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Mexico City Air Quality Research Initiative

Volume II
Problem Definition, Background, and Summary of Prior Research

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Volume II
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ACRONYM LIST

CIT	see footnote p. 23
CFE	Comisión Federal de Electricidad (Federal Electricity Commission
CNE	Comisión Nacional de Ecología (National Ecology Commission)
CNG	Compressed natural gas
DDF	Departamento del Distrito Federal (Federal District Department—Mexico City government)
DF	Distrito Federal (Federal District)
EKMA	Imperical kinetic modeling approach
EM	Estado de México (State of Mexico)
EPA	Environmental Protection Agency
HOTMAC	a three-dimensional, time-dependent mesoscale computer model
IMECA	Indice Metropolitano de Calidad del Aire (Metropolitan Air Quality Index)
INE	Instituto Nacional de Ecología (National Institute of Ecology)
IMP	Instituto Mexicano del Petróleo (Mexican Petroleum Institute)
JICA	Japan International Cooperation Agency
LANL	Los Alamos National Laboratory
MARI	Mexico Air Quality Research Initiative
MCMA	Mexico City Metropolitan Area
MOBILE 4	EPA automotive emissions model
OZIP-4	A version of an EKMA model
PAN	Organic Peroxyacyl Nitrates
PEMEX	Petróleos Mexicanos (Mexican Petroleum Co.)
PICCA	Programa Integral Contra la Contaminación Atmosférica (Integrated Program Against Atmospheric Contamination)
PM	Particulate Matter
PM-10	Particulate Matter with particles 10 μm or less in diameter
RAMA	Red Automática Monitereo Atmosférico (Automatic Atmospheric Monitoring Network)
RAPTAD	a Monte Carlo dispersion and transport model
SEDESOL	Secretaría de Desarollo Social (Secretariat for Social Development)
SEDUE	Secretaría de Desarollo Urbano y Ecologia (Urban Development and Ecology Secretariat), precursor to SEDESOL
STI	Secretariado Técnico Intergubernamental (Intergovernmental Technical Secretariat)
TSP	Total Suspended Particulates
TÜV	TÜV Reinland, German Consulting Firm

UAM	Universidad Autónoma Metropolitana (Atonomous Metropolitan University)
UNAM	Universidad Nacional Autónoma de México (Atonomous National University of Mexico)
VOC	Volatile Organic Compounds
WHO	World Health Organization

A. OVERVIEW

The Valley of Mexico, where in the fourteenth century the Aztecs founded a city that was organized to maintain a natural balance with its environment, has experienced extremely rapid growth in population, urban sprawl, and industry in the second half of the twentieth century. The valley is at an altitude of 2240 meters above sea level. It is inhabited by more than 15 million people and has economic activities that are comparable in total dollars to those of Argentina or Portugal. Mexico City generates more than 30% of the country's industrial production, has a per capita income of 4,400 dollars per year, and has one of the highest per capita energy consumption totals in the country. Mexico City endures 30 million person-trips per day, generates 18,000 tons of garbage per day, and consumes water at a rate of more than 60 cubic meters per second.

Because of this level of activity, the challenges faced by the city in urban administration, economic change, and environmental management are extremely complex. Because of the effects of an economic crisis and necessary economic reform, the environmental problems and urban deterioration seem endless: accelerated increase of pollutants in the air and water, accelerated destruction of green areas, unhealthy open-air garbage dumps, a total lack of control over hospital and industrial wastes, a public transport system that was characterized by its technological backwardness in environmental technology, and unclean industry with high water and energy consumption.

After the 1985 earthquakes, which caused major destruction but also demonstrated the extraordinary response capacity of the inhabitants of Mexico City, firm steps were taken to begin to solve its problems. An ecological law and institutional infrastructure to protect the environment were developed, and a diagnosis of the problems, based on their systematic measurement, was made. A mid-term program to be implemented over some ten years was established to improve air quality, save water, decrease urban growth, create new ecological reserves, and restore areas with high environmental value. It would also institute a mid-term transportation program, shut down permanently open-air garbage deposits, establish a mid-term waste management program, and require technological changes in vehicles (introducing catalytic converters) and industries. Very difficult decisions have become imperative: severe restrictions on the use of automobiles, temporary shutdowns of industry, a complete shutdown of the refinery, massive expropriations of land for the purpose of creating areas of vegetation, and the largest reforestation program in the city's history. All of the decisions have been made possible by the cooperation and support of the city's inhabitants.

Air pollution in Mexico City has increased along with the growth of the city, the movement of its population, and the growth of employment created by industry. The main cause of pollution in the city is energy consumption. Therefore, it is necessary to take into account the city's economic development and its prospects when considering the technological relationships between well-being and energy consumption. Air pollution in the city from dust and other particles suspended in the air is an old problem. However, pollution as we know it today began about 50 years ago with the growth of industry, transportation, and population. The pace of pollution growth has been staggering. Trends during the last decade have been such that in the next twelve years the pollution levels could double. The thought that between the years 1988 and 200 pollution could double again means that grave consequences could ensue for the population.

The level of well-being attained in Mexico City implies a high energy use that necessarily affects the valley's natural air quality. However, the pollution has grown so fast that the city must act urgently on three fronts: first, following a comprehensive strategy, transform the economic foundation of the city with nonpolluting activities to replace the old industries, second, halt pollution growth through the development of better technologies; and third, use better fuels, emission controls, and protection of wooded areas.

In his inauguration speech in December 1988 President Carlos Salina de Gortari said, "I am giving precise, urgent, and imperative instructions to the Mayor of the Federal District to act immediately and efficiently to promote community participation in the fight against pollution."

B. THE MEXICO CITY METROPOLITAN AREA (MCMA)

1. The Physical Environment

a. Topography

Mexico City is located in a high mountain valley that is almost completely enclosed by mountains. The topography of Mexico City is shown in Figure B.1. The city occupies the southeast corner of the basin as shown by the yellow area, which was defined by estimated carbon monoxide (CO) emission densities. The two white points represent the tops of the two volcanoes, which exceed 5000 meters in elevation. The valley bottom is about 2200 meters in elevation, while the mountains to the southwest form a barrier with heights over 3500 meters. There is a slight opening in the basin to the northeast that permits moisture and winds from the Gulf of Mexico to influence the basin. The area enclosed in the white boundaries is the Distrito Federal (DF) while the remainder of the Mexico City Metropolitan Area (MCMA) is in the state of Mexico.

b. Meteorology

The meteorology is greatly influenced by the topography. The high mountains produce a summer monsoon, so that afternoon thundershowers are common from May through September. The dry months are December through March.

The topography also greatly influences the winds within the basin. On clear nights, cold air drains off the mountain slopes and produces nearly stagnant air over the city. After sunrise the mountain slopes southwest of the city become heated, and the winds tend to blow across the city from the northeast. Late in the afternoon the mountain winds may link with a sea-breeze from the Gulf of Mexico to bring strong winds from the northeast.

Aloft, 200 meters above the surface, the winds tend to be from the west or southwest, so that there is considerable wind shear. On a clear night the pollutants generated by the city accumulate over the city and perhaps drift to the northeast. In the morning, the winds reverse and the pollutants move back across the city to the southwest. The highest ozone (O_3) concentrations are normally found on the southwestern or western sides of the city. Pollutants from the afternoon emissions tend to be carried up the mountain slopes where they may be caught by the upper-level winds and carried back across the basin at heights high above the surface. Wind shear and strong turbulence in the afternoon may cause some of the pollution to be mixed down to the surface and join the freshly emitted pollutants. Alternatively, the pollutants may not reach the tops of the mountains before the nighttime down-slope breezes begin and they are carried back down into the city with the cold air draining off the mountains.

The formation of clouds with their strong influence on the radiative heating and cooling gives different conditions than those expected for clear days and nights. Thunderstorms can also remove some of the pollutants and produce more rapid dilution of other pollutants.

2. Urban Activities

a. Land use

Figure B.2 depicts the land coverage in the vicinity of Mexico City and the mountainous area to the southwest of the city. Thirteen categories are used to define land coverage. These categories are shown in Table B.1.

The satellite data were developed by University of Utah researchers from a LANDSAT image taken during the late morning on February 17, 1991.

b. Transportation

1. *Traffic Patterns.*

In the DF, the road infrastructure is composed of primary roads and secondary roads:

- Primary roads—1371 km, with 131 km of expressways (continuous circulation roads), 290 km of high-priority avenues (ejes viales) and 950 km of main roads
- Secondary roads—8150 km

The expressways and the main roads with a high traffic capacity are clearly defined within the DF (as shown in Figure B.3). In the bordering areas, between the DF and the Cuautitlan-Texcoco Valley, there are some difficulties in identifying major roadways because of heavy traffic that results in highly congested areas. Table B.2 shows the primary roads that exist in the Mexico City Metropolitan Area.

Early in September 1990 there were traffic lights at 2888 street crossings in the DF. Eight hundred and ten (810) of those traffic lights were operated through a computer system. These lights are located within areas demarcated by the Periferico expressway to the west, the Eje 2 East (La Viga) to the east, and the Circuito Interior (Inner Circle Expressway) to the south and north. The total number of kilometers of streets controlled by computer-aided traffic lights in the DF is 222.

Activities and traffic in the city increase sharply from 6:00 a.m. to 9:00 a.m., then they decrease slightly and remain almost constant until 5:00 p.m. when people begin to leave the city center, increasing traffic slightly until 10:00 p.m. There is a steep decrease from 10:00 p.m. to midnight.

2. *Fleet Characteristics.*

The MCMA consists of the urban area of the DF and 17 municipalities of the Estado de México (State of Mexico—EM). It is home to over 18 million people, and there are close to 3 million vehicles. According to official data, the population relies on several means of transportation to carry out their daily activities at offices, schools, shopping centers, and entertainment centers. The transportation sector is considered to be the main contributor to the gross emissions in the MCMA. Table B.3 lists the types of transportation used in the MCMA.

It is important to point out that the majority of the vehicles in the MCMA are characterized by old engines running at very high altitudes. For example, the average age of the private car fleet is estimated to be 12 years. However, the composition of total registered or operating vehicles is not indicative of the number of persons transported by the mode of transportation because the vehicles have different capacities, which can be estimated as follows:

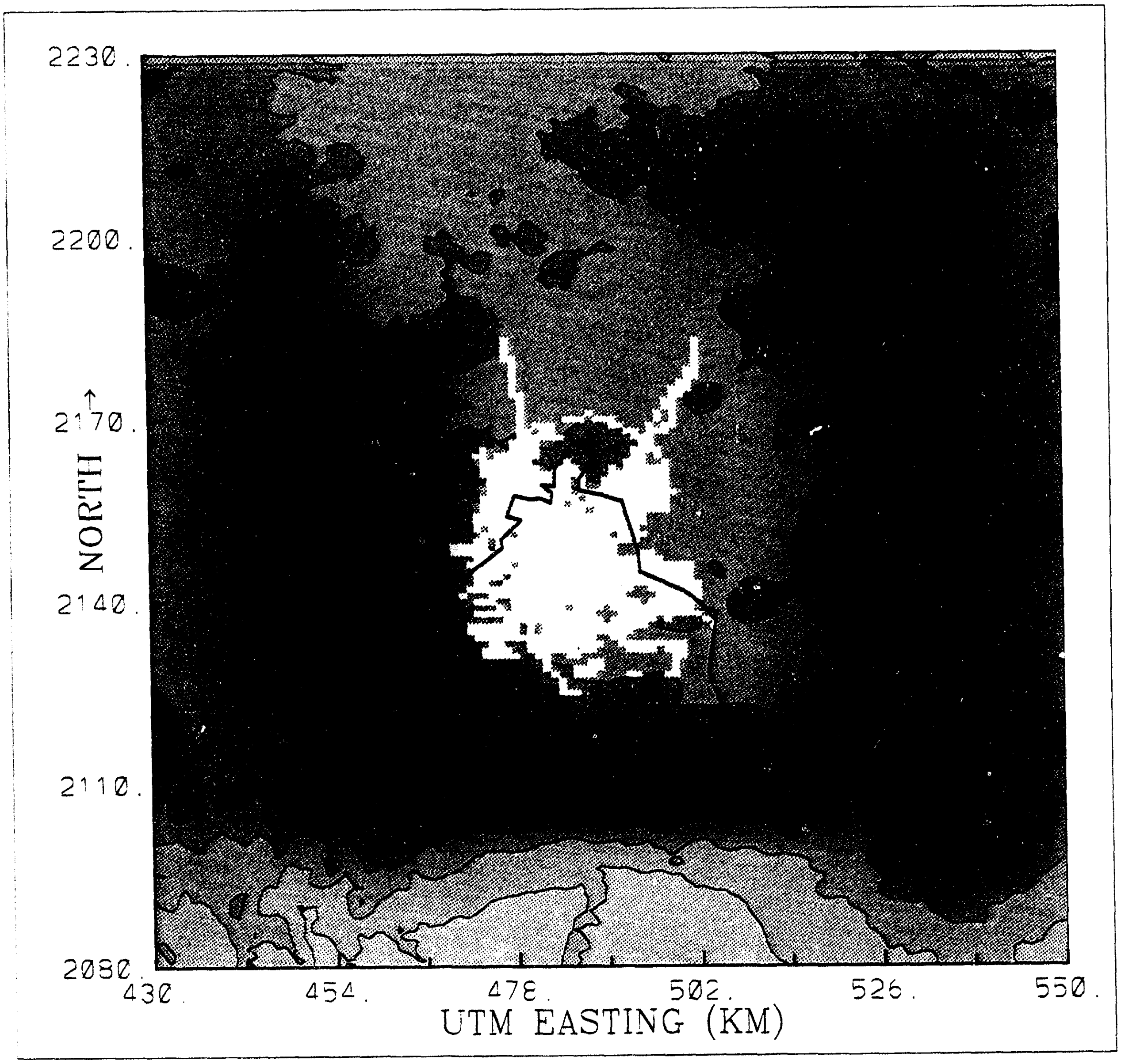
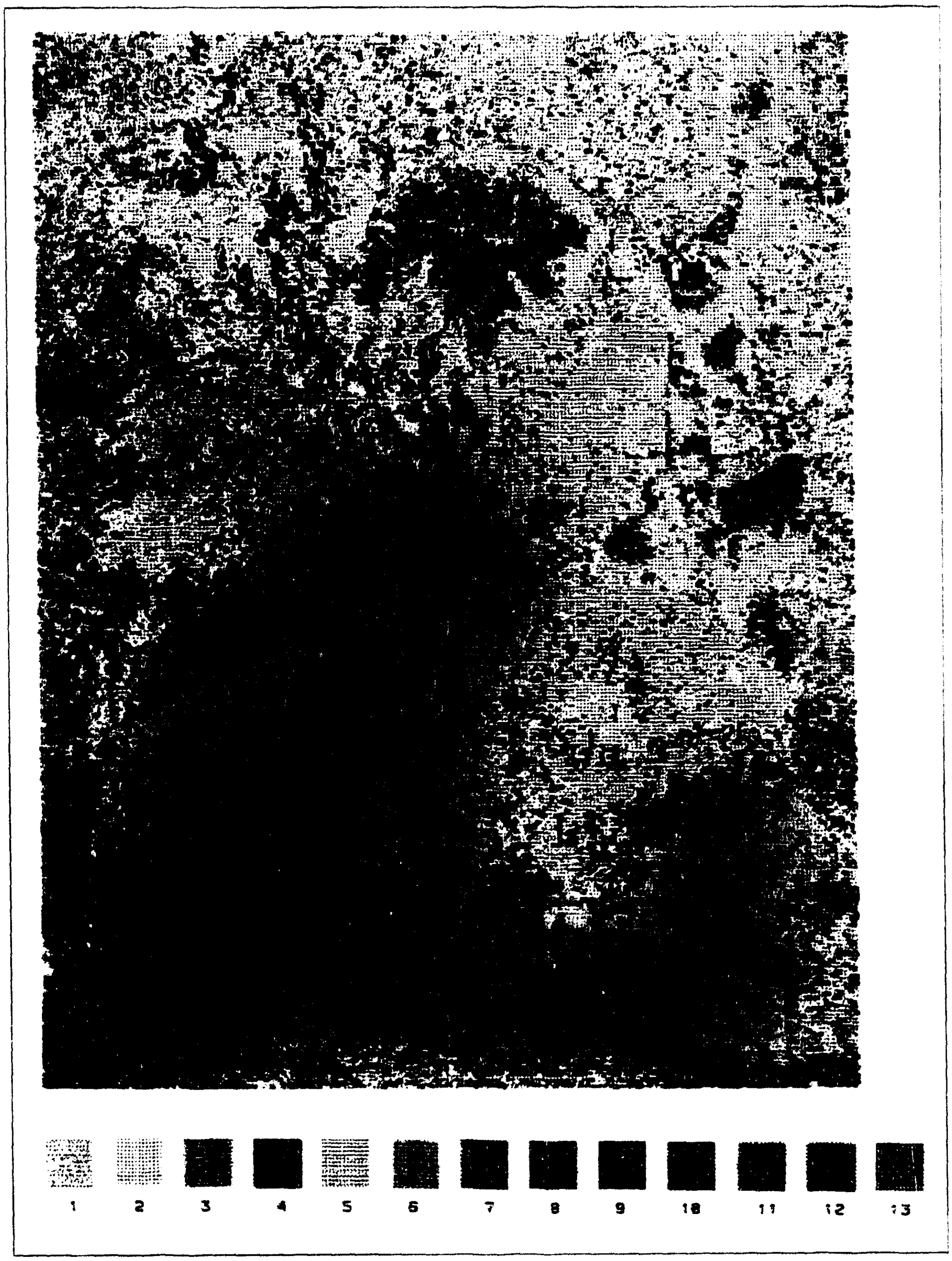


Figure B.1. The topography of Mexico City, which is located in a high mountain valley and is almost completely enclosed by mountains.



Value	Class Name	Value	Class Name
1	Vegetation	8	Dark Urban Material
2	Mostly Bare Soil	9	Urban Material Mix
3	Dark Soil	10	Urban/Mostly Downtown
4	Shadow/Volcanic/Urban	11	Vegetation Mix
5	Urban/Lower Income	12	Mountain Vegetation
6	Vegetation/Foothills & City	13	Vegetation & Rock Mixture Mountain
7	Water		

Figure B.2. Water, land use, and vegetation, obtained from satellite photos of the vicinity of Mexico City and the mountainous area to the southwest of the city.

TABLE B.1 Categories used to Determine Surface Features in the Valley of Mexico

Categories
1. vegetation (golf course fairways were placed in this category)
2. mostly bare soil (dry tilled fields and sandy areas are examples)
3. dark soil (irrigated tilled fields would be an example)
4. shadow-volcanic-urban (basalts and shaded urban areas for example)
5. urban lower income (lighter urban areas)
6. vegetation-foothills-city
7. water
8. dark urban material
9. urban material mixture
10. urban (mostly downtown)
11. vegetation mix
12. mountain vegetation
13. a mountain vegetation and rock mixture

5 passengers for private car
3 passengers per route per taxi cab
70 passengers per private company buses
100 passengers for Ruta 100 buses
9-12 passengers per "combi" collective taxis
27-31 passengers per "microbus" collective taxis
200 passengers per metro subway car
100 passengers per trolley bus
150 passengers per light rail unit

The extension of the urban area forces the population to travel long distances to conduct their daily business. It has been estimated that 29.5 million trips are made every day, of which 39.0% are made in private cars, 5.6% in taxis, 20.0% in combis and minibuses, 17.8% in urban and suburban buses, 16.3% in the Metro, and 1.3% in trolley and light rail. Among these transportation modes, taxis and private cars emit the largest quantity of pollutants per passenger-kilometer.

