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MEXICO CITY AIR QUALITY: PROGRESS OF AN INTERNATIONAL COLLABORATIVE PROJECT TO DEFINE AIR QUALITY MANAGEMENT OPTIONS

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Abstract—The Mexico City Air Quality Research Initiative was a 3-yr international collaborative project to develop or adapt a set of air quality management decision analysis tools for Mexico City and make them available to Mexican policy makers. The project comprised three tasks: modeling and simulation, characterization and measurement, and strategic evaluation. A prognostic, mesoscale meteorological model was adapted to the region of Mexico City and linked to a 3-D airshed model. These were extensively tested against data from the air quality monitoring network and from three intensive field campaigns. The interaction between policy and science was promoted through the development of a formal multiattribute decision analysis model to evaluate alternative control strategies. The project benefited by having researchers from both nations working side by side as peers, by having both nations investing resources and having an interest in the success of the project, and by having an objective, not of advocacy, but of the application of science to problem solving.

Key word index: Mexico City air quality, prognostic model, airshed model, aerial measurements, lidar, decision analysis.

INTRODUCTION

Urban air pollution is an environmental problem in many cities around the world that has serious immediate and long-term implications for the health of the population and for the physical environment. Mexico City, in particular, faces a severe air pollution problem due to a combination of circumstances. The city is in a high mountain basin at a subtropical latitude. The basin setting inhibits dispersion of pollution and contributes to frequent wintertime thermal inversions that further trap pollutants near the surface. The elevation and latitude combine to provide plentiful sunshine which, in comparison to more northern latitudes, is enhanced in the UV radiation that drives atmospheric photochemistry to produce secondary pollutants such as ozone. The Mexico City Metropolitan Area (MCMA) is defined to include the 16 delegations of the Federal District (D.F.) and 17 highly urbanized municipalities in the State of Mexico which border the D.F. The 1990 census (XI Censo General de Población y Vivienda de 1990) records that slightly over 15 million people live in the MCMA. There are numerous other nearby communities that are in the airshed region of Mexico City, but that are not included in the definition and population of the MCMA.

More than 30,000 industrial establishments are located in the MCMA of which 1500–1800 fall in the medium and large categories and are likely to be significant contributors to air pollution. There are 12,000 commercial/service facilities utilizing combustion processes (restaurants, bakeries, hotels, public baths, etc.) and a large number of non-combustion sources such as dry cleaning, printing and solvent use. The transportation sector includes 2.6 million private vehicles, 56,500 taxicabs, 7500 buses, 54,500 "Combi" and "Microbus" collective vehicles, 196,000 gasoline-fueled trucks, 60,000 diesel-fueled trucks and railway and airport facilities. All of this activity requires fuel: 20 million liters of gasoline and diesel, 1.8 million liters of fuel-oil and 340 million cubic feet of natural gas are consumed each day (STI, 1990). An illustration of the air pollution problem is shown in Fig. 1 in which the number of ozone violation days is plotted by year for the five sectors of the city. The IMECA

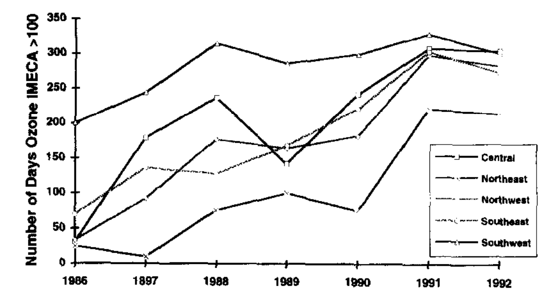

Fig. 1. Trends in the number of ozone violation days for the five sectors of Mexico City.

scale is a normalized air pollution scale in which a value of 100 equals the air quality standard for each pollutant. The air quality standard for ozone in Mexico is 0.11 ppm. From mid-1988 to the end of 1991 gasoline sales in the Valley of Mexico rose 33% so there is a strong correlation between increasing fuel sales and increasing violations of the ozone air quality standard.

Solving an air pollution problem requires much more than engineering solutions. The Mexico City Air Quality Research Initiative (MARI) examined the complex relationship between air pollution, economic growth, societal values, and air quality management policies. The project utilized a systems approach that included airshed modeling, comprehensive measurement studies of Mexico City's air pollutants, and socioeconomic analysis. It provided a set of decision analysis tools to assist Mexican policy makers in determining optimum strategies from amongst a vast array of options suggested to control the air pollution problem. Analysis of the actual air-quality benefits of options utilized state-of-the-art mesoscale meteorological, transport and diffusion, and airshed models.

