X.; Xie, X.; Gao, Y. Time series analysis on the relationship between air pollution and daily mortality in Beijing; *J. Hygiene Research* **2003**, *32*(6), 565-568.

99. Xu, X.; Dockery, D.W.; Christiani, D.C.; Li, B.; Huang, H. Association of air pollution with hospital outpatient visits in Beijing; *Arch. Environ. Health* **1995**, *50*, 214-220.

100. Chang, G.; Wang, L.; Pan, X. Study on the association between ambient air pollutant and hospital outpatient visit or emergency room visit in Beijing; *China J. of School Doctor* **2003**, *17*(4), 295-297.

101. Wang, L.; Xu, X.; Zhou, Y.; Zhang, J.; Zeng, B.; Du, Z.; Chen, A.; Huang, X. Relationship between air pollution and changes in children’s peak expiratory flow (PEF); *J. Environ. Health* **1994**, *11*(6), 243-246.

102. Zhang, J.; Wang, L.; Pan, X. The effects of air pollution on pupil's pulmonary function in Beijing; *J. Environ. Health* **1995**, *12*(5), 206-209.

103. Xu, X.; Wang, L. Synergistic effects of air pollution and personal smoking on adult pulmonary function; *Arch. Environ. Health* **1998**, *53*, 44-53.

104. Xu, X.; Ding, H.; Wang, X. Acute effects of total suspended particles and sulfur dioxides on preterm delivery: A community-based cohort study; *Arch. Environ. Health* **1995**, *50*, 407-415.

105. Sanhueza, P.; Vargas, C.; Jiménez, J. Daily mortality in Santiago and its relationship with air pollution; *Rev. Medica de Chile* **1999**, *127*(2), 235-242.

106. Cifuentes, L.A.; Vega, J.; Köpfer, K.; Lave, L.B. Effect of the fine fraction of particulate matter versus the course mass and other pollutants on daily mortality in Santiago, Chile; *JAWMA* **2000**, *50*(8), 1287-1298.

107. Koyano, M.; Endo, O.; Katoh, M.; Valdivia, R.; Marileo, M.I.; Morita, K.; Goto, S.; Matsushita, H. Polynuclear aromatic hydrocarbon concentration and mutagenicity of airborne particles in urban air: Comparison of Tokyo area and Santiago; *J. of Health Sci.* **2002**, *48*(3), 256-262.

108. Ochoa-Acuña, H.; Roberts, S.M. An estimation of cancer risks posed by exposure to particulate matter in air in Santiago, Chile; *Toxicol. Sci.* **2003**, *72*(1), 1909.

109. Ilabaca, M.; Olaeta, I.; Campos, E.; Villaire, J.; Tellez-Rojo, M.M.; Romieu, I. Association between levels of fine particulate and emergency visits for pneumonia and other respiratory illnesses among children in Santiago, Chile; *JAWMA* **1999**, *49*(PM), PM154-PM163.

110. Cifuentes, L.A.; Bravo, M.A. *Differential Mortality Effects of PM10 by Educational Level and Residence in Santiago, Chile,* presentation at the Health Effects Institute Annual Meeting, May 1-4, 2004, Boston, MA.

111. Saldiva, P.H.N.; Lichtenfels, A.J.F.C.; Paiva, P.S.O.; Barone, I.A.; Martins, M.A.; Massad, E.; Pereira, J.C.R.; Xavier, V.P.; Singer, J.M.; Bohm, G.M. Association between air pollution and mortality due to respiratory diseases in children in São Paulo, Brazil: A preliminary report; *Environ. Res.* **1994,** *65*(2), 218-225.

112. Saldiva, P.H.N.; Pope, C.A., III; Schwartz, J.; Dockery, D.W.; Lichtenfels, A.J.F.C.; Salge, J.M.; Barone, I.; Bohm, G.M. Air pollution and mortality in elderly people: A time-series study in São Paulo, Brazil; *Arch. Environ. Health* **1995,** *50*(2), 159-163.

113. Braga, A.L.F.; Saldiva, P.H.N.; Pereira, L.A.A.; Menezes, J.J.C.; Conceicão, G.M.S.; Lin, C.A.; Zanobett, A.; Schwartz, J.; Dockery, D.W. Health effects of air pollution exposure on children and adolescents in São Paulo, Brazil; *Pediatric Pulmonology* **2001**, *31*, 106-113.

114. Saldiva, P.H.N.; King, M.; Delmonte, V.L.; Macchione, M.; Parada, M.A.C.; Daliberto, M.L.; Sakae, R.S.; Criado, P.M.; Silveira, P.S.P.; Zin,W.A.; Bohm, G.M. Respiratory

alterations due to urban air pollution: an experimental study in rats. *Environ Res.* **1992,** 57. 19-33.

115. Saldiva, P.H.N.; Pope, C.A.; Schwartz, J.; Dockery, D.W.; Lichtenfels, A.J.F.C.; Salge, J.M.; Barone, I.A.; Bohm, G.M. Air pollution and mortality in elderly people: a time series study in São Paulo, Brazil. *Arch. Environ. Health* **1995,** *50*,159-163.

116. Braga, A.L.F.; Conceição, G.M.S.; Pereira, L.A.A.; Kishi, H.S.; Pereira, J.C.R.; Andrade, M.F.; Gonçalves, F.L.T.; Saldiva, P.H.N.; Latorre, M.R.D.O. Air pollution and pediatric respiratory hospital admissions in São Paulo, *Brazil. J. Environ. Med.* **1999,** *1*, 95-102.

117 Braga, A.L.F.; Saldiva, P.H.N.; Pereira, L.A.A.; Menezes, J.J.C.; Conceição, G.M.S.; Lin, C.A.; Zanobetti, A.; Schwartz, J.; Dockery, D.W. Health effects of air pollution exposure on children and adolescents in São Paulo, Brazil. *Pediatr. Pulmonol.* **2000.**

118. Gouveia, N.; Mendonça, G.A.; Leon, A.P. Correia, J.E.M.; Washington, L.; Freitas, C.U.; Daumas, R.P.; Martins, L.C.; Giussepe, L.; Conceição, G.M.; Manerich, A.; Cruz, J.C. Air pollution and health effects in two Brazilian metropolises. *Epidemiologia e Serviços de Saúde* **2003,** *12*, 29-40.

119. Gouveia, N.; Bremner, S.; Novaes, H.M.D.; The association between air pollution and birth weight in Sao Paulo, Brazil. *Journal of Epidemiology and Community Health* **2004,** *58*, 11-17

120. Watson, J.G. Visibility: Science and regulation; *JAWMA* **2002**, *52*(6), 628-713.

121. Bergin, M.H.; Cass, G.R.; Xu, J.; Fang, C.; Zeng, L.M.; Yu, T.; Salmon, L.G.; Kiang, C.S.; Tang, X.Y.; Zhang, Y.H.; Chameides, W.L. Aerosol radiative, physical, and chemical properties in Beijing during June 1999; *J. Geophys. Res.* **2001**, *106*(D16), 17969-17980.

122. Yang, D.; Yan, P.; Xu, X. Characteristics of aerosols under dust and sand weather in Beijing; *J. Appl. Meteorol.* **2002**, *13*, 185-194.

123. Song, Y.; Tang, X. Source apportionment on fine particles in Beijing; *Environ. Sci.* **2002**, *23*(6), 11-16.

124. Health Canada. *National ambient air quality objectives for particulate matter: Aesthetic effects*; 2003. http://www.hc.sc.gc.ca/hecs-sesc/air_quality/publications/particulate_matter_exec_summary/aesthetic_effects.htm.

125. Cáceres, T.; Rubio, M.A.; Lissi, E. Rain water composition in Santiago de Chile; *Contribuciones Científicas y Tecn.* **1980**, *48*(XVII).

126. Cáceres, T.; Soto, H.; Lissi, E.; Cisternas, R. Indoor house pollution: Appliance emissions and indoor ambient concentrations; *Atmos. Environ.* **1983**, *17*(5), 1009-1013.

127. Ortiz, J.; Solezzi, S.; Préndez, M.M. Size composition of particles in the atmosphere of Santiago; *Bol. Soc. Chil. Quim.* **1982**, *27*(1), 286-289.

128. Sanhueza, E.; Lisi, E.; Rubio, M.A. Comparative study of the emission levels in two Latin American capital: Caracas and Santiago. In *5th International Congress on Pure Air*, Buenos Aires, Argentina, 1982.

129. Trier, A. Observations on inhalable atmospheric particulates in Santiago, Chile; *J. Aerosol Sci.* **1984**, *15*, 419-421.

130. Trier, A.; Silva, C. Inhalable urban atmospheric particulate matter in a semi-arid climate; *Atmos. Environ.* **1987**, *21*, 977-983.

131. Trier, A.; Horvath, H. A study of the aerosol of Santiago de Chile - II. Mass extinction, coefficients, visibilities and Angström exponents; *Atmos. Environ.* **1993**, *27A*(3), 385-395.

132. Trier, A.; Firinguetti, L. A time series investigation of visibility in an urban atmosphere; *Atmos. Environ.* **1994**, *28*(5), 991-996.

133. Horvath, H.; Catalan, L.; Trier, A. A study of aerosol of Santiago de Chile III: Light absorption measurements; *Atmos. Environ.* **1997**, *31*(22), 3737-3744.

134. Gramsch, E.; Catalán, L.; Ormeño, I.; Palma, G. Traffic and seasonal dependence of the absorption coefficient in Santiago de Chile; *Appl. Opt.* **2000**, *39*(27), 4895-4901.

135. Gramsch, E.; Catalán, L.; Ormeño, I.; Palma, G.; Oyola, P. Monitoring of the light absorption coefficient in Santiago de Chile and comparison with aerosol and elemental carbon mass; *Rev. Mex. Fis.* **2002**, *48*(3), 128-130.

136. Torriero, E.A. As Egyptians burn hay, black clouds smell like city is on fire; *Chicago Tribune* **2002**. http://www.bradenton.com/mld/bradenton/news/world/4840088.htm.

137. Tabbara, A. *Cairo's mysterious 'black cloud'*; 2003. http://middle-east-online.com/english/?id=7600=7600&format=0.

138. El-Shahawy, M.A.; Hanna, A.F. Meteorological conditions leading to air-pollution episodes in greater Cairo City (Egypt); *Geophys. Res. Abstracts* **2003**, *5*(00103). http://www.cosis.net/abstracts/EAE03/00103/EAE03-J-00103.pdf.

139. AFP (Agence France Presse). Cairo's 'black cloud' sparks debate; *Business Day* **2004**. http://www.bday.co.za/bday/content/direct/1,3523,1471013-6078-0,00.html.

140. Sirri, O. Black and still black; *Cairo Time* **2002**, *6*(38 (Nov. 28-Dec 11, 2002)). http://www.cairotimes.com/news/pollution0638.html.

141. NAPAP. *1990 Integrated Assessment Report, 24 Volumes*; National Acid Precipitation Assessment Program: Washington, D.C., 1990.

142. Galloway, J.N. Anthropogenic mobilization of sulphur and nitrogen: Immediate and delayed consequences; *Annu. Rev. Energy Environ.* **1996**, *21*, 261-292.

143. Paerl, H.W. Enhancement of marine primary productivity by nitrogen-enhanced acid rain; *Nature* **1985**, *316*, 747-749.

144. Owens, N.J.P.; Galloway, J.N.; Duce, R.A. Episodic atmospheric nitrogen deposition to oligotrophic oceans; *Nature* **1992**, *357*, 397-399.

145. Michaels, A.F.; Siegel, D.A.; Johnson, R.J.; Knap, A.H.; Galloway, J.N. Episodic inputs of atmospheric nitrogen to the Sargasso Sea: Contributions to new production and phytoplankton blooms; *Global Biogeochem. Cycles* **1993**, *7*, 339-351.

146. Stevens, C.J.; Dise, N.B.; Mountford, J.O.; Gowling, D.J. Impact of nitrogen deposition on the species richness of grasslands; *Science* **2004**, *303*, 1876-1879.

147. Kojima, M., Brandon, C., and Shah, J. J. Improving Urban Air Quality in South Asia by Reducing Emissions from Two-Stroke Engines Vehicles. *The World Bank*, Washington DC, USA, 2000.

148. Krupnick, A.; Harrington, W. Energy, Transportation, and Environment: Policy Options for Environmental Improvement. ESMAP Paper No. 224, *The World Bank*, Washington DC, USA, 2000.

149. Yienger, J. J.; Galanter, M.K.; Holloway, T.A.; Phadnis, M.J.; Guttikunda, S.K.; Carmichael, G.R.; Moxim, W.J.; Levy II, H. The episodic nature of air pollution transport from Asia to North America; *J. Geophy. Res.*, **2000**, *105*, 26931-26945.

150. Guttikunda, S.K.; Carmichael, G.R.; Calori, G.; Eck, C.; Woo, J.H. The contribution of megacities to regional sulfur pollution in Asia; *Atmos. Environ.* **2003**, *37*(1), 11-22.

151. NRC. *Rethinking the Ozone Problem in Urban and Regional Air Pollution*; National Academy Press: Washington, DC, 1991.

152. Chameides, W.L.; Kasibhatla, P.S.; Yienger, J.; Levy, H., II. Growth of continental-scale metro-agro-plexes, regional ozone pollution and world food production; *Science* **1994**, *264*, 74-77.

153. Chameides, W.L.; Hu, H.; Liu, S.C.; Bergin, M.; Zhou, X.; Mearns, L.; Wang, G.; Kiang, C.S.; Saylor, R.D.; Luo, C.; Huang, Y.; Steiner, A.; Giorgi, F. Case study of the effects of atmospheric aerosols and regional haze on agriculture: An opportunity to enhance crop yields in China through emission controls; *Proceed. Nat. Acad. Sci.* **1999**, *26*, 3626-3633.

154. Chameides, W.L.; Li, X.S.; Tang, X.Y.; Zhou, X.J.; Luo, C.; Kiang, C.S.; St.John, J.; Saylor, R.D.; Liu, S.; Lam, K.S.; Wang, T.; Giorgi, F. Is ozone pollution affecting crop yields in China? *Geophys. Res. Lett.* **1999**, *26*, 867-870.

155. Akimoto, H. Global air quality and pollution; *Science* **2003**, *302*, 1716-1719.

156. Gregg, J.W.; Jones, C.G.; Dawson, T.E. Urbanization effects on tree growth in the vicinity of New York City; *Nature* **2003**, *424*, 183-187.

157. Fenn, M.E.; Bauer, L.I.; Hernandez-Tejeda, T. *Urban Air Pollution and Forests*, Fenn, M.E., Bauer, L.I., Hernandez-Tejeda, T., Eds.; Springer: New York, 2002.

158. Cohan, D.S.; Xu, J.; Greenwald, R.; Bergin, M.H.; Chameides, W.L. Impact of atmospheric aerosol light scattering and absorption on terrestrial net primary productivity; *Global Biogeochem. Cycles* **2002**, *16*, doi:10.1029/2001GB001441.

159. Kaiser, D.P.; Quian, Y. Decreasing trends in sunshine duration over China for 1954-1998: Indication of increased haze pollution?; *Geophys. Res. Lett.* **2002**, *29*, doi:10.1029/2002GL016057.

160. Bergin, M.H.; Greenwald, R.; Xu, J.; Berta, Y.; Chameides, W.L. Influence of aerosol dry deposition on photosynthetically active available radiation to plants; *Geophys. Res. Lett.* **2001**, *28*, 3605-3608.

161. IPCC. *Climate Change 2001: The Scientific Basis*, Houghton, J.T., Ed.; Cambridge University Press: Cambridge, 2001.

162. Krüger, O.; Braßl, H. Albedo reduction by absorbing aerosols over China; *Geophys. Res. Lett.* **2004**, *31*, doi:10.1029/2003GL019111.

163. Quian, Y.; Giorgi, F. Regional climatic effects of anthropogenic aerosols? The case of southwestern China; *Geophys. Res. Lett.* **2000**, *27*, 3521-3524.

164. Menon, S.; Hansen, J.E.; Nazarenko, L.; Luo, Y. Climate effects of black carbon aerosols in China and India; *Science* **2002**, *297*(5590), 2250-2252. http://www.sciencemag.org/cgi/reprint/297/5590/2250.pdf.

165. Rosenfeld, D. Suppression of rain and snow by urban and industrial air pollution; *Science* **2000**, *287*, 1793-1796.

166. Ackerman, A.S.; Toon, O.B.; Stevens, D.E.; Heymsfield, A.J.; Ramanathan, V.; Welton, E.J. Reduction of tropical cloudiness by soot; *Science* **2000**, *288*(5468), 1042-1047.

167. UNEP (United Nations Environment Program). *North east Asian dust and sand storms growing in scale and intensity - UNEP News Release 2004/17*; 2004. http://www.unep.org/Documents.Multilingual/Default.Print.asp?DocumentID=389&ArticleID=4401&1=en.

168. Fang, X.; Li, L.; Xie, Y. Difference of air pollution during the dust storm process in Beijing; *J. Beijing Normal University (Natural Science)* **2003**, *39*, 407-411.

169. Meng, Z.; Hu, M.; Guo, X.; Li, D.; Pan, X. Studies on effects of duststorm on human health; *Chin. J. Public Health* **2003**, *19*, 471-472.

170. Berntsen, T.K.; Karlsdottir, S.; Jaffe, D.A. Influence of Asian emissions on the composition of air reaching the north western United States; *Geophys. Res. Lett.* **1999**, *26*, 2171-2174.

171. Jacob, D.J.; Logan, J.A.; Murti, P.P. Effect of rising Asian emissions on surface ozone in the United States; *Geophys. Res. Lett.* **1999**, *26*, 2175-2178.

172. Stohl, A.; Trickl, T. A textbook example of long range transport: Simultaneous observations of ozone maxima of stratospheric and North American origin in the free troposphere over Europe; *J. Geophys. Res.* **1999**, *104*, 30445-30462.

173. Yienger, J.J.; Galanter, M.; Holloway, T.A.; Phadnis, M.J.; Guttikunda, S.K.; Carmichael, G.R.; Moxim, W.J.; Levy, H. The episodic nature of air pollution transport from Asia to North America; *J. Geophys. Res.* **2000**, *105*, 26931-26945.

174. Edwards, D.P.; Lamarque, J.F.; Attie, J.L.; Emmons, L.K.; Richter, A.; Cammas, J.P.; Gille, J.C.; Francis, G.L.; Deeter, M.N.; Warner, J.; Ziskin, D.C.; Lyjak, L.V.; Drummond, J.R.; Burrows, J.P. Tropospheric ozone over the tropical Atlantic: A satellite perspective; *J. Geophys. Res.* **2003**, *108*(4237), doi:10.1029/2002JD002927.

175. NAPAP. *Acid Deposition: State of Science and Technology, Volume I - Emissions, Atmospheric Processes, and Deposition*; National Acid Precipitation Assessment Program: Washington, DC, 1991.

176. NRC. *Protecting Visibility in National Parks and Wilderness Areas*; National Academy Press, 1993.

177. Kiehl, J.T.; Schneider, T.L.; Portmann, R.W.; Solomon, S. Climate forcing due to tropospheric and stratospheric ozone; *J. Geophys. Res.* **1999**, *104*, 31239-31254.

178. Gauss, M.; Myhre, G.; Pitari, G.; Prather, M.J.; Isaksen, I.S.A.; Berntsen, T.K.; Brasseur, G.P.; Dentener, F.J.; Derwent, R.G.; Hauglustaine, D.A.; Horowitz, L.W.; Jacob, D.J.; Johnson, M.; Law, K.S.; Mickley, L.J.; Müller, J.F.; Plantevin, P.H.; Pyle, J.A.; Rogers, H.L.; Stevenson, D.S.; Sundet, J.K.; van Weele, M.; Wild, O. Radiative forcing in the 21st century due to ozone changes in the troposphere and the lower stratosphere; *J. Geophys. Res.* **2003**, *108*(D9), 4292, doi:10.1029/2002JD002624.

179. Houghton, J.T.; Ding, Y.; Griggs, D.J.; Noguer, M.; van der Linden, P.J.; Dai, X.; Maskell, K.; Johnson, C.A. *Climate Change 2001: The Scientific Basis*, Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., Eds.; Intergovernmental Panel on Climate Change, 2001.

180. Ramanathan, V.; Crutzen, P.J. New directions: Atmospheric brown clouds; *Atmos. Environ.* **2003**, *37*, 4033-4035.

181. Prinn, R.G.; Huang, J.; Weiss, R.F.; Cunnold, D.M.; Fraser, P.J.; Simmonds, P.G.; McCulloch, A.; Harth, C.; Salameh, P.; O'Doherty, S.; Wang, R.H.J.; Porter, L.; Miller, B.R. Evidence for substantial variations of atmospheric hydroxyl radicals in the past two decades; *Science* **2001**, *282*, 1882-1998.

182. Dentener, F.; Peters, W.; Krol, M.; van Weele, M.; Bergamaschi, P.; Lelieveld, J. Interannual variability and trend of CH4 lifetime as a measure for OH changes in the 1979-1993 time period; *J. Geophys. Res.* **2003**, *108*, 4442-4453. doi:10.1029/2002JD002916.