Vehicle emissions represent 76% of the total quantity of pollutants expelled into the atmosphere of the MCMA, and private cars emit more than half of the total mobile source emissions. Taxis, commercial passenger vans, and minibuses together emit 24% of the total mobile source emissions. The total fleet of taxis, commercial passenger vans, and minibuses is limited by the government to 49,000 vehicles. Those vehicles represent the category that has the highest contribution of pollution per trip. At the end of 1990, the buses owned by Ruta 100, because of their program of maintaining and changing motors, will emit fewer than 1% of the pollutants originated by transportation. Gasoline-fueled cargo trucks emit more than 2% of mobile source emissions. Diesel-powered trucks emit more than 2.6% of mobile source emissions. Diesel powered trucks registered in the city represent around 2% of the pollution emitted by motor vehicles; however, their contribution to sulfur dioxide (SO_2) and particle emissions is very high.

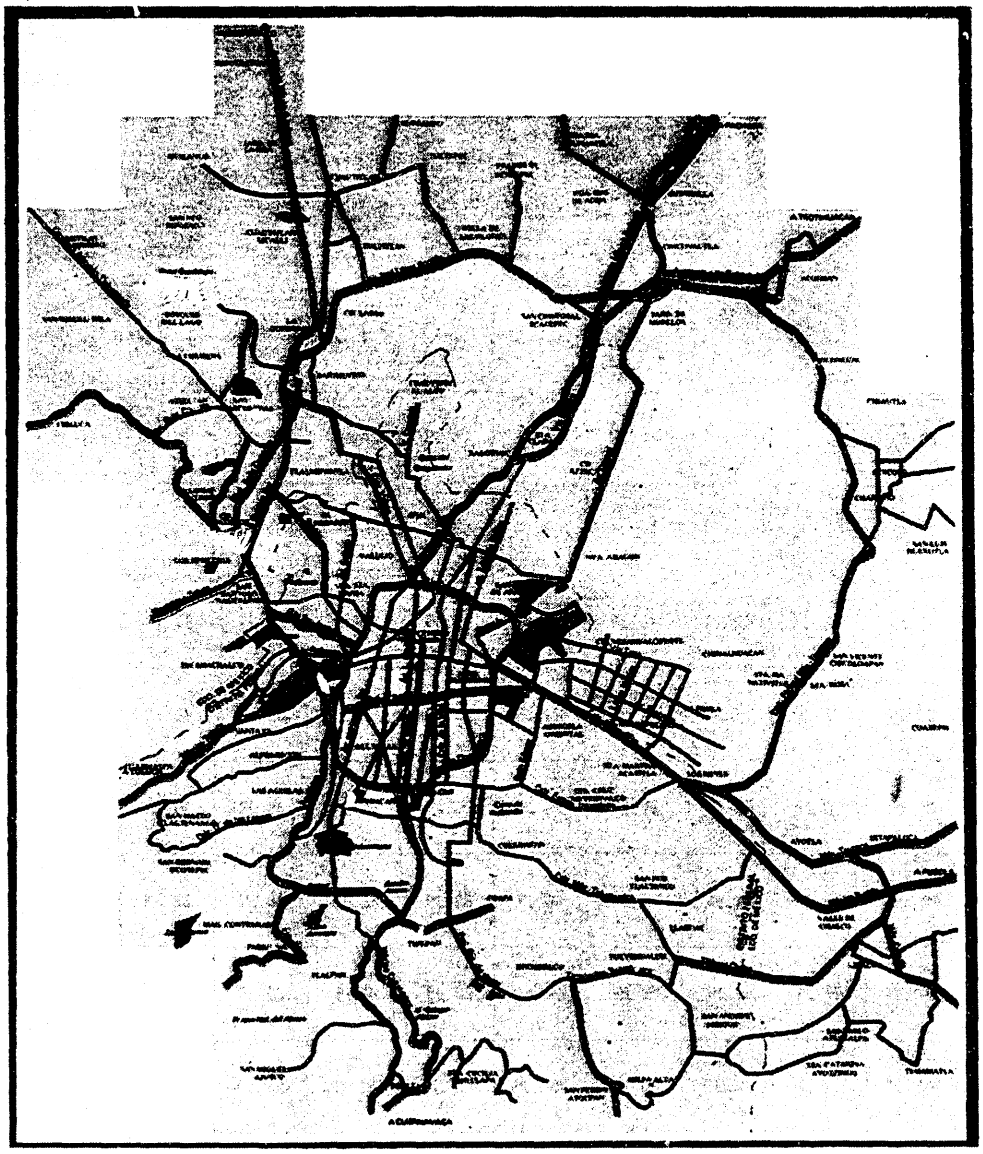


Figure B.3. The expressways and the main roads of the DF.

TABLE B.2 Primary Roads in the State of Mexico

Type of Road	Length
Urban Expressway	48 km
Primary Roads	597 km
Interurban Limited Access Highways	46 km
Interurban Roads	258 km
Total	949 km

TABLE B.3 Transportation used in the MCMA

Transportation	Total
Private Cars	2.6 million
Taxi Cabs	56,500
Ruta 100 Buses	3,500
Private Company Buses	4,000
"Combi" Collective Taxi Cabs	47,500
Trolley Buses	450
Subway Cars	2,241
Light Rail Cars for Electrical Transport	12
Transport Trucks	196,000
Diesel Heavy Duty Trucks	60,000
Aircraft	
Rail	
Others	

The main action currently used by the DF and the State of Mexico authorities to manage transport demand is the "A Day Without a Car" program ("Hoy no Circula"), which proposes a reduction of up to 20% in the private car operating fleet from Monday through Friday.

c. Industry

MCMA is a great economic sphere occupying about 40% of the national gross domestic product. The economic scale of MCMA is considered to be $80 billion U.S. dollars.

The economic structure of MCMA, with a large share of the service sector (65.7%) and a very small share of agriculture (0.09%) is characteristic of major cities. Mining, manufacturing, construction, and electrical power plants together contribute 30% to the total economic structure, and transportation and communications contribute 3%.

The total number of business establishments in the MCMA in 1985 was about 305,000, of which 71% were in the DF and 29% in the EM. The distribution by sectors in the MCMA was: commerce including hotels and restaurants 178,000 (58.55%), followed by service 89,000 (29.3%) and manufacturing 34,000 (11.4%). About 70% of the manufacturers are located in the DF and the rest are located in the EM.

The number of factories in the DF increased rapidly during the 1960s and reached a peak in 1975 of about 30,000. Then the number of factories began to decrease. During the 10 years between 1975 and 1985, the number of factories decreased by 5,000. On the other hand, the number of factories in the 17 municipalities of the EM steadily increased by a factor of ten in 25 years, from about 1,000 in 1960 to about 10,000 in 1985. However, a survey in 1986 showed that the number of factories in the EM had decreased to about 8,000. Considering the past trend, the number of factories located in the MCMA may be estimated to be 28,000 in 1990.

1. *Petroleum Refineries.*

The "18 de Marzo" Refinery began operating in 1933 in Azcapotzalco, one of the DF delegations.* At that time the refinery was situated away from Mexico City. As the refinery began to expand, it evolved considerably. Table B.4 shows the expansions for the refinery. Table B.5 shows the installed capacity distribution for 1990.

* A delegation is a large political subdivision of the Departamento del Distrito Federal (Federal District Department—DDF).

The plants in operation in 1990 included the following:

- Primary Distillation 1
- Primary Distillation 2
- Vacuum Distillation
- Visbreaking
- Fluid Catalytic Cracking
- Catalytic Desulfurization 1
- Catalytic Desulfurization 2
- Fluorhydric Acid Alkylation
- Gas and Gasoline Fractionation
- Turbosine Treatment
- Sulfur Recovery
- Propylen Tetramer
- Dodecylbenzene
- Electricity and Auxiliary Services
- Distribution Facility

TABLE B.4 Expansion of "18 de Marzo" Refinery from 1933 to 1990

Year	Stage	Installed Capacity Barrels/Day
1933	Start of Operations	7,500
1936	First Enlargement	11,000
1946	Second Enlargement	50,000
1955	Third Enlargement	100,000
1990	Final Enlargement	105,000

TABLE B.5 Installed Capacity Distribution for 1990

Product	Capacity Barrels/Day	% National Production	% MCMA Supply
Liquefied Gas	2,500	1.0	4.5
Gasoline	39,600	8.5	39.7
Turbosine	3,500	6.2	63.3
Diesel	20,600	7.2	65.0
Fuel Oil	34,200	6.9	113.0

The refinery storage capacity was 4,668,700 barrels with 222 tanks. The emissions of pollutant is shown in Table B.6.

2. *Power Plants.*

The MCMA has three major power plants. The installed capacity, type of power generation and fuel consumption for 1991 are shown in Table B.7.

TABLE B.6 Emission Rates for Pollutants Generated by "18 de Marzo" Petroleum Refinery

Pollutants	Tons/Year
Hydrocarbons (HC)	37,468
CO	5,729
NO_X	13,598
SO_2	16,917
Others	11,288

3. *Major and Minor Industries in the MCMA.*

In 1985, there were approximately 24,000 factories in the DF. Of these factories, 30% were food manufacturers, followed by metal producers at 12%, publishing and printing at 10%, apparel and wood products 9%, general machinery at 5%, textiles at 4%, and rubber and plastic at 4%. In the DF, food factories account for the largest number of establishments at about 7,000. Corn flour and tortilla factories account for more than half of the food factories at 3,600, followed by dairies at 1,400, and grain milling and agricultural products 1,300. These three sectors occupy 90% of the total distribution of factories. The metal product factories account for the second largest percentage of factories at about 2,900, of which more than half are engaged in the production of steel frames, tanks, and boilers (including those made with cast-iron).

TABLE B.7 Installed Capacity, Power Generation and Fuel Consumption for the Three Major Power Plants in 1991

Power Plant	Type	Installed Capacity MW	Fuel	Fuel Consumption $m^3 \times 10^6$
Valley of Mexico (Acolman EM)	Steam	730	Natural Gas	1058.6
			Fuel Oil	20.77
	Gas Turbine	88	Natural Gas	9.05
	Total	818	Natural Gas	1067.65
			Fuel Oil	20.77
Jorge Luque (Lechería EM)	Steam	224	Natural Gas	240.4
			Fuel Oil	5.23
	Gas Turbine	138	Natural Gas	14.95
	Total	362	Natural Gas	255.35
			Fuel Oil	5.23
Nonoalco DF	Gas Turbine	148	Natural Gas	9.00
MCMA	Total	2508	Natural Gas	1332.00
			Fuel Oil	26.00

The number of factories located in the 17 municipalities of EM was about 8,100 in 1989. The number of factories making metal products was 1,700 (21% of the total), followed by food factories at 15%, wood products at 9%, general machinery at 6%, non-metallic minerals at 6%, chemicals at 5%, apparel at 5%, and rubber and plastic at 5%. Among the 1,700 metal products factories, the number of factories producing steel frames, tanks and boilers is the largest, as is the case in the DF, with about 1,100. Of about 1,200 food factories, dairy factories count for 900, constituting 73%. (In the survey by the EM, there is a possibility that corn flour and tortilla making factories were not included.)

For all of the MCMA, food manufacturing factories occupy the highest percentage (26%) of the total number of factories. They are followed by metal products factories at 14%, wood products at 9%, apparel at 8%, publishing and printing at 8%, general machinery at 6%, rubber and plastic at 4%, textile at 4%, and electric machinery at 3%.

The scale of establishments in Mexico is classified into four categories by two factors: 1) number of employees, and 2) ratio of annual sales to general minimum annual wage. Table B.8 shows the distribution of factories in the MCMA.

In the DF, 1% of the total number of factories are ranked as large, 2% are ranked as medium, 20% as small, and the remaining 76% as micro industries. The large number of small- or micro-scale factories that exist in the DF are responsible for metal products, apparel, publishing and printing, and food. In the whole EM, 5% of the factories are ranked as large, 7% as medium, 29% as small, and 41% as micro.

The number of large-scale factories in the MCMA is estimated to total 700; medium factories are estimated to be 1000. The type of industry in which large scale factories are concentrated and their estimated numbers are shown below in Table B.9.

3. Social, Economic, and Political Characteristics of the Population in the MCMA

Mexico City is located in the southwest part of the Valley of Mexico basin at 2240 meters above sea level. The city was built over the ruins of the Gran Tenochtitlan, the capital of the Aztec empire, and it has been the capital of the Estados Unidos Mexicanos since Mexico's independence. Mexico City was embedded in the DFl although rapid growth has caused the city to extend into the territory of neighboring EM.

TABLE B.8 Scale Distribution of Factories in the MCMA

Scale Category	Number of Employees	Annual Sales/Minimum Annual Wage
Large	251 or more	2111 or more
Medium	101–250	1116–2110
Small	16–100	111–1115
Micro	15 or less	110 or less

TABLE B.9 Industries Involving Large-Scale Factories

Industry Activity	Number of Large-Scale Factories
Chemical	70
Textile	60
Rubber and Plastic	60
Electrical Machinery	50
Metal Products	50
Food Products	50
General Machinery	50

The DF was created by the 1824 constitution, and in 1941 the Organic Law of the DDF declared Mexico City as the capital of the DF. (González 1990)

Today the part of the MCMA that belongs to the DF is governed by Mexico City's mayor who is the head of the DDF. The part of the MCMA that belong to the EM is governed by the governor of that state. The governor is represented in the municipalities that form part of the MCMA by the mayors (Presidentes Municipales) of those municipalities.

The MCMA is formed by 16 delegations of the DF and 17 municipalities of the EM. The MCMA comprises an area of more than 2000 km^2. (Quadri and Sánchez 1992)

From 1970 to 1980, the population in the MCMA grew at a rate of 4.3%, with a corresponding 2.4% growth for the DF and 9.6% growth rate for the urban municipalities that belong to the EM. (González 1990) Some 14,987 million people live in this area, according to the 1990 census (PICCA 1990), 55% living in the DF and 45% in the EM. The MCMA contributes 20% of Mexico's total population and occupies only 0.4% of the national territory. The population of MCMA produces 36% of the gross domestic product of Mexico and consumes 17% of the total energy produced. The MCMA population is expected to grow at a 1.4% annual rate and total more than 20 million people by the year 2010. (PICCA 1990) Figure B.4 shows population growth in the MCMA from 1940 to 1990. (González 1990 & PICCA 1990)

Some other characteristics of Mexico City are

- It is the principal economic and financial center in the country.
- Population in this area has the highest educational level.
- 18% of all economic units (industrial, commercial, and services) are located in this area, and 22% of working people work here.

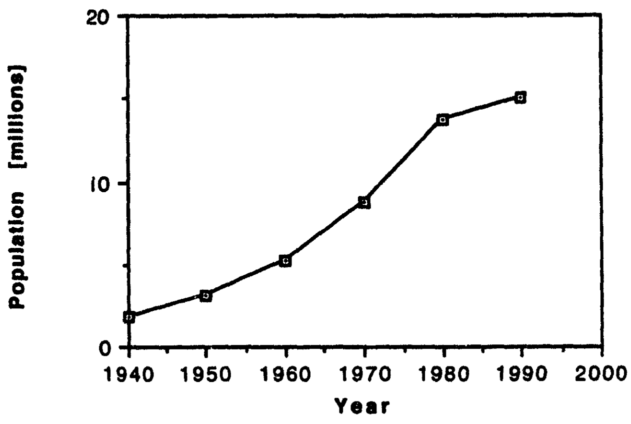


Figure B.4. Population growth in the MCMA from 1940 to 1990.

- 68% of people in this area are employed in trading activities, 27% in the manufacturing sector, and only 0.1% in the land and cattle sector.
- Mexico's Banking activity in the MCMA controls 74.8% of resources and spends only 48.9 % of its credits in this region. (Departamento 1993)

The economically active population (EAP) for MCMA in 1980 was 4.8 million, with 68.2% residing in the DF and the rest in the EM. For this EAP, 8% had no income, 15.1% made up to 72% of minimum wage (MW), 32.6% made between 73% and 132% of MW, 20.2% made between 133% and 242% of MW, 7.7% made between 243% and 444% of MW, 4.6% made more than 445% of MW, and 11.8 % did not respond. (González 1990)

In August 1992, in the MCMA, 77.9% of the male population and 33.7% of the female population (a total of 54.8% of the population, considering only people older than 12 years) contributed to the MCMA income. (Indicadores 1992)

Today, the average income per inhabitant in the MCMA is three times larger than the national level, 31% of the economically active population receives up to 2 times the MW, 30% earns between 2 and 5 times the MW, 10% earns between 5 and 10 times the MW, 10% earns between 10 and 20 times the MW, and 7 % earns more than 30 times the MW. Evolution of the MW for the MCMA is shown in Figure B.5. (Indicadores 1992)

Figure B.6 shows the evolution of the annual inflation compared with the annual increase of the MW for Mexico City. (Indicadores 1992 and Indices 1993)

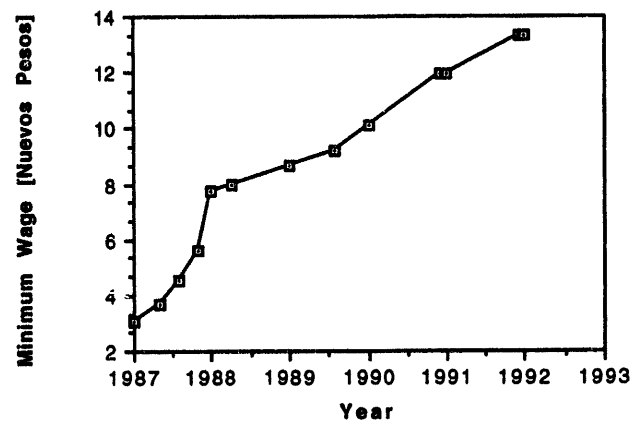


Figure B.5. The evolution of the minimum wage for the MCMA from 1987 to 1993.

Although Mexico City could be considered the most populated city in the world, its unemployment rate, 3.8%, is low if we compare it with other cities, e.g., New York 5.8%, Paris 10.4%, Buenos Aires 8.8%, and Montreal 8.0%.

Housing in the MCMA has been a problem because of the rapid population growth in this area. From 1970 to 1980, the number of houses in the MCMA increased 68%, with some municipalities in the EM showing growth rates of up to 400% (Atizapán de Zaragoza). (Aguilera et al. 1989) In 1980 there were 2,583,900 houses in the MCMA for 13,734,700 inhabitants—an average 5.3 persons per house, and 4.6 persons per room. This is certainly higher than the international standard that establishes a maximum of 3 persons per room. (González 1990) From 1988 to 1993, in an attempt to alleviate this problem, the government authorized 83,955 projects for building houses: 72,170 projects for low-income housing and the rest for medium-level income housing. (Monge 1993)

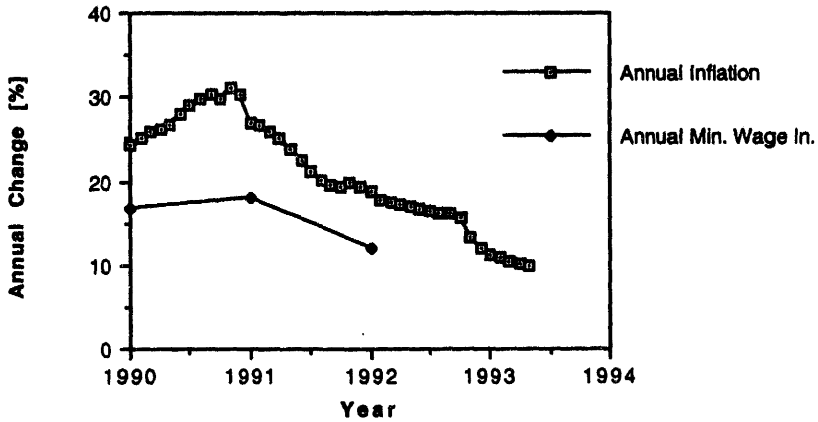


Figure B.6. A comparison of the evolution of the annual inflation rate with the annual increase of the minimum wage for Mexico City.