The Initiative stemmed from discussions in Mexico City in February 1989 between U.S. State Department officials and the Mexican government to identify cooperative technology-oriented initiatives. The air pollution problem was identified and subsequently the Instituto Mexicano del Petróleo (IMP) and the Los Alamos National Laboratory (LANL) were nominated to be the lead institutions. Scientists from IMP and LANL wrote a comprehensive proposal during a series of reciprocal visits. This proposal was used to seek sponsorship for the collaboration. Mexico's Petróleos Mexicanos (PEMEX) agreed to sponsor IMP to collaborate in the Mexico City Air Quality Research Initiative for a period of 3 yr beginning in the spring of 1990 at a total of U.S. $4.5 million. The U.S. Department of Energy (DOE) agreed to sponsor LANL, also for 3 yr at a total of $4.5 million, beginning in October 1990. In July 1991 the DOE and IMP signed the Memorandum of Understanding for the Exchange of Technical Information and for Cooperation in the Field of Air Quality Research between the Department of Energy of the United States and the Mexican Petroleum Institute.

While the Mexican Petroleum Institute and Los Alamos National Laboratory were designated as the lead institutions for this project, there was substantial and important support and participation from other institutions in both nations. These include, in Mexico, the Secretariat for Social Development (SEDESOL, formerly SEDUE), the government of the Federal District (DDF), the National University (UNAM) and the National Polytechnic Institute (IPN). In the U.S., the University of Denver, Carnegie-Mellon University, the University of Utah, the National Center for Atmospheric Research (NCAR) and the EPA have all contributed significantly.

Mexico City faces a challenging air quality problem that includes frequent exceedance of standards for ozone and fine particulate matter and occasional violations of the carbon monoxide standard. The fine particle content produces degraded visibility so that the polluted character of the air becomes very evident. The problems are aggravated by the high altitude and the basin topology that traps the pollution during certain weather conditions. The Mexico City Air Quality Research Initiative provided a unique opportunity for Mexico and the United States to address an environmental issue of immediate concern to their citizens and of long-range concern to the global community. The results of this research initiative are relevant to urban pollution problems around the world.

The MARI project was designed to be a comprehensive study of Mexico City's air pollution problem and to provide the tools and methodology to make environmental and socioeconomic evaluations of proposed mitigation strategies. The project was not designed to make or recommend policy, but to provide a socioeconomic 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 the application of existing models for meteorology, dispersion, and atmospheric chemistry with adaptation to the unique conditions of the Valley of Mexico. The applicability of the modified codes to Mexico City was verified by comparing the code's results with extensive measurements obtained during the MARI field campaigns and with data from the Mexico City network of air quality monitoring stations. The mesoscale meteorological code HOTMAC and linked transport and dispersion code RAPTAD were used to calculate daily wind patterns and dispersion of pollutants. The EPA moving-box photochemical model, OZIPM-4, was used to provide preliminary information about the ozone formation chemistry in Mexico City. Three-dimensional airshed modeling for ozone and secondary pollutants was done using the CIT (California Institute of Technology, Carnegie Institute of Technology) model. Initial and boundary conditions for these codes were obtained from the measurement campaigns 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 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 utilized to observe the Mexico City atmosphere during that period. In response to uncertainties pointed to by modeling, 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 ambient hydrocarbon concentrations with canister sampling and GC or GC/MS analysis.

The strategic evaluation task provided the link between the modeling and measurements and the decision-makers responsible for developing the policies for combating air pollution in Mexico City. When a bewildering array of options, each ostensibly leading to improved air quality, is available to the decision maker, cost effectiveness, cost-benefit, institutional and political realities must all be considered in addition to the purported air quality benefit. The first step in strategic evaluation was to generate a strategy by selecting a subset of options from a lengthy list of options that were offered to improve air quality in Mexico City. For this portion of the evaluation, the strategies were selected by finding the least-cost group of options that would satisfy some objective such as reducing the peak ambient concentration of some pollutant to a specified level. Other objectives, as well as constraints, could be utilized in this linear programming exercise to generate different strategies. The strategies that were generated by the linear programming solution were then further evaluated using multi-attribute decision theory. The basis of this technique is to utilize a weighted decision tree that comprises all the important attributes that should be considered when evaluating a policy to improve air quality. The decision tree and attribute weights were generated by a panel of experts consisting of personnel from those institutions in Mexico City that are responsible for developing air quality policy.