183. Bates, T.S.; Huebert, B.J.; Gras, J.L.; Griffiths, F.B.; Durkee, P.A. International Global Atmospheric Chemistry (IGAC) Project's First Aerosol Characterization Experiment (ACE 1): Overview; *J. Geophys. Res.* **1998**, *103*(D13), 16297-16318.

184. Ridley, B.A.; Robinson, E. The Mauna Loa Observatory Photochemistry Experiment; *J. Geophys. Res.* **1992**, *97*(10285).

185. Atlas, E.A.; Ridley, B.A. The Mauna Loa Observatory Photochemistry Experiment: Introduction; *J. Geophys. Res.* **1996**, *101*, 10285.

186. Atlas, E.L.; Ridley, B.A.; Cantrell, C.A. The Tropospheric Ozone Production about the Spring Equinox (TOPSE); *J. Geophys. Res.* **2003**, *108*, doi:10.1029/2002JD003172.

187. Huebert, B.J.; Bates, T.; Russell, P.B.; Shi, G.; Kim, Y.J.; Kawamura, K.; Carmichael, G.; Nakajima, T. An overview of ACE-Asia: Strategies for quantifying the relationships between Asian aerosols and their climatic impacts; *J. Geophys. Res.* **2003**, *108*, 8633-8652, doi:10.1029/2003JD003550.

188. Hoell, J.M.; Davis, D.D.; Liu, S.C.; Newell, R.; Shipham, M.; Akimoto, H.; McNeal, R.J.; Bendura, R.J.; Drewry, J.W. Pacific Exploratory Mission-West A (PEM- West A): September-October 1991; *J. Geophys. Res.* **1996**, *101*, 1641.

189. Hoell, J.M.; Davis, D.D.; Liu, S.C.; Newell, R.; Akimoto, H.; McNeal, R.J.; Bendura, R.J. The Pacific Exploratory Mission-West Phase B: February-March 1994; *J. Geophys. Res.* **1997**, *102*(28223).

190. Hoell, J.M.; Davis, D.D.; Jacob, D.J.; Rodgers, M.O.; Newell, R.E.; Fuelberg, H.E.; McNeal, R.J.; Raper, J.L.; Bendura, R.J. Pacific exploratory mission in the tropical Pacific; *J. Geophys. Res.* **1999**, *104*, 5567-5583.

191. Talbot, R.W. Chemical characteristics of continental outflow from Asia to the troposphere over the western Pacific Ocean during February-March 1994: Results from PEM-West B; *J. Geophys. Res.* **1997**, *102*(28255).

192. Raper, J.L.; Kleb, M.M.; Jacob, D.J.; Davis, D.D.; Newell, R.E.; Fuelberg, H.E.; Bendura, R.J.; Hoell, J.M.; McNeal, R.J. Pacific exploratory mission in the tropical Pacific: PEM-Tropics B, March-April 1999; *J. Geophys. Res.* **2001**, *106*, 32401-32426.

193. Jacob, D.J.; Crawford, J.; Kleb, M.M.; Connors, V.S.; Bendura, R.J.; Raper, J.L.; Sachse, G.W.; Gille, J.; Emmons, L.; Heald, J.C. Transport and chemical evolution over the Pacific (TRACE-P) mission: Design, execution, and first results; *J. Geophys. Res.* **2003**, *108*(9000), doi:10.1029/2002JD003276.

194. Davis, D.D. An assessment of western North Pacific ozone photochemistry based on springtime observations from NASA's PEM-West B (1994) and TRACE-P (2001) field studies; *J. Geophys. Res.* **2003**, *108*(8829), doi:10.1029/2002JD003232.

195. Carmichael, G.R. Regional-scale chemical transport modeling in support of intensive field experiments: Overview and analysis of the TRACE-P observations; *J. Geophys. Res.* **2003** , *108*(8823), doi:10.1029/2002JD003117.

196. Lelieveld, J.; Crutzen, P.J.; Ramanathan, V.; Andreae, M.O.; Brenninkmeijer, C.A.M.; Campos, T.; Cass, G.R.; Dickerson, R.R.; Fischer, H.; de Gouw, J.A.; Hansel, A.; Jefferson, A.; Kley, D.; de Laat, A.T.J.; Lal, S.; Lawrence, M.G.; Lobert, J.M.; Mayol-Bracero, O.L.; Mitra, A.P.; Novakov, T.; Oltmans, S.J.; Prather, K.A.; Reiner, T.; Rodhe, H.; Scheeren, H.A.; Sikka, D.; Williams, J. The Indian Ocean Experiment: Widespread air pollution from South and Southeast Asia; *Science* **2001**, *291*(5506), 1031-1036.

197. Russell, P.B.; Hobbs, P.V.; Stowe, L.L. Aerosol properties and radiative effects in the United States East Coast haze plume: An overview of the Troposphere Aerosol Radiative Forcing Observational Experiment (TARFOX); *J. Geophys. Res.* **1999**, *104*(D2), 2213-2222.

198. Prados, A.I.; Dickerson, R.R.; Doddridge, B.G.; Milne, P.A.; Moody, J.L.; Merrill, J.T. Transport of ozone and pollutants from North America to the North Atlantic Ocean during the 1996 Atmosphere/Ocean Chemistry Experiment (AEROCE) intensive; *J. Geophys. Res.* **1999**, *104*(26219).

199. Raes, F.; Bates, T.; McGovern, F.; Van Liedekerke, M. The 2nd Aerosol Characterization Experiment (ACE-2): General overview and main results; *Tellus B* **2000**, *52*, 111-125.

200. Fehsenfeld, F.C.; Daum, P.; Leaitch, W.R.; Trainer, M.; Parrish, D.D.; Hubler, G. Transport and processing of O3 and O3 precursors over the North Atlantic: An overview of the 1993 North Atlantic Regional Experiment (NARE) summer intensive; *J. Geophys. Res.* **1996**, *101*(28877).

201. Penkett, S.A.; Volz-Thomas, A.; Fehsenfeld, F.C. Preface to Special Section: North Atlantic Regional Experiment (NARE II); *J. Geophys. Res.* **1998**, *103*(13353).

202. Cowling, E.B.; Chameides, W.L.; Kiang, C.S.; Fehsenfeld, F.C.; Meagher, J.F. Introduction to special section: Southern Oxidants Study Nashville/Middle Tennessee Ozone Study; *J. Geophys. Res.* **1998**, *103*(22209).

203. Meagher, J.F.; Cowling, E.B.; Fehsenfeld, F.C.; Parkhurst, W.J. Ozone formation and transport in southeastern United States: Overview of the SOS Nashville/Middle Tennessee Ozone Study; *J. Geophys. Res.* **1998**, *103*(22213).

204. Hübler, G.; Alvarez, R.; Daum, P.; Dennis, R.; Gillani, N.; Kleinman, L.; Luke, W.; Meagher, J.; Rider, D.; Trainer, M.; Valente, R. An overview of the airborne activities during the Southern Oxidants Study (SOS) 1995 Nashville/Middle Tennessee Ozone Study; *J. Geophys. Res.* **1998**, *103*(22245).

205. Croes, B.E.; Fujita, E.M. Overview of the 1997 Southern California Ozone Study (SCOS97-NARSTO); *Atmos. Environ.* **2003**, *37*(Suppl. 2), S3-S26, doi:10.1016/S1352-2310(03)00379-0.

206. Ryerson, T.B.; Trainer, M.; Angevine, W.M.; Brock, C.A.; Dissly, R.W.; Fehsenfeld, F.C.; Frost, G.J.; Goldan, P.D.; Holloway, J.S.; Hubler, G.; Jakoubek, R.O.; Kuster, W.C.; Neuman, J.A.; Nicks, D.K., Jr.; Parrish, D.D.; Roberts, J.M.; Sueper, D.T.; Atlas, E.L.; Donnelly, S.G.; Flocke, F.; Fried, A.; Potter, W.T.; Schauffler, S.; Stroud, V.; Weinheimer, A.J.; Wert, B.P.; Wiedinmyer, C.; Alvarez, R.J.; Banta, R.M.; Darby, L.S.; Senff, C.J. Effect of petrochemical industrial emissions of reactive alkenes and NO_X on tropospheric ozone formation in Houston, Texas; *J. Geophys. Res.* **2003**, *108*(D8), ACH 8-1-ACH 8-24, doi:10.1029/2002JD003070.

207. Mallet, M.; Roger, J.C.; Despiau, S.; Dubovik, O.; Putaud, J.P. Microphysical and optical properties of aerosol particles in urban zone during ESCOMPTE; *Atmos. Res.* **2003**, *69*(1-2), 73-97.

208. Volz-Thomas, A.; Geiss, H.; Kalthoff, N. Precursor Experiment (SLOPE): Scientific background and main results; *J. Geophys. Res.* **2000**, *105*, 1553-1562.

209. Volz-Thomas, A.; Geiss, H.; Hofzumahaus, A.; Becker, K.H. Introduction to special section: Photochemistry Experiment in BERLIOZ; *J. Geophys. Res.* **2003**, *108*, doi:10/1029/2001JD002029.

210. Neftel, A.; Spirig, C.; Prevot, A.S.H.; Furger, M.; Stutz, J.; Vogel, B.; Hjorth, J. Sensitivity of photooxidant production in the Milan basin: An overview of results from a EUROTRAC-2 limitation of oxidant production field experiment; *J. Geophys. Res.* **2002**, *107*(8188), doi:10.1029/2001JD001263.

211. Winsemius, P. *Guest at Home, Reflections on Environmental Management*, Samson, H.D., Tjeenk Willink Publisher, Alphen aan den Rijn, the Netherlands. **1986**, 1-227.

212. Watson, J.G.; Chow, J.C.; DuBois, D.W.; Green, M.C.; Frank, N.H.; Pitchford, M.L. Network design principles for population-oriented monitoring of suspended particles, in *Proceedings, Health Effects of Particulate Matter in Ambient Air*, Vostal, J.J., Ed.; Air and Waste Management Association: Pittsburgh, PA, 1998, pp. 461-472.

213. Chow, J.C. Critical review: Measurement methods to determine compliance with ambient air quality standards for suspended particles; *JAWMA* **1995**, *45*(5), 320-382.

214. Blanchard, C.L. Methods for attributing ambient air pollutants to emission sources; *Annu. Rev. Energy Environ.* **1999**, *24*, 329-365.

215. Watson, J.G.; Zhu, T.; Chow, J.C.; Engelbrecht, J.P.; Fujita, E.M.; Wilson, W.E. Receptor modeling application framework for particle source apportionment; *Chemosphere* **2002**, *49*(9), 1093-1136.

216. Watson, J.G.; Chow, J.C.; Fujita, E.M. Review of volatile organic compound source apportionment by chemical mass balance; *Atmos. Environ.* **2001**, *35*(9), 1567-1584. ftp://ftp.cgenv.com/pub/downloads/Watson.pdf.

217. IPURGAP. EI-Workshop. In Integrated Program on Urban, Regional and Global Air Pollution *Workshop on Mexico Emissions Inventory*, México D.F., México, 2003. February 25-26, 2003; 2003. http://www-eaps.mit.edu/megacities/workshops/emissions/emission.html

218. NARSTO. *Workshop on Innovative Methods for Emission-Inventory Development and Evaluation, University of Texas, Austin, October 14-17, 2003*; 2004. http://www.cgen.com/Nartso/EmissionsWorkshop.html.

219. NRC (National Research Council). *Modeling Mobile Source Emissions*; National Academy Press: Washington, DC, 2000.

220. Schifter, I.; Diaz, L.; Duran, J.; Guzman, E.; Chavez, O.; Lopez-Salinas, E. Remote sensing study of emissions from motor vehicles in the metropolitan area of Mexico City; *Environ. Sci. Technol.* **2003**, *37*(2), 395-401.

221. Pokharel, S.S.; Bishop, G.A.; Stedman, D.H.; Slott, R.S. Emissions reductions as a result of automobile improvement; *Environ. Sci. Technol.* **2003**, *37*(22), 5097-5101.

222. Singer, B.C.; Harley, R.A. A fuel-based inventory of motor vehicle exhaust emissions in the Los Angeles area during summer 1997; *Atmos. Environ.* **2000**, *34*(11), 1783-1795.

223. Slott, R.S. Finding high emitters. In *Proceedings of the 14th CRC On-Road Workshop, Coordinating Research Council*, 2004.

224. Moosmüller, H.; Mazzoleni, C.; Barber, P.W.; Kuhns, H.D.; Keislar, R.E.; Watson, J.G. On-road measurement of automotive particle emissions by ultraviolet lidar and transmissometer: Instrument; *Environ. Sci. Technol.* **2003**, *37*(21), 4971-4978.

225. ARB. 2004. http://arb.ca.gov/msprog/obdprog/obdprog.htm.

226. NetworkCar. *Press Release*; 2003. http://www.networkcar.com/networkcar/pub/pressrelease013.

227. US EPA. *US EPA's Clean Air Excellence Award* ; 2003. http://www.epa.gov/air/caaac/2003awar.html.

228. Kristensson, A.; Johansson, C.; Westerholm, R.; Swietlicki, E.; Gidhagen, L.; Wideqvist, U.; Vesely, V. Real-world traffic emission factors of gases and particles measured in a roal tunnel in Stockholm, Sweden; *Atmos. Environ.* **2004**, *38*(5), 657-673.

229. Pierson, W.R.; Gertler, A.W.; Bradow, R.L. Comparison of the SCAQS tunnel study with other on-road vehicle emission data; *JAWMA* **1990**, *40*(11), 1495-1504.

230. Kirchstetter, T.W.; Singer, B.C.; Harley, R.A.; Kendall, G.R.; Traverse, M. Impact of California reformulated gasoline on motor vehicle emissions 1. Mass emission rates; *Environ. Sci. Technol.* **1999**, *33*(2), 318-328.

231. Kittelson, D.B.; Watts, W.F.; Johnson, J.P. Nanoparticle emissions on Minnesota highways; *Atmos. Environ.* **2004**, *38*(1), 9-19, doi: 10.1016/j.atmosenv.2003.09.037.

232. Jiménez, J.L.; McManus, J.B.; Shorter, J.H.; Nelson, D.D.; Zahniser, M.S.; Koplow, M.; McRae, G.J.; Kolb, C.E. Cross Road and Mobile Tunable Infrared Laser Measurements of Nitrous Oxide Emissions from Motor Vehicles, *Chemosphere: Global Change Sci.* **2000,** 2, 397-412.

233. Vogt, R.; Scheer, V.; Casati, R.; Benter, T. On-road measurement of particle emission in the exhaust plume of a diesel passenger car; *Environ. Sci. Technol.* **2003**, *37*(18), 4070-4076.

234. Tierney, G. EPA's plans to estimate the criteria air pollutant emissions of highway vehicles and off-highway equipment with MOVES. In *NARSTO Workshop on Innovative Methods for Emission Inventory Development and Evaluation*, University of Texas, Austin, 2003.

235. European Commission. *Automotive Industry*; 2004. http://www.google.com/search?q=cache:1FVM5QNKh4gJ:europa.eu.int/comm/enterprise/automotive/mveg_meetings/meetings95/note_on_iuc.pdf+EPA+PEMS&hl=en&ie=UTF-8.

236. Eisinger, M.; Burrows, J.P. Tropospheric sulfur dioxide observed by the ERS-2 GOME instrument; *Geophys. Res. Lett.* **1998**, *25*(22), 4177-4180.

237. Spichtinger, N.; Wenig, M.; James, P.; Wagner, T.; Platt, U.; Stohl, A. Satellite detection of a continental-scale plume of nitrogen oxides from boreal forest fires; *Geophys. Res. Lett.* **2001**, *28*(24), 4579-4582.

238. Wenig, M.; Spichtinger, N.; Stohl, A.; Held, G.; Beirle, S.; Wagner, T.; Jahne, B.; Platt, U. International transport of nitrogen oxide pollution plumes; *Atmos. Chem. and Physics* **2003**, *3*, 387-393.

239. Wagner, T.; Heland, J.; Zoger, M.; Platt, U. A fast H_2O total column density product from GOME - Validation with in-situ aircraft measurements; *Atmos. Chem. and Physics* **2003**, *3*, 651-663.

240. Ladstatter-Weissenmayer, A.; Heland, J.; Kormann, R.; von Kuhlmann, R.; Lawrence, M.G.; Meyer-Arnek, J.; Richter, A.; Wittrock, F.; Ziereis, H.; Burrows, J.P. Transport and build-up of tropospheric trace gases during the MINOS campaign: Comparison of GOME, in situ aircraft measurements and MATCH-MPIC-data; *Atmos. Chem. and Physics* **2003**, *3*, 1887-1902.

241. Damoah, R.; Spichtinger, N.; Forster, C.; James, P.; Mattis, I.; Wandinger, U.; Beirle, S.; Wagner, T.; Stohl, A. Around the world in 17 days - hemispheric-scale transport of forest fire smoke from Russia in May 2003; *Atmos. Chem. Physics Discussion* **2004**, *4*, 1449-1471.

242. Eckhardt, S.; Stohl, A.; Beirle, S.; Spichtinger, N.; James, P.; Forster, C.; Junker, C.; Wagner, T.; Platt, U.; Jennings, S.G. The North Atlantic Oscillation controls air pollution transport to the Arctic; *Atmos. Chem. and Physics* **2003**, *3*, 1769-1778.

243. Stohl, A.; Huntrieser, H.; Richter, A.; Beirle, S.; Cooper, O.R.; Eckhardt, S.; Forster, C.; James, P.; Spichtinger, N.; Wenig, M.; Wagner, T.; Burrows, J.P.; Platt, U. Rapid intercontinental air pollution transport associated with a meteorological bomb; *Atmos. Chem. and Physics* **2003**, *3*, 969-985.

244. Borrell, P.; Burrows, J.P.; Richter, A.; Platt, U.; Wagner, T. New directions: New developments in satellite capabilities for probing the chemistry of the troposphere; *Atmos. Environ.* **2003**, *37*, 2567-2570.

245. Vedal, S. Critical review - Ambient particles and health: Lines that divide; *JAWMA* **1997**, *47*(5), 551-581.

246. Dye, T.S.; MacDonald, C.P.; Anderson, C.B. Air quality forecasting for the SPARE the Air Program in Sacramento, California: Summary of four years of ozone forecasting. In *11th Joint Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Association*, Long Beach, CA, 2000.

247. NOAA (National Oceanic and Atmospheric Administration). *Air quality forecasting: A review of federal programs and research needs*; NOAA Aeronomy Laboratory: Boulder, CO, 2001.

248. Stockwell, W.R.; Artz, R.S.; Meagher, J.F.; Petersen, R.A.; Schere, K.L.; Grell, G.A.; Peckham, S.E.; Stein, A.F.; Pierce, R.V.; O'Sullivan, J.M.; Whung, P.Y. The scientific basis of NOAA's air quality forecasting program; *EM* **2002**(Dec.), 20-27.

249. Zolghadri, A.; Monsion, M.; Henry, D.; Marchionini, C.; Petrique, O. Development of an operational model-based warning system for tropospheric ozone concentrations in Bordeaux, France; *Environ. Modelling & Software* **2004**, *19*, 369-382.

250. Russell, A.G.; Dennis, R. NARSTO critical review of photochemical models and modeling; *Atmos. Environ.* **2000**, *34*(12-14), 2283-2324.

251. McRae, G.J.; Seinfeld, J.H. Development of a second-generation mathematical model for urban air pollution II. Evaluation of model performance; *Atmos. Environ.* **1983**, *17*, 501-522.

252. Harley, R.A.; Russell, A.G.; McRae, G.J.; Cass, G.R.; Seinfeld, J.H. Photochemical modeling of the Southern California Air Quality Study; *Enivron. Sci. Technol.* **1993**, *27*(2), 378-388.

253. West, J.J.; Zavala, M.A.; Molina, L.T.; Molina, M.J.; San Martini, F.; McRae, G.J.; Sosa-Iglesias, G.; Arriaga-Colina, J.L. Modeling ozone photochemistry and evaluation of hydrocarbon emissions in the Mexico City metropolitan area; *J. Geophys. Res.* **2004**, in press.

254. Carter, W.P.L. *Documentation of the SAPRC-99 Chemical Mechanism for VOC Reactivity Assessment*; prepared for California Air Resources Board by University of California, Riverside, 2000.

255. Griffin, R.J.; Dabdub, D.; Seinfeld, J.H. Secondary organic aerosol 1. Atmospheric chemical mechanism for production of molecular constituents; *J. Geophys. Res.* **2002**, *107*, 4332-4357.

256. Byun, D.W.; Ching, J.K.S. *Science algorithms of the EPA MODELS-3 community multiscale air quality (CMAQ) modeling system*; EPA/600/R-99/030; Office of Research and Development, U.S. Environmental Protection Agency: Washington, DC, 1999.

257. Gery, M.W.; Whitten, G.Z.; Killus, J.P.; Dodge, M.C. A photochemical kinetics mechanism for urban and regional scale computer modeling; *J. Geophys. Res.* **1989**, *94*, 12925-12956.

258. Stockwell, W.R.; Middleton, P.; Chang, J.S.; Tang, X. The second generation regional acid deposition model chemical mechanism for regional air quality modeling; *J. Geophys. Res.* **1990**, *95*, 16343-16367.