In 1988, in the DF, the potential demand for education consisted of 4.4 million people from 4 to 24 years old. Some 2.6 million required basic-level education, .6 million required senior high school, and 1.2 million required high-level education. Fifty-one percent of the demand for basic-level education was met, 27.5% of the demand for senior high school education was met, and 87% of the high-level education demand was covered. (González 1990) The DF is considered to have low indexes of illiteracy; in 1993 there were estimated to be only 228,000 people, or 6% of the total over the age of fifteen, who did not have reading or writing skills. (Monge 1993)

C. THE AIR QUALITY IN THE MCMA

1. Pollution Problems

Air Quality criteria have been set by the Mexican government as a way to evaluate the extent to which health is currently endangered. The IMECA (Indice Metropolitano de la Calidad del Aire—Metropolitan Air Quality Index) value of 100 corresponds to the Mexican Air Quality Standard for each pollutant. An IMECA value of 500 corresponds to levels that have significant evidence of damaging health effects. A description of the levels for the IMECA values is shown in Table C.1.

The primary air pollution problem that has been identified in the MCMA is the formation of photochemical smog, primarily O_3. Particulates may also be a problem in the MCMA, but they have not been studied as extensively.

a. Formation of Photochemical Smog

Photochemical oxidants are gaseous substances formed in the atmosphere by chemical reactions involving nitrogen oxides (NO_X) and organic compounds in the presence of solar radiation. The main photochemical oxidant is O_3, whose formation is accompanied by a range of other secondary pollutants photochemically generated including aldehydes, organic peroxyacyl nitrates, nitric acid, hydrogen peroxide, sulfate and nitrate aerosols.

Higher levels of O_3 and other photochemical oxidants are frequently observed in urban and rural areas as a result of the emission of precursor compounds. This level of photochemical oxidants was first observed in the Los Angeles basin during the 1940s. Photochemical pollution episodes (also called photochemical smog) are frequently observed during summer and can cause eye irritation, respiratory disorders, crop damage and increased deterioration rate of material.

Oxidant concentrations are generally higher in nonurban locations than in urban locations, and are found to cause damage to some crops and trees. A reduction in visibility is also associated with photochemical aerosols. Because of their oxidizing properties, photochemical oxidants accelerate the conversion of the SO_2 into sulfate. Ozone acts also as a "greenhouse gas," and it has been calculated that the doubling of

TABLE C.1 The Metropolitan Air Quality Index

IMECA Value	Air Quality	O_3 (1 hr)	CO (8 hrs)	NO_2 (1 hr)	SO_2 (24 hrs)	PM-10* (24 hrs)	TSP** (24 hrs)
0–100	Satisfactory	0.11 ppm	13 ppm	0.21 ppm	0.13 ppm	150 $\mu g/m^3$	275 $\mu g/m^3$
100–200	Not Satisfactory	0.23 ppm	22 ppm	0.66 ppm	0.35 ppm	350 $\mu g/m^3$	546 $\mu g/m^3$
200–300	Bad	0.35 ppm	31 ppm	1.10 ppm	0.56 ppm	420 $\mu g/m^3$	627 $\mu g/m^3$
400	Very Bad	0.48 ppm	41 ppm	1.55 ppm	0.78 ppm		819 $\mu g/m^3$
500	Very Bad	0.60 ppm	50 ppm	2.0 ppm	1.0 ppm	600 $\mu g/m^3$	1000 $\mu g/m^3$

*Particles less than 10 micrometers (10 μm) in diameter.
**Total suspended particles.

the tropospheric O_3 content may increase the surface temperature by nearly 1°C.

b. Role of Volatile Organic Compounds

Organic compounds are important primary air pollutants, emitted both from natural and man-made sources. The organic compounds involved in photochemical air pollution include HCs (those .ompounds containing hydrogen and carbon only) and their derivatives; the term "volatile organic compounds" (VOC) is frequently used to include hydrogen and carbon and their derivatives.

Natural emissions include methane, produced by the anaerobic fermentation of organic matter, and ethene, isoprene, and monoterpenes emitted by vegetation. Natural emissions mostly occur during the vegetation period, but there is considerable controversy regarding their magnitude on a worldwide level.

The VOC emitted by human activities include linear and cyclic saturated and unsaturated HCs, aromatic HCs, aldehydes, ketones, esters, ethers, acids and their halogenated derivatives. The most important man-made sources of non-methane VOC result from incomplete combustion of fuel in motor vehicle exhaust.

The chemical composition and the concentration of VOCs in the atmosphere vary considerably (in time and space). Emissions from man-made activities are predominant in urban and industrialized zones, where concentrations of VOCs are well above the natural level. There is uncertainty about the relative contribution of man-made VOCs in rural areas.

The most frequently used approach to asses the impact of VOCs on the formation of photochemical pollution is based on the use of models. Their design includes the modeling of the physicochemical and meteorological process involved in the formation of photochemical pollutants. Model studies are limited by the accuracy of precursor emissions, meteorological data availability, and the adequacy of the chemical mechanism used to represent the formation of O_3 and other secondary pollutants.

Models must also be validated using air quality data. Modeling studies have shown the nonlinearity of phenomena related to photochemical pollution (there is not a direct relationship between precursor concentrations and the quantity of O_3 formed), and have indicated the importance of the meteorological conditions, the chemical structure of the organics, and the VOC/ NO_X ratio in the atmosphere, which is linked to the characteristics of industrial and urban emissions.

2. Emissions Inventory

An emissions inventory is a database that ideally contains the temporal, spatial and detailed chemical composition of emissions from anthropogenic and biogenic sources. The emissions need to be classed as point (industry, power plants), line (major traffic arteries) and area or distributed (residential, commercial, other traffic). A further breakdown by type of industry, commerce or vehicle is needed to explore emissions control options.

The emissions inventory is a *sine qua non* for airshed modeling; obviously there can be no description of the behavior and fate of air pollution if there are no pollution sources. The emissions inventory, coupled with simulation, also forms the starting point for most air quality improvement strategies; it is almost universal to forecast a certain improvement in air quality if emissions are reduced a certain percentage. The translation of that percentage to tons of emissions reductions required is, of necessity, based on the emissions inventory.

The greatest uncertainty in input to air quality simulations is always the emissions inventory, particularly for HCs, a critical precursor to O_3 formation. There is a growing body of evidence that the HC emissions inventories are severely underestimated in urban areas around the world. Before this was understood, less than satisfactory simulation results, whether from the empirical kinetic modeling approach (EKMA) or the airshed approach, were often used for air quality management planning. This led to frustration in achieving air quality improvement because a certain number of tons reduction of HC emissions is actually a much smaller percentage reduction than expected when compared to the realistic emissions inventory. Consequently, a much smaller percentage improvement in air quality (referring to O_3) is achieved than was anticipated.

To conclude this brief discussion, the development of a good emissions inventory is a difficult project, usually entailing many refinements and iterations from the starting point. In process, the emissions of the study area are always changing; new emissions controls have gone into effect, population and concomitant traffic have grown, industry has grown or departed, etc. Because air quality management studies look at "what-if" scenarios starting from some base case, it is necessary to fix the emissions inventory for some specific year and develop the base case for that year. Only occasionally should an updated emissions inventory be adopted because it necessitates a new cycle of base case development and scenario simulation.

Base case simulations for this project were set to several dates in February 1991. Thus, a 1991 emissions inventory was needed. In February 1991 the Petróleos Mexicanos (Mexican National Petroleum Co.—PEMEX) 18 de Marzo refinery was still operating (it was closed by Presidential decree the following month) so the emissions inventory used and presented here includes the refinery.

The emissions inventory developed for modeling purposes in this project was adapted and derived from several sources, none of which meet the ideal criteria set forth at the beginning of this section. However, the DDF well recognizes the importance of a good emissions inventory and has supported and continues to support projects designed to improve the inventory for the MCMA.

The first effort to produce an emissions inventory for the MCMA was a collaborative effort between the DDF and the Japan International Cooperation Agency (JICA) begun in 1986 with the report issued in 1988. (JICA 1988) This inventory, for NO_X, SO_2 and CO, was established for a 1 km^2 grid covering the MCMA. Traffic volume surveys coupled with dynamometer testing of a selection of used vehicles were used to calculate mobile emissions. A voluntary survey taken of 361 factories for information on types of activities and processes, fuel usage, chimneys and flue gas volume and temperature, and installed pollution control equipment was used in conjunction with U.S. Environmental Protection Agency (EPA) emission factors to calculate emissions for these large sources. Spot-check measurements were made on a small number of stacks. Business license data from the DDF for 4,739 commercial and service establishments were used to obtain business type and fuel use. U.S. EPA emission factors were again used to calculate emissions.

The second emissions inventory for the MCMA is for 1989 and is presented in the Programa Integral Contra la Contaminación Atmosférica de la Zona Metropolitana de la Ciudad de México, universally referred to as PICCA, (Comprehensive Program Against Air Pollution of the MCMA) published by the Secretariado Técnico Intergubernamental in 1990. (PICCA 1990) We do not know many details of the development of this inventory, presented in Table C.2, except that a version of MOBILE 4 (an EPA automotive emissions model) adapted to the MCMA was used along with U.S. EPA emission factors for industry and commerce. However, this inventory bears the imprimatur of numerous federal secretariats, the DDF, PEMEX, the EM and the Comisión Federal de Electricidad (Federal Electricity Commission—CFE) so it served as the primary base to develop the inventory used in this project.

TABLE C.2 PICCA Emissions Inventory (metric tons/year)

Sources/Emissions	CO	VOC	NO_X	PST	SO_2
Stationary					
PEMEX	52,645	31,730	3,233	1,154	14,781
Power Plants	560	113	6,613	3,545	58,247
Industry	15,816	9,981	28,883	10,242	65,732
Commercial	466	121	3,988	2,469	22,060
Total Stationary	69,487	71,945	42,717	17,410	160,820
Mobile					
Private Cars	1,328,133	141,059	41,976	4,398	3,557
Taxis	301,162	31,986	9,518	997	806
Collectives & Minibuses	404,471	42,748	10,059	1,062	856
DDF Buses (R-100)	6,260	2,439	8,058	240	5,224
State of Mexico Buses	12,612	5,298	18,262	601	13,062
Gasoline Trucks	779,585	67,864	16,994	1,186	955
Diesel Trucks	16,515	7,293	26,126	923	20,063
Other (trains, airplanes, etc.)	5,040	1,693	2,698	142	251
Total Mobile	2,853,778	300,380	133,691	9,549	44,774
Ecological					
Eroded Areas				419,439	
Fires & Other Processes	27,362	199,776	931	4,201	131
Total Ecological	27,362	19, 776	931	423,640	131
Grand Total	2,950,627	572,101	177,339	450,599	205,725

A brief look at the data of Table C.2 shows that mobile sources contribute 97% of the CO, 53% of the HCs, 75% of the NO_X and 22% of the SO_2. Stationary sources contribute only 2.4% of the CO, 13% of the HCs, and 25% of the NO_X, but a significant 78% of the SO_2.

The third major source of data for the emissions inventory for this project was the pilot study undertaken in 1990 and 1991 by a collaboration between the German consulting firm, TÜV-Rheinland, and the DDF. (TÜV 1991) In this study a slice of dimensions roughly 5 km by 20 km was taken across the northern part of the MCMA. This slice included parts of the EM municipalities of Naucalpan de Juárez and Tlalnepantla and the DDF political delegations Azcapotzalco and Gustavo A. Madera. Two data sets were used for stationary emissions: data on industrial plants supplied by SEDESOL and data on fuel usage at combustion sites supplied by TecnoConsult. Mobile source emissions were derived from traffic surveys and MOBILE-MCMA. The report acknowledges several shortcomings to this inventory, particularly in stationary sources, but since this is the most recent information available, we applied the ratio of emissions from the TÜV study compared to the JICA study as a general scale-up ratio for the remainder of the MCMA.

Final preparation of the emissions inventory in a form suitable for input to the CIT (Center for Investigation and Advanced Studies*) simulations required a combination of distributing/grouping the data from the studies discussed above into a 5 km^2 grid. Temporal distribution of mobile emissions was calculated from a composite of traffic surveys and for stationary emissions from an electric power hourly demand chart. On occasion, when the emissions inventories presented seemingly unreconcilable data, judgments had to be made. The procedures and assumptions that went into preparation of the emissions inventory for this project were presented to the technical staff of the DDF, and they granted approval.

The PICCA and TÜV inventories show the ratio of the emissions of HCs to the emissions of NO_X to be slightly higher than 3:1. Assuming that early morning emissions obey the same ratio, it is easy to see that this HC/NO_X ratio is far too low. As discussed in Volume IV, HC measurements in Mexico City showed very high ambient concentrations. With NO_X levels measured at the same time, the HC/NO_X ratio is calculated to be in the range of 15:1 or higher. Modeling results, discussed further in Volume III, showed that the onset, slope, and peak of O_3 production could in no way be simulated with the base emissions inventory. Further, HC concentrations in the simulation calculated using the base emissions inventory were far lower than measured ambient values. An arbitrary but reasoned multiplicative factor of four, when applied to all HC emissions, led to significant improvement in model performance for O_3 prediction and HC-concentration tracking. Consequently, the HC emissions inventory used in this project for airshed modeling was also adjusted by a factor of four. It is recognized that this is a gross factor, but it serves to highlight the severe underestimation of HC emissions in the MCMA. Refinement in identifying the underestimated sources and the temporal and spatial distribution needed for a reliable emissions inventory remains to be done.

*CIT is derived from the California Institute of Technology and the Carnegie Institute of Technology at Carnegie Mellon University, the two institutions responsible for developing the model.

3. Pollutant Trends and Evolution

a. Ozone

Ozone is a highly reactive form of molecular oxygen that resides in organic and biological compounds. Ozone is not a pollutant that is emitted from a pollution source. Rather, it is formed, in the presence of sunlight, by the combination of volatile organic compounds (VOC) and NO_X. The formation of O_3 is based on the photochemical dissociation of nitrogen dioxide (NO_2) by ultraviolet light. In the presence of HCs, the reactions involved are very complex, and the final product is a mixture of O_3, organic compounds with oxygen in their molecular structure, NO_X. Figure C.1 shows two general cycles of reactions and the roles of VOCs and NO_X in the formation of O_3.

The main factors in the formation of O_3 are the chemical reactivity of the HCs involved, the intensity of the solar radiation, and the ratio of VOCs to increase the ultraviolet radiation. In the case of MCMA, the latitude and altitude of the city are factors that increase the ultraviolet radiation. Figure C.2 shows how solar radiation varies with the latitude and Figure C.3 demonstrates how the reaction rate constant varies with the altitude above sea level.

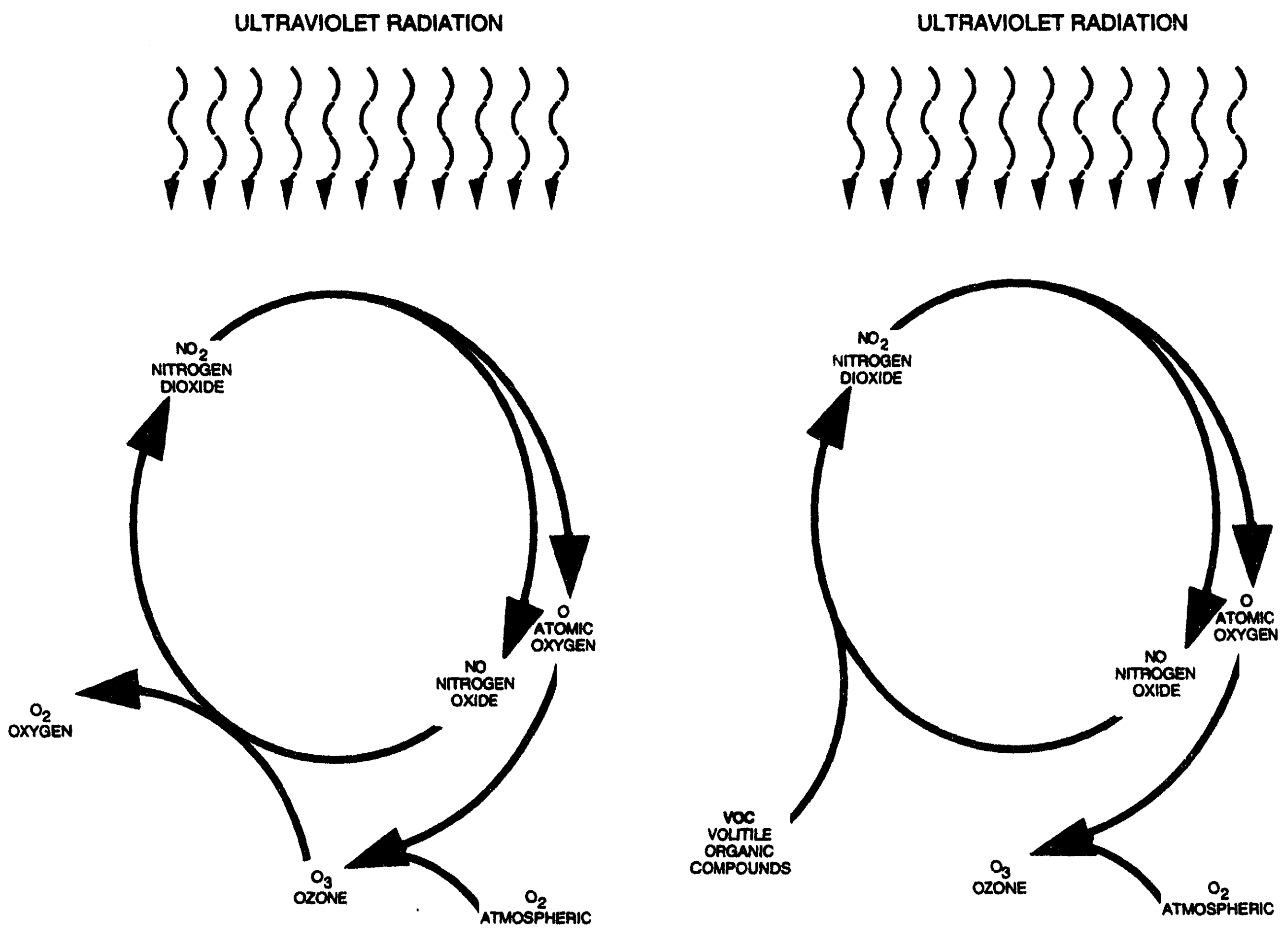


Figure C.1. Two general cycles of reactions that illustrate the roles of VOCs and NO_X in the formation of O_3.