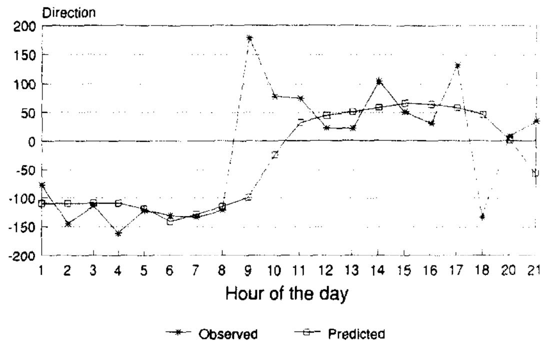

Fig. 2a. Comparison of modeled and measured wind direction on 22 February 1991 at the Plateros monitoring site (station U) in the southwest sector of Mexico City.

MODELING AND SIMULATION: TASK ONE

Developing a simulation capability for use in making air quality management decisions requires a system of models. For the most part existing models were used, but with significant effort to adapt them to describe the physical and chemical processes that occur in the Valley of Mexico airshed. Development of the modeling system is described in more detail in Williams *et al.* (1992, 1993). Continuing adaptation and testing of the models is based upon satellite remote sensing data, updated emissions inventory, and further assimilation of data from the experimental campaigns. Model results have demonstrated good correspondence with the patterns and trends of meteorology and air quality in Mexico City. Figure 2a is a comparison of simulated and measured wind directions at one of the Mexico City air quality monitoring stations. The simulation was made with the three-dimensional mesoscale meteorological model, HOTMAC, and the agreement is quite good. The large change in direction between 8 a.m. and 9 a.m. arises from small fluctuations in light winds; a situation that the model is not expected to reproduce. Figure 2b shows a comparison of simulated transport and dispersion of NO_x with the concentrations measured at four monitoring stations on 22 February 1991. At this time in the morning (10 a.m.) photochemistry is not yet a significant factor so the non-reactive particle transport model, RAPTAD, was used.

The high levels of ozone experienced in Mexico City result from photochemistry involving the precursor emissions, NO_x and VOC (volatile organic compounds). Photochemistry was evaluated and simulated by two different models, an EPA standard photochemical box model, OZIPM-4, and the full three-dimensional CIT airshed model. The fundamental importance of photochemistry is that the energy of sunlight dissociates some trace species in the air. The rate at which this occurs for a certain compound is the photolysis rate. The reactive fragments then drive the production of secondary

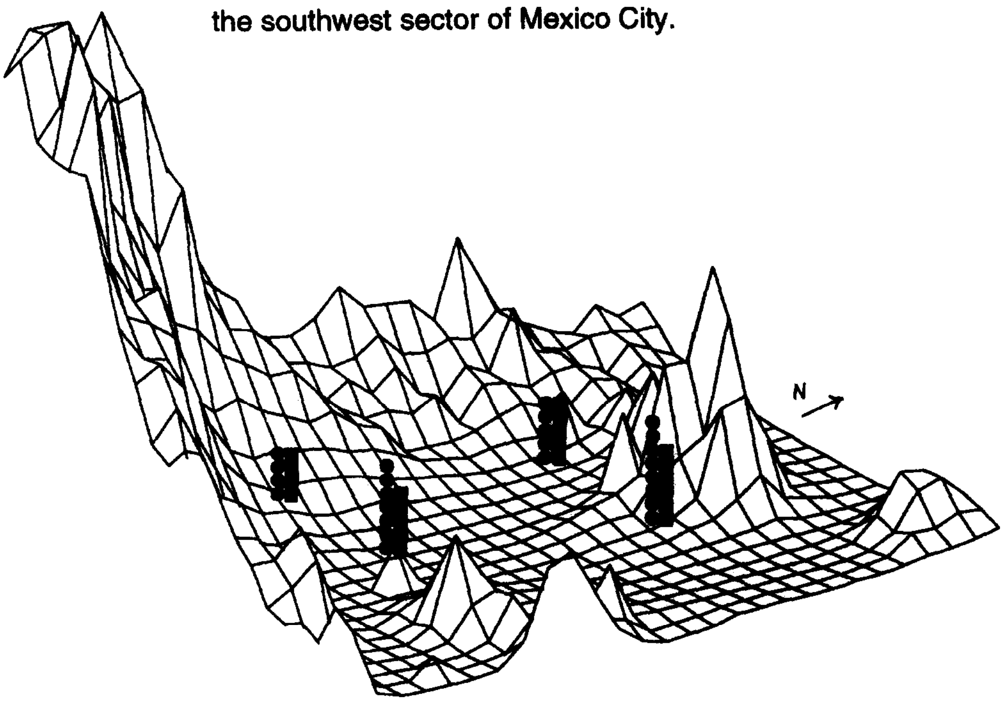

Fig. 2b. Observed (circles) and modeled (squares) NO_x concentrations at four monitoring stations on 22 February 1991 at 10:00 a.m.