259. ENVIRON International Corporation. *User's Guide: Comprehensive Air Quality Model with Extensions (CAMx) v4.00*; 2003. http://www.camx.com.

260. Reynolds, S.D.; Roth, P.M.; Seinfeld, J.H. Mathematical modeling of photochemical air pollution: I-Formulation of the model; *Atmos. Environ.* **1973**, *7*, 1033-1061.

261. Reynolds, S.D.; Liu, M.K.; Hecht, T.A.; Roth, P.M.; Seinfeld, J.H. Mathematical modeling of photochemical air pollution—III. Evaluation of the model; *Atmos. Environ.* **1974**, *8*, 563-596.

262. Roth, P.M.; Roberts, P.W.; Liu, M.K.; Reynolds, S.D.; Seinfeld, J.H. Mathematical modeling of photochemical air pollution - II. A model and inventory of pollutant emissions; *Atmos. Environ.* **1974**, *8*, 97-130.

263. Pleim, J.E.; Chang, J.S. A non-local closure model for vertical mixing in the convective boundary layer. *Atmos. Environ.*, **1992**, 26A, 965-981.

264. Grell, G.A.; Emeis, S.; Stockwell, W.R.; Schoenemeyer, T.; Forkel, R.; Michalakes, J.; Knoche, R.; Seidl, W. Application of a multiscale, coupled MM5/chemistry model to the complex terrain of the VOTALP valley campaign; *Atmos. Environ.* **2000**, *34*, 1435-1453.

265. Seaman, N.L.; Stauffer, D.R.; Lario-Gibbs, A.M. A multiscale four-dimensional data assimilation system applied in the San Joaquin Valley during SARMAP. Part I: Modeling design and basic performance characteristics; *Appl. Meteorol.* **1995**, *34*(8), 1739-1761.

266. Nenes, A.; Pandis, S.N.; Pilinis, C. ISORROPIA: A new thermodynamic equilibrium model for multiphase multicomponent inorganic aerosols; *Aquatic Geochemistry* **1998**, *4*, 123-152.

267. Kim, Y.P.; Seinfeld, J.H.; Saxena, P. Atmospheric gas-aerosol equilibrium II. Analysis of common approximations and activity coefficient calculation methods; *Aerosol Sci. Technol.* **1993**, *19*(2), 182-198.

268. Ackermann, I.J.; Hass, H.; Memmesheimer, M.; Ebel, A.; Binkowski, F.S.; Shankar, U. Modal aerosol dynamics model for Europe: Development and first applications; *Atmos. Environ.* **1998**, *32*(17), 2981-3000.

269. Koo, B.; Ansari, A.S.; Pandis, S.N. Integrated approaches to modeling the organic and inorganic atmospheric aerosol components; *Atmos. Environ.* **2003**, *37*(34), 4757-4768.

270. Schell, B.; Ackermann, I.J.; Hass, H.; Binkowski, F.S.; Ebel, A. Modeling the formation of secondary organic aerosol within a comprehensive air quality model system; *J. Geophys. Res.* **2001**, *106*(D22), 28275-28293.

271. Jenkin, M.E.; Saunders, S.M.; Wagner, V.; Pilling, M.J. Protocol for the development of the Master Chemical Mechanism, MCM v3 (Part B): Tropospheric degradation of aromatic volatile organic compounds; *Atmos. Chem. and Physics* **2003**, *3*, 181-193.

272. Saunders, S.M.; Jenkin, M.E.; Derwent, R.G.; Pilling, M.J. Protocol for the development of the Master Chemical Mechanism, MCM v3 (Part A): Tropospheric degradation of non-aromatic volatile organic compounds; *Atmos. Chem. and Physics* **2003**, *3*, 161-180.

273. Volkamer, R.; Platt, U.; Wirtz, K. Primary and secondary glyoxal formation from aromatics: Experimental evidence for the bicycloalkyl-radical pathway from benzene, toluene, and p-xylene; *J. Phys. Chem.* **2001**, *105*, 7865-7874.

274. Volkamer, R.; Klotz, B.; Barnes, I.; Imamura, T.; Wirtz, K.; Washida, N.; Becker, K.H.; Platt, U. OH-initiated oxidation of benzene I. Phenol formation under atmospheric conditions; *Phys. Chem. Chemical Phys.* **2002**, *4*, 1598-1610.

275. Bethel, H.L.; Arey, J.; Atkinson, R. Products of the OH radical-initiated reaction of 3-hexene-2,5-dione; *Environ. Sci. Technol.* **2001**, *35*(22), 4477-4480.

276. Klotz, B.; Volkamer, R.; Hurley, M.D.; Anderson, M.P.S.; Nielsen, O.J.; Barnes, I.; Imamura, T.; Wirtz, K.; Becker, K.H.; Platt, U.; Wallington, T.J.; Washida, N. OH-initiated oxidation of benzene Part II. Influence of elevated NO_X concentrations; *Phys. Chem. Chemical Phys.* **2002**, *4*, 4399-4411.

277. Calvert, J.G.; Atkinson, R.; Becker, K.H.; Kamens, R.H.; Seinfeld, J.H.; Wallington, T.J.; Yarwood, G. *The Mechanisms of Atmospheric Oxidation of Aromatic Hydrocarbons*; Oxford University Press: Oxford, 2002.

278. Olariu, R.I.; Klotz, B.; Barnes, I.; Becker, K.H.; Mocanu, R. FT-IR study of the ring-retaining products from the reaction of OH radicals with phenol, o-, m-, and p-cresol; *Atmos. Environ.* **2002**, *36*, 3685-3697.

279. Bloss, C.; Wagner, V.; Jenkin, M.E.; Volkamer, R.; Bloss, W.J.; Lee, J.D.; Heard, D.E.; Wirtz, K.; Martin-Reviejo, M.; Rea, G.; Wenger, J.C.; Pilling, M.J. Development of a detailed chemical mechanism (MCMv3.1) for the atmospheric oxidation of aromatic hydrocarbons; *Atmospheric Chemistry and Physics Discussion* **2004**, submitted.

280. Bloss, C.; Wagner, V.; Bonzanini, A.; Jenkin, M.E.; Wirtz, K.; Martin-Reviejo, M.; Pilling, M.J. Evaluation of detailed aromatic mechanisms (MCMv3 and MCMv3.1) against environmental chamber data; *Atmospheric Chemistry and Physics Discussion* **2004**, submitted.

281. Wagner V, Jenkin ME, Saunders SM, Stanton J, Wirtz K, Pilling MJ (2003) Modelling of the photooxidation of toluene: conceptual ideas for validating detailed mechanisms. *Atmospheric Chemistry and Physics* **3,** 89-106.

282. Grell, G.A.; Dudhia, J.; Stauffer, D.R. *A description of the fifth-generation Penn State/NCAR mesoscale model (MM5)*; NCAR Tech. Note NCAR/TN-398+STR; Natl. Cent. for Atmos. Res.: Boulder, CO, 1994.

283. Seaman, N.L. Meteorological modeling for air-quality assessments; *Atmos. Environ.* **2000**, *34*(12-14), 2231-2259.

284. Scire, J.S.; Robe, F.R.; Fernau, M.E.; Yamartino, R.J. *A user's guide for the CALMET meteorological model (version 5)*; Earth Tech, Inc.: Concord, MA, 2000. http://www.src.com.

285. Pielke, R.A.; Cotton, W.R.; Walko, R.L.; Tremback, C.J.; Lyons, W.A.; Grasso, L.D.; Nicholls, M.E.; Moran, M.D.; Wesley, D.A.; Lee, T.J.; Copeland, J.H. A comprehensive meteorological modeling system -RAMS; *Meteorol. Atmos. Phys.* **1992**, *49*, 69-91.

286. Martilli, A.; Clappier, A.; Rotach, M.W. An urban surface exchange parameterisation for mesoscale models; *bound lay met* **2002**, *104*(2), 261-304.

287. Michalakes, J.; Chen, S.; Dudhia, J.; Hart, L.; Klemp, J.; Middlecoff, J.; Skamarock, W. Development of a next generation regional weather research and forecast model. In *Developments in Teracomputing: Proceedings of the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology 2001*, 2001.

288. Madronich, S. The Tropospheric Visible Ultra-violet (TUV) model web page; National Center for Atmospheric Research, Boulder, CO, **2002**. http://www.acd.ucar.edu/TUV/.

289. Castro, T.; Madronich, S.; Rivale, S.; Mar, B. The influence of aerosols on photochemical smog in Mexico City. *Atmos. Environ*. **2001**, 35, 1765-1772.

290. Walsh, M.P. Motor Vehicle Pollution in China: An Urban Challenge in *China's Urban Transport Development Strategy* (eds.) Stephen Stares and Liu Zhi, World Bank Discussion Paper 352. World Bank. Washington, D.C., 1998.

291. Han, W.J.; Haq, G.; Kim, C.; Gopalan, H.; Lee, J.H.; Schwela, D.. R*egional Action Plans for Urban Air Quality Management in Asia*. 2002. UNEP/WHO Program Paper.

292. Bose, R.K.; Nesamani, K.S. *Urban Transport, Energy and Environment: A case of Delhi.* Tata Energy Research Institute, 2000.

293. Lakshmanan, T.R. Asian Megacities Experience. In Report of the Seventh Workshop on Mexico City Air Quality, January 18-21, 2004, Mexico City, Mexico; MIT-IPURGAP, 2004.

294. Lloyd, A.C.; Cackette, T.A. 2001 Critical review - Diesel engines: Environmental impact and control; *JAWMA* **2001**, *51*(6), 809-847.

295. NRC (National Research Council of the National Academies). 2004. Air Quality Management in the United States, January 2004, The National Academy Press, Washington, D.C.

296. Fairley, P. Hybrids' rising sun: Gas-electric cars are transforming the auto industry. Toyota's head start has Detroit scrambling to catch up; *Technology Review* **2004**(April).

297. Mostashari, A. Design of robust emission reduction strategies for road-based public transportation in the Mexico City Metropolitan Area; Master Thesis MIT, 2003.

298. Wald, M.L. Questions about Hidrogen Economy; *Scientific American*, May 2004, 66-73.

299. US DOE. *Hydrogen fuel*; 2004. http://www.eere.energy.gov/hydrogenfuel/.

300. DeCicco, J.M. *Fuel cell vehicles: Technology, market, and policy issues*; SAE Research Report RR-010; Society of Automotive Engineers, 2001.

301. Weiss, M.A.; Heywood, J.B.; Drake, E.M.; Schafer, A.; AuYeung, F.F. *On the road in 2020: A life-cycle analysis of new automobile technologies*; MIT EL 00-003; Massachusetts Institute of Technology, Energy Laboratory: Cambridge, MA, 2000. http://web.mit.edu/energylab/www/pubs/el00-003.pdf.

302. AQMD (South Coast Air Quality Management District). *Response to Joseph Romm's op-ed article in Los Angeles Times on March 28, 2004*; 2004. http://www.aqmd.gov/news1/2004/response_to_joseph_romm.html.

303. Chow, J.C. 2001 Critical review discussion - Diesel engines: Environmental impact and control; *JAWMA* **2001**, *51*(9), 1258-1270.

304. ICCT (International Council for Clean Transportation). *Sulfur Statement, June 3, 2003*; 2003. http://www.cleantransportcouncil.org/index.php.

305. United States Environmental Protection Agency. *Deposition of air pollutants to the great waters*; EPA-453/R-00-005; Office of Air Quality Planning and Standards: Research Triangle Park, NC, 2000.

306. CSE (Center for Science and Environment). *Need for a technological leapfrog in Asia for clean air*; 2004. http://www.cseindia.org/aboutus/press_releases/press_20040330.htm.

307. Nguyen, H.T.; Takenaka, N.; Bandow, H.; Maeda, Y.; de Oliva, S.T.; Botelho, M.M.F.; Tavares, T.M. Atmospheric alcohols and aldehydes concentrations measured in Osaka, Japan and in Sao Paulo, Brazil; *Atmos. Environ.* **2001**, *35*, 3075-3083.

308. Harrington, W.; Morgenstern, R.D. Economic incentives versus command and control. What's the best approach for solving environmental problems? *Resources for the Future* **2004** (Fall/Winter).

309. Ellerman, A.D.; Joskow, P.L.; Schmalensee, R.; Montero, J.P.; Bailey, E.M. *Markets for Clean Air: The U.S. Acid Rain Program*; Cambridge University Press: Cambridge, UK, 2000.

310. Wiener, J. International emissions trading in climate policy addressed by new issues; *Resources for the Future* **1997** (October).

311. SCAQMD (South Coast Air Quality Management District). *Annual RECLAIM audit report for the 2001 compliance year*; 2003. http://www.aqmd.gov/hb/030336a.html

312. London Assembly Transport Committee. *Congestion charging: A first review February 2004*; Greater London Authority: London, 2004. http://london.gov.uk/assembly/reports/transport/congestion_charging_feb04.pdf.

313. TTI. Highway congestion worsens: Traffic solutions and impacts examined; *Texas Transportation Researcher* **2003**, *39*(4), 2-3.

314. Santos, G. *Road pricing on the basis of congestion costs: Consistent results from two historic UK towns*; Transportation Research Board, 1999.

315. AQMD *Historic Ozone Air Quality Trends*, 2004. http://www.aqmd.gov/smog/o3trend.html.

316. AQMD (Los Angeles County Air Pollution Control District). 1997. *The Southland's War on Smog: Fifty Years of Progress Toward Clean Air.* Published May 1997. http://www.aqmd.gov/news1/marchcov.html

317. Califonria Air Resources Board, CARB website, http://www.arb.ca.gov

318. South Coast Air Quality Management District, AQMD website, http://www.aqmd.gov

319. Lezama, J.L.; Favela, R.; Galindo, L.M.; Ibarrarán, M.E.; Sánchez, S.; Molina, L.T. Forces driving pollutant emissions in the MCMA, in *Air Quality in the Mexico Megacity: An Integrated Assessment*, Molina, L.T., Molina, M.J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002, pp. 61-104.

320. Garza, G.; Ruiz, C. La ciudad de México en el sistema urbano nacional, in *La Ciudad de México en el fin del Segundo Milenio*; El Colegio de México: Mexico, 2000.

321. Garza, G. *La Ciudad de México en el fin del Segundo Milenio*; El Colegio de México: Mexico, 2000.

322. INEGI (Instituto Nacional de Estadistica, G.e.I. *Resultados preliminares del censo general de población y vivienda*; Mexico, 2000.

323. Ward, P. *Mexico City*; John Wiley and Sons: New York, 1998.

324. Colorado AQCC (Colorado Air Quality Control Commission). *Report to the General Assembly on Motor Vehicle Emissions Adjustment and Repair*; 1998.

325. Beaton, S.P.; Bishop, G.A.; Stedman, D.H. Emission characteristics of Mexico City vehicles; *JAWMA* **1992**, *42*(11), 1424-1429.

326. Garza, G. Uncontrolled air pollution in Mexico City; *Cities* **1996**, *13*(5), 315-328.

327. Bossert, J. E. (1997) An investigation of flow regimes affecting the Mexico City region, *Journal of Applied Meteorology*, 36: 119-140.

328. Fast, J.D.; Zhong, S. Meteorological factors associated with inhomogeneous ozone concentrations within the Mexico City basin; *J. Geophys. Res.* **1998**, *103*(D15), 18927-18946.

329. Doran, J.C.; Abbott, J.L.; Archuleta, J.; Bian, X.; Chow, J.C.; Coulter, R.L.; de Wekker, S.F.J.; Edgerton, S.A.; Fernandez, A.; Fast, J.D.; Hubbe, J.M.; King, C.W.; Langley, D.; Leach, J.M.; Lee, J.T.; Martin, T.J.; Martinez, D.; Martinez, J.L.; Mercado, G.; Mora, V.; Mulhearn, M.; Pena, J.L.; Petty, R.; Porch, W.M.; Russell, C.; Salas, R.; Shannon, J.D.; Shaw, W.J.; Sosa, G.; Watson, J.G.; Templeman, B.; White, R.; Whiteman, C.D.; Wolfe, D. The IMADA-AVER boundary layer experiment in the Mexico City area; *Bull. Am. Meteor. Soc.* **1998**, *79*(11), 2497-2508.

330. Whiteman, C.D.; Zhong, S.; Bian, X.; Fast, J.D.; Doran, J.C. Boundary layer evolution and regional-scale diurnal circulations over the Mexico basin and Mexican plateau; *J. Geophys. Res.* **2000**, *105*(D8), 10081-10102.

331. Molina, M.J.; Molina, L.T.; West, J.; Sosa, G.; Sheinbaum-Pardo, C.; San-Martini, F.; Zavala, M.A.; McRae, G. Air pollution science in the MCMA: Understanding source-receptor relationships through emissions inventories, measurements, and modeling, in *Air Quality in the Mexico Megacity: An Integrated Assessment*, Molina, L.T., Molina, M.J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002, pp. 137-202.

332. JICA (Japan International Cooperation Agency). *The study on air pollution control plan in the Federal District, Final Report*; JICA in collaboration with Departamento del Distrito Federal: Mexico City, 1988.

333. JICA (Japan International Cooperation Agency). *The study on air pollution control plan of stationary sources in the Metropolitan Area of the city of Mexico, Final Report*; JICA in collaboration with Departamento del Distrito Federal: Mexico City, 1991.

334. DDF (Departamento del Distrito Federal). *Programa integral contra la contaminación atmosférica: un compromiso común (PICCA)*; Departamento del Distrito Federal: Mexico City, 1990.

335. Fujita, E.M.; Croes, B.E.; Bennett, C.L.; Lawson, D.R.; Lurmann, F.W.; Main, H.H. Comparison of emission inventory and ambient concentration ratios of CO, NMOG, and NO_x in California's South Coast Air Basin; *JAWMA* **1992**, *42*(3), 264-276.

336. Fujita, E.M.; Watson, J.G.; Chow, J.C.; Lu, Z. Validation of the chemical mass balance receptor model applied to hydrocarbon source apportionment in the Southern California Air Quality Study; *Enivron. Sci. Technol.* **1994**, *28*(9), 1633-1649.

337. Fujita, E.M.; Watson, J.G.; Chow, J.C.; Magliano, K.L. Receptor model and emissions inventory source apportionments of nonmethane organic gases in California's San Joaquin Valley and San Francisco Bay Area; *Atmos. Environ.* **1995**, *29*(21), 3019-3035.

338. DDF (Departamento del Distrito Federal, G.d.E.d.M.S.d.M.A.R.N.y.P.a.S.d.S. *Programa para mejorar la calidad del aire en el Valle de México, 1995-2000 (PROAIRE)*; Mexico City, 1996.

339. INE (Instituto Nacional de Ecologia). *Segundo informe sobre la Calidad del aire en Ciudades Mexicanas*; 1998.

340. CAM (Comisión Ambiental Metropolitana). *Inventario de Emisiones 1996 de la Zona Metropolitana del Valle México*; CAM: Mexico City, 1999.

341. CAM (Comisión Ambiental Metropolitana). *Inventario de Emisiones 1998 de la Zona Metropolitana del Valle México. Preliminary version (reported in August, 2001)*; CAM: Mexico City, 2001.

342. CAM (Comisión Ambiental Metropolitana). *Inventario de Emisiones de la Zona Metropolitana del Valle de México*; CAM: Mexico City, 2003.

343. Bravo, A.H.; Viniegra, O.G. Informe preliminar acerca de la polución atmosférica en la Ciudad de México. In *Memorias de la XII Reunión Anual de la Sociedad Mexicana de Higiene Industrial*; Puebla, Mexico, 1958.

344. Bravo, A.H. *La Contaminación en México*; Ed. Fundación Universo Veintiuno: México D.F., 1987.

345. PAHO (Pan American Health Organization) *Red Panamericana de Muestreo de la Contaminación del Aire: Informe Final 1967-1980*; PAHO: Perú, 1982.

346. DDF (Departamento del Distrito Federal) *Programa integral contra la contaminación atmosférica: un compromiso común (PICCA)*; Departamento del Distrito Federal: Mexico City, 1990.

347. DDF (Departamento del Distrito Federal, Gobierno del Estado de México, Secretaría de Medio Ambiente Recursos Naturales y Pesca, and Secretaría de Salud) *Programa para*

mejorar la calidad del aire en el Valle de México, 1995-2000 (PROAIRE); Mexico City, 1996.

348. Rodríguez, N. Mexican Perspective on Fuel and Technology. In *Summary Report of the IUAPPA Joint Seminar on Reducing the Impact of Vehicles on Air and Environment Quality in Cities, January 22–23, 2004, Mexico City, Mexico*; MIT-IPURGAP: Cambridge, MA, 2004b; pp 24.

349. Natural Resources Canada. *Land and freshwater areas in Canada, 2001*; 2001. http://atlas.gc.ca/site/english/facts/surfareas.html.

350. Statistics Canada. *Canada's population, preliminary estimates*; 2003. http://www.statcan.ca/Daily/English/030625/d030625e.htm.

351. Statistics Canada. *Population density, 2001 census of Canada*; 2003. http://geodepot.statcan.ca/Diss/Maps/ThematicMaps/population/National/pop_dens_colour_e.pdf.