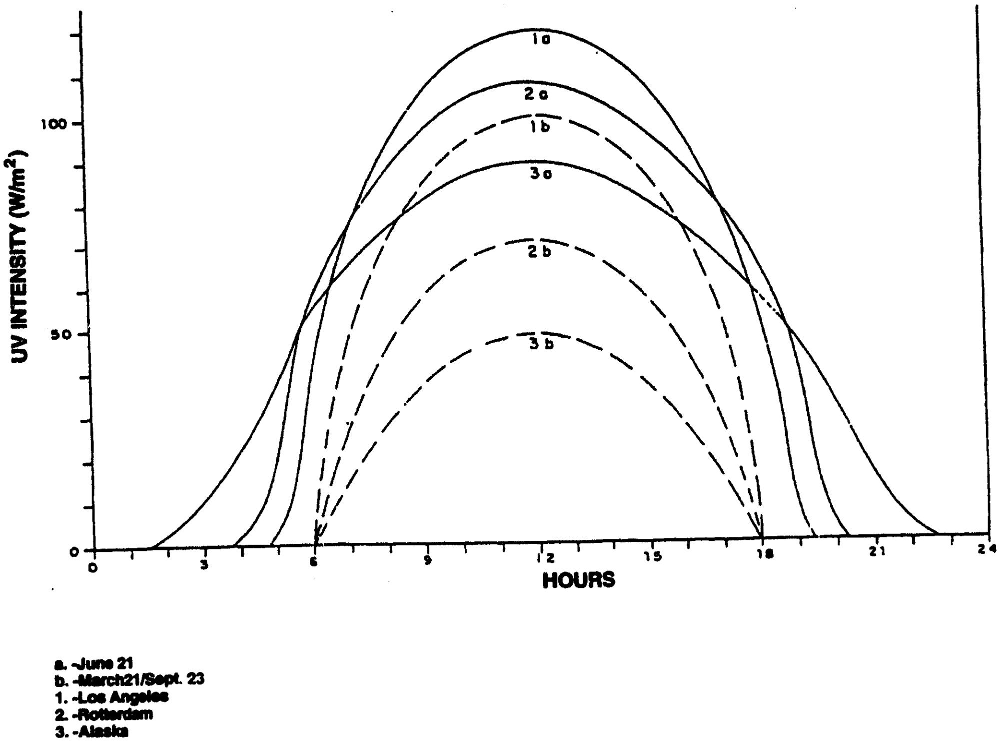


Figure C.2. How solar radiation varies with latitude.

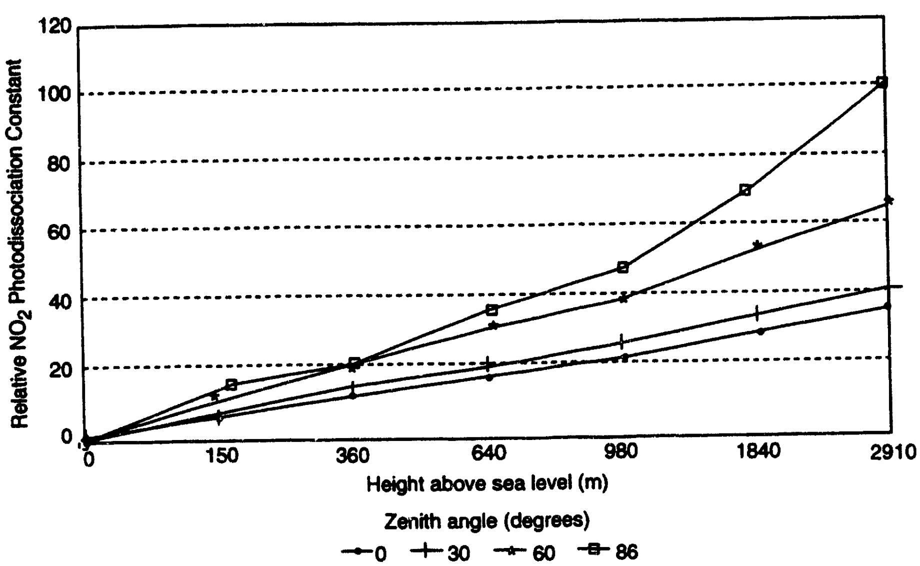


Figure C.3. The relative increase in the NO_2 photolysis rate constant as a function of altitude above sea level is shown. The values for each zenith angle are relative to a normalized value of 1.0 for that zenith angle at sea level.

Ozone and NO_2 levels in the atmosphere are closely related. Figure C.4 shows this relation over time. Early in the morning, NO_X emissions from vehicles, combustion sources, and processes, start increasing. By the middle of the morning, the sunlight starts the dissociation process, and the O_3 level that was very low in the early morning begins to increase. This situation is very important because of the synergistic effect of these pollutants.

The ratio of VOCs to NO_X in the ambient air determines the predominance of the HC or NO_X emissions in the O_3 formation. The VOC/NO_X ratio is the subject of much debate in the U.S. Many atmospheric scientists believe that if VOC/NO_X ratio is greater than 10, O_3 production is limited by NO_X, and reductions in VOC levels, unless they are very large, result in relatively little reduction of O_3. On other hand, if the VOC/NO_X ratio is less than 8, O_3 is thought to be VOC-limited, and controlling reactive VOCs should give the maximum benefit. Currently, very little data exist on VOC/NO_X ratios in the MCMA so it is difficult to determine which pollutant is most important in forming O_3.

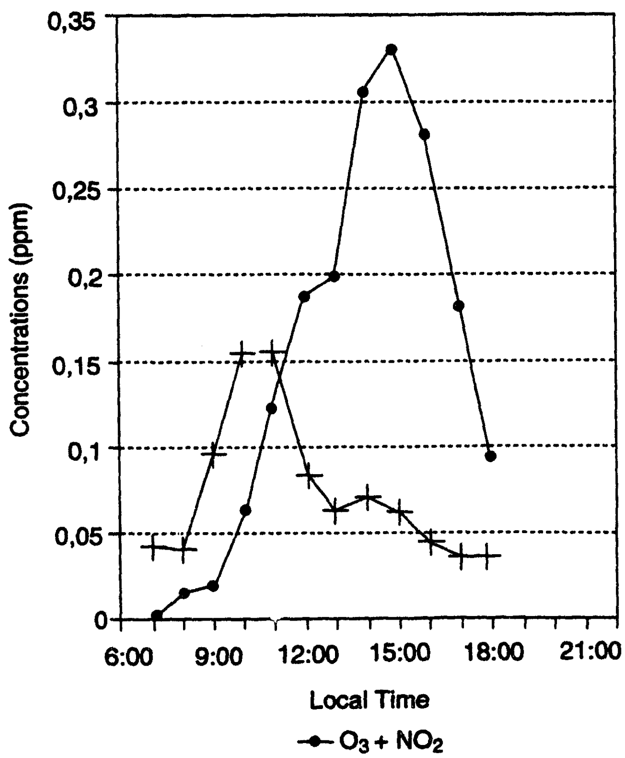


Figure C.4. The relationship between O_3 and NO_2 levels in the atmosphere.

Air quality criteria have been set by the Mexican government as a way to evaluate the extent to which health is currently endangered. The Mexican one-hour criterion for O_3 is 0.11 ppm. By comparison, the one-hour ambient O_3 standard set by the U.S. EPA is 0.12 ppm, and the World Health Organization (WHO) advisory criterion is 0.10 ppm.

Ozone levels in Mexico City are high and appear to be getting worse (Figure C.5). From 1986 to 1992, the Mexican criterion for O_3 levels was exceeded 71% of the days in 1986 and increased in 1992 to 98% of the days in the year (Figure C.6). Individual occurrences exceeded the standard by up to 300% (three days in 1991, and 8 days in 1992). The highest concentration ever recorded in MCMA was in March 16, 1992 with a value of 398% of the standard. This value was measured in the southwest zone of the city.

The air in Mexico City violated international health norms 254 out of 273 days (January-September 1992). Unlike the majority of the cities in the northern hemisphere, where the tropospheric O_3 phenomenon is only present during the summer days (when the solar radiation is significantly higher than the rest of the year), the MCMA presents favorable conditions for the formation of O_3 throughout the year. High concentrations of O_3 are observed at the end of the winter and the beginning of the spring (Figure C.7). This explains why there was such a high number of days in which the standard was exceeded.

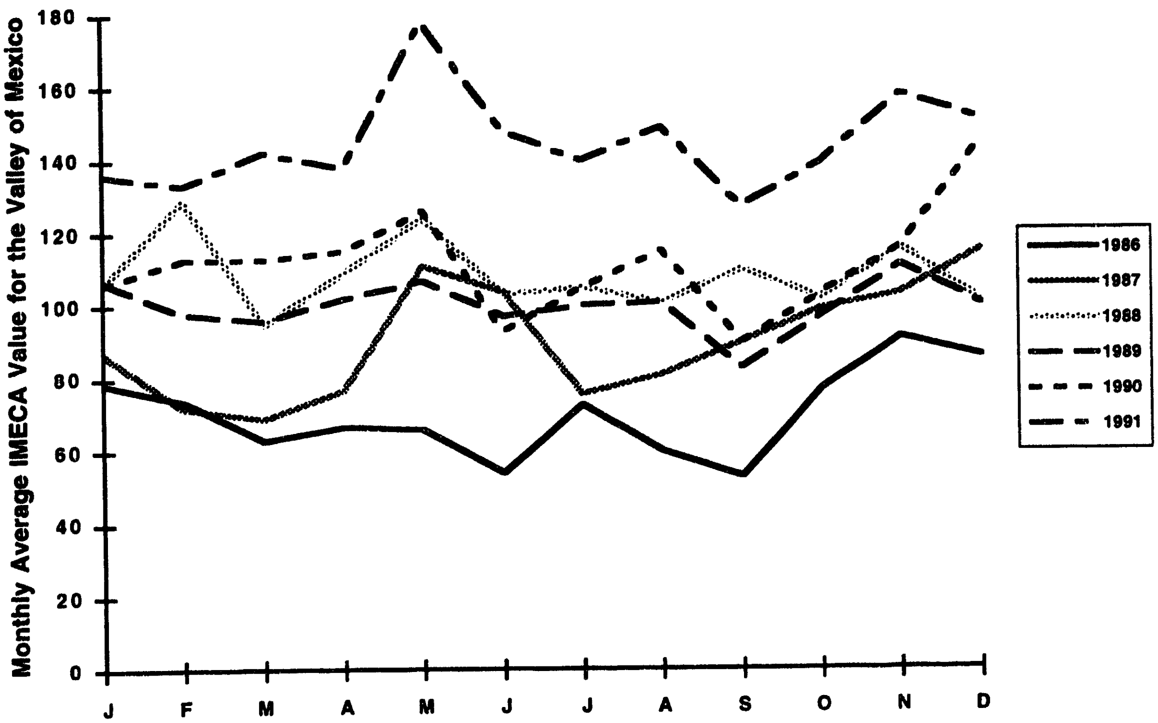


Figure C.5. The Mexico City O_3 levels, which are high and appear to be only getting worse.

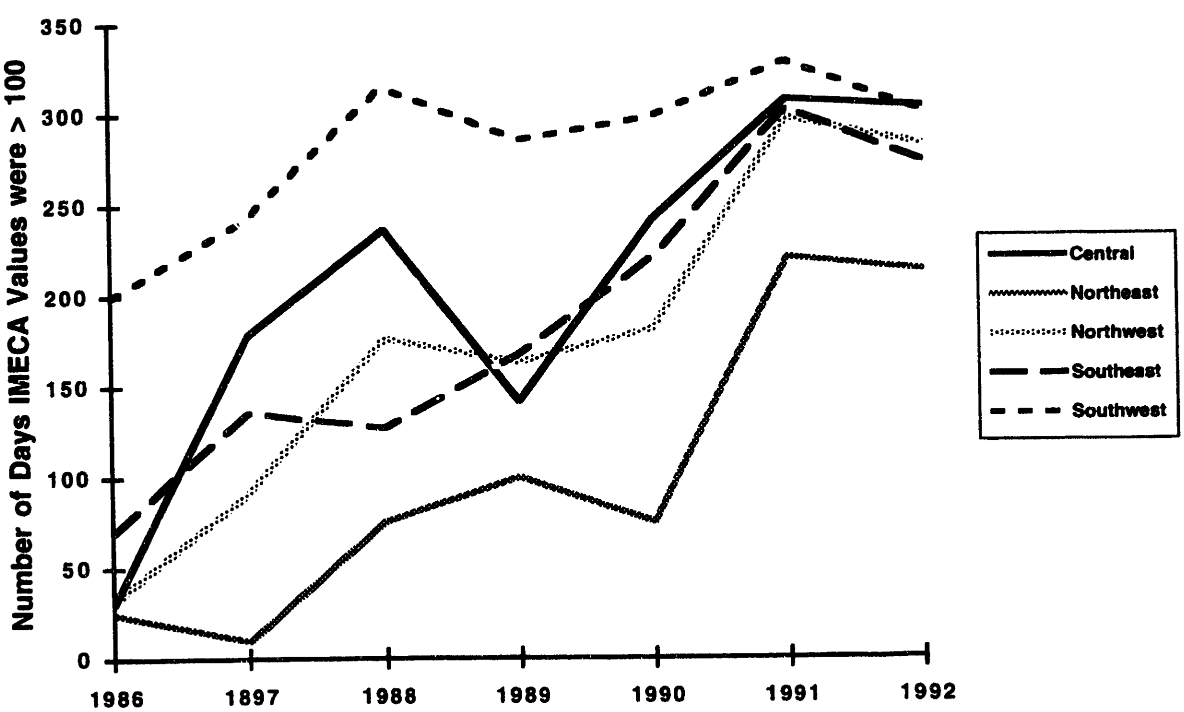


Figure C.6. The number of days O_3 exceed the standard for Mexico City. From 1986 to 1992, the standard was exceeded 71% of the days during the year and increased 1992 to 98% of the days in the year.

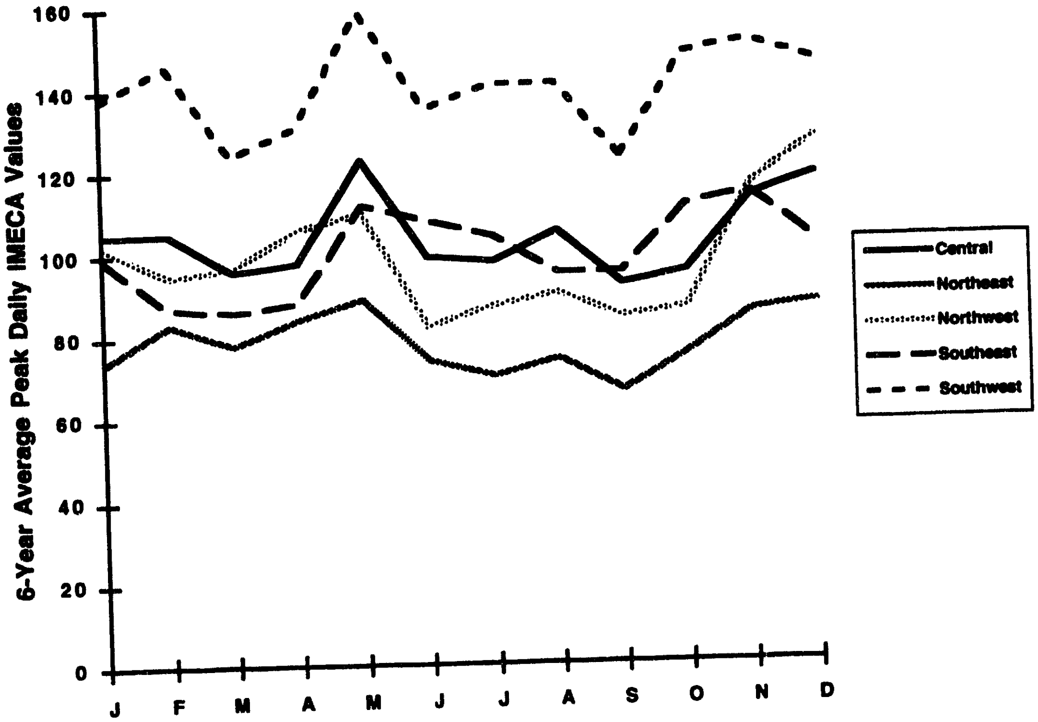


Figure C.7. The high concentrations of O_3 that are observed at the end of the winter and the beginning of the spring.

b. Particulate Matter

Particulate matter includes a variety of suspended particles, such as aerosols, organic and metal vapors, combustion particles and road dust. The PM-10 particles pose a greater threat to health because they penetrate deeper into the lung. Major types of PM-10 are those produced by combustion (diesel and stationary sources), vapors, and aerosol particles (organic, sulfate, and nitrate) formed by photochemical reactions.

PM-10 has been associated with various effects such as reduced visibility, soiling, and acid deposition damage to materials and buildings. In the MCMA, the reduction in visibility is one of the most important effects detected by the public. In the past, the most common view of Mexico City was a landscape with hills and mountains behind it (Figure C.8), but since the 1950s, the reduction in visibility has become very apparent in the city (Figure C.9). The soiling of construction materials, trees and other vegetation, and the deterioration of historical and colonial buildings downtown is also very important.

In the MCMA current measurements of particulate matter are made by the high-volume method that only measures TSP without any classification according to size. For this reason, it is impossible to know if the very high particulate matter concentrations measured include a high or low concentration of PM-10 particles. Theoretical evaluations based on possible sources of the particulate matter show that the portion of PM-10 in the total quantity of suspended particles measured in the MCMA is between 10% and 60%.

To protect against short-term health effects, Mexico has a 24-hour health advisory criterion of 270 mg/m^3. Mexico's criterion is based on TSP. In 1987, the U.S. changed its standard for TSP to a PM-10 standard in order to focus on the respirable fraction. Before the change to PM-10, the U.S. EPA 24-hour standard was 260 mg/m^3, and its annual average standard was 75 mg/m^3. Mexico does not have an annual average standard.

Ambient levels of TSP in the MCMA exceed the criterion even more extensively than O_3 levels. In recent years, the 24-hour highest recorded values ranged from 1100 mg/m^3 to 1300 mg/m^3 (these values correspond to the period from 1990 to 1991 when particulate concentrations were measured). The values are shown in Figures C.10 and C.11. These values were recorded in an industrial zone located in the northeast sector of MCMA. The TSP ambient levels exceeded the Mexican standard more than 90% of the time. All the monitoring stations in the MCMA record annual average values that far exceed the old EPA annual average of 75 mg/m^3. These stations reported annual averages ranging from 150 to 520 mg/m^3.

The highest concentrations measured in the MCMA correspond to the northeast sector during the dry season when high winds occur. For this reason, the TSP concentrations measured are probably mostly soil particles, which are larger than 10 micrometers in diameter. However, is important consider that in the wet months the standards are also exceeded, and this suggests that the contributions of particulates by vehicles and industry sources are contributing significantly to the particulate matter levels. To generate data on actual PM-10 levels in the MCMA, SEDESOL is planning to install ten PM-10 samplers in the same locations as the ten TSP high-volume samplers to ascertain the contribution of PM-10 particles to the overall problem of particulate matter.

c. Nitrogen Oxides

Nitrogen oxides include a variety of species of which the most prevalent and the most injurious to health is NO_2. Other negative effects of NO_X pollution are a reduction in visibility and an increase in acid deposition (acid rain). The reduction in visibility is due to NO_2's absorption of light and also to the nitrates present in atmospheric aerosols. In the case of Mexico City, the reduction in visibility from NO_X is very important, producing the smog over the city that is the typical brownish color of NO_2. The acid deposition of nitrates affects vegetation and some materials. In the case of vegetation, the main effect is tissue damage by necrosis; in the case of materials, it is corrosion and loss of cement in limestone and other construction materials. However, all (NO_X) species contribute to the formation of O_3. Nitrogen oxides combine with VOCs to form O_3 in the presence of sunlight.