pollutants such as ozone. For adaptation to Mexico City, photolysis rate constants have been calculated for 22 February for NO_2, HCHO, CH_3CHO, O_3 and other minor species. In comparison to the default values calculated in OZIPM-4 for the same day and latitude, these photolysis rates range from 5% higher for NO_2 to 75% higher for the O_3 to $O(^1D)$ reaction. These values are due to the lower, but normal, concentration of stratospheric O_3 over Mexico City in late winter which is incorporated into the specific calculations as compared to the default model. Compared to a base case simulation for Mexico City, the substitution of specifically calculated photolysis rates increased the 1 h peak ozone by 10% and shifted the peak 20 min earlier.

The first ever three-dimensional airshed model simulation of Mexico City, carried out in Mexico City, was performed at IMP in April 1992. This effort attempted to describe the ozone levels measured across the city on 22 February 1991, a date in the midst of an intensive experimental campaign involving up to 100 U.S. and Mexican scientists. The first

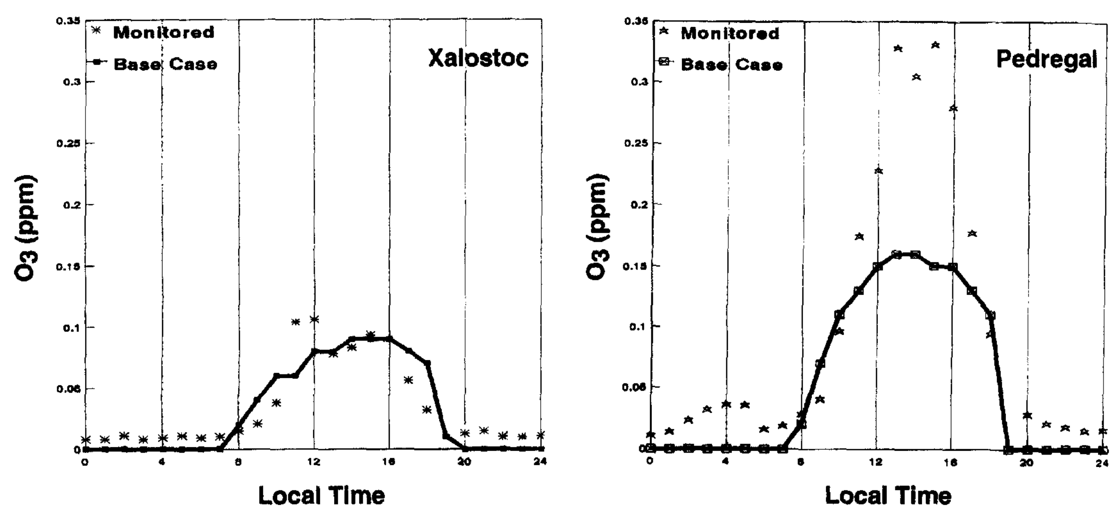

Fig. 3. Airshed simulation results for two locations in Mexico City: Xalostoc (NE) and Pedregal (SW).

airshed simulations of Mexico City air quality were performed at Carnegie-Mellon University, in collaboration with IMP researchers and the codes were then transferred to IMP. The simulation performed at IMP in April made use of an improved windfield data set calculated at LANL, a revised emissions inventory, and photolysis rates calculated for local conditions (Ruiz-Suárez *et al.*, 1993). The results are encouraging, but demonstrate the need for updating and improvement in the spatial, temporal and total components of the emission inventory. Figure 3 shows the O_3 predictions of an airshed calculation compared to measured O_3 at Xalostoc (in the NE sector of the city) and Pedregal (in the SW sector of the city). The emissions inventory used at the time seemed adequate to explain the atmospheric chemistry of the air parcel which reaches Xalostoc; however, it was sorely inadequate to explain the very high ozone concentrations at Pedregal. This demonstrates the need for accuracy in both the spatial and temporal description of the emissions inventory.