352. City of Toronto. *Strategic Directions: City of Toronto's Environmental Plan*; City of Toronto, 2000.

353. Phillips, D. *The climates of Canada*; Environment Canada, 1990.

354. Smith, J.; Lavender, B.; Auld, H.; Broadhurst, D.; Bullock, T. *Adapting to climate variability and change in Ontario*; Environment Canada, 1998.

355. Environment Canada. What *is the Air Quality Index?* http://www.ns.ec.gc.ca/airquality/whatis_index_e.html (accessed Nov 2003).

356. Toronto Public Health. *Toronto's Air: Let's Make It Healthy*, Toronto, Ontario 2000.

357. Ontario Ministry of Environment. *Air quality Ontario*; 2003. http://www.airqualityontario.com.

358. Ontario Ministry of Environment. *Air quality in Ontario, 2001 report*; Toronto, 2001.

359. Chtcherbakov, A. *Personal Communication*; Ontario Ministry of Environment, 2003.

360. Lee, P.K.H.; Brook, J.R.; Dabek-Zlotorzynska, E.; Mabury, S.A. Identification of the major sources contributing to $PM_{2.5}$ observed in Toronto; *Environ. Sci. Technol.* **2003**, *37*(21), 4831-4840.

361. Government of Canada (2003) *Clean Air in Canada Progress Report on Particulate Matter and Ozone,* Ottawa, August.

362. Simmons, G. Canadian Regulation of Air Pollution from Motor Vehicles, *Toronto: Greenpeace and Sierra Legal Defense Fund*, 2002.

363. Transport Canada. *Transportation in Canada 2002 Annual Report*, Ottawa: Minister of Public Works and Government Services, 2002.

364. Ontario Public Health Association. Fueling Clean Air: Municipal Fuel Purchasing Policies that Reduce Emissions Contributing to Poor Air Quality and Climate Change, 2003.

365. Ontario Ministry of Environment News Release, August 7, 2002.

366. Ontario Ministry of Environment News Release, December 21, 2003

367. Ogilvie, K. *Air Water and Soil Quality: Issue Paper no. 2*, Toronto: Neptis Foundation. 2003.

368. Ontario Ministry of Environment. Ontario Regulation made under the Environmental Protection Act: Emissions Trading, available at http://www.ene.gov.on.ca/envision/air/etr/index.htm,

369. Government of Ontario, Discussion Paper on Ontario's Clean Air Plan for Industry: Developing NOx and SO_2 Emissions Limits. 2002.

370. Ontario Ministry of Environment. *Ontario's Anti-Smog Action Plan.* **2002**, 1-38.

371. Pollution Probe. *Pollution Probe's Clean Air Campaign and Commute*. http://www.pollutionprobe.org/whatwedo /Cleanaircommute.htm.

372. Clean Air Foundation. *Clean Air Foundation Programs*. http://www.cleanairfoundation.org/clean_air/caf_eng /html/clean_air_programs.asp.

373. Varshney, C.K.; Aggarwal, M. Ozone pollution in the urban environment of Delhi; *Atmos. Environ.* **1992**, *26B*, 291-294.

374. Singh, A.; Sarin, S.M.; Shanmugam, P.; Sharma, N.; Attri, A.K.; Jain, V.K. Ozone distribution in the urban environment of Delhi during winter months; *Atmos. Environ.* **1997**, *31*(20), 3421-3427.

375. ESD (Economic Survey of Delhi). *Economic survey of Delhi 2001-02*; Planning Department, Government of National Capital Territory of Delhi, Delhi Secretariat: New Delhi, 2002.

376. Tully, M. *Ram Chandler's Story*; Penguine Books Ltd.: London, 1995.

377. Gurjar, B.R.; Lelieveld, J.; van Aardenne, J. Air quality and emission trends in a megacity: The case of Delhi. In *Proceedings of the 4th International Conference on Urban Air Quality: Measurement, Modelling and Management, Charles University,* Sokhi, R.S., Brechler, J., Eds., Prague Czech Republic, **2003**, pp. 187-190.

378. DOE (Department of Environment). *Towards cleaner air: A case study of Delhi*; Department of Environment, Government of NCT of Delhi and Delhi Pollution Control Committee: New Delhi, 2003.

379. Varshney, C.K.; Padhy, P.K. Total volatile organic compounds in the urban environment of Delhi; *JAWMA* **1998**, *48*(5), 448-453.

380. CPCB (Central Pollution Control Board). *Air quality in Delhi (1989-2000)*; Central Pollution Control Board, 2001.

381. TERI (The Energy and Resources Institute). *Review of past and on-going work on urban air quality in India*; TERI Report No. 2001EE41; TERI: New Delhi, 2001.

382. CPCB (Central Pollution Control Board). *Air quality of Delhi*; 2004. http://cpcb.delhi.nic.in/bulletin/bul.htm.

383. TERI (The Energy and Resources Institute). *State of environment report for Delhi 2001*; TERI Report No. 2000EE65; TERI: New Delhi, 2001.

384. Singh, M.P.; Goyal, P.; Basu, S.; Agarwal, P.; Nigam, S.; Kumari, M.; Panwar, T.S. Predicted and measured concentrations of traffic carbon monoxide over Delhi; *Atmos. Environ.* **1990**, *24A*(4), 801-810.

385. Singh, M.P.; Goyal, P.; Panwar, T.S.; Agarwal, P.; Nigam, S. Predicted and observed concentrations of SO_2, SPM and NO_X over Delhi; *Atmos. Environ.* **1990**, *24A*(4), 783-788.

386. CPCB (Central Pollution Control Board). *Pollution statistics*; Central Pollution Control Board: New Delhi, 1994.

387. Saxena, S.; Dayal, V. Total exposure as a basis for the economic valuation of air pollution in India; *Energy Environ. Monitor* **1997**, *13*(2), 93-102.

388. Mitra, A.P. Introductory comments: Methodology for producing inventory of GHGs and other pollutants. In *Proceedings of Workshop of IGES/APN Mega-city Project, January 23-25, 2002, Kitakyushu, Japan*, 2002.

389. AFPR (Auto Fuel Policy Report). *Report of the expert committee on Auto Fuel Policy*; Ministry of Petroleum and Gas, Govt. of India: New Delhi, 2002.

390. Sharma, C.; Dasgupta, A.; Mitra, A.P. Future scenarios of inventories of GHGs and urban pollutants from Delhi and Calcutta. In *Proceedings of workshops of IGES.APN mega-city project, January 23-25, 2002, Kitakyushu, Japan*, 2002.

391. Sharma, C.; Dasgupta, A.; Mitra, A.P. Inventory of GHGs and other urban pollutants from agriculture and waste sectors in Delhi and Calcutta. In *Proceedings of workshops of IGES.APN mega-city project, January 23-25, 2002, Kitakyushu, Japan*, 2002.

392. Sharma, C.; Dasgupta, A.; Mitra, A.P. Inventory of GHGs and other urban pollutants from transport sector in Delhi and Calcutta. In *Proceedings of workshops of IGES.APN mega-city project, January 23-25, 2002, Kitakyushu, Japan*, 2002.

393. DOE (Department of Environment). *Towards cleaner air: a case study of Delhi*; Department of Environment, Government of NCT of Delhi and Delhi Pollution Control Committee: New Delhi, 2003.

394. Goyal, P.; Sidhartha Present scenario of air quality in Delhi: a case study of CNG implementation; *Atmospheric Environment* **2003**, *37*, 5423-5431.

395. CSE (Center for Science and Environment) *In the Supreme Court of India Civil Appellate Jurisdiction Writ Petition (CIVIL) NO.13029 OF 1985*; Petitioner, Mehta April 2002. http://www.cseindia.org/campaign/apc/cng/pdf/Order.pdf (accessed March 2004)

396. Fu, L.X.; Yuan, Y., Beijing recent efforts on reducing motor vehicle emissions, Clean Air Regional Workshop: Fighting Urban Air Pollution, from Plan to Action, February 13-14, 2001.

397. Shi, Z.; Shao, L.; Jones, T.P.; Whittaker, A.G.; Lu, S.; Berube, K.A.; He, T.; Richards, R.J. Characterization of airborne individual particles collected in an urban area, a satellite city and a clean air area in Beijing, 2001; *Atmos. Environ.* **2003**, *37*(29), 4097-4108, doi: 10.1016/S1352-2310(03)00531-4.

398. He, K.; Yang, F.; Ma, Y.; Zhang, Q.; Yao, X.; Chan, C.K.; Cadle, S.; Chan, T.; Mulawa, P. The characteristics of $PM_{2.5}$ in Beijing, China; *Atmos. Environ.* **2001**, *35*(29), 4959-4970.

399. He, K.B.; Huo, H.; Zhang, Q. Urban air pollution in China: Current status characteristics and progress; *Ann. Rev. Energy Environ.* **2002**, *27*, 397-431.

400. Shao, M.; Zhao, M.; Bai, Y.; Li, J.; Tang, X. The research on NMHC emissions from anthropogenic source in Beijing; *China Experimental Sci.* **1994**, *14*(1), 6-11.

401. Wang, Z.; Bai, Y.; Zhang, S. A biogenic volatile organic compounds emission inventory for Beijing; *Atmos. Environ.* **2003**, *37*, 3771-3782.

402. Wang, Y.; Zhou, L. The organic compounds - The precursor of organic aerosol in Beijing; *Climate and Environ. Res.* **2000**, *5*(1), 13-19.

403. He, K.; Yu, X.; Lu, Y.; Hao, J.; Fu, L. Integrated analysis of urban air pollution control; *Urban Environ. & Urban Ecology* **2003**, *16*(6), 267-269.

404. He, K.; Yu, X.; Lu, Y.; Hao, J.; Fu, L. Characterization of urban air pollution sources; *Urban Environ. & Urban Ecology* **2003**, *16*(6), 269-271.

405. CSE (Center for Science and Environment) *Need for a technological leapfrog in Asia for clean air*, posted on March 30, 2004. http://www.cseindia.org/aboutus/press_releases/press_20040330.htm

406. AFP (Agence France Presse) China bans coal-fire power plants in major cities; *Terra Wire*, October 8, 2003. http://www.terradaily.com/2003/031009044627.pyrminwy.html

407. CAI (Clean Air Initiatives for Asian Cities). *Policies and Institutions*, 2004. http://www.cleanairnet.org/caiasia/1412/article-34755.html

408. CAI (Clean Air Initiatives for Asian Cities). *National technical strategy for vehicle emission control*, 1999. http://www.cleanairnet.org/caiasia/1412/article-36876.html

409. CAI (Clean Air Initiatives for Asian Cities). *China Set to Act on Fuel Economy.* http://www.cleanairnet.org/caiasia/1412/article-56010.html

410. Costabile, F. Traffic Air Pollution Control. In Summary Report of the IUAPPA Joint Seminar on Reducing the Impact of Vehicles on Air and Environment Quality in Cities, January 22–23, 2004, Mexico City, Mexico; MIT-IPURGAP: Cambridge, MA, 2004; pp 27-28.

411. Bodini, H. Geografía Urbana de Chile, in *Instituto Geográfico Militar*, Santiago, 2003.

412. Energy Information Agency. US DOE. July 2002. http://greennature.com/article1576.html

413. Lissi, E.; Rubio, M.A. Daily air pollution profile in Santiago; *Bull. Soc. Chilena de Quimica* **1980**, *25*(3), 249.

414. Préndez, M.; Ortiz, J.; Cortés, E.; Cassorla, V. Elemental composition of airborne particulate matter from Santiago, Chile; *JAPCA* **1984**, *34*, 54-56.

415. Horvath, H.; Trier, A.; Catalán, L. The relationship between indoor and outdoor soot concentration in an urban environment; *J. Aerosol Sci.* **1989**, *20*, 1273-1276.

416. Romero, H.; Ihl, M.; Rivera, A.; Zalazar, P.; Azocar, P. Rapid urban growth, land-use changes and air pollution in Santiago, Chile; *Atmos. Environ.* **1999**, *33*(24-25), 4039-4047.

417. Rappengluck, B.; Oyola, P.; Olaeta, I.; Fabian, P. The evolution of photochemical smog in the metropolitan area of Santiago de Chile; *J. Appl. Meteorol.* **2000**, *39*(3), 275-290.

418. Kavouras, I.G.; Koutrakis, P.; Tsapakis, M.; Lagoudaki, E.; Stephanou, E.G.; Von Baer, D.; Oyola, P. Source apportionment of urban particulate aliphatic and polynuclear aromatic hydrocarbons (PAHs) using multivariate methods; *Environ. Sci. Technol.* **2001**, *35*(11), 2288-2294.

419. Chen, T.Y.; Simpson, I.J.; Blake, D.R.; Rowland, F.S. Impact of the leakage of liquefied petroleum gas (LPG) on Santiago air quality; *Geophys. Res. Lett.* **2001**, *28*(11), 2193-2196.

420. Kavouras, I.G.; Koutrakis, P.; Cereceda-Balic, F.; Oyola, P. Source apportionment of PM_{10} and $PM_{2.5}$ in five Chilean cities using factor analysis; *JAWMA* **2001**, *51*(3), 451-464.

421. Tsapakis, M.; Lagoudaki, E.; Stephanou, E.G.; Kavouras, I.G.; Koutrakis, P.; Oyola, P.; Von Baer, D. The composition and sources of $PM_{2.5}$ organic aerosol in two urban areas of Chile; *Atmos. Environ.* **2002**, *36*(23), 3851-3863.

422. Gramsch, E.; Catalán, L.; Ormeño, I.; Palma, G. Traffic and seasonal dependence of the light absorption coefficient in Santiago de Chile, *Applied Optics* **2000**, *39*, 4895 – 4901.

423. Rojas, C.M.; Artaxo, P; Van Grieken, R. Aerosols in Santiago de Chile: a study using receptor modeling with X-Ray Fluorescence and single particle Analysis. *Atmospheric Environment* **1990**, <u>*24B*</u>, *2*, 227-241,.

424. Artaxo, P.; Oyola, P.; Martinez, R. Aerosol composition and source apportionment in Santiago de Chile. *Nuclear Instruments and Methods in Physics Research B,* **1999**, *150,* 409-416.

425. Government of Chile, Transantaigo, http://www.transantiago.cl/transantiago_home.html.

426. Oyola, P. Measuring Progress on Air Quality Management. In *Report of the Seventh Workshop on Mexico City Air Quality, January 18-21, 2004, Mexico City, Mexico*; MIT-IPURGAP, 2004.

427. Oyola, P. Santiago de Chile Experience. In *Summary Report of the IUAPPA Joint Seminar on Reducing the Impact of Vehicles on Air and Environment Quality in Cities, January 22–23, 2004, Mexico City, Mexico*; MIT-IPURGAP: Cambridge, MA, 2004.

428. Grosjean, D.; Miguel, A.H.; Tavares, T.M. Urban air pollution in Brazil: Acetaldehyde and other carbonyls; *Atmos. Environ. Part B: Urban Atmosphere* **1990**, *24B*(1), 101-106.

429. Tanner, R.L.; Miguel, A.H.; de Andrade, J.B.; Gaffney, J.S.; Streit, G.E. Atmospheric chemistry of aldehydes: Enhanced peroxyacetyl nitrate formation from ethanol-fueled vehicular emissions; *Enivron. Sci. Technol.* **1988**, *22*(9), 1026-1034.

430. CETESB. *Relatorio de qualidade do ar no estado de São Paulo - 2002*; CETESB: Companhia de tecnologia de saneamento ambiental de São Paulo, 2002.

431. Sanchez-Ccoyllo, O.R.; de Fatima Andrade, M. The influence of meteorological conditions on the behavior of pollutants concentrations in São Paulo, Brazil; *Environ. Poll.* **2002**, *116*(2), 257-263.

432. Castanho, A.D.A.; Artaxo, P. Wintertime and summertime São Paulo aerosol source apportionment study; *Atmos. Environ.* **2001**, *35*(29), 4889-4902.

433. Alonso, C.D.; Martins, M.H.R.B.; Romano, J.; Godinho, R. Sao Paulo aerosol characterization study; *JAWMA* **1997**, *47*(12), 1297-1300.

434. Miranda, R.M.; Andrade, M.F.; Worobiec, A.; van Grieken, R. Characterization of aerosol particles in the Sao Paulo Metropolitan Area; *Atmos. Environ.* **2002**, *36*, 345-352.

435. Pereira, A. Planning Transportation Perspectives, São Paulo Metropolitan Area. In *Summary Report of the IUAPPA Joint Seminar on Reducing the Impact of Vehicles on Air and Environment Quality in Cities, January 22–23, 2004, Mexico City, Mexico*; MIT-IPURGAP: Cambridge, MA, 2004b; pp 39-41.

436. Vasconcellos, E.A. Transportation and Air Quality in São Paulo. In *Summary Report of the IUAPPA Joint Seminar on Reducing the Impact of Vehicles on Air and Environment Quality in Cities, January 22–23, 2004, Mexico City, Mexico*; MIT-IPURGAP: Cambridge, MA, 2004b; pp 9-11.

437. Bogota Distrito Capital. *Bogotá en cifras*; 2004. http://www.bogota.gov.co/bogota/decide.php?patron=1.08.

438. Behrentz, E. *Research Project Concept Note, ANALYSIS OF GREENHOUSE GAS EMISSIONS IN BOGOTA CITY*; prepared for Advance Institute on Urbanization, Emissions, and the Global Carbon Cycle, Universidad de Los Andes, Bogotá, Columbia by Environmental Science and Engineering Program, School of Public Health, University of California: Los Angeles, CA, 2003. http://www.bol.ucla.edu/~ebehrent/bogota.pdf.

439. Veeduria Distrital. Indice de condiciones de vida y condiciones del aire en Bogotá 2002; *Boletín Vivir en Bogotá: Indicadores Sociales* **2003**, *12*.

440. STT (Secretaría de Tránsito y Transporte de Bogotá D.C.), Asistencia Técnica a la Secretaría de Tránsito y Transporte de Bogotá para la Reorganización del Sistema de Transporte Público Colectivo, *Contrato PNUD COL/01/23 with Logit-Logitrans*. 2003

441. Hidalgo, D. Colombia Transportation Measures for Abating Air Pollution in Megacities. In *Summary Report of the IUAPPA Joint Seminar on Reducing the Impact of Vehicles on Air and Environment Quality in Cities, January 22–23, 2004, Mexico City, Mexico*; MIT-IPURGAP: Cambridge, MA.

442. Napoleón Franco & Cía. Encuesta Annual de Percepción Ciudadana. *Annual Survey "Bogotá ¿Cómo Vamos?* http://eltiempo.terra.com.co/PROYECTOS/RELCOM/RESCON/BOTCOM/home/ARCHIVO/ARCHIVO-270023-0.pdf

443. Bogota Transmilenio website, http://www.transmilenio.gov.co/Transmilenio.htm

444. Ardila A. and Rodriguez D. How Chaos Builds Ridership: Operations of an Exclusive Busway Carrying Over 35,000 Passengers Per Hour Per Direction. Preprint 00-0643. Transportation Research Board 2000 Annual Meeting.

445. Hidalgo, D. Bogotá and its Transportation System. In *Second International Conference on Urban Transportation Systems, organized by ASCE and APTA, Alexandria, VA, USA, April 14-18, 2002*; 2002.

446. JICA (Japan International Cooperation Agency). *Santa Fe de Bogotá Transport Master Plan Study*; Chodai Co. Ltd, Yachiyo Engineering Co. Ltd., JICA: Santa Fe de Bogotá, 1997.

447. SITM. Estudio del Sistema Integrado de Transporte Masivo para la Sabana de Bogotá. *Ingetec-Bechtel-Systra for FONADE-DNP:* Bogota, 1997.

448. Alcaldía Mayor. Plan de Desarrollo Económico, Social y de Obras Públicas 1998-2001 - Por la Bogotá que Queremos; *Development Plan, City Council Accordance 6 1998*; 1998.

449. Alcaldía Mayor. Plan de Desarrollo Económico, Social y de Obras Públicas 2001-2004 – Bogota para Vivir: Todos del Mismo Lado; *Development Plan, City Decree 2001*; 2001.

450. Development Planning Unit. Sustainable Urbanisation: Bridging the Green and Brown Agendas. Allen, A. & You N. (eds.). *DPU in collaboration with UN-Habitat and the support of DFID.* London: University College London. 2002.

451. Fulton, L. *Bus Systems for the Future, Achieving Sustain-able Transport Worldwide*; International Energy Agency: Paris, 2002.

452. Stockholm Partnerships. *Winners of the Stockholm Partnerships Award.* The Stockholm Partnerships for Sustainable Cities, City of Stockholm Economic Development Agency; 2002. http://www.partnerships.stockholm.se/index.html

453. Bank 2002. Cities on the Move: A World Bank Urban Transport Strategy Review. K. Gwilliam (ed.). Washington DC; World Bank

454. Wright, L. Module 3b: Bus Rapid Transit; In *Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities*; Breithaupt, M.; GTZ: Frankfurt, 2003.

455. Hidalgo, D. Sustainable Mobility Strategy. In *Second International Conference on Urban Transportation Systems, organized by ASCE and APTA, Alexandria, VA, USA, April 14-18, 2002*; 2002b.