To protect against short-term health effects, Mexico has a one-hour advisory level for NO_2 of 0.21 ppm. This is the same as the WHO standard and is more stringent that the State of California's one-hour standard of 0.25 ppm. The EPA has set an annual average standard of 0.053 ppm.

The concentrations of the background NO_X are attributed to the transportation sector and to a lesser extent, the industrial sector. Daily behavior of NO_X includes emissions from both of these sectors and also participation in the different photochemical processes that form secondary pollutants. In the winter there is a higher

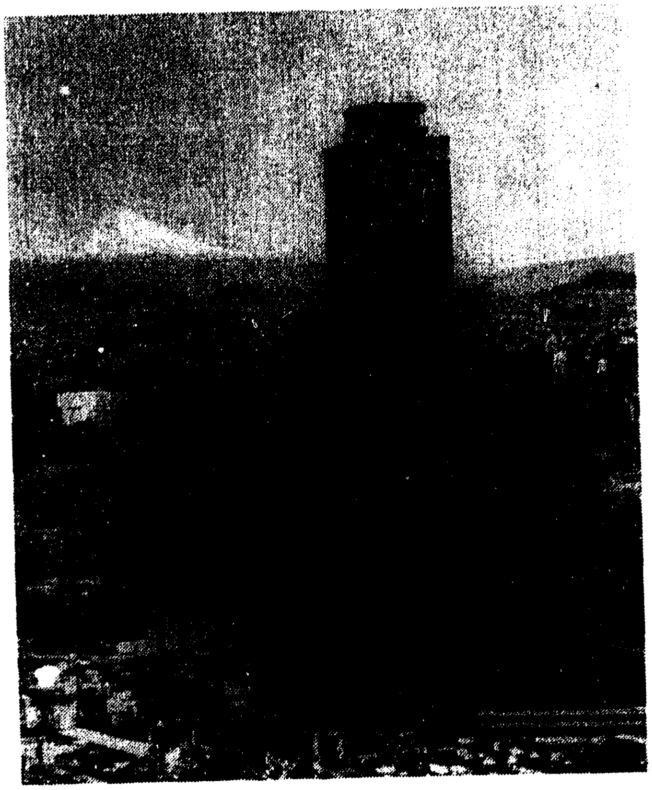


Figure C.8. What used to be the most common view of the city: a landscape with volcanoes behind it.

Figure C.9. How the reduction in visibility has changed the character of Mexico City. The city is now marked by the soiling of construction materials, trees, and other vegetation, as well as the deterioration of buildings.

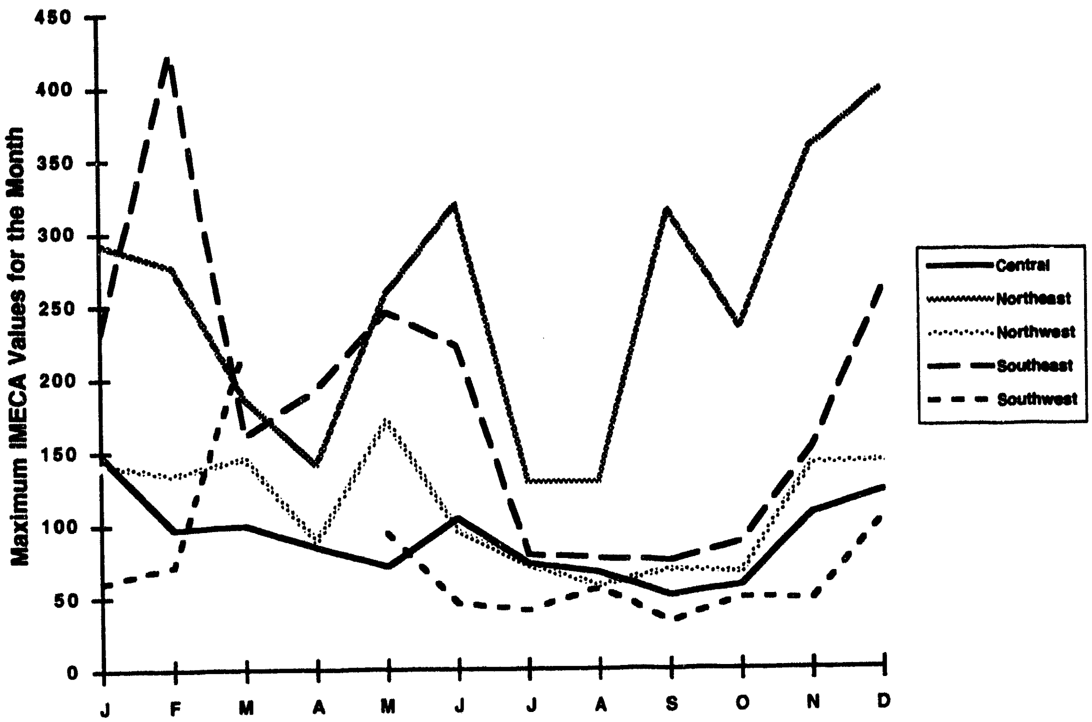


Figure C.10. The 24-hour highest recorded IMECA values for TSP in 1990. The value was 1100 mg/m^3.

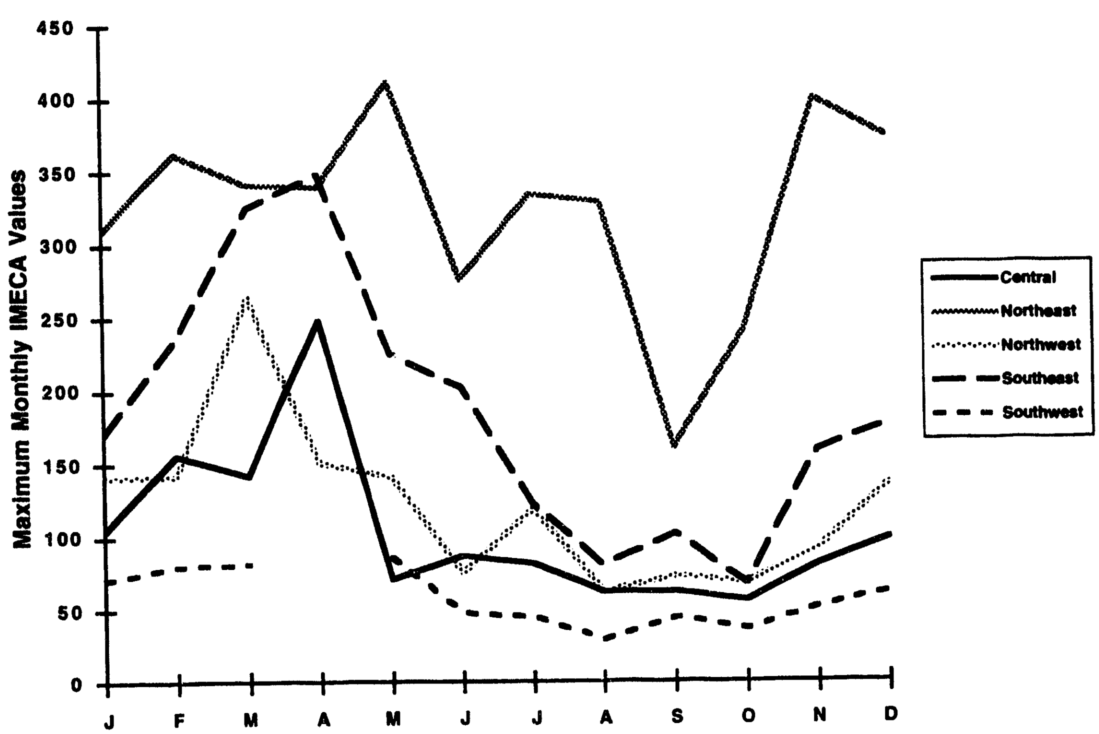


Figure C.11. The 24-hour highest recorded IMECA values for TSP in 1991. The value was 1300 mg/m^3.

incidence of days on which NO_2 levels exceed standards. From April to September the rains, along with higher rates of solar radiation and temperature, increase the reactivity, thereby reducing NO_2 levels (Figure C.12).

Ambient levels of NO_2 in the MCMA are highest in downtown Mexico City. At a downtown monitoring site, the highest one-hour value recorded in recent years was 0.32 ppm. This site has also recorded annual averages of 0.13 ppm.

d. Sulfur Oxides

Sulfur oxides (SO) are emitted during the combustion fossil fuels that contain sulfur. The dominant species within SO is SO_2. It is a colorless gas that reacts with a variety of airborne particles and water droplets to form sulfates, aerosols, and acid precipitation.

To protect against short-term health effects, Mexico has a 24-hour advisory limit for SO_2 of 0.13 ppm. This is slightly more stringent than EPA's 24-hour standard of 0.14 ppm. The EPA has also set an average annual standard of 0.03 ppm. Mexico does not have an average annual standard.

Ambient levels of SO_2 in the MCMA have been declining, probably in response to the reduced sulfur content in fuels. In recent years very few excesses of the 24-hour standard have occurred (Figure C.13). During the second half of the 1980s, the annual average concentration of SO_2 decreased from 0.062 to 0.049 ppm.

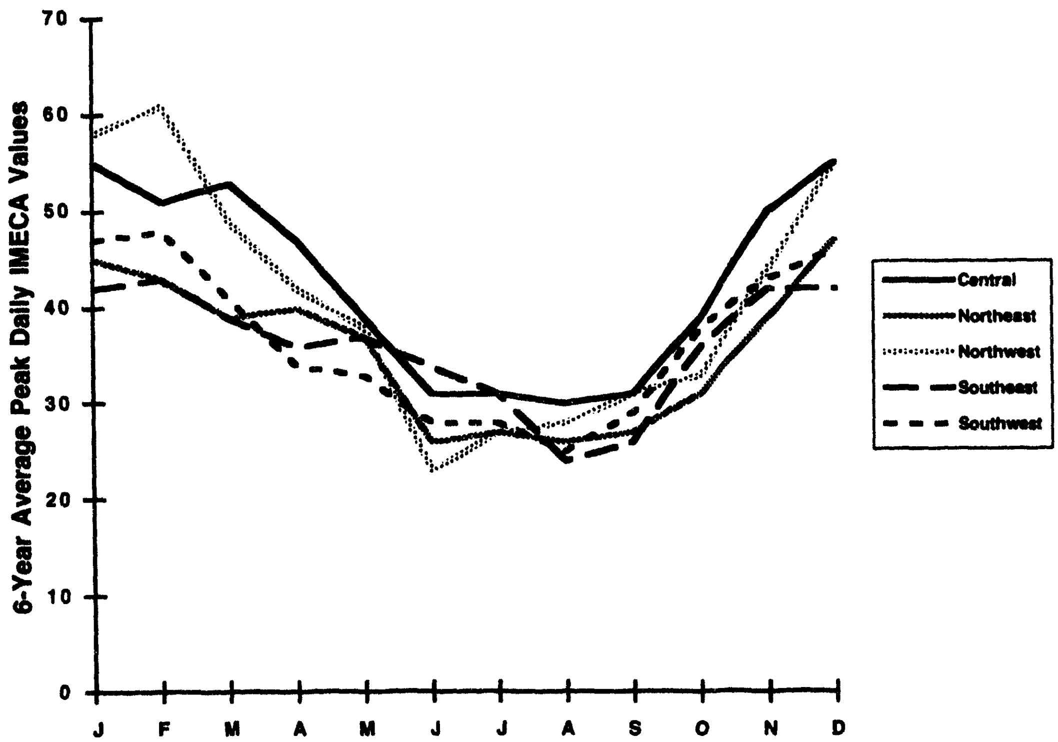


Figure C.12. NO_2 levels, which are reduced during the period April to September as a result of increased number of rains and higher rates of solar radiation and increased reactivity as a result of higher temperatures.

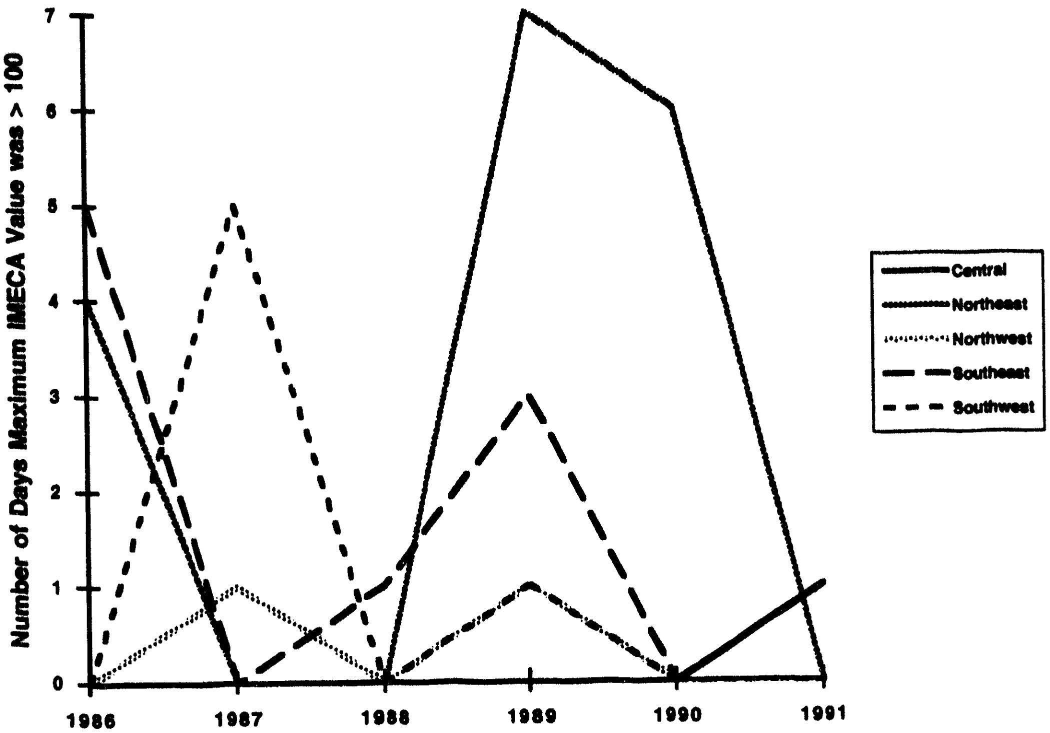


Figure C.13. The relatively low number of days the SO_2 exceeded the standard in the MCMA.

e. Carbon Monoxide

Carbon monoxide is a colorless, tasteless gas that is slightly lighter than air. The most important source of CO is the incomplete combustion of gasoline in motor vehicles. Concentrations of this pollutant in Mexico City vary according to the time of day and are in direct proportion to traffic variations; street-level concentrations may be much higher than monitoring data indicate. Figure C.14 shows the highest daily pattern of CO concentrations occurs at 8:00 a.m. and just after 10:00 p.m.

Because CO is emitted near to the ground, and in general in canyon-type streets, the dispersion pattern of CO-produced ambient concentrations at the monitoring stations, usually

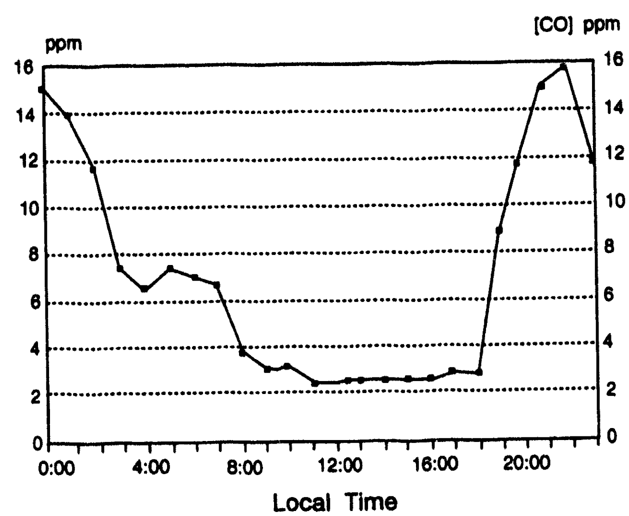


Figure C.14. The daily pattern of CO concentrations in the southwest sector. The concentrations are usually highest before 8:00 a.m. and just after 10:00 p.m.

located on rooftops, are several times lower than the peak values measured in the streets. For this reason the values measured at the monitoring stations do not represent the levels to which people in vehicles and on the streets are exposed. It is not possible, therefore, to produce an isopleth map for this pollutant because the values measured do not represent the actual conditions encountered at street level.

Carbon monoxide is emitted in the MCMA in greater amounts than all other pollutants combined. It is emitted primarily by mobile sources. Mexico has an 8-hour standard for CO of 13 ppm. The U.S. EPA has a 40% more stringent standard of 9 ppm, as well as a 1-hour standard of 35 ppm. The WHO standard for 8 hours is also 9 ppm. The highest recent 8-hour levels monitored in the MCMA were found near very busy traffic intersections in the downtown area. These values reached levels of 24 ppm.

f. Lead

The presence of ambient lead is largely a result of the combustion of leaded gasoline in motor vehicles. The lead concentration in the MCMA has decreased as a consequence of successive reformulations of gasoline. As a result, ambient lead concentrations in 1987 were 50% lower than they were in 1982. Figure C.15 shows lead concentrations from 1988 to 1992. Only in the northeast sector are lead levels higher than the ambient lead standards set in the U.S. In Mexico people ingest lead from other sources: high concentrations of lead salts leached from metal cans containing acidic products (fruit juices, chili sauces, and chili preparations) and from lead enamel on pottery used for drinking and eating. No data exist for the relative contribution of the several sources of lead to the exposed Mexican population.