456. Steer Davies Gleave, 1999 "Diseño Operacional de TransMilenio", Steer Davies Gleave, STT, Bogota, 1999

457. McKenzey Co , 1999 "Estudio Gerencial de TransMilenio",., PNUD, Bogota, 1999

458. Capital Corp, 1999 "Estructuración Financiera de TransMilenio", STT, Bogota, 1999

459. Proyecta Ltda., 1999 "Plan Maestro de Ciclorrutas", IDU, Bogota 1999

460. Kenworthy, J.; Laube, F.; Newman, P.; Barte, P. *Indicators of Transport Efficiency in 37 Global Cities*; World Bank, 1997.

461. Levinson, H.; et. al. *Bus Rapid Transit*; Transit Coop-erative Research Program Report 90, Vol. 1 Case Studies in Bus Rapid Transit; Transportation Research Board: Washington DC, 2003.

462. Hidalgo, D. The backbone of the mobility strategy of Bogotá: TransMilenio; *Public Transport International Magazine* **2003**, *5*. http://www.uitp-pti.com/current_iss/

463. Hidalgo, D. TransMilenio: The Bus Rapid Transit System of Bogotá. In *55th UITP World Congress on The Challenges of Integration: Turning Multimodality into Seamless Mobility!, Madrid, May 4-9, 2003*; 2003b.

464. Nasralla, M.M. Air pollution in greater Cairo. In *Proceeding of the Italian-Egyptian Study-Days on the Environment, Cairo, Egypt, October 9-20, 1994*; 1994.

465. Sturchio, N.; Sultan, M.; Sharkaway, M.E.; Maghraby, A.E.; Taher, A. *Concentration and isotopic composition of lead in urban particulate air, Cairo, Egypt*; Argonne National Laboratory, Argonne, IL, and Center for Environmental Hazard Mitigation, Cairo University, Cairo, Egypt, 1996.

466. Rodes, C.E.; Nasralla, M.M.; Lawless, P.A. *An assessment and source apportionment of airborne particulate matter in Cairo, Egypt*; Activity report No. 22; prepared for USAID Mission to Egypt under EHP activity No. 133-RCm delivery order No. 7 by, 1996.

467. Abu-Allaban, M.; Gertler, A.W.; Lowenthal, D.H. A preliminary apportionment of the sources of ambient PM_{10}, $PM_{2.5}$, and VOCs in Cairo; *Atmos. Environ.* **2002**, *36*(35), 5549-5557.

468. Labib, M.W.; Khalik, M.H. Ambient PM and lead levels in the greater Cairo area for Y 2000 and Y 2001. In *Proceedings of the AWMA Conference on Air Quality Measurement Methods*, San Francisco, CA, 2002.

469. Chemonics International, I. *Cairo Air Improvement Project, Draft Year 1 Work Plan*; prepared for USAID/Egypt and Egyptian Environmental Affairs Agency by, 1997.

470. EEAA. Achievement and Planned Activities from the Ministry of State for Environmental Affairs, *Egyptian Environmental Affairs Agency*; 2003. http://www.eeaa.gov.eg/English/main/accomp1.asp (accessed March 2004)

471. Abu-Allaban, M.; Gertler, A.W.; Lowenthal, D.H. A Preliminary Apportionment of the Sources of Ambient PM10, PM2.5, and VOCs in Cairo; *Atmos. Environ.* **2002**, *36*, 5549-5557.

472. Labib, M.W.; Khalil, M.H. Ambient PM and Lead Levels in the Greater Cairo Area for Y 2000 and Y 2001. In *Proceedings of the AWMA Conference on Air Quality Measurement Methods, San Francisco, CA, October 30 - November 1, 2002;* 2002.

473. CSE (Center for Science and Environment) *Asia's challenge: Tackling two- and three-wheel vehicles*; posted on March 31, 2004. http://www.cseindia.org/aboutus/press_releases/press-index.htm (accessed April 2004)

474. Daily Times, Two-stroke rickshaws to be banned from next year, 22 March 2004 http://www.dailytimes.com.pk/default.asp?page=story_18-3-2004_pg7_20 (Accessed March 30, 2004)

475. Krebs, D.J. A Tale of Two Cities: The Regulation of Particulate Air Pollution in Mexico City and Los Angeles; MIT Master Thesis, MIT-IPURGAP Report No. 1: Cambridge, MA, 1999.

FIGURE CAPTIONS

Figure 1. World map showing the locations of the 20 megacities and the 9 case study cities (Map designed by M. A. Ernste, UNEP GRID - Sioux Falls)

Figure 2. Weekly cycle of mean tropospheric NO_2 vertical column densities for six urban centers (Source: Beirle, 2004, private communication).

Figure 3. Map of the LA Basin (Source: California Air Resources Board)

Figure 4. Ozone trend (peak 1-hr concentrations) in the South Coast Air Basin and the MCMA. (Source: Ref 7 and Ref 30)

Figure 5. PM_{10} trend (maximum 24-hr concentrations) in the South Coast Air Basin and the MCMA. (Source: Ref 7 and Ref 30)

Figure 6. Number of days with ozone exceedences for Beijing, South Coast Air Basin and Mexico City. Smog alert days for Greater Toronto Area.

Figure 7. Topographical map of the Mexico City Metropolitan Area indicating expansion from 1910 to 2000.

Figure 8. Trends in criteria pollutant concentrations for the MCMA showing the annual averages of data at five representative monitoring sites, which represent five sectors of the urban area. (Source: Ref 30)

Figure 9. Percentage of emissions from the MCMA in 2000 by source category for $PM_{2.5}$, PM_{10}, NOx and VOCs. (Source: 2000 Emission Inventory for the MCMA, http://www.sma.df.gob.mx)

Figure 10. Maps of Central Ontario Region

Figure 10a. Satellite Photo showing City of Toronto and the Greater Toronto Area (Source: http://geogratis.cgdi.gc.ca/download/landsat/l5_city/)
Figure 10b. Map of Central Ontario Region (Source: This image is under copyright, printed with permission of the Queen's Printer for Ontario)

Figure 11. Annual means for ozone and PM 2.5 for selected sites within the Central Ontario Region for 2001.

Figure 12. Map of Delhi (Source: http://www.webindia123.com/city/delhi/map/mapindex.html?cat=City%20Map)

Figure 13. Averaged Annual Ambient air Quality Trends (1994-2003) in Delhi

Figure 14. Maps of Beijing

Figure 14a. Image of Beijing from NASA s Landsat7 (Source: http://www.wordiq.com/knowledge/upload/5/5f/Large_Beijing_Landsat.jpg)

Figure 14b. This image of Beijing was taken from the Space Shuttle (in late April-early May 1998) and is one of the best photographs of the city taken from orbit. (Source: http://eol.jsc.nasa.gov/EarthObservatory/Beijing,China.htm)

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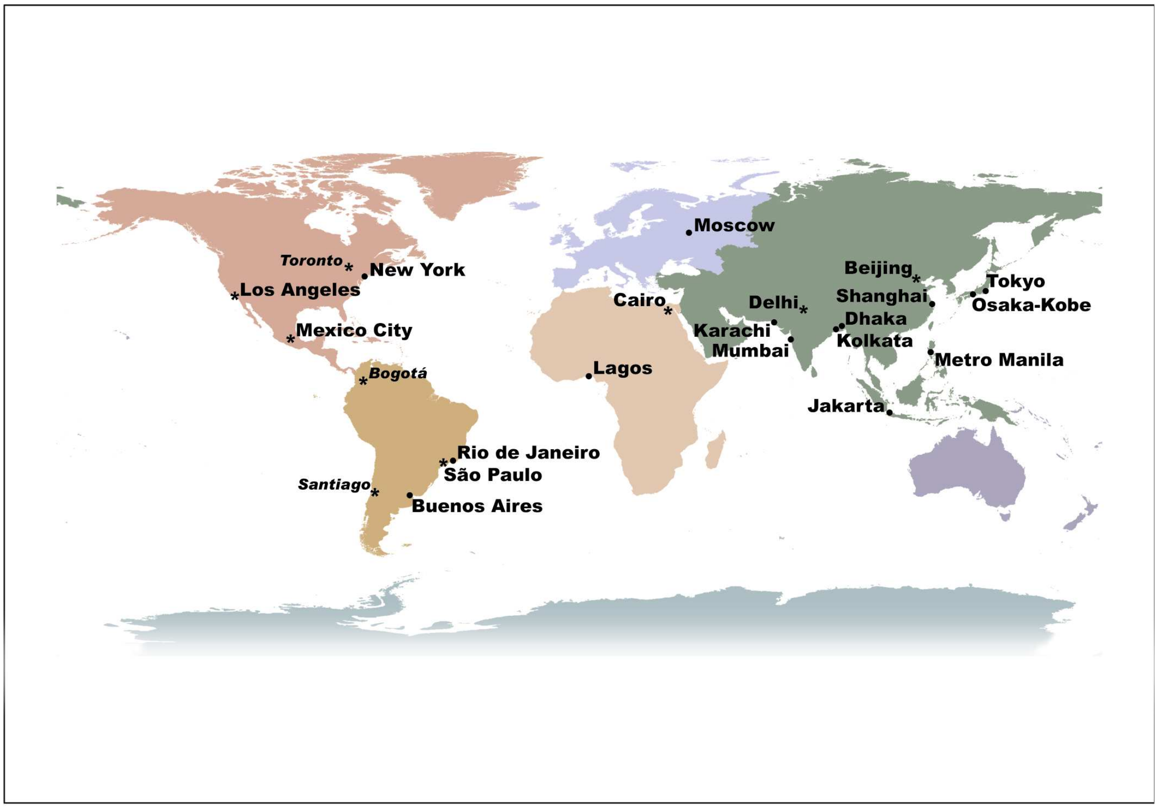

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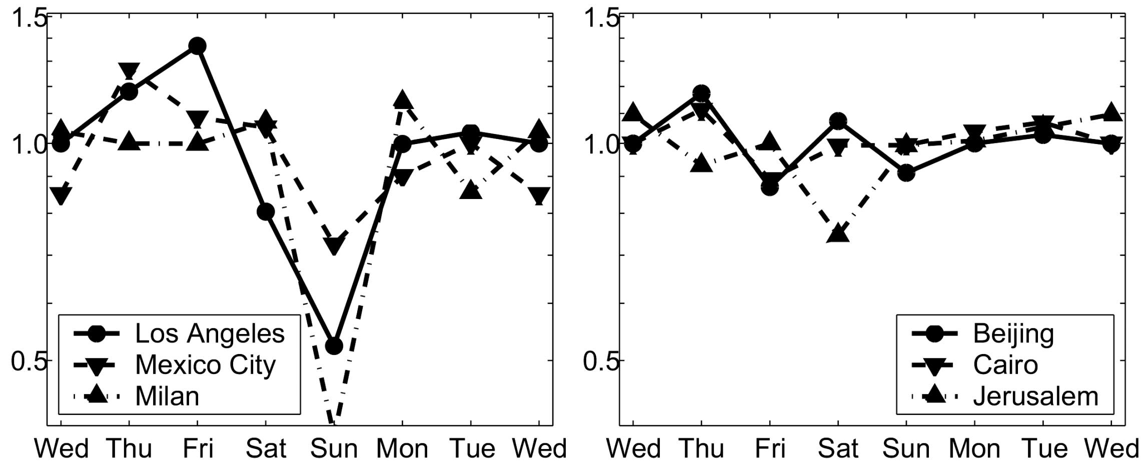

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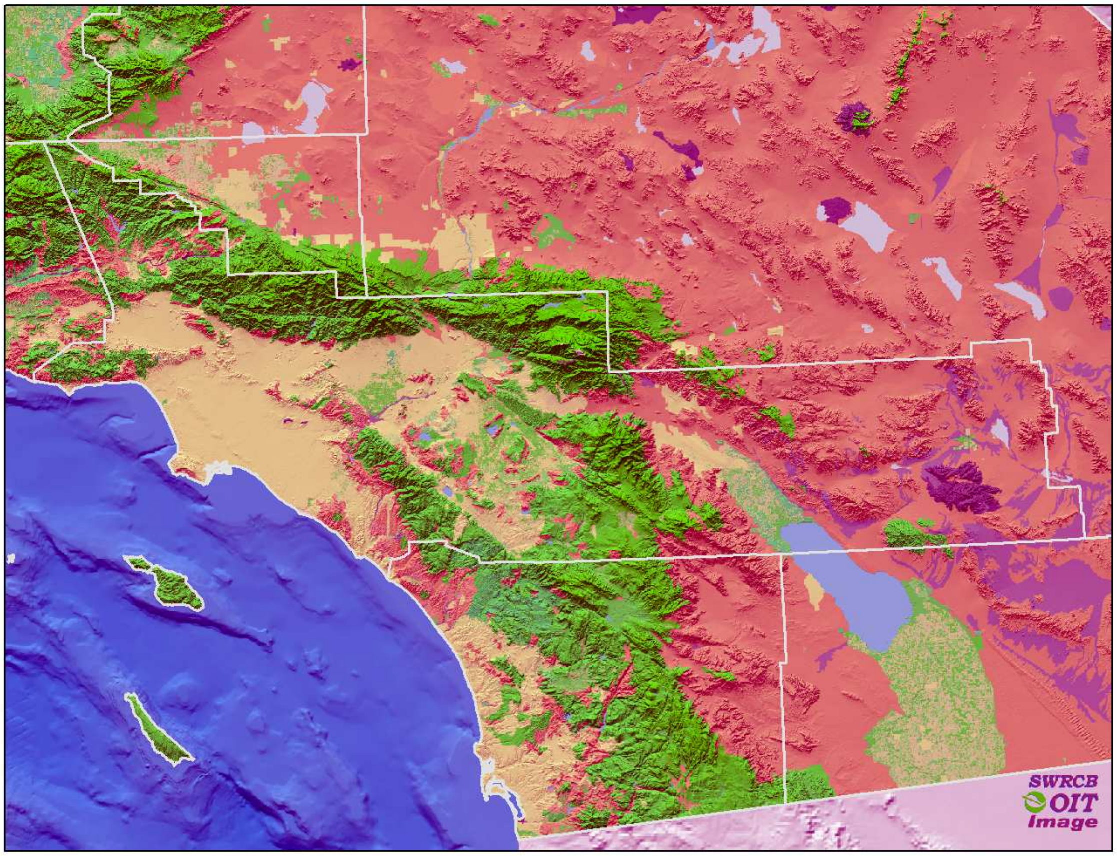

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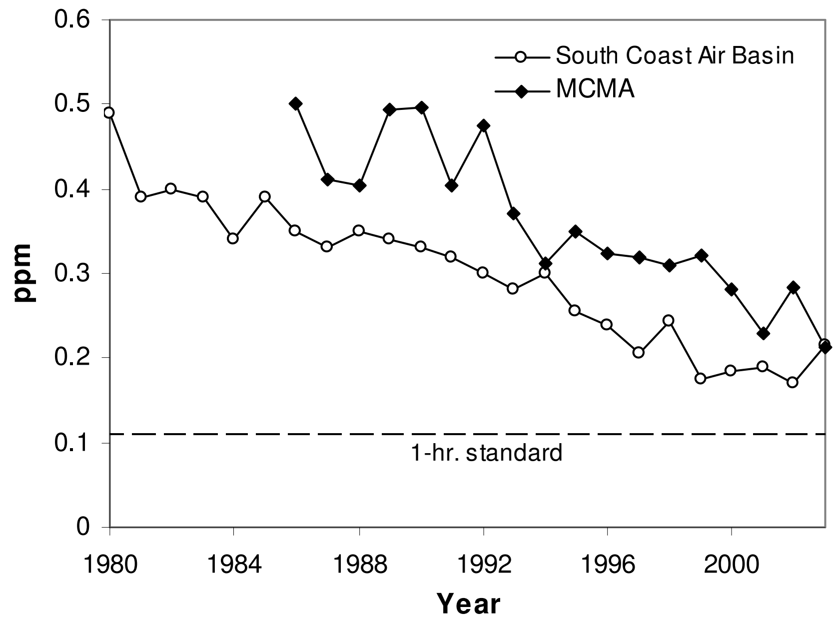

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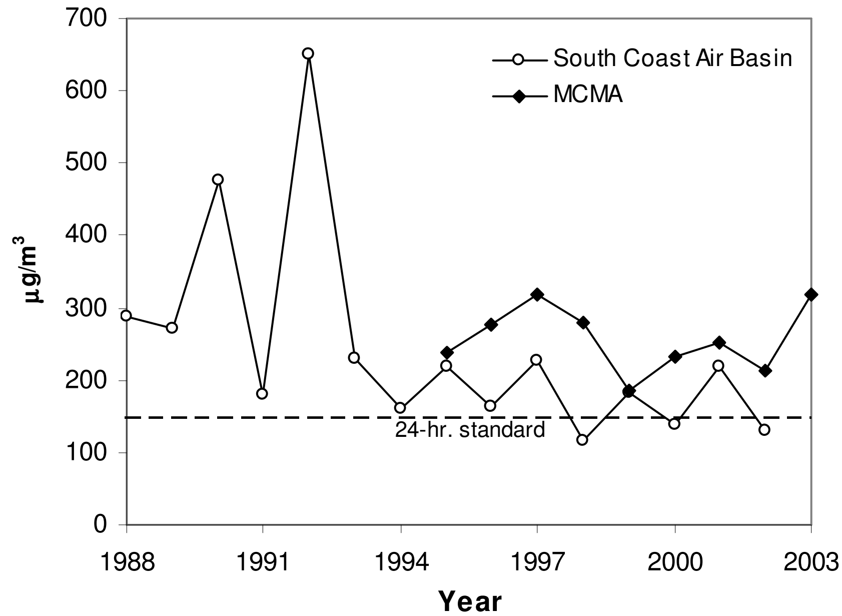

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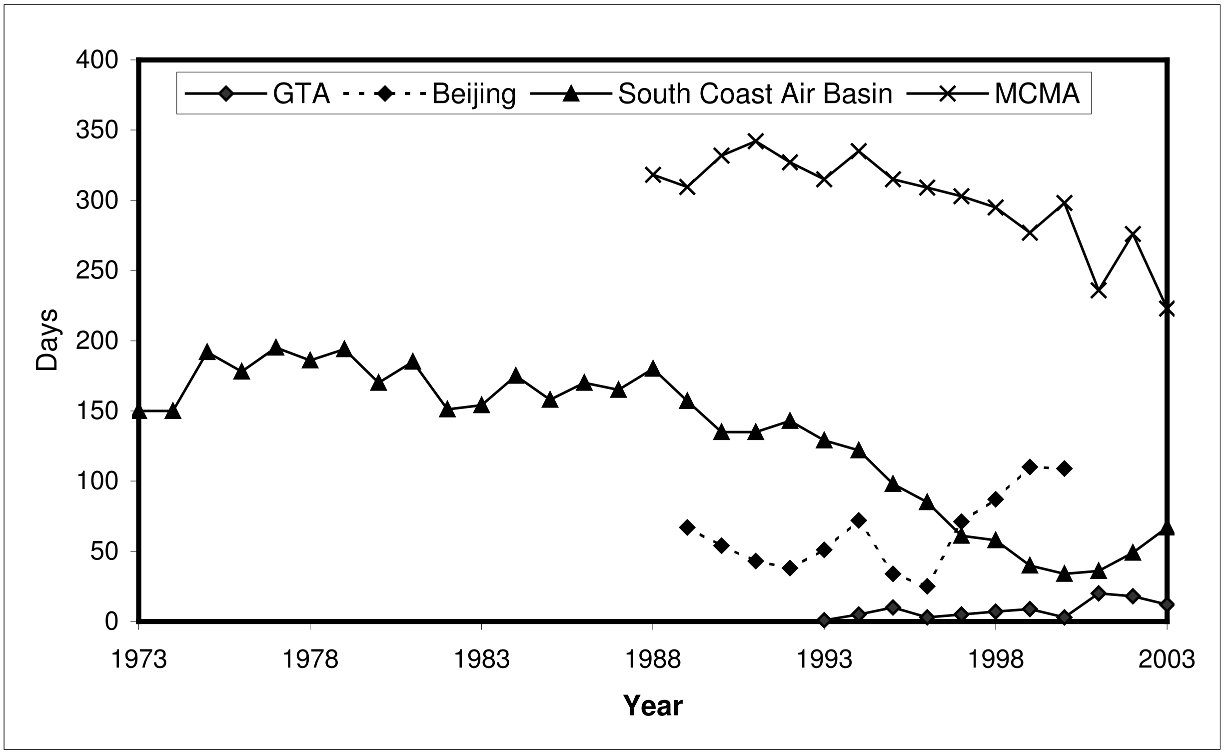

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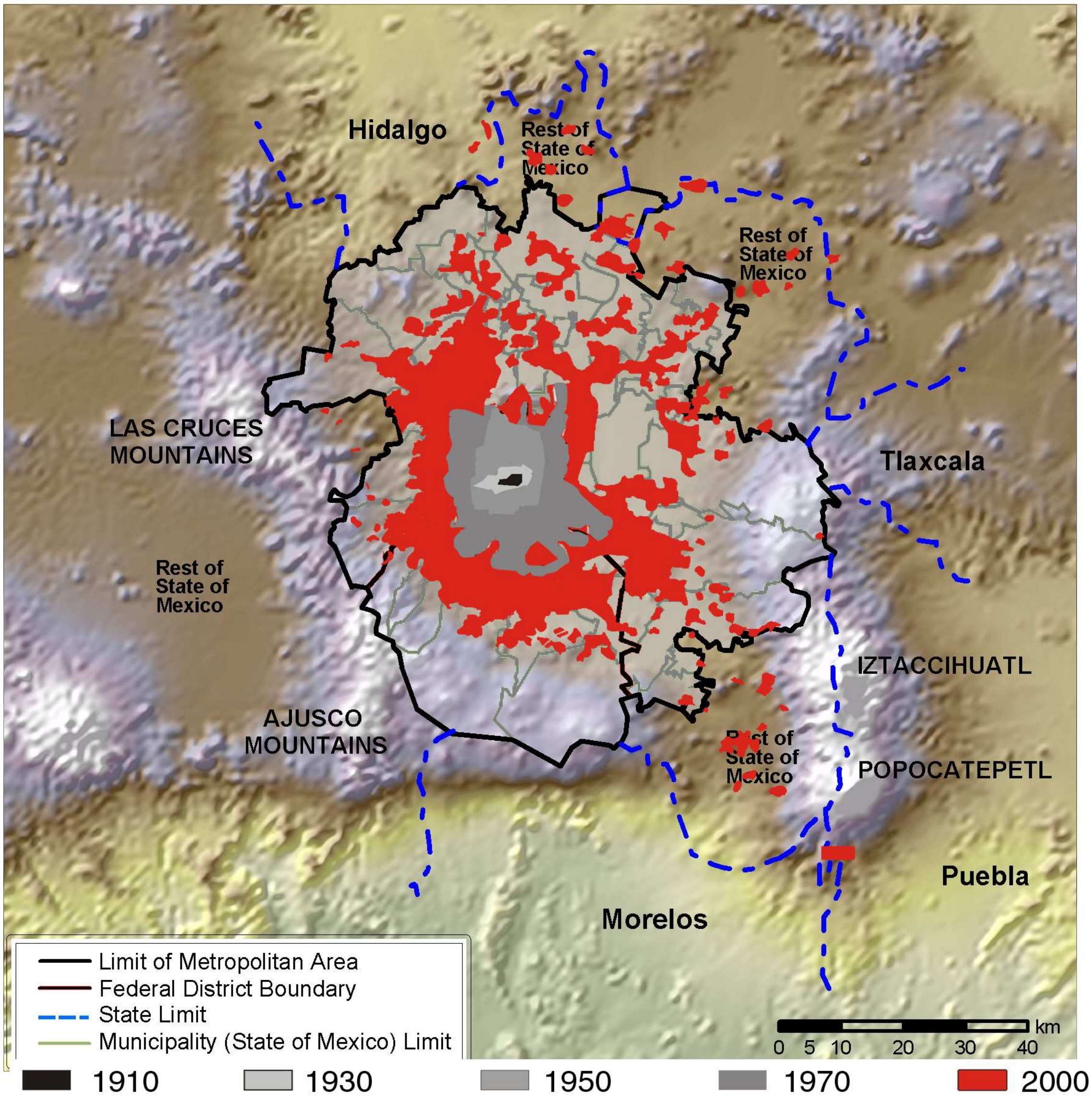

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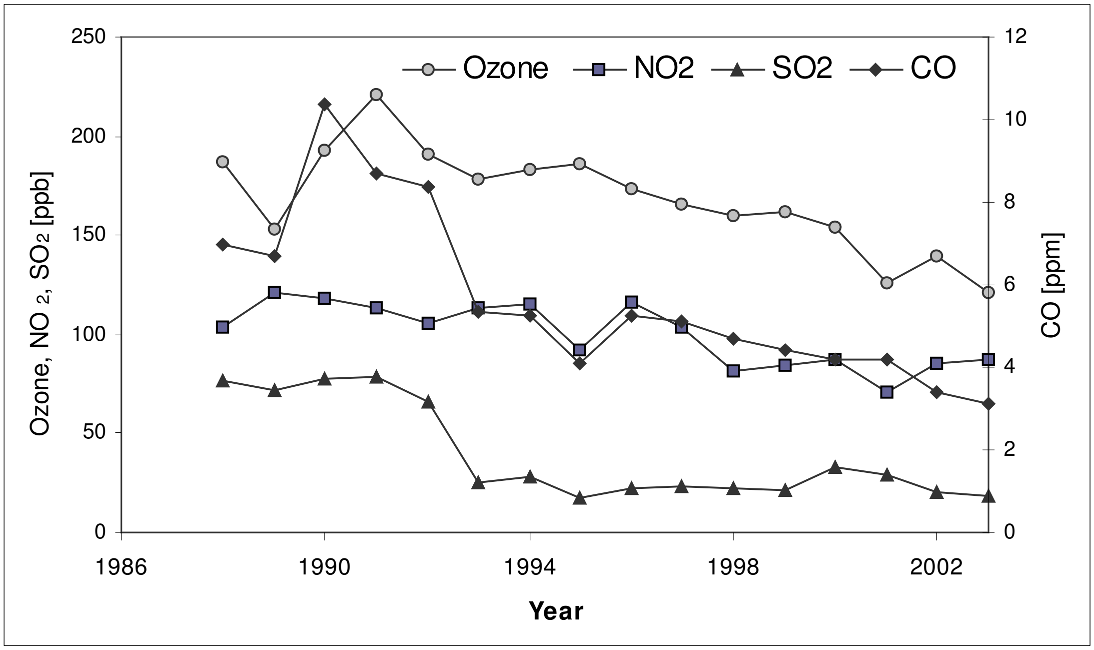

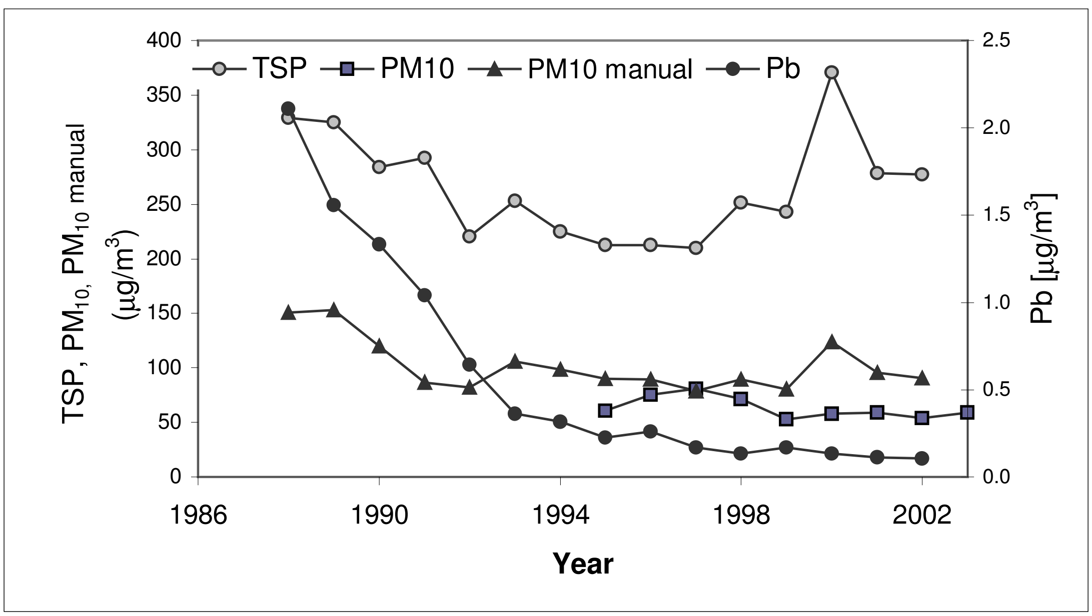

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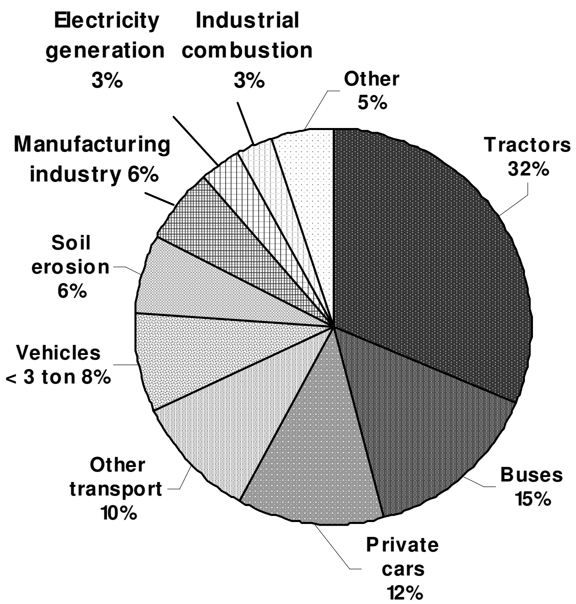
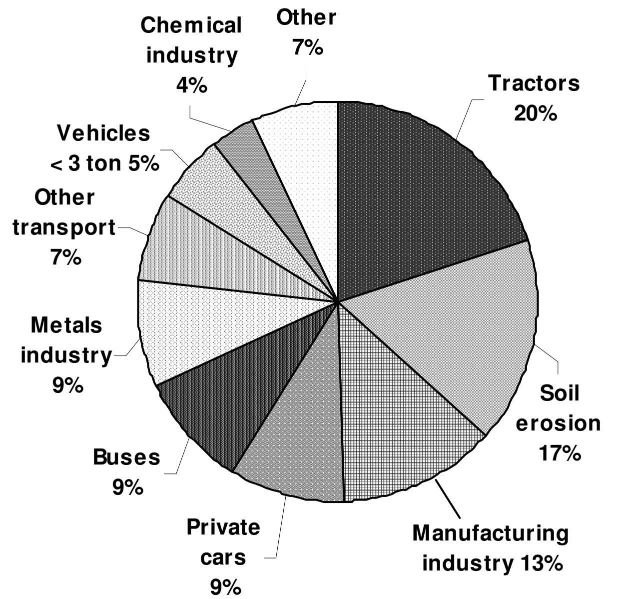


(a) $PM_{2.5}$



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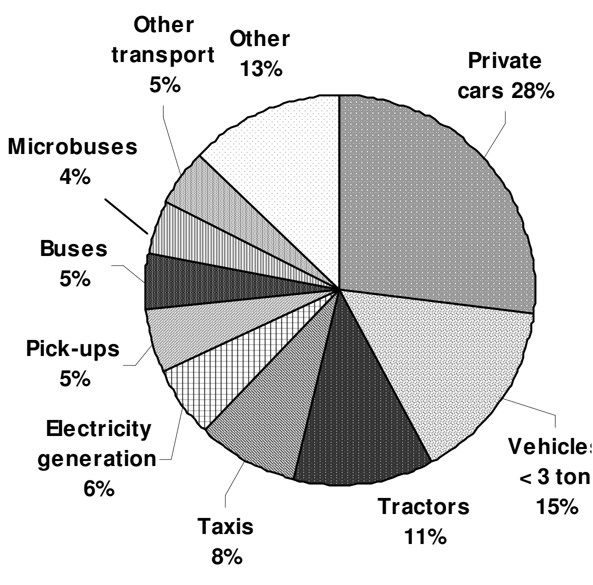

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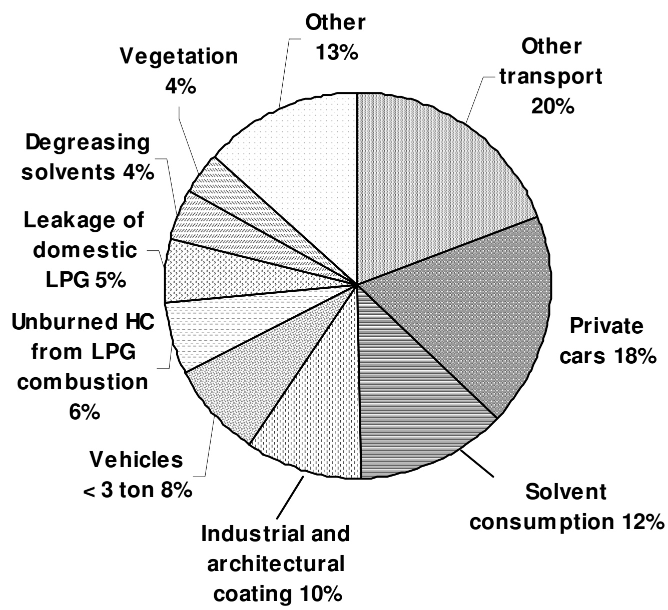

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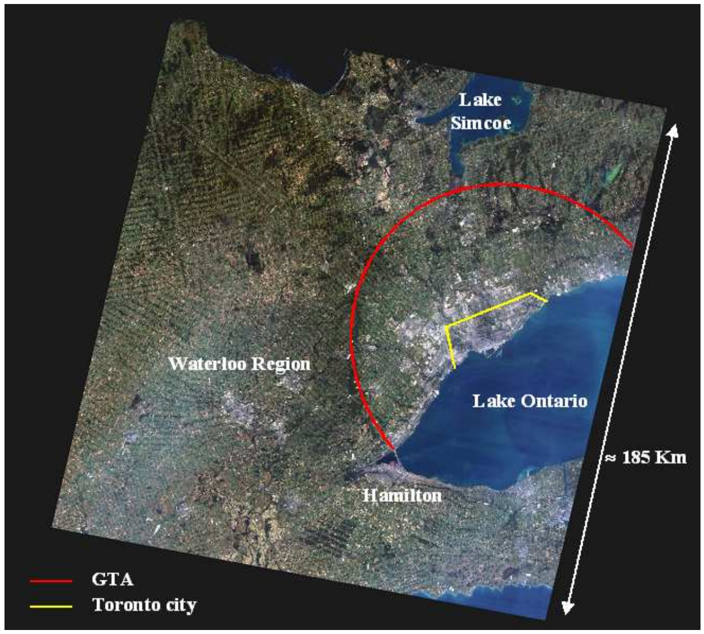

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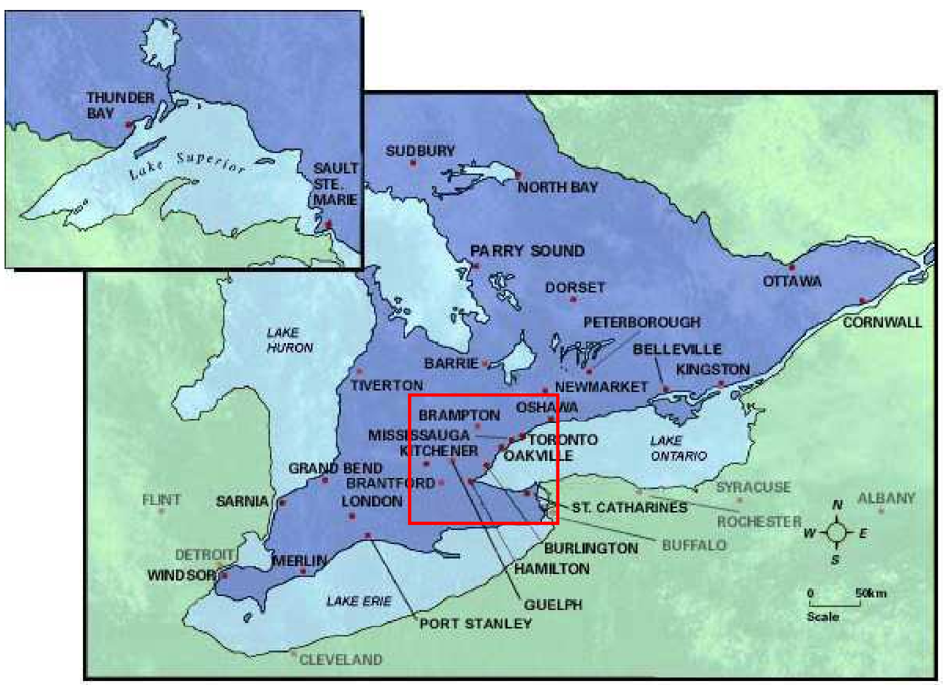

Central Ontario Region (COR)

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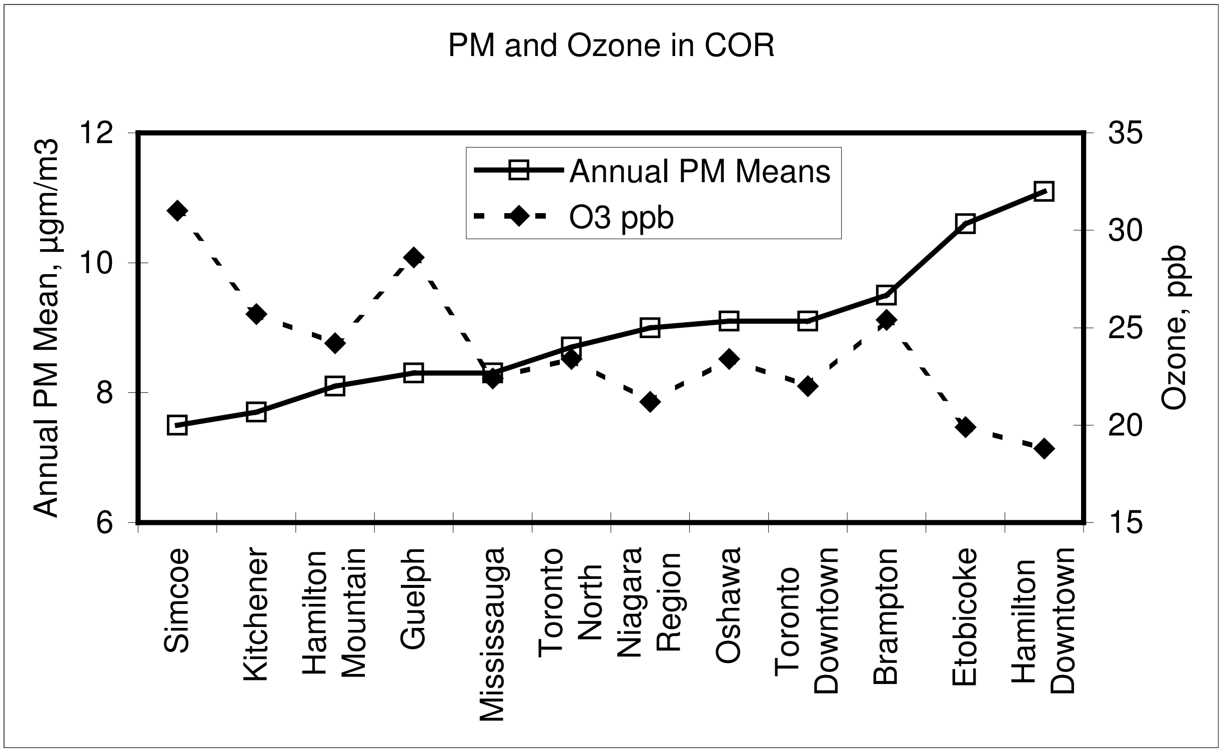
(Source: Queen's Printer for Ontario, 2004. This image is under copy write, printed with permission of the Queen's Printer for Ontario)



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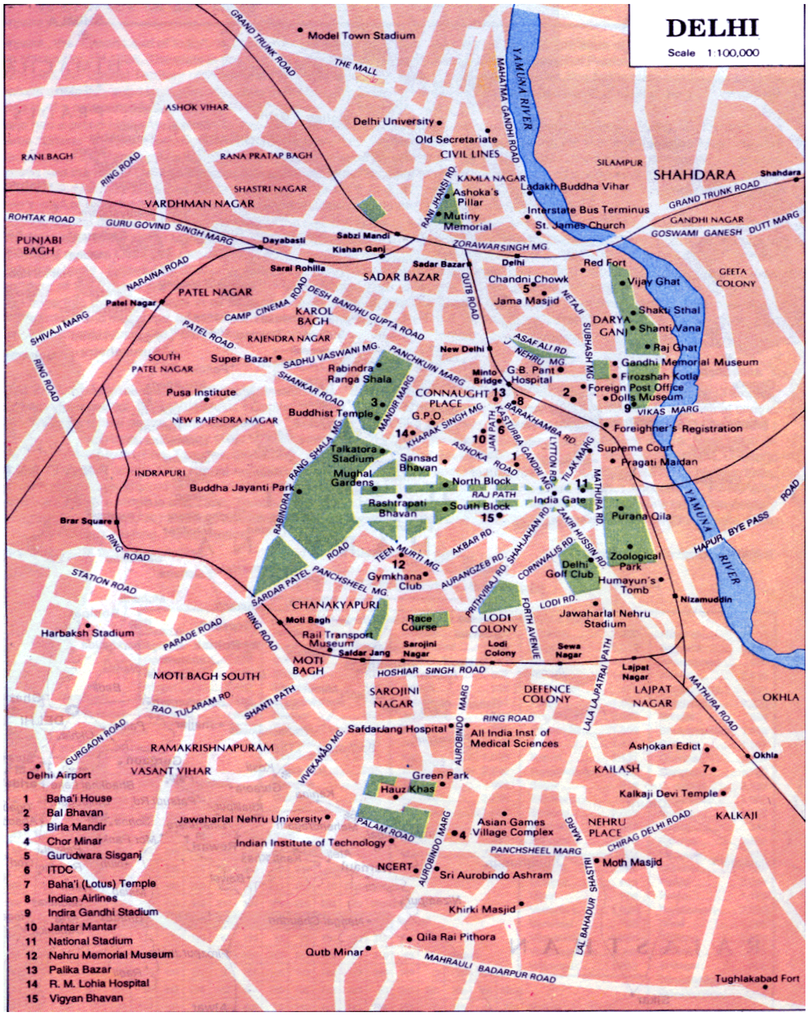