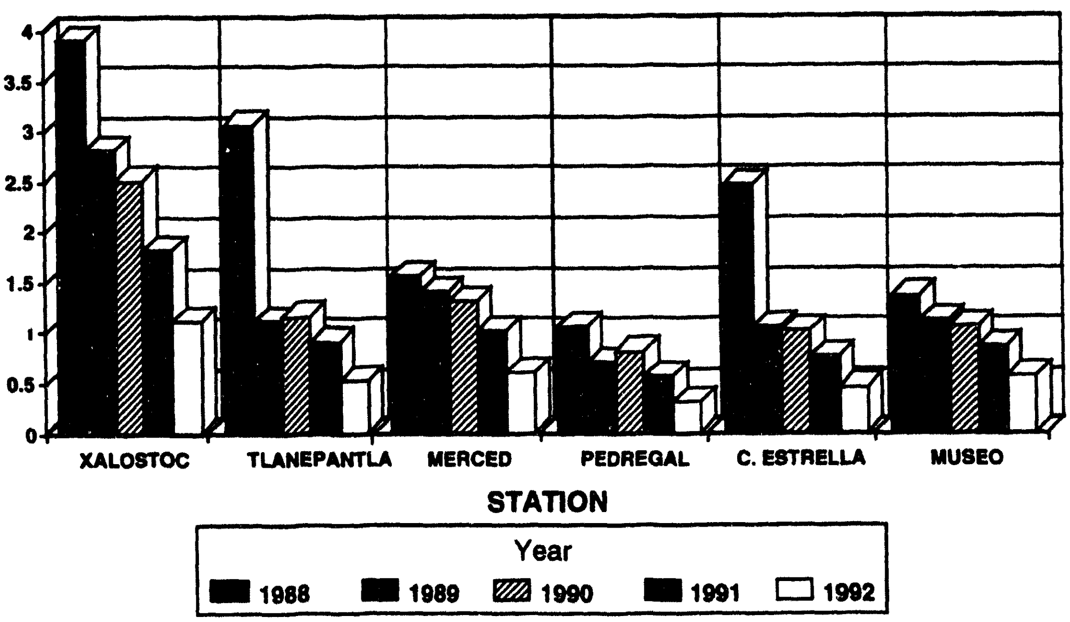


Figure C.15. Lead concentrations from 1988 to 1992.

g. Summary

In order to show the variability of the air quality during the year, Figure C.16, presents the average daily peak IMECA values for the MCMA by month (1986 and 1992). Those values that correspond to situations where the standard was exceeded (IMECA values >100) at least once during the day for the various pollutants are illustrated in Figure C.17. Standard are exceeded throughout the year, but there were temporary variations. During the month of May peak O_3 levels are reached for most sectors of the city. This can be attributed to higher temperature, intense solar radiation, and other climatic factors that produce a higher photochemistry reactivity in the atmosphere. September has the lowest O_3 levels; the only exception to this pattern is in the southeast zone, which has lower O_3 levels in February, March and April (Figure C.18).

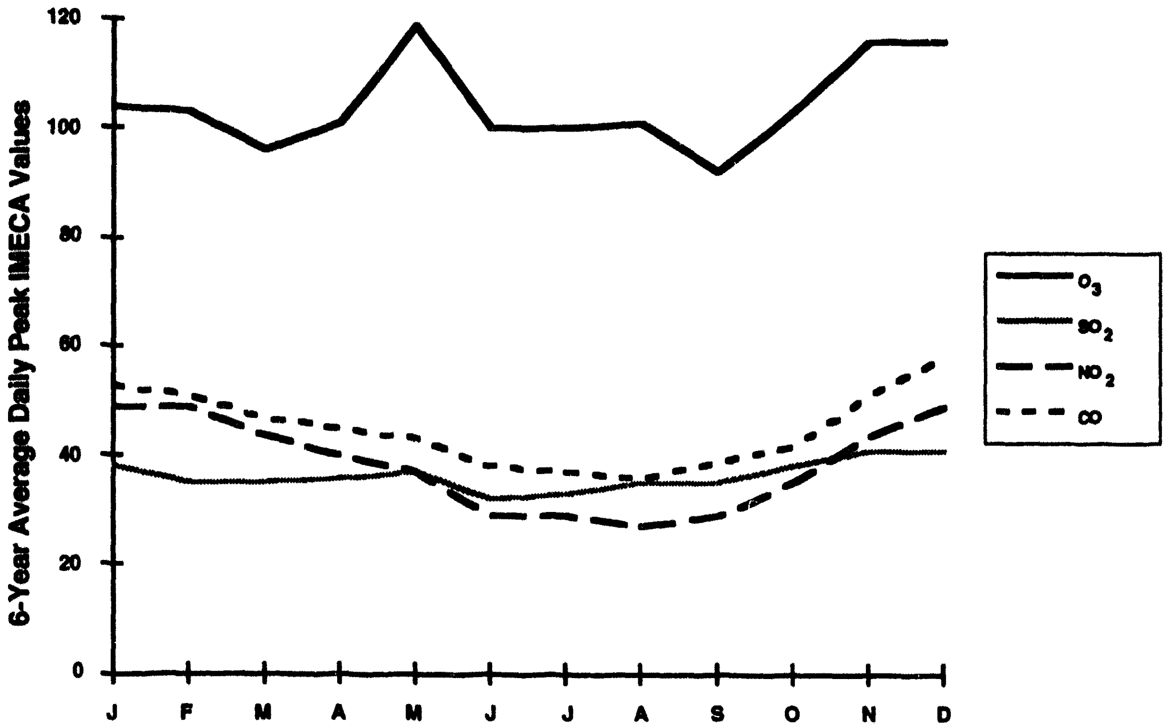


Figure C.16. The average daily peak IMECA values for the MCMA by month (1986 and 1992).

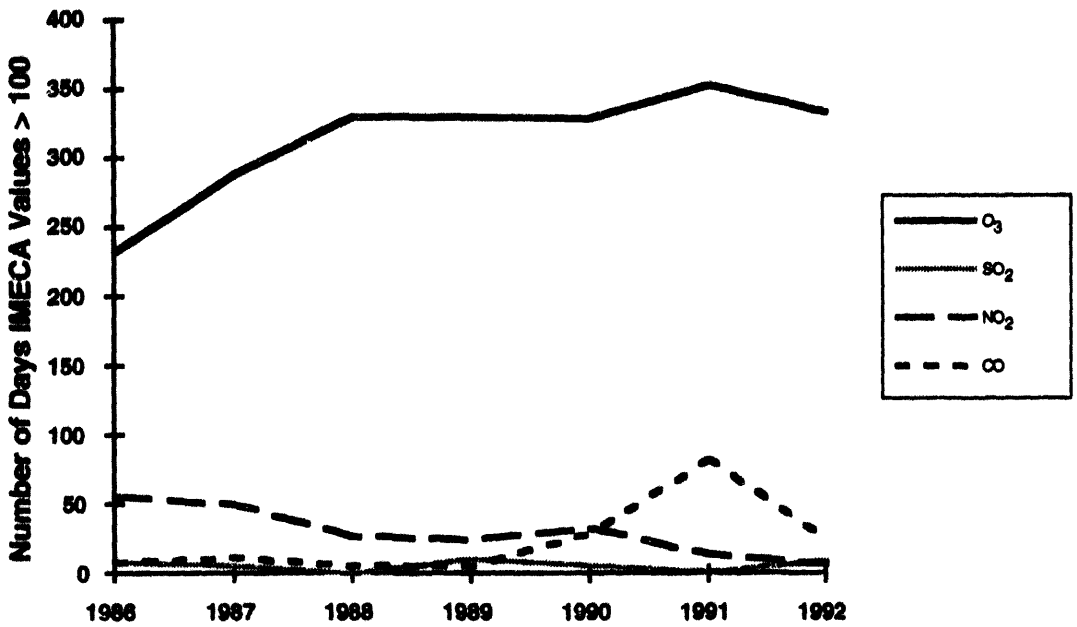


Figure C.17. Number of days in the year when the standard was exceeded at least once for four pollutants.

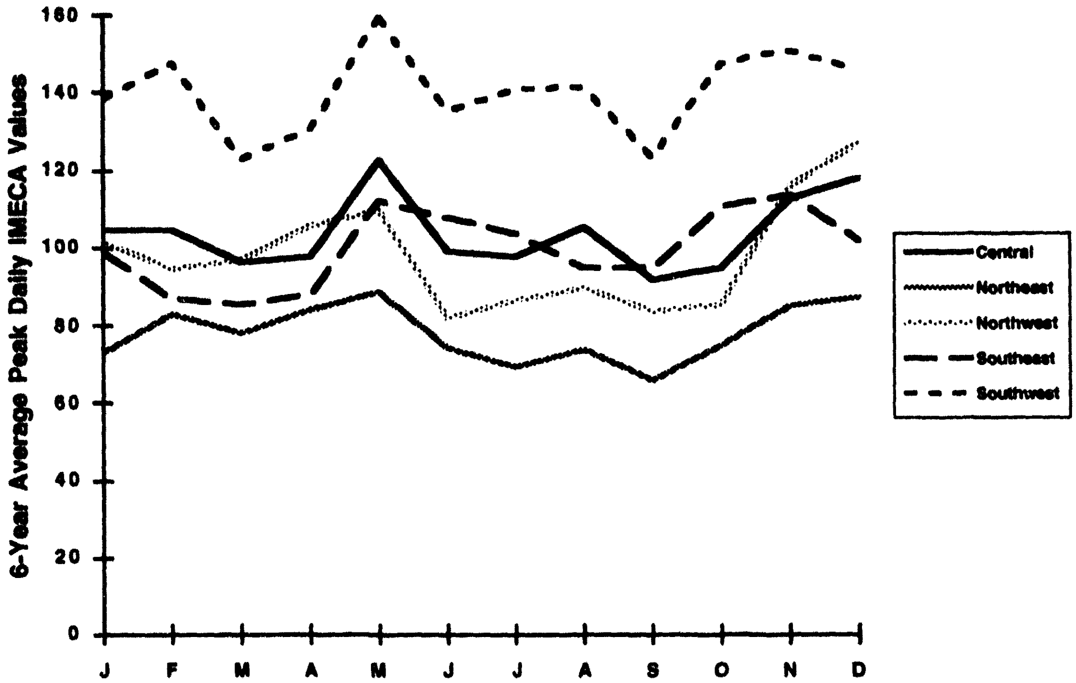


Figure C.18. Monthly variation in Ozone levels. Usually September has the lowest number of days when the standard is exceeded; however, in the southeast zone there were fewer excesses in February, March, and April.

D. THE MCMA AIR QUALITY MANAGEMENT

1. Authorities and Institutions

a. SEDESOL

The SEDESOL is headed by the secretary and consists of three undersecretariats, three institutes and one attorney's office. One of the institutes and the attorney's office are the entities within SEDESOL that are in charge of all environmental affairs.

The General Law of Ecological Equilibrium and Environmental Protection and the Organic Law of Public Administration assign to SEDESOL the responsibilities and facilities for environmental and ecological management in Mexico. Two organizations in SEDESOL, the National Institute of Ecology (Instituto Nacional de Ecología—INE) and the Federal Attorney's Office for Environmental Protection PFPA (Procuraduría Federal de Protección al Ambiente) are responsible for environmental affairs. The INE responsibilities are to establish the national policy for ecological matters, standards for the environment, national environmental restoration policy; to report environmental impacts that fall under federal providence; to study and analyze environmental risks; and to perform research and development. The PFPA is in charge of citizen participation and the enforcement of environmental and ecological regulations.

b. Secretariat for Energy, Mining and State Owned Industry (Secretaría de Energía, Minas e Industría Paraestatal—SEMIP)

The SEMIP was created in December 1982 and its Internal Law was modified in July 1993. The new Internal Law appeared in the Official Diary of the Federation (Diario Oficial de la Federación, Julio 1 de 1993). Among the most important responsibilities of SEMIP is the surveying and dictating of guidelines to state-owned companies, the most important ones being PEMEX and the CFE. It is also in charge of approving the issuing of concessions, authorizations, permits, licenses, and in general any document that allows the use, exploitation, tapping of the non-renewable natural resources, and the cancellation of these permits. SEMIP is also in charge of approving the installation and operation of plants for exploiting radioactive minerals and the fabrication of components for nuclear systems, as well as the decommissioning of nuclear and radioactive facilities.

c. The DDF

The DDF is headed by the mayor of Mexico City and is in charge of the government of the DF. The DF was created by the 1824 constitution, and in 1941 the Organic Law of the DDF designated Mexico City as the capital of the DF. (González 1990)

The General Law of Ecological Equilibrium gives the DDF legal power to prevent and control stationary and mobile emission sources in the DF, as well as the capability to collaborate with other secretariats. In January 1992 the Mexico City Metropolitan Commission for Pollution Prevention and Control was created by presidential decree; all the environmental affairs for the DDF are now managed by the commission with the collaboration of the DDF and other official entities, as explained in Section D.1.g.

d. PEMEX

By constitutional mandate, PEMEX has the responsibility as a decentralized public institution of controlling, handling, and managing all the HCs in Mexico's territory. It controls the activities of exploration, exploitation, refining, transformation, transportation, storage, distribution, and selling of petroleum and natural gas, as well as products derived from petroleum used as basic raw materials for industry.

The Petróleos Mexicanos Organic Law of July 16 1992, gives the basic guidelines for the reorganization:

- To keep state control of the petroleum industry and its property;
- To modernize the organizational structure, providing centralized strategic planning and guidance appropriate to an integrated petroleum enterprise; and
- To institute all the required changes in the basic legal framework.

Within PEMEX the organization responsible for industrial security auditing, environmental protection, and energy savings will be responsible for the lead in environmental policy. This organization will undertake strategic planning, setting guidelines for emissions, developing standards and environmental guidelines, reviewing and promoting better practices and new technologies, and consolidating information for the evaluation of goals and institutional objectives.

The setting of goals will be in support of the General Directorate for Early Detection and Correction of Deviations from Programs. This responsibility will be carried out with a series of actions. The most important of these actions are

- Evaluation of performance of the subsidiary organizations;
- Development and establishment of information systems for executives; and
- Establishment of formal auditing programs.

e. CFE

On August 14, 1937, the law created the CFE and provided it with a legal and economic basis. On January 14, 1949 the decree in which CFE was given legal status as a decentralized parastatial organization was issued.

On April 21, 1960 the nationalization process of the electrical industry began, finishing on December 29 of the same year.

Today CFE is a parastatial organization in the Federal Administration and is governed by the Law of Electrical Energy Public Service, published in the "Diario Oficial de la Federación" (Official Federal Journal) on December 22, 1975, and modified by decrees published in the same journal on December 27, 1983; December 31, 1986; December 27, 1989; and December 23, 1992. Article 8 of this law defines CFE status.

The CFE mission in Mexico is to ensure electrical energy supply for the entire nation and to provide quality service; at the same time it is to promote social development, protect the environment, and respect people's customs and moral values wherever CFE works.

1. *Environmental Protection and CFE Evolution.*

Until the 1970s all environmental protection matters were controlled by the engineers in charge of projects, construction, and production. In the early 1980s, the first environmental protection office was formed. From 1982 to 1985, the offices of environmental protection for thermoelectric, hydroelectric and geothermoelectric plants were formed.

The strategic program for the electrical sector states that the priority of this sector is to use natural resources rationally and to protect the environment. The CFE created the Environmental Protection Management Office in April 1992 to provide environmental protection for its projects.

2. *Organization.*

The Environmental Protection Management Office is a separate office in the CFE. There are also groups in the areas of construction, production, and distribution, which are responsible for environmental protection and are the direct responsibility of the offices they belong to. The Environmental Protection Management Office sets standards and assesses and supports the work of these groups. It is the office in the CFE that is in charge of collaborations with SEDESOL and the other authorities on environmental protection issues. The Environmental Protection Management Office's mission is to insure that agreements established by the CFE are acted upon both inside the CFE and in areas outside of its purview. The principal objective of this office is to minimize the negative impact of CFE activities on the environment while taking into account costs and social benefits of each option. The office is also required to pay special attention to human health and environmental impacts in the planning and execution of projects.

3. *CFE Environmental Policy.*

CFE environmental policy includes the following:

- To consider the environmental impact of each CFE action and quantify it in order to assure a favorable balance between benefits and costs, internal and external.
- To treat the national standards for ecological protection as the minimum level to which the environment should be protected, and whenever it is rationally justified to provide more protection than is required.
- To collaborate with authorities in order to develop or improve standards and methods for environmental protection.
- To incorporate in the conception, design, and application of CFE environmental protection activities the points of view and recommendations of external experts.
- To take into account the opinions of groups with legitimate interests in the areas of impact of CFE projects.
- To support education, research, and technological development in the field of environmental protection within the capabilities of CFE.

4. *Principal Functions of The Environmental Protection Management Office.*

- To define standards, criteria and procedures;
- To ensure the observance of those standards;
- To coordinate the institutional program for environmental protection;
- To encourage education and development of personnel;
- To perform or supervise environmental impact studies and define preventive and compensatory actions for CFE activities;
- To manage SEDESOL's approval of studies of environmental impact and restoration; and
- To be the corporate representative of CFE in environmental protection affairs.

f. The EM

Within the government of the EM the Secretariat of Ecology is the entity in charge of pollution control in the whole state. Therefore it has pollution control responsibility for the part of Mexico City that is in the EM. The Secretariat of Ecology was created in January 1992 with the General Law of Environment Protection for the State of Mexico. The secretariat has the responsibility to set regulations to control and prevent atmospheric and water pollution, taking into account their impact and environmental risk, as well as the Internal Regulation in which the organization and structure of the secretariat is defined. The structure of the secretariat includes one secretary, one undersecretary, and four general directors: the General Director of Standards, Regulations and Environmental Impact, the General Director of Ecological Studies and Projects, the General Director of Prevention and Restoration, and the General Director of Citizen Concerns and Participation.

The General Director of Standards, Regulations and Environmental Impact has the duty and power to institute projects, measures, and directions for environmental protection, as well as to preserve the ecological equilibrium. This General Director also has the power to institute programs for environmental restoration, to evaluate the environmental impact and possible risks caused by construction activities, to evaluate legal aspects of actions, to impose administrative sanctions, to establish emissions inventory and residual waters discharge records, to establish monitoring systems for water and air quality, and to authorize and control operation of vehicular verification centers in all the municipalities and urban zones of the DF except where it is superseded by federal law. (Gaceta del Gobierno, June 92)

g. Mexico City Metropolitan Commission for Pollution Prevention and Control.

The Mexico City Metropolitan Commission for Pollution Prevention and Control was created by presidential decree in January 1992. The commission's objectives are to define and coordinate environmental policies, programs, and projects in the Valley of Mexico and to verify the execution of air pollution control actions. The commission is a permanent organization and consists of the secretaries of the National Departments of Social Development; Treasure; Energy, Mines and State-Owned Industry; Communications and Transportation; and Health. The commission also works with the local authorities involved (the DDF government and the EM Government), the General Director of PEMEX, and other government bodies as needed. Mexico City's mayor was appointed President of the Metropolitan Commission for the first two years. The Governor of the State of Mexico will assume the post for the next two years, beginning in 1994, and the Urban Development Secretary will succeed to the position for the third term.

The commission has a council in charge of analyzing opinions and proposals for coordinating programs, projects and actions performed by the commission. The council is formed by representatives from the scientific community, environmental specialists, representatives of private social organizations, and members of the Mexican Congress.

The commission includes a technical secretariat that issues the annual program of the commission and prepares programs and projects to obtain donations, credits, and governmental economic support for actions to prevent and control pollution in Mexico City. The commission also surveys these actions and reports periodically about their status and accomplishments. The head of this secretariat is appointed by the President of Mexico.

2. Programs

a. Early DDF Programs

On February 14, 1986, after several pollution episodes 21 measures to control air pollution in the MCMA were published in a presidential decree. The measures were announced by the Comisión Nacional de Ecología (National Commission of Ecology—CNE). Eleven months later, in January 1987, by instructions of the Mexican President, 100 actions to fight against water, air, and soil pollution were announced. These were directed not only in the MCMA but were country-wide in scope. The CNE was in charge of these actions.

Most of the 21 measures and most of the air control options for the MCMA within the "100 Actions" program are mentioned below to provide examples of the kind of pollution mitigation options that were proposed:

21 Measures

Public Transportation, Traffic and Land use.

- 2,800 new buses for Ruta-100 with new engines and pollution controlling devices.
- Improvement of the public electrical transport.
- Encouragement of public transportation in the downtown area and enlargement of pedestrians zones.