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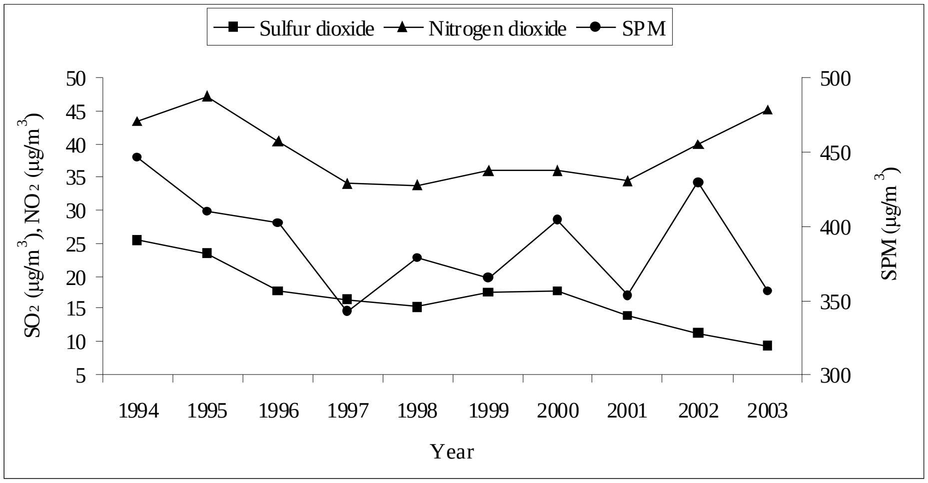

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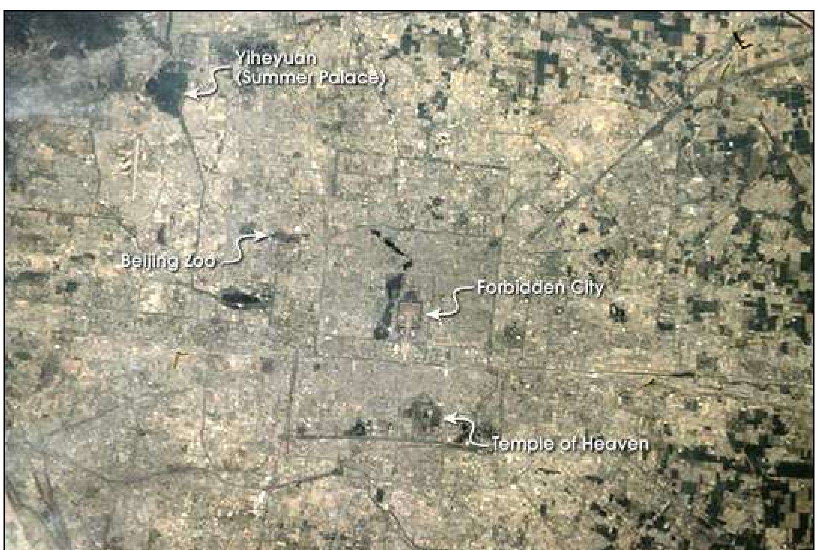

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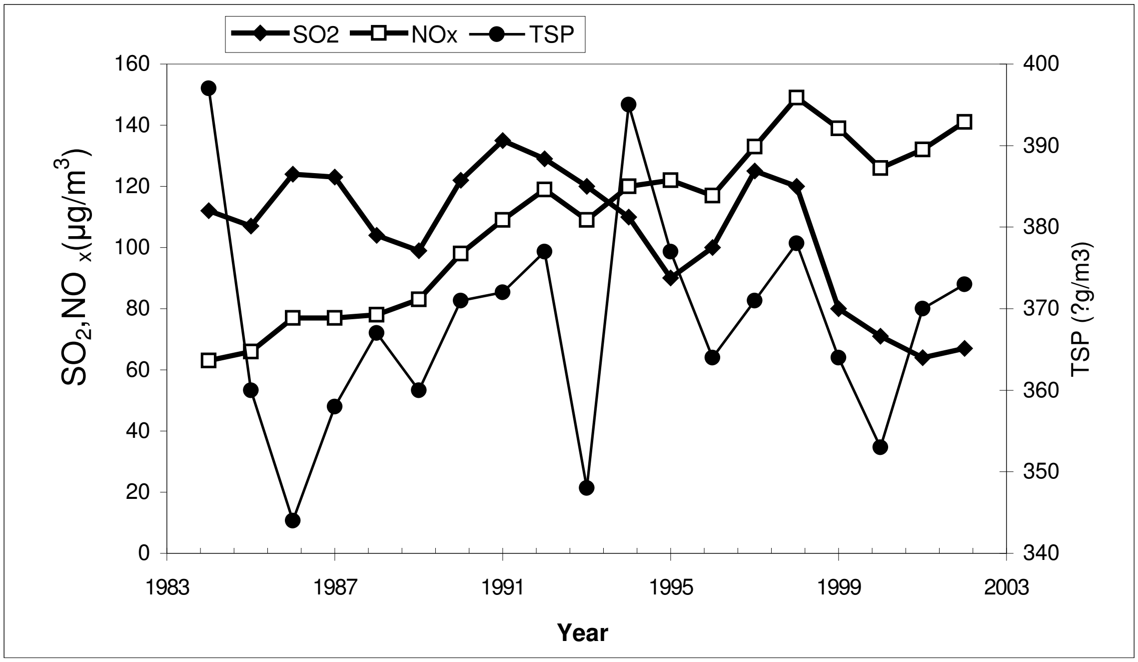

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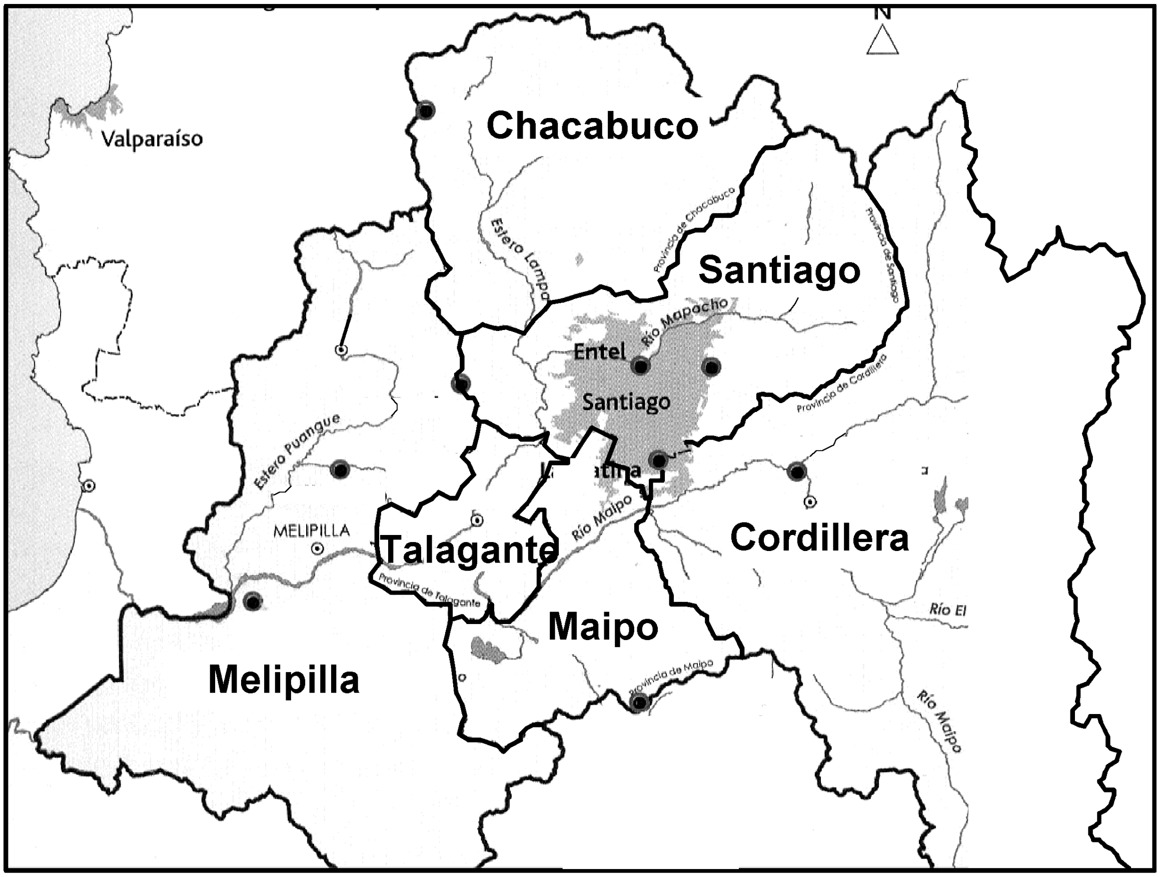

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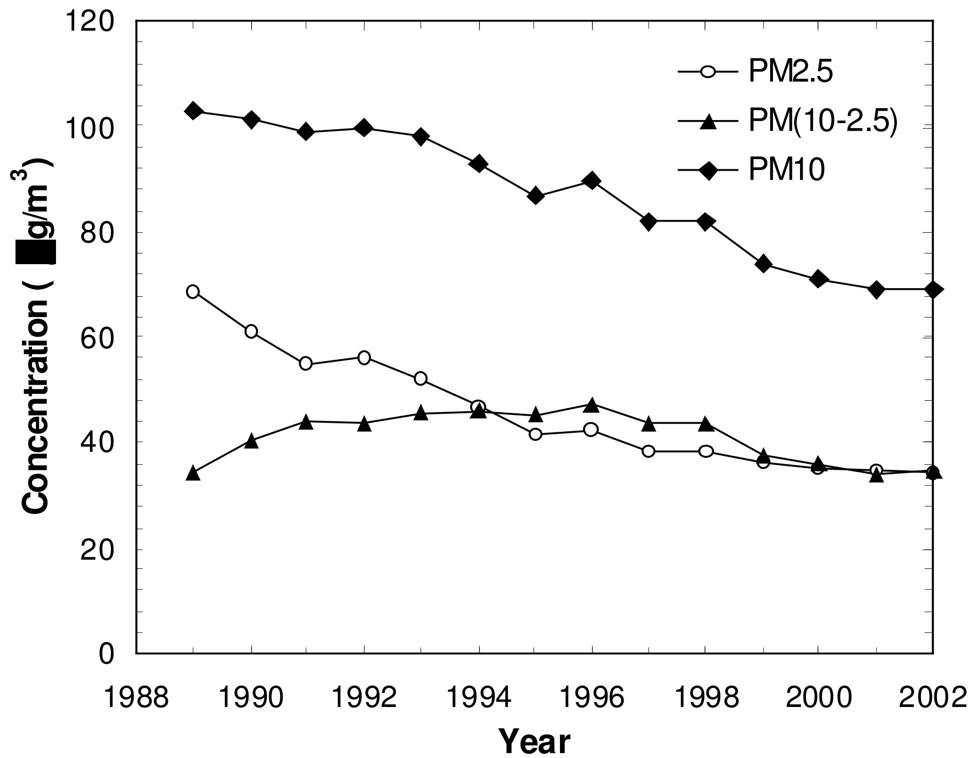

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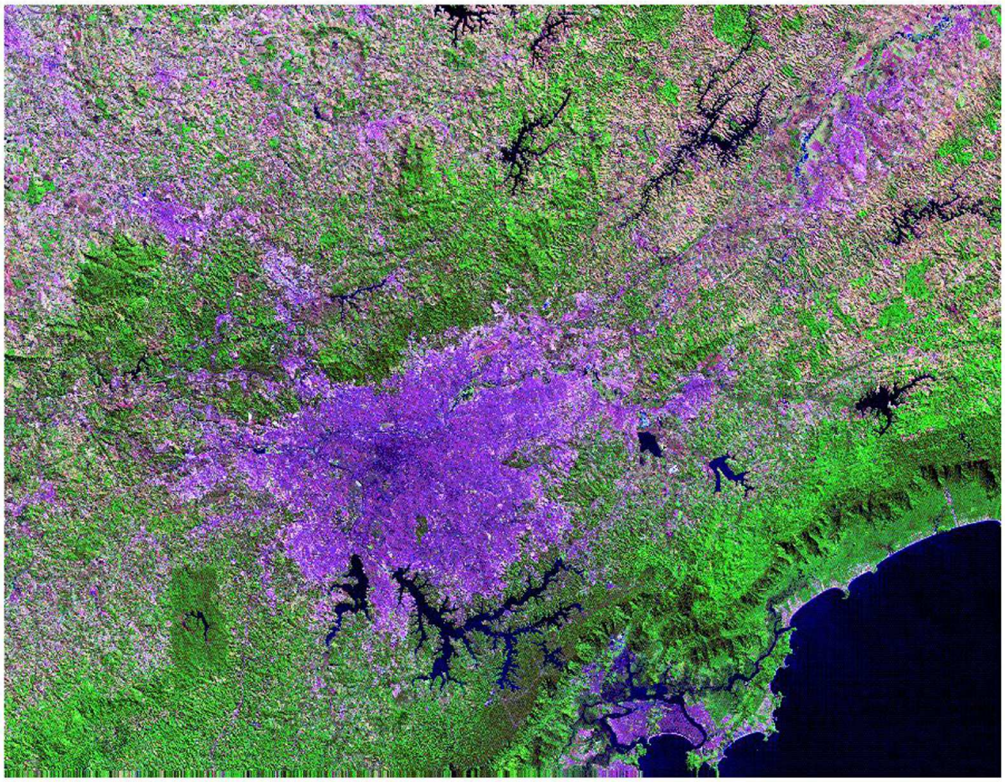

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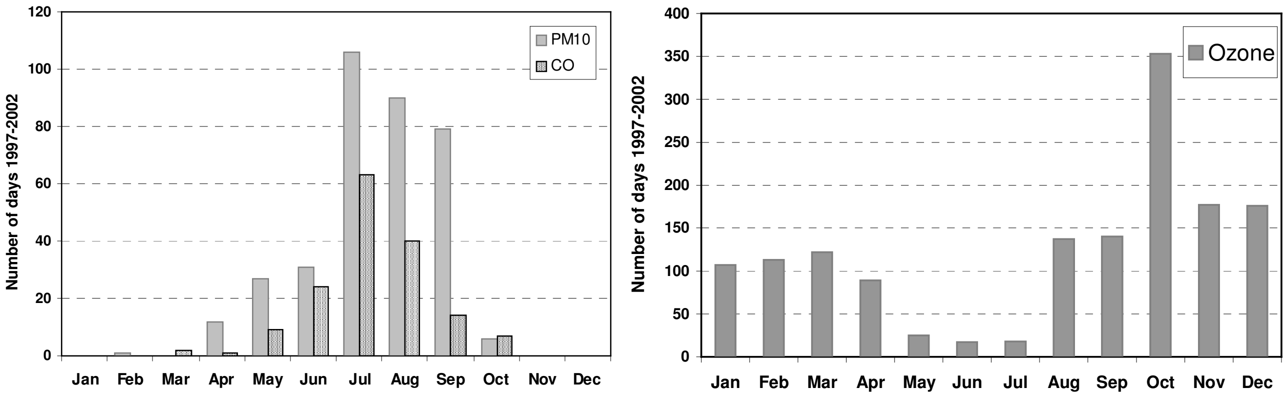

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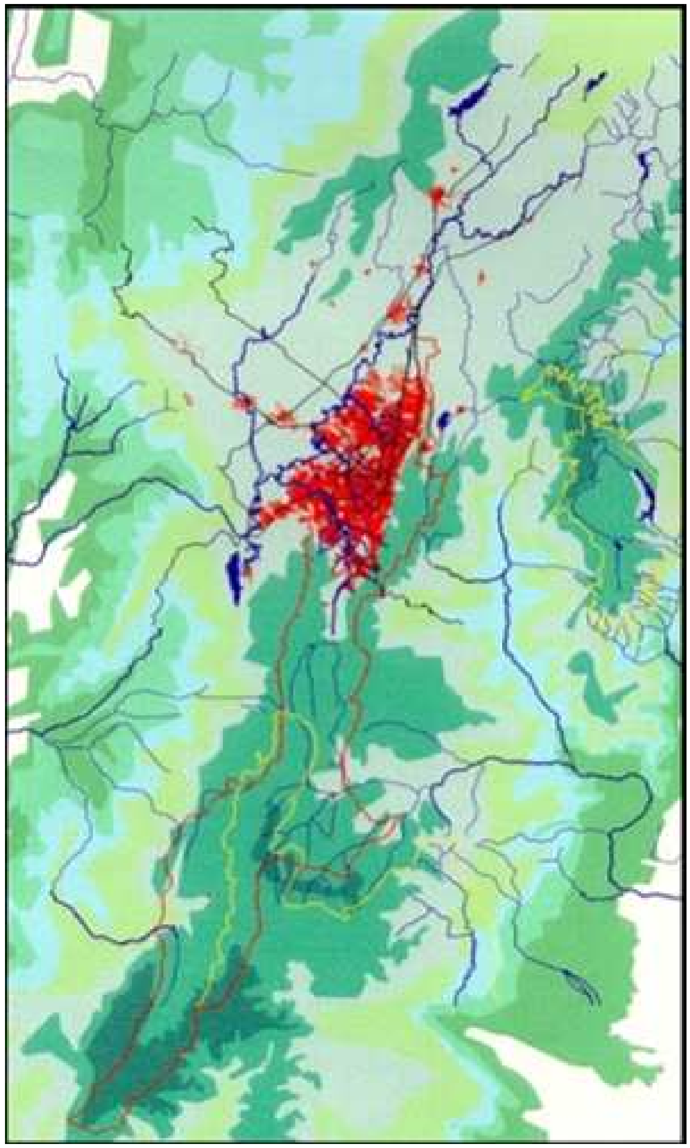

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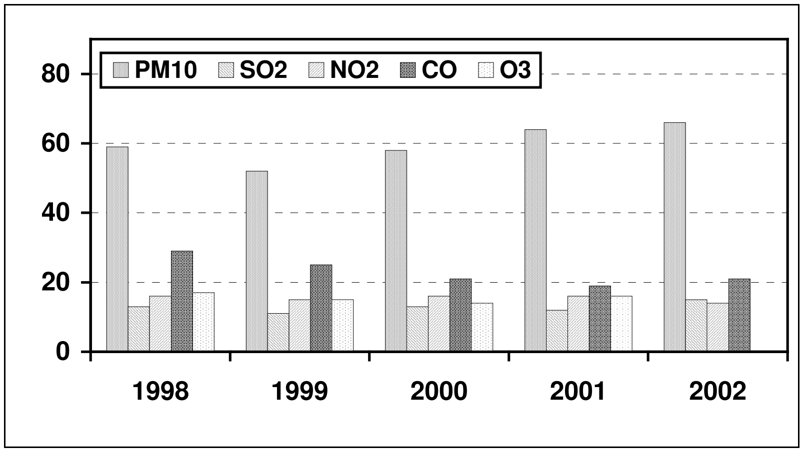