Cars and Gasoline

- Pollutant emission inspections on 300,000 private and official vehicles during 1986 and 1987.
- Reduction of the lead content in gasoline sold in the MCMA from 2.5 to 1.0 ml/gal.
- Distribution of gasoline with oxygenated additives in the MCMA starting in June 1986.
- Requirement for new vehicles to use emission control devices.

Energy

- Gradual substitution of fuel oil by compressed natural gas (CNG) in the "Valle de Mexico" power plant.
- 60 % of the fuel distribution tanker trucks improved with turbochargers.

Industry and Services

- Construction of two industrial parks to relocate industries affected by the 1985 earthquake
- Negotiations to move high-polluting and water-intensive industries out of the city within three years.

Land and Urban Development

- 36 million new trees for the MCMA.
- Closure of about 6,500 clandestine open dumps and distribution of more than 1,000 trash containers.
- Education programs to protect forests in the MCMA.
- New housing developments in the MCMA restricted to medium and small apartment buildings.
- Street maintenance work during night shifts to avoid traffic congestion.

100 Actions

Mobile Sources

- Application of new technologies to reduce emissions in new vehicles.
- Implementation of mandatory engine inspection for the vehicular fleet.
- Tax incentives for shops to acquire equipment to inspect and diagnose engines.
- Production of better fuels.
- Expansion of nonpolluting public transport.
- Maintenance and tuning of Ruta-100 buses.
- Incentives to promote collective transportation in schools, unions, enterprises, and public offices.
- Certification of industrial and commercial fleets required before winter season.
- Campaign to reduce the number of vehicles on the streets. Programs to improve traffic such as synchronizing traffic lights.
- New traffic scheme to improve circulation in the downtown, San Angel, and Coyoacan sectors.
- Special night schedules for goods delivery.

Stationary Sources

- Require new industries to comply with new emissions standards.
- Establish pollution controls for each type of industry.
- Offer tax-incentive mechanisms to promote acquisition of pollution prevention technologies and equipment.
- Supervise combustion processes.
- Establish permanent CO, PST, SO_2, NO_X, and HC control program for those industries participating in the contingency plan.
- Relocate polluting industry outside the MCMA
- Establish regulations and standards to control industrial emissions.
- Improve the stationary sources emissions inventory in the MCMA.

- Perform emissions inventory for the 300 most hazardous industries in the MCMA during 1987 use CNG instead of fuel oil in the power plants in the MCMA.
- Mandate electric energy savings.
- Disallow expansion of the 18 de Mayo refinery and establish control of the emissions from storage tanks.
- Relocate foundries to outside the MCMA
- Improve publication of the IMECA index.
- Continue air quality monitoring
- Implement by March 1987 the Secretaría de Desarrollo Urbano Y Ecología (Urban Development and Ecology Secretariat—SEDUE) central laboratory, the information system, and the models to predict high pollution episodes.

b. The Air Quality Monitoring Network

Mexico City has a large automatic system of monitoring equipment (Red Automática Monitereo Atomsférico—RAMA) that monitors the meteorology and pollutants and provides the basis for a daily report of the air quality. The RAMA was established in 1986 for the purposes of monitoring the metrology and pollutant levels in Mexico City. It and the network established in the Los Angeles basin in the U.S. represent the two most complete air pollution monitoring networks in any city in the world. During the extent of the Mexico Air Quality Research Initiative (MARI) the RAMA consisted of 25 automatic monitoring stations grouped into five zones in Mexico City. (The network has recently been expanded to 32 stations). Seventeen of the stations measured SO_2 concentrations, 15 measured O_3 concentrations, 18 measured CO concentrations, 10 measured NO_2 and NO_X concentrations. Ten stations reported meteorological data. The names of the stations and the quantities that they measure are presented in Table D.1 and their locations in Mexico City are shown in Figure D.1.

The air quality is reported in Mexico City as IMECA values. The IMECA values are calculated from hourly averages of pollutant concentrations, and an IMECA value of 100 points corresponds to the standard for each contaminant. The determination of IMECA values is shown in Table D.2. For reporting purposes the monitoring stations are grouped into five sectors for the city. The reported IMECA value for a sector is the highest recorded by the stations in that sector. Daily reports of the IMECA values are carried by Mexico City newspapers.

The RAMA provides a wealth of data that were used to compare with model predictions of meteorology and air pollution. This comparison assisted MARI researchers in determining the accuracy of the model results and helped illuminate some of the shortcomings of the models and the input data. For example, comparison of model predictions for O_3 with various measuring stations indicated that HC emissions were seriously underestimated. This was later confirmed in canister measurements of HC concentrations.

c. PICCA

The PICCA was developed in 1989 by the Intergovernmental Technical Secretariat consisting of the Secretariats of Ecology and Urban Development; Treasury and Credit; Programming and Budget; Commerce and Industrial Development; Communications and Transport; Energy, Mining, and Parastatial Industry; Agriculture and Hydraulic Resources; Health; the DF; the

TABLE D.1 List of the Monitoring Stations for RAMA and the Parameters Measured at Each Station

#	Station Name	Sector	SO_2	O_3	CO	NO_X/NO_2	Particulates	Meteorology
1	Lagunilla	C		X	X			
2	Vallejo	NW	X					
3	Santa Ursula	SW	X					
4	Tacuba	NW	X	X	X	X		X
5	ENEP-Acatlán	NW	X	X	X	X		X
6	Los Laureles	NE	X					
7	La Presa	NE	X				X	
8	La Villa	NE	X				X	
9	San Agustín	NE	X	X		X		X
10	Azcapotzalco	NW	X	X				
11	Tlanepantla	NW	X	X	X	X	X	X
12	Xalostoc	NE	X	X	X	X	X	X
13	Merced	C	X	X	X	X	X	X
14	Pedregal	SW	X	X	X	X	X	X
15	Cerro de la Estrella	SE	X	X	X	X	X	X
16	Plateros	SW		X	X			X
17	Hangres	NE	X	X	X	X	X	X
18	UAM Iztapalapa	SE		X	X		X	
19	Aragón	NE	X		X			
20	Netzahualcóyotl	NE	X		X		X	
21	IMP	NW		X				
22	Benito Juárez	SW		X	X	X		
23	Taxqueña	SE		X	X		X	
24	Insurgentes	C			X			
25	Cuitláhuac	NW			X			

EM; the municipal governments of the urban zone; PEMEX; the CFE; and the IMP. Each participating agency was included in a working group along with national scientists and specialists from the environmental agencies of Japan, Germany, England, France, Canada, and the U.S.

The Intergovernmental Technical Secretariat analyzed national and international scientific and technological advances in the field and canvassed opinions from citizens, environmental groups, the Federal District Council of Representatives, and the Congress of the Union. Each working group assessed the trends in air pollution and studied projects to reduce the pollution growth rate in its area of responsibility. The groups reviewed existing options within a strict analytical framework defined by health risks, cost/environmental benefits, technical possibility, and financial feasibility. The actions that were recommended as a result of these studies will not enable the city to recover the air quality it had half a century ago because the population in the Valley of Mexico has increased from 1.5 million inhabitants to 15 million and because of the change from agriculture and mining to an economy sustained by industry, transportation, and services. However, it will start the long process required to clean the air in Mexico City.

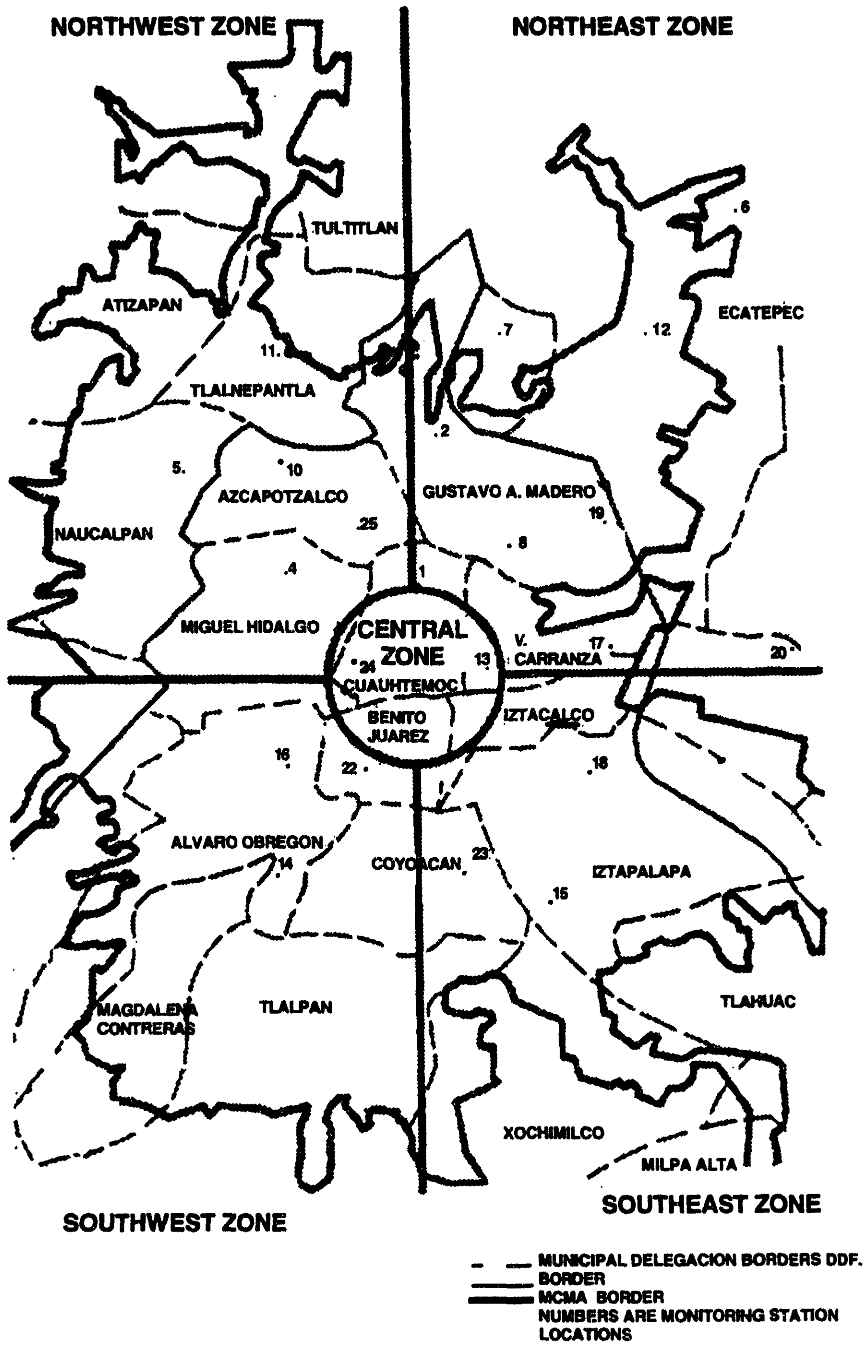


Figure D.1 Locations of automatic monitoring stations in the Mexico City air quality monitoring network.

TABLE D.2 Definition of IMECA Values for Mexico City

IMECA Value	Air Quality	PST (24 h.)	PM10 (24 h.)	SO_2 (24 h.)	NO_2 (1 h.)	CO (8 h.)	O_3 (1 h.)
		Contaminant and Time Period for Averaging					
0-100	Satisfactory	275 $\mu g/m^3$	150 $\mu g/m^3$	0.13 ppm	0.21 ppm	13 ppm	0.11 ppm
100-200	Not Satisfactory	546 $\mu g/m^3$	350 $\mu g/m^3$	0.35 ppm	0.66 ppm	22 ppm	0.23 ppm
200-300	Bad	637 $\mu g/m^3$	420 $\mu g/m^3$	0.56 ppm	1.10 ppm	31 ppm	0.35 ppm
300-500	Very Bad	1000 $\mu g/m^3$	600 $\mu g/m^3$	1.00 ppm	2.00 ppm	50 ppm	0.60 ppm

The PICCA has recommended that 41 specific actions be taken to learn more about and to reduce the air pollution in Mexico City. These actions would reduce emissions by improving the quality of fuels being supplied in Mexico City, reduce emissions from the production and distribution of fuels, reduce the emissions from the vehicular fleet, reduce traffic, require conversions to cleaner-burning fuels and emission control measures for public transport and industry, and begin a program to reforest the Valley of Mexico. Also, the program calls for the development of technical expertise in air quality in Mexico and for studies to determine the best policy for attacking the air pollution problem. In 1989 the program was estimated to cost 2.5 billion dollars and would reduce emissions of most pollutants by 26% to 80%. Subsequent revisions to PICCA have added more actions, increasing the cost but also projecting a greater improvement in the air quality.

The government has taken steps to implement the recommendations in PICCA and in some cases has gone beyond the recommendations. The Comprehensive Program is a medium-term program, a program for the 1990s. The projects it includes will be completed within one to five years. However, actions begun by this program must be sustained for decades.

E. PRIOR RESEARCH

1. Research by Mexican Universities and Government Organizations

Numerous studies on various aspects of the Mexico City air pollution problem have been undertaken by the faculty in universities in Mexico City. Often these studies have been done with the collaboration of other researchers from the United States. The studies described below are not an exhaustive list of the university studies that have been done but are presented to acknowledge the work that has been done in the Mexican university system on the air pollution problem.

Statistical studies on the SO_2 distribution and its effects on health have been done by faculty at the Universidad Autónoma Metropolitana (UAM) at Azcapotzalco in collaboration with faculty from the University of Illinois at Chicago. (Sanchez and Babcock 1989) These studies have examined emissions from mobile sources and have tested a methodology to determine their health effects in Mexico City. Examination and compilation of the emissions from mobile sources have also been done at UAM. (Espinosa and Medina 1990)

Ozone measurements and analysis, especially on the effect of gasoline formulations on the production of O_3 have been done at the Universidad Nacional Autónoma de Mexico (UNAM). One of the studies examined some tends in O_3 levels in Mexico City. (Bravo et al. 1991a) Other studies examined the effects of new blends of gasoline (Garcia-Gutierrez et al. 1991) and the effect on O_3 formation of gasoline additives. (Bravo et al. 1991b)

Ozone measurements were also carried out in the nonurban regions around Mexico City. (Miller et al. 1992) These measurements were compared with similar measurements in Los Angeles. It was found that although the Mexico City levels were not as high as the peak recordings around Los Angeles, the levels near Mexico City tended to remain high the year around while the Los Angeles readings decreased in the winter.

The cost-effectiveness of controls of mobile sources was examined in a DDF program done in cooperation with Radian Corp. (Klausmeler et al. 1991) The three items that were identified as the most cost-effective were: an inspection and maintenance program, vapor recovery in the gasoline distribution system, and replacement of the taxi fleet. Conversion of vehicles to LPG (liquefied petroleum gas) was also identified as being cost-effective depending on the availability of LPG supplies.

Another concern in Mexico City has been aerosols and dust. There have been a number of studies that have investigated this problem. Most of the studies have examined the composition of the aerosols (Aldape et al 1991a & b, Bravo et al. 1989, and Salazar et al. 1989). Sampling of the PM-10 has also been carried out in Mexico City. (Falcón et al. 1989)

These are only a few of the many studies that have been done by universities, government organizations, and others in Mexico City to try to better understand the air quality problem that exists. The number of studies that have been done illustrates the importance that people in Mexico City attach to the air pollution problems and their desire to understand the problem more fully.

2. International Studies

a. Cooperative Studies with the Japanese

In response to a request from the government of Mexico, the Japanese government agreed to prepare an Air Pollution Control Plan in the DF, and the study was entrusted to the JICA. The purpose of the study was to prepare guidelines for control measures against air pollution in the MCMA based on on-site investigations. Emphasis was placed on the estimation and evaluation of the effects of the many air pollutant control measures already being considered effective for the MCMA and being planed or implemented by the Mexican Government.

The meteorology was investigated during the period September 1987 to May 1988 by on-site observations at ground level and in the upper levels by captive balloons. Existing meteorological data for ground and upper levels was collected during the period January 1986 to December 1986. Particular emphasis was placed on obtaining ground-level data from the Secretaria de Desarrollo Urbano y Ecología's (Urban Development and Ecolocy Secretariat—SEDUE) ten air quality monitoring stations from December 1986 to November 1987.

Ambient air quality was measured using a combination of fixed stations, mobile laboratories, and with a simplified method at major and minor road crossings. The periods of these observations varied, but spanned from September 1987 to September 1988. Collection of data from SEDUE's 25 ground-level air quality monitoring stations was also performed.

The study also gathered existing data on mobile sources and performed on site investigations to refine it. For instance, automobile traffic volume, driving speed, emission factors, number of automobiles, and aircraft were investigated. Similarly, pollutants from stationary sources were assessed taking into consideration four main categories: large sources, small sources, sulfur content in fuel, and pollutant emissions.

Air quality simulations conducted in this study attempted to find quantitative relations between ambient air quality, its sources, and influential factors. Also, they estimated the effect of control measures. The simulations employed a source model, a meteorological model, and a dispersion model. The dispersion model applied basically the plume equation proposed by Holland in 1953 for point sources under windy conditions. (Holland 1953)

The study mentions that a comparison of the pollutant concentration levels found in the MCMA with those in Japan yielded higher SO_2, O_3, CO, VOC, and TSP concentrations in Mexico, while NO and NO_2 concentrations are similar to Japan. It also established that high pollution levels tend to occur during the dry season from December to February and identified the low wind speed, the thermal inversions, and little precipitation as the main affecting factors. They found that air quality simulation model performance was satisfactory for SO_2 and CO and less so for NO_X and NO_2.

The results of this JICA study indicated that there would be a great degree of improvement if all of the control measures considered by the Mexican government were implemented. However, they also point out that the estimate did not take into account possible growth of the vehicular fleet. The JICA study also made some recommendations. It recommended that the

Mexican government install secondary air supply to vehicles, reduce sulfur in gasoline, and designate one weekday that each passenger car could not be operated. It mentioned that the General Law for Ecological Balance and Environmental Protection provides an adequate legal framework, but it was urgent to enact the corresponding rules and regulations. A third recommendation addressed the need to monitor and inspect stationary sources, if possible, by automatic measuring devices. It also recommended that it is necessary to strengthen the air quality monitoring network, possibly after a study on the existing network was performed. The last recommendation focuses on the need for more and better-trained personnel to undertake all the tasks in the different local and federal agencies.

b. Study Financed by the World Bank—Air Pollution Control in the MCMA, The Short-Term Program

The report known as "Air Pollution Control in the Mexico City Metropolitan Area, Results for the Short-Term Program, Consolidated Final Report" completed in June 1991, presents the results of the Air Quality Management Program for the MCMA. Contained in this report are the assessments of the air quality, its related health effects, and descriptions of the existing regulatory, economic, and transportation framework. Technical and economic assessments for each proposed control measure are included, as well as the implementation strategies, which incorporate institutional, regulatory, and economic components. Cost-effective, pollutant-weighted, and environmentally beneficial methodologies are described and their results presented for each proposed control measure.

The Air Quality Management Program is part of the overall Mexican Air Pollution Control Comprehensive Program in the MCMA. (PICCA 1990) Under the direction of President Carlos Salinas de Gortari, the government of Mexico City, together with other federal and local Mexican agencies, has initiated an ambitious effort to control air pollution in this major urban area. The effort consists of an Emergency Program, a Short-Term Program, for measures that were to be implemented during the 1991-1992 period, and a Medium-Term Program for measures that will be initiated during 1992-1997. The last two programs are included in the PICCA framework.

The PICCA includes control strategies for the transportation sector, industry, fuel production, and service and commercial facilities. The Air Quality Management Program was responsible for the analysis of transportation control strategies that were included in the Short-Term Program. The Air Quality Management Program was divided into two phases. Phase 1, which ended on December 1990, analyzed those control measures that could be implemented immediately. Phase 2, which began on December 1990, analyzed measures with longer implementation times. The tasks performed in this program were conducted by three teams: The Vehicle Team, the Air Resources Management Team, and the Urban Transport and Traffic Demand Team. International and Mexican consultants, working with DDF, composed the work teams.

The report was organized in accordance with World Bank recommendations. (World Bank 1992) The introduction (Section 1) gives the background. A diagnosis of the air quality and the current urban transport situation in the MCMA are presented in sections 2 and 3. Sections 4 and 5 contain the regulatory, economic, legislative, and institutional frameworks to address air pollution management in the MCMA. The PICCA is described in section 6. Section 7 contains the Resources Management Team's work on the MCMA emissions inventory, air quality modeling, the RAMA, and an evaluation of the cost-effectiveness of control actions. In Section 8 the vehicle subteam evaluated several control actions for the MCMA. Among these actions were the inspection-maintenance program, the conversion of gasoline-powered delivery trucks to alternative fuels, the retrofitting of emission control devices on high-use vehicles, the replacement of older taxis with newer vehicles, the heavy-duty-vehicle roadside inspection program, new vehicle emission standards, and the retrofitting of particulate traps and other controls.

According to the emissions inventory available when this program was developed, vehicles were responsible for more than 70% of the total mass of pollutants discharged to the atmosphere. Many measures were studied to decrease the pollution coming from this source. Some of the actions were directed towards traffic improvement. Among such actions were the Indios Verdes-Insurgentes Norte project, the Periférico-Eastern Segment Project, Ecatepec Extension and Widening of Adjacent Avenues project, the study of six congested urban street crossings, modernization and extension of traffic control in the DF program, and the improvement of 1,500 speed bumps. There were also recommendations that dealt with the public transportation system such as the acquisition of 200 trolley buses, new trolley bus routes on Auditorio-La Villa and Santa Isabel Tola-Ciudad Univesitaria, a new and improved Ruta-100 control workshop, a program to redistribute the street-use to encourage collective transport, the construction of Metro line 8, the modernization and reorganization of the electric transport service company, the improvement of the public transport image, and a general financing policy for urban transport pollution reduction.

There were also several miscellaneous programs and recommendation such as the vehicle census to update the mobile source emissions inventory; the public information service on traffic conditions; recommendations on transport, traffic, and parking; the organization and regulation of public and private parking; the improvement of Park-n-Ride parking lots; the establishment of taxi stands to reduce empty taxi operation; the establishment of an urban toll system; and the use of staggered work schedules.

Other sections of the report consist of a chapter on the general financing policy for urban transport pollution reduction. Section 9 contains the vehicle subteam information. Section 10 contains the fuel subprogram, which basically deals with vapor recovery. The ranking and selection of transport air quality measures, the financing plan for the transport air quality management, and environmental benefits of the air quality management program are discussed in Sections 11, 12, and 13, respectively. Sections 14 and 15 deal with the economic, regulatory, legislative, and institutional needs to the proposed programs. Section 16 contains the description of the medium-term program.

c. The SEDUE-France Study

Currently, there are only few simulation studies dealing with the O_3 photochemical formation process in the MCMA. One of such studies is "Etude de I'Impact du Changement de la Composition de I'Essence Mexicaine sur la Formation des Oxydants Photochimiques dans la Ville de Mexico" (Impact of the Gasoline Composition Change on the Formation of Photochemical Oxidants in Mexico City Study). This study was performed by SEDESOL (at that time SEDUE), the Groupe de Recherche sur la Pollution de I'Air et la Physicochimie Atmospherique, Laboratoire de Cinetique et Chimie de la Combustion, Universite des Sciences et Techniques de Lille, and the Department de Chirnie et Environment, and Ecole Nationale Superieure des Techniques Industrielles et des Mines at Douai, France on July 1990.

The project's goal was to assess the effect on the O_3 formation of the introduction to the market in 1986 of a new gasoline (Nova Plus). The model used to perform this evaluation was the EKMA model, OZIPM-4 version. The photochemical mechanisms used were the Carbon Bond 3, Carbon Bond X, and the Carbon Bond 4. The method used to calculate the wind field was an algorithm that used a weighted interpolation of the baricentric type. The most important finding this study provided was that the impact on the O_3 formation from the introduction in 1986 of the Nova Plus was negligible. Nevertheless, the results from this study should not be taken as conclusive. At the time this model was run, many variables essential to the precision of the results were not properly defined. It was not until the period 1991-1992, and within the MARI framework, that these variables (mixing height, VOC/NO_X ratios, quantification of the different atmospheric hydrocarbon species, etc.) were more accurately defined.

F. THE MARI

1. Legal Basis for Research on Air Quality in Mexico City

Research is one of the basic mechanisms of any solid environmental policy. The Ley Federal de Protección al Ambiente (Federal Law for the Protection of the Environment, LFPA) states in its Article 8 " ..the Secretaría de Desarrollo Urbano y Ecología (Urban Development and Ecology Secretariat, SEDUE) will encourage and support research studies and other technical and scientific activities to develop new systems, methods, and equipment to protect the environment. SEDUE must invite the scientific institutions of the highest level to participate in the solution of the environmental problem..."

The scientific research is authorized in the Ley Federal para la Prevención y Control de la Contaminación Ambiental (Federal Law to Prevent and Control Environmental Pollution, LFPCCA). In its Article 7 it grants the president the power to encourage and support research studies and other technical and scientific activities to develop new systems, methods, and equipment to protect the environment. The emphasis in the LFPA is to support technological solutions to the air quality problem. Nevertheless, it does not exclude purely scientific research, which is the basis for solid control technologies and control strategies. In fact, the LFPCCA in its Article 13 states the need to implement a program that would research and evaluate the air quality in the areas the President considers necessary.

Therefore, the scope of MARI is not only considered in the federal laws, but once the PICCA program was designed, MARI was included as one of its components within the research, education, and information strategy.

2. Focus

The MARI project was designed to be a comprehensive study of Mexico City's air pollutants and environmental chemical reactions. The project also involved extensive data analysis and state-of-the-art computer modeling. The project was not designed to make or recommend policy, but to provide a socio-economic evaluation of proposed mitigation strategies, together with an evaluation of their environmental impact. Although the project was designed to take a systems approach to studying the air pollution problem in Mexico City, the project can be broken down into three distinct areas of effort: modeling and simulation, measurements, and strategic evaluation.

The modeling and simulation task focused primarily on adapting existing codes for meteorology, dispersion, and air chemistry for the unique conditions existing in Mexico City. The applicability of the modified codes to Mexico City was verified by comparing the code's results with extensive measurements made during the MARI measuring campaigns and the information from the existing network of meteorological and pollutant monitoring stations in Mexico City. Dispersion and meteorological codes HOTMAC and RAPTAD were used to describe daily wind patterns and dispersion of pollutants. The box model, atmospheric chemistry code OZIPM-4 was used to provide preliminary information about the O_3 formation chemistry in Mexico City. Detailed 3-D airshed modeling of O_3 formation was done using the CIT model. Initial and boundary conditions for these codes were obtained from the measurement campaign conducted as part of the MARI.

The measurement task included three field campaigns for the purpose of obtaining a comprehensive data set describing the meteorology, dynamics, and chemistry of the Mexico City airshed. Some of the data were used to develop realistic input descriptions for the simulation models, but much of the data were used for comparison to model predictions to determine whether they were accurately portraying Mexico City. In September 1990 a meteorological team from Los Alamos National Laboratory (LANL) and the National Oceanic and Atmospheric Administration conducted tethersonde and ozonesonde measurements for two weeks. The ozonesonde measurements were the first measurements in Mexico City of a pollutant above ground level. In February 1991 a major field campaign, and the largest ever in Mexico City for environmental purposes, was conducted over three weeks at several city locations. About 14 different measurement techniques were applied to observe the Mexican atmosphere during that period. The list of measurements is shown in Table F.1. In response to questions raised by the models about the slope wind flows and the concentration of hydrocarbons in the Mexico City atmosphere, a third campaign was conducted in March 1992. This campaign measured slope wind flows using a mini-lidar (light detection and ranging) and Doppler sodar (sound detection and ranging) and measured the hydrocarbon concentrations with canister measurements. Another measurement that was done to increase the knowledge about the situation in Mexico City was to remotely measure emissions from vehicles operating on the streets of Mexico City. These measurements were utilized by the strategic evaluation group to determine the effect of removing the worst polluting vehicles from the streets and for estimating the effects of requiring catalytic converters on new vehicles.

The strategic evaluation task was to provide the link between the modeling and measurements and the people responsible for developing the policies for combating air pollution in Mexico City. To provide this link the strategic evaluation team developed a two-step methodology for providing an analysis of different policies for improving air quality. The first step in the process was to generate a strategy by selecting a subset of options from a list of possible options that could be used to reduce pollutant emissions in Mexico City. For this portion of the MARI, the strategies were selected by finding the least-cost group of options that would reduce the pollutants to a specified level. Other factors and constraints could be utilized in the linear programming to generate different strategies. The strategies that were generated by the linear program were then compared using multi-attribute decision theory. The basis of this technique was to generate a decision tree that contained all the important attributes that should be considered when evaluating a policy to improve air quality. Weights were assigned to each attribute in the decision tree, and these were multiplied times the strategy score for the attribute and summed for all the attributes to provide a ranking of the strategies. The decision tree, attribute weights, and strategy scores for

TABLE F.1 List of the Measurements Accomplished in the Second Measurements Campaign

Tethersonde - LANL - a tethered balloon obtained vertical profiles of temperature, humidity, wind speed, wind direction and pressure up to 1 km above the surface.

Ozonesonde - LANL - flown with the tethered balloon to obtain vertical profiles of O_3 concentration

Laser ceilometer - LANL - range-resolved, 1-D atmospheric aerosol profiles investigated mixing height and structure of atmospheric layers. Deployed at the tethersonde sites.

Time-lapse photography - LANL - visibility and near surface visual layers. Two cameras were deployed on the 14th floor of the IMP tower, approximately 180° apart looking north and south. Images were taken every one-half hour from 19 Feb. 1930 hours to 1 March 1200 hours.

Air sampling - LANL - adsorption tube sampling for hydrocarbon and aldehyde analyses. A total of 18 samples (12 for hydrocarbons and 6 for aldehydes) were obtained at different times and locations throughout the city. Sample recovery and analysis for the hydrocarbon samples was, disappointingly, substantially poorer than anticipated, and only qualitative hydrocarbon data was obtained.

Elastic scatter lidar - LANL - range-resolved 2-D and 3-D atmospheric structure, plume dynamics and source analysis. Several hundred lidar scans were obtained. The emphasis was on vertical atmospheric structure, but horizontal structure and source characterization were included. Sources noted or examined included a glass factory, highways and a barbecue restaurant.

Auto emissions - University of Denver (subcontractor to LANL) - remote, real time detection of CO, CO_2 and hydrocarbon content of automobile exhausts. Approximately 30,000 vehicles were measured. These measurements were carried out at four different city locations, and differences could be noted in average fleet age and emissions. In general, though, emissions are very high and higher even than pre-1974 vehicles measured in Los Angeles. This indicates that inspection and maintenance could be a significant option for improvement in Mexico City. Videotape recording of license plates provides a record from which emissions as a function of vehicle model and year can be derived for those vehicles registered in the DF.

NCAR King Air instrumented aircraft - National Center for Atmospheric Research (subcontractor to IMP) - aircraft platform measurements of meteorological parameters; concentrations of CO, SO_2, O_3 and NO_X; aerosol concentrations and size distribution; surface temperature and UV radiometer. Forty hours of flight time were used for fifteen flights. Data were obtained in a relatively vertical profile during ascent and descent legs of the flights and the majority of the flight time was used for horizontal legs at different altitudes following an "E "pattern over the city. Data from these measurements were used in analysis of the temporal evolution of atmospheric layers and also in an analysis of correlation and patterns in contaminant concentrations aloft with surface measurements below the flight paths.

Automated surface air quality monitoring network - SEDUE- city-wide measurements of meteorological parameters, O_3, CO, SO_2, NO_2 and NO_X. These data were used to examine correlations with mixing height and with aircraft measurements.

SO_2 DIAL (differential absorption lidar) - Mexican Electric Research Institute - remote sensing lidar for range- resolved measurements of atmospheric SO_2 concentrations. This lidar was deployed with the elastic scatter lidar at the Valle de México power plant and at the 18 de Marzo refinery when the other instruments were moved to the National Polytechnic Institute.

Rawinsondes - National Meteorological Service - free-flying balloons launched at a schedule of 7 per day from the airport. Atmospheric meteorological parameters are returned via telemetry. These data were used for calculation of inversion levels. Data are being used in conjunction with tethersonde and lidar data to analyze atmospheric layers and in conjunction with SEDUE data to examine correlations of pollutant concentrations with mixing height.

Solar radiation - UNAM Institute of Geophysics - instrumentation deployed at the same location as the tethersonde and at the UNAM campus. Campus measurements included direct, diffuse and global solar radiation as well as measurements of UV, long-wave and wide-band solar radiation. Measurements at the experimental sites included direct and wide-band solar radiation.

Suspended particulates - UNAM Institute of Geophysics - measurements deployed at the tethersonde sites. Measurements included atmospheric turbidity, particle-size fraction by electrical mobility, Hi-Vol total particulate sampling and Hi-Vol particle-size fractionation in five size bands.

TSP and PM-10 - IMP and National Institute of Nuclear Research - measurement of particulate concentrations and PIXE (proton-induced x-ray emission) analysis for airborne metals. These samples were obtained at the IMP site in northern Mexico City.

Viable particles - UNAM Center of Atmospheric Sciences - measurement of airborne bacteria.

Biomonitoring - IMP - long-term sampling of atmospheric metals through uptake by lichens.

Visibility - National Meteorological Service - measurements of visibility by observation of objects or lights in different directions from the Tacubaya Central Observatory in the southwest area of Mexico City.

the attributes were generated by a panel of experts consisting of personnel from those institutions in Mexico City that are responsible for developing air quality policy. A list of the institutions represented on the panel of experts is presented in Table F.2. Results of the air quality models were used in the evaluation process to determine the pollution reduction due to the reduction in emissions and to determine the air quality effect of implementing the options in a strategy.

Overall the focus of the MARI was to provide a systems approach to examining the air quality problems in Mexico City and to integrate techniques developed for other applications and expertise existing in different organizations into a unified approach to increase understanding of the total problem of air quality in Mexico City. The two lead organizations, Instituto Mexicano del Petróleo (IMP) and LANL worked very closely together to achieve this goal of a focused, systems approach to the problem.

TABLE F.2 List of organizations represented on the panel of experts

Instituto Mexicano del Petróleo
Departmento del Distrito Federal
Petróleos Mexicanos
Comisión Federal de Electricidad
Estato de México
Secretaría de Desarrollo Social
Secretaría de Salud
Los Alamos National Laboratory

3. Project Characteristics

a. Interdisciplinary

One of the strengths of IMP and LANL is the wide range of expertise available in their organizations. The MARI was able to take advantage of this availability of talent during the course of the project. Thus, laser experts could be utilized in the lidar measurements, computer experts were used for visualization, automobile testing facilities were available to determine vehicular emissions, statisticians were used to analyze the results of the measurements, and experts in air flow and air chemistry were used in the code development and modification. When the expertise was not available in IMP or LANL organizations that had the expertise were identified and brought into the project. This meant that use could be made of the monitoring network established by Mexico City, remote measuring methods developed by the University of Denver, economic evaluation of options by UNAM, and hydrocarbon measurements done by the EPA, to name a few. This ability to bring a large range of expertise into the project meant that the most up-to-date methods could be used to measure and simulate the conditions existing in Mexico City, increasing the accuracy of the understanding of the mechanisms involved in Mexico City's air pollution and improving the chances for success in attacking the air pollution problems.

b. Multi-Institutional

In addition to IMP and LANL a large number of institutes also participated in the MARI. A list of the organizations that participated is given in Table F.3. As stated above these institutions brought in expertise and techniques that were not available in either IMP or LANL and thus contributed significantly to the success of the project. Two particularly significant multi-institutional aspects of the project were the steering committee that was in charge of advising and directing the MARI focus and the panel of experts that was used to develop the economic, environmental, technical, and social/economic attributes that were used to compare different approaches to addressing the air quality problem.

The steering committee consisted of representatives from the Department of Energy, U.S. Congress, EPA, Department of State and LANL on the U.S. side and representatives from PEMEX, Comisión Metropolitana-DDF, INE-SEDESOL, and IMP on the Mexican side. The purpose of the steering committee was to evaluate the work being done in the MARI and to provide guidance on its direction and scope. The charge for the steering committee was

> The Steering Committee provides independent guidance and review for this important environmental initiative. Membership consists of five representatives each from Mexico and the United States. These members represent organizations which have ongoing interests in the resolutions of the urban air pollution problem in the Mexico City Basin. The Steering Committee meets twice a year to review the project status, accomplishments, and plans. Their input is vital to the future planning of the project, assuring that all the necessary concerns are addressed.

The panel of experts developed the list of attributes and determined their importance for evaluating the different strategies to address the

TABLE F.3 Institutions that participated in the MARI project

From Mexico	From the United States
Mexican Petroleum Institute	Los Alamos National Laboratory
SEDESOL (Secretariat of Social Development)	University of Denver
Electric Research Institute	Environmental Protection Agency
National Autonomous University of Mexico	University of Utah
National Meteorological Service	National Center for Atmospheric Research
National Insititue of Nuclear Research	Carnegie Mellon University
PEMEX (Petróleos Mexicanos)	International Business Machines Corp.
Federal District (DDF)	Department of Energy
Federal Electricity Commission	Department of State
State of Mexico	University of Illinois
Polytechnic Institute	
National Commission of Ecology	

air pollution problem in Mexico City. The panel included personnel from the various organizations in Mexico City that were responsible for developing air pollution policy. The use of this panel insured that the attributes used to evaluate different strategies reflected the thinking of those people who were in charge of setting policy in Mexico City. Hopefully this increases the relevance of the evaluations being done in MARI.

c. International Collaboration

The main international cooperation that occurred in the MARI was, of course, the cooperation between the U.S. and Mexico exemplified by the cooperation between LANL and the IMP. These two organizations established a close working relationship that was successful in developing and applying the tools to address the air pollution problem in Mexico City. In addition to this cooperation between two organizations in Mexico and the U.S., other U.S. and Mexican organizations contributed significantly to the project, widening the amount of cooperation that took place between organizations in the two countries.

The MARI was not only cooperation between the U.S. and Mexico; information and expertise from other international organizations, generally commissioned by the DDF, were also used in the project. Emissions inventory information obtained by the JICA and TÜV, were used for data input into models. Options generated by SOGELERG, a French firm specializing in transportation issues, were used in the strategic evaluation work. One of the most important information sources on benefits and costs for various options to reduce emission was a study commissioned by the World Bank. (World Bank 1992)

Not only was information generated by international organizations used in the MARI, the success of the MARI has generated considerable international interest. Discussions have been held on doing similar projects in Santiago, Chile; São Paulo, Brazil; Cairo, Egypt; and Columbia. The success of the MARI should provide a model for other international cooperative projects that are attempting to solve air pollution problems in other cities in the world.

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