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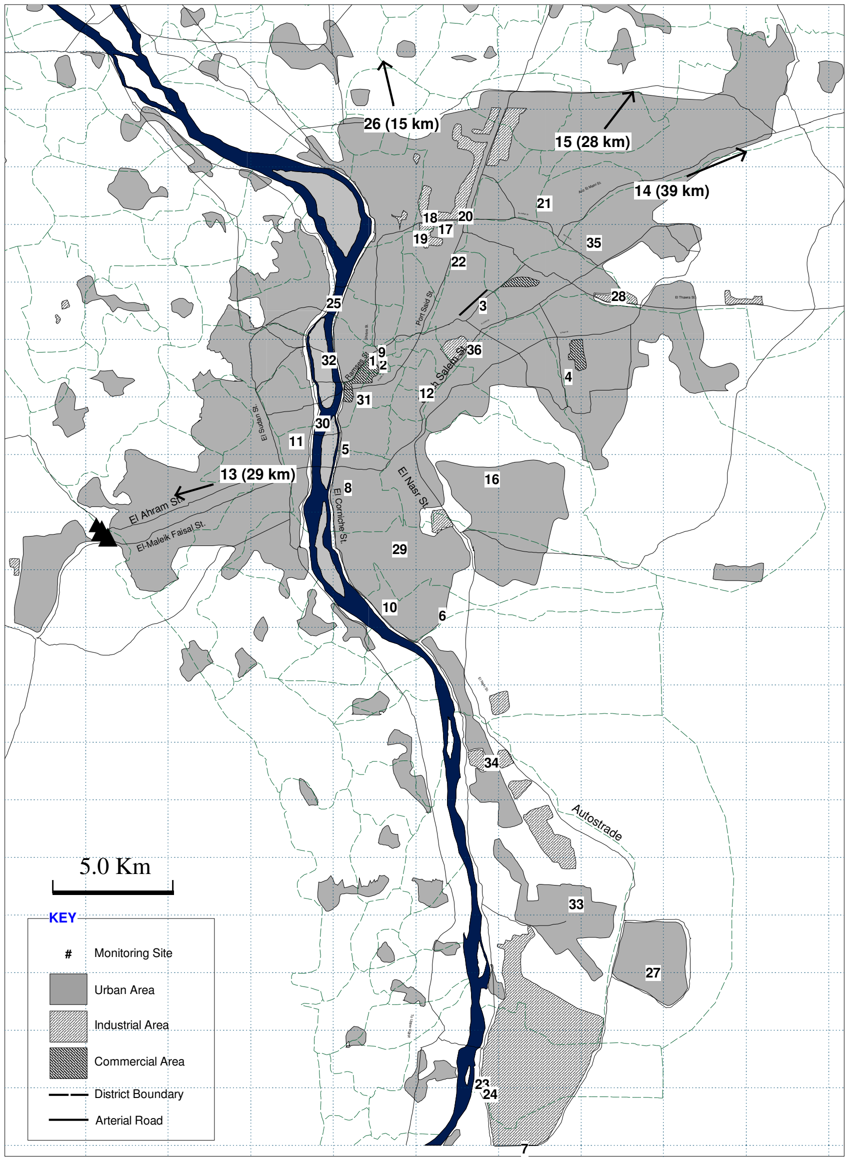

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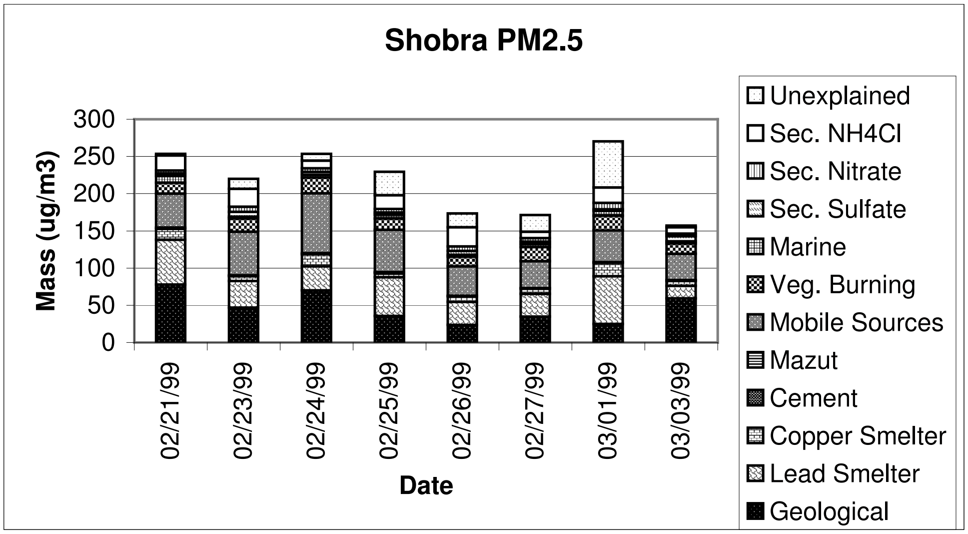

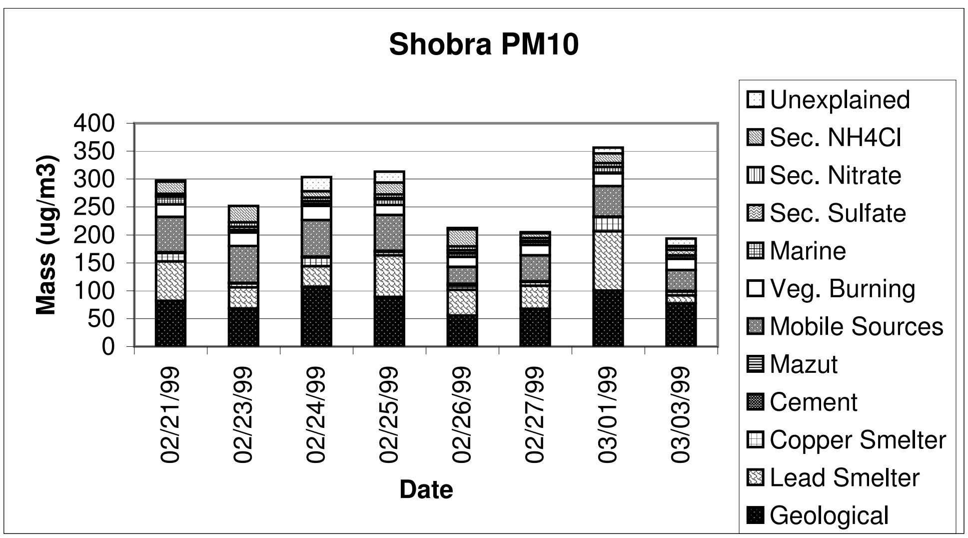

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Figure 27. Delhi traffic.

Table 1. Distribution of Global Population by Size of Settlement (1950-2030)

	Population (in billions)				
Major area	**1950**	**1975**	**2000**	**2003**	**2030**
Total population					
World	2.52	4.07	6.07	6.30	8.13
More developed regions	0.81	1.05	1.19	1.20	1.24
Less developed regions	1.71	3.02	4.88	5.10	6.89
Urban population					
World	0.73	1.52	2.86	3.04	4.94
More developed regions	0.43	0.70	0.88	0.90	1.01
Less developed regions	0.31	0.81	1.97	2.15	3.93
Rural population					
World	1.79	2.55	3.21	3.26	3.19
More developed regions	0.39	0.34	0.31	0.31	0.23
Less developed regions	1.40	2.21	2.90	2.95	2.96

Source: United Nations Population Division, World Urbanization Prospects, The 2003 Revision.

Table 2. Statistics and ambient air quality data for the nine case study cities

City	Los Angeles	Mexico City	Toronto	Delhi	Beijing	Santiago	Sao Paulo	Bogotá	Cairo
Population (2000) (millions)	12	19	7 (COR in 2003)	14	11	5.3	18	6.5	11
Population Density (thousands per km^2) central / total	/ 1 [4]	12 / 3 [4]	7 / 3	25 / [11]	/ 1 [17]	7 / [20]	8 / [20]	4 / [25]	5 / [27]
Area, thousands km^2	28 [4]	5 [4]	17 (in COR)	1.4 [12]	17 [17]	2.3 [20]	8 [20]	1.7 [25]	0.3 [27]
Fuel Consumption (gasoline) million liters per day	76 (in 1999) [4]	18 (in 1999) [4] 19 (in 2003) [6]	41 (for Ontario in 2002) [8]	2 (in 1999) [10]		8.9 (for Chile in 2001) [21]	18 (Sao Paulo State, 2003) [24]		50 [28]
Fuel Consumption (diesel) million liters per day	10 (in 1999) [4]	4.4 (in 1999) [4] 4.1 (in 2003) [6]	12 (for Ontario in 2002) [8]	3 (in 1999) [10]		5.9 (total for Chile in 2001) [21]	24.4 (Sao Paulo State, 2003) [24]		
Vehicles (millions)	9.3 (in 1999) [4]	3 (in 1999) [4] 3.3 (in 2000)	9.1 (in Ontario in 2003) [8]	3 (in 2001) [10]	2 [16]	1 (private cars)	6 [23]	1 [26]	0.5 (in 2000) [27]
GDP per capita (entire country in 2002)	$36,300 [5]	$8,900 [5]	$29,300 [5]	$900 (for Delhi) [10]	$3,800 [18]	$10,000 [5]	$7,600 [5]	$6,100 [5]	$4,000 [4]
NO_2 (ppb) Peak 1 hour / Annual Average (year)	167 (2001) [7]	208 (2002) [30]	/ 27 (in Toronto 2000) [9]	/ 45 (2003) [14]	/ 40 (2002) [19]		146 (in 2002) [23]	160 / 14 (2002) [27]	
$PM_{2.5}$ ($\mu g/m^3$) Peak 1 hour / Peak 24 hour (year)	121 / 98 (2001) [7]		/ 51 (in Toronto 2001) [9]	Ave. concentration (Feb.-May 1998) 175 (residential) 267 (commercial) 199 (industrial) [15]		350 / 121 (in 2003) [31]			
PM_{10} ($\mu g/m^3$) Peak 1 hour / Peak 24 hour (year)	/ 106 (2001) [7]	894 (2002) [30]	/ 74 (in COR 2001) [9]	Ave. concentration (Feb.-May 1998) 455 (residential) 658 (commercial) 553 (industrial) [15]	166 (annual average in 2002) [19]	572 / 276 (2003) [22]	/ 149 (2002) [23]	/ ~220 (2002) [27]	

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TSP (μg/m^3)		832 (peak 24 hour in 1999) [30]	56 (annual mean in COR 2001) [9]	356 (annual mean in 2003) [14]	373 (annual average in 2002) [19]			347 (peak 24 hour in 2002) [27]	
SO_2 (ppb)	50 (peak 1 hour in 2001) [7]	386 (peak 1 hour in 2002) [30]	24 (peak 24-hour in COR 2001) [9]	9.5 (annual average in 2003) [14]	26 (annual average in 2002) [19]	3.4 (annual average in 2002) [22]	6 (annual average in 2002) [23]	60 (peak 24 hour in 2002) [27]	
CO (ppm)	11.7 (peak 1 hour in 2001) [7]	46 (peak 1 hour in 2002) [30]	6.5 (peak 1 hour in Toronto West in 2001) [9]		2.2 (annual average in 2002) [19]	23.1 (peak 1 hr in 2002) [22]	8 (peak 8 hour in 2002) [23]	20 (peak 1 hour in 2002) [27]	
Ozone (ppb) peak 1 hour	164 in 2001 [7]	284 in 2002 [30]	109 (in COR in 2001) [9]	34–126 in winter 1993 [13]	192 in 1998 [19]	169 in 2002 [22]	136 (2002) [23]	160 in 2002 [27]	

Table 3. Megacities of The World

City	Population[a] (millions)		
	1975	**2000**	**2003**
Tokyo, Japan	26.6	34.4	35.0
Mexico City, Mexico	10.7	18.1	18.7
New York, USA	15.9	17.8	18.3
São Paulo, Brazil	9.6	17.1	17.9
Mumbai, India	7.3	16.1	17.4
Delhi, India	4.4	12.4	14.1
Kolkata, India	7.9	13.1	13.8
Buenos Aires, Argentina	9.1	12.6	13.0
Shanghai, China	11.4	12.9	12.8
Jakarta, Indonesia	4.8	11.0	12.3
Los Angeles, USA	8.9	11.8	12.0
Dhaka, Bangladesh	2.2	10.2	11.6
Osaka-Kobe, Japan	9.8	11.2	11.2
Rio de Janeiro, Brazil	7.6	10.8	11.2
Karachi, Pakistan	4.0	10.0	11.1
Beijing, China	8.5	10.8	10.8
Cairo, Egypt	6.4	10.4	10.8
Moscow, Russian Federation	7.6	10.1	10.5
Metro Manila, Philippines	5.0	10.0	10.4
Lagos, Nigeria	1.9	8.7	10.1

a. Source: United Nations Population Division, World Urbanization Prospects, The 2003 Revision.
City population is the number of residents of the city as defined by national authorities and reported to the United Nations. Mostly, the city refers to urban agglomerations.

Table 4. Ambient air quality standards for the nine case study cities (countries)

	CO			SO_2			O_3			NO_2			PM_{10}		$PM_{2.5}$		Lead	
	ppm	µg/m³ x 10³	Time	ppm	µg/m³	Time	ppm	µg/m³	Time	ppm	µg/m³	Time	µg/m³	Time	µg/m³	Time	µg/m³	Time
WHO	26 9	30 10	1 h 8 h	0.13 0.05	350 125	1 h 24 h	0.08 0.06	160 120	1 h 8 h	0.21 0.08	400 150	1 h 24 h					0.5-1	1 yr
US National	35 9	40 10	1 h 8 h	0.14 0.03	365 80	24 h 1 yr	0.12 0.08	235 160	1 h 8 h	0.05	100	1 yr	150 50	24 h 1 yr	65 15	24 h 1 yr	1.5	qtr
Los Angeles	20 9	23 10	1 h 8 h	0.25 0.04	655 105	1 h 24 h	0.09	180	1 h	0.25	470	1 h	50 20	24 h 1 yr	12	1 yr	1.5	30 d
Mexico	11	13	8 h	0.13 0.031	350 80	24 h 1 yr	0.11	216	1 h	0.21	400	1 h	150 50	24 h 1 yr			1.5	qtr
India[a]	1.7 0.87	2 1	1 h 8 h	0.011 0.006	30 15	24 h 1 yr				0.016 0.008	30 15	24 h 1 yr	75 50	24 h 1 yr			0.75 0.50	24 h 1 yr
India[b]	3.5 1.7	4 2	1 h 8 h	0.031 0.023	80 60	24 h 1 yr				0.043 0.032	80 60	24 h 1 yr	100 60	24 h 1 yr			1.0 0.75	24 h 1 yr
India[c]	8.7 4.4	10 5	1 h 8 h	0.046 0.031	120 80	24 h 1 yr				0.064 0.043	120 80	24 h 1 yr	150 120	24 h 1 yr			1.5 1.0	24 h 1 yr
Colombia	35 10.5	40 12	1 h 8 h	0.13 0.03	350 80	24 h 1 yr	0.08 0.06	160 120	1 h 8 h	0.17 0.12	320 220	1 h 24 h	160 60	24 h 1 yr				
Brazil	35 9	40 10	1 h 8 h	0.14 0.03	365 80	24 h 1 yr	0.08	160	1 h	0.17 0.053	320 100	24 h 1 yr	150 50	24 h 1 yr				
Chile				0.14 0.03	365 80	24 h 1 yr	0.08	160	1 h	0.053	100	1 yr	150	24 h				
Canada	30	34	1 h	0.06 0.011	160 30	24 h 1 yr	0.05	100	1 h	0.032	60	1 yr	30	24h	50	24 h		
China[a]	8.7 3.5	10 4	1 h 24 h	0.058 0.019 0.008	150 50 20	1 h 24 h 1 yr	0.06	120	1 h	0.064 0.043 0.021	120 80 40	1 h 24 h 1 yr	50 40	24 h 1 yr			1.5 1.0	Qtr 1 yr
China[b]	8.7 3.5	10 4	1 h 24 h	0.19 0.058 0.023	500 150 60	1 h 24 h 1 yr	0.08	160	1 h	0.064 0.043 0.021	120 80 40	1 h 24 h 1 yr	150 100	24 h 1 yr			1.5 1.0	Qtr 1 yr
China[c]	17.5 5.2	20 6	1 h 24 h	0.27 0.096 0.039	700 250 100	1 h 24 h 1 yr	0.10	200	1 h	0.13 0.064 0.043	240 120 80	1 h 24 h 1 yr	250 150	24 h 1 yr			1.5 1.0	Qtr 1 yr

Note: The conversion from µg/m³ to ppm is using 25°C and 1 atm.
[a] Sensitive areas; [b] residential areas; [c] Industrial areas

Table 5. South Coast Air Basin Emissions Inventory (tonnes per day)

	TOG	ROG	CO	NOx	SOx	PM	PM_{10}	$PM_{2.5}$
STATIONARY SOURCES	482	133	72	104	26	18	15	12
AREA-WIDE SOURCES	332	173	143	29	0	487	245	67
ON-ROAD MOTOR VEHICLES	341	314	3,163	598	5	17	16	12
OTHER MOBILE SOURCES	142	130	809	272	28	18	18	16
NATURAL SOURCES	5	3	88	5	0	18	17	15
TOTAL	1303	753	4274	1009	59	558	311	122
STATIONARY SOURCES	37%	18%	2%	10%	44%	3%	5%	10%
AREA-WIDE SOURCES	25%	23%	3%	3%	1%	87%	79%	55%
ON-ROAD MOTOR VEHICLES	26%	42%	74%	59%	7%	3%	5%	9%
OTHER MOBILE SOURCES	11%	17%	19%	27%	48%	3%	6%	13%
NATURAL SOURCES	0%	0%	2%	0%	0%	3%	6%	13%

Source: http://www.arb.ca.gov/app/emsinv/emseic1_query.php

Note: TOG – total organic gases; ROG – reactive organic gases

Table 6. 2000 MCMA Emission Inventory by sector (tonnes per day)

	PM_{10}	$PM_{2.5}$	SO_2	CO	NOx	COT	CH_4	COV	NH_3
STATIONARY SOURCES	8	2	28	27	68	62	0	60	1
AREA-WIDE SOURCES	1	1	0	18	29	1147	462	542	36
ON-ROAD MOTOR VEHICLES	9	7	11	5479	370	556	31	513	6
OTHER MOBILE SOURCES	6	5	1	52	61	22	1	20	0
VEGETATION AND SOILS	5	1	N/A	N/A	2	42	N/A	42	N/A
TOTAL	28	17	40	5577	530	1829	494	1177	42
STATIONARY SOURCES	27%	9%	70%	0%	13%	3%	0%	5%	1%
AREA-WIDE SOURCES	5%	8%	0%	0%	5%	63%	93%	46%	84%
ON-ROAD MOTOR VEHICLES	31%	45%	27%	98%	70%	30%	6%	44%	15%
OTHER MOBILE SOURCES*	20%	31%	3%	1%	11%	1%	0%	2%	0%
VEGETATION AND SOILS	17%	6%	N/A	N/A	0%	2%	N/A	4%	N/A

* Not including construction equipment and locomotives (included in Area-Wide Sources)
Source: 2000 Emission Inventory for the MCMA, http://www.sma.df.gob.mx
N/A: Not applicable; N/S: Not Significant; N/E: Not Estimated

Table 7. 1995 COR emission by Source Category (tonnes per day)*

	VOCs	NOx	CO	SO_2	PM_{10}	$PM_{2.5}$
STATIONARY SOURCES	195	167	1715	296	33	19
AREA-WIDE SOURCES	499	112	304	58	162	63
ON-ROAD MOTOR VEHICLES	238	285	2077	11	16	11
OTHER MOBILE SOURCES	93	153	729	52	101	36
TOTAL	1025	718	4825	416	312	129
STATIONARY SOURCES	19%	23%	36%	71%	11%	15%
AREA-WIDE SOURCES	49%	16%	6%	14%	52%	49%
ON-ROAD MOTOR VEHICLES	23%	40%	43%	3%	5%	9%
OTHER MOBILE SOURCES	9%	21%	15%	13%	32%	28%

*Data for all sources were obtained from Chtcherbakov.[359] Mobile emissions were processed using the MOBILE 5b model (US EPA). Off-road mobile sources represent emissions from all transportation devices not operated on roads (e.g. construction/agricultural equipment, marine vessels, etc)

Table 8. Vehicular emissions (tonnes per day) in Delhi

Pollutant	SO_2	TSP	NOx	CO	HC
1990-91	6–10	1–19	44–139	243–492	82–200
1995-96	14–15	26–28	120–397	373–781	123–493
2000-01	18	35–196	261–860	447–4005	156–1542
Average decadal increase factor	2.2	11.6	6.1	6.1	6

Source: Gurjar et al., 2003

Table 9. Percent contribution of emissions and ambient concentrations to PM_{10}, SO_2 and NO_x in Beijing urban districts in 1999

Source	**PM_{10}**		**SO_2**		**NO_x**	
	Emissions	Concentration	Emissions	Concentration	Emissions	Concentration
Industry	26.9	21.6	23.9	39.6	25.9	13.2
Heating	10.2	6.4	26.2	48.1	11.3	8.1
Civil	4.1	8.6	1.0	4.0	1.5	2.7
Traffic	8.2	13.8	-	-	34.5	73.6
Fugitive dust	39.5	48.7	-	-	-	-
Other sources	11.1	0.9	48.9	8.3	26.8	2.4
Total	100	100	100	100	100	100

Source: He et al., 2003.[404]

Table 10. Modal Share, Average Travel Time and Public Perception of Transport System 1998-2002

	1998	**2002**
Modal Share		
Transit	72%	73%
Private Vehicle	16%	11%
Non Motorized	9%	13%
Other	3%	3%
Average Travel Time		
Bogotá ¿Como Vamos? (1998-2002)	48 min	42 min
STT (2000-2003)	58 min	51 min
Public Perception Transport System	2,78/5,00	3,47/5,00

Source: Bogotá ¿Como Vamos? (2002), involving 1513 telephone interviews;
STT (2003), involving 7600 direct interviews.

Table 11. An estimation of Emission Reductions (1998-2002) resulting from implementation of the TransMilenio Program

Ton/year (% of mobile source emissions)	**Replacement of fleet plus more efficient operations**	**Modal Shift (from private vehicle to transit and non-motorized transport)**
CO	5,282 (4%)	8,918 (7%)
NOx	6,347 (8%)	924 (1%)
VOC (HC)	9,633 (9%)	897 (1%)