CHARACTERIZATION AND MEASUREMENT: TASK TWO

Three field campaigns were staged in Mexico City as part of this project for the purpose of obtaining comprehensive data sets 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 so that it could be determined if they were accurately portraying Mexico City. This, of course, is essential before the air-quality effects of mitigation options could be computed. In September 1990 a meteorological team from Los Alamos and the National Oceanic and Atmospheric Administration in Oak Ridge, TN conducted tethersonde and ozonesonde measurements for a total of two weeks divided between Xochimilco (south) and the Los Galeana sports complex 4 km north of the airport (east). Vertical profiles of wind velocity, temperature, humidity and ozone were obtained at each site at up to 1 km above the surface. To our knowledge, this was the first time in Mexico City that a chemical species or pollutant had been measured above the surface. One of the most interesting findings was the existence and persistence throughout the night of an elevated layer containing a high concentration of ozone. This layer was isolated from the surface by a slight temperature inversion and was thus able to maintain a reservoir of ozone when the surface concentration was very low due to surface deposition and reaction with fresh automotive emissions.

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. A list of measurement techniques and participating institutions is given in Table 1. In the first week the tethersonde and lidar experiments were co-located at the Valle de México thermoelectric plant (NE of the city). In the second week the tethersonde and other experiments were moved to a soccer stadium at the National Polytechnic Institute and the two lidars were set up at the CINVESTAV site of the IPN about 1 km to the northeast (north-central). In the third week the tethersonde team returned to Xochimilco while the SO_2 lidar was moved to the "18 de Marzo" refinery (west) and the elastic scattering lidar was moved to the UNAM Botanical Gardens (southwest). Concurrent with these efforts the NCAR King Air research aircraft was flying 40 h of measurement time and the University of Denver automotive emissions remote sensing FEAT experiment was deployed at several locations around the city.

The data from the February 1991 campaign were analyzed and incorporated into the simulation effort or the strategic analysis effort. The campaign was largely directed toward the measurement of the diurnal cycle of atmospheric dynamics with the meteorological instrumentation and the elastic scattering lidar (Porch *et al.*, 1992a, b; Quick *et al.*, 1993a). The elastic scattering lidar is a remote sensing technique that provides a picture of atmospheric motion, mixing and turbulence by recording light reflected from layers or plumes of aerosols in the air. As a general result for February, it can be said that during the early morning hours, a concentrated aerosol layer is often present at an altitude of a few hundred meters. After sunrise, and as the level of activity in the city increases, the layer diffuses and moves upwards, reaching a height well above 1 km by 12–1 p.m. Figure 4 shows the excellent agreement between data obtained by lidar and data from the ascent leg of an NCAR flight near the same time. The meteorological and lidar campaigns provided information on multidimensional interactions within the atmosphere, including thermal plumes, convective eddies, low-level jets, and the mixing of clean, free atmosphere into the planetary boundary layer. Lidar data proved that the interactions between the surface and the atmosphere within the planetary boundary layer are highly variable throughout the area studied.

Other efforts included the measurement and analysis of incident solar radiation, both direct and scattered, and the automotive emissions measurements. The solar radiation analysis was important to the photochemical simulation effort and the automotive emissions were important for the emissions database and for the development of mitigation options. The FEAT, developed at the University of Denver, was deployed at five sites in Mexico City over a 10-day period from 11 February 1991 through 21 February 1991 (Beaton *et al.*, 1992). This device measured the percentage of CO, HC and CO_2 in the exhaust streams of passing vehicles.

The FEAT unit utilizes a collimated infrared light source placed on the side of a single-lane roadway and a detector unit placed on the other side. The detector

Table 1. Mexico City air quality research initiative: February 1991 joint field campaign in Mexico City

Measurement or technique	Participant (other than LANL or IMP)	Description
Tethersonde		A tethered balloon to obtain vertical profiles of temperature, humidity, wind speed, direction and pressure up to 1 km above the surface
Ozonesonde		Electrochemical cell flown with the tethered balloon to obtain vertical profiles of ozone concentration
Laser ceilometer		Range resolved one-dimensional atmospheric aerosol profiles
Time lapse photography		Two cameras located in the IMP tower to record diurnal visibility
Air sampling		Adsorption tube sampling for hydrocarbon and aldehyde analyses
Elastic scatter lidar		Range resolved two- and three-dimensional atmospheric structure, plume dynamics and source analysis
FEAT auto emissions	University of Denver	Remote, real time detection of CO, CO_2 and hydrocarbon content of automobile exhausts
King Air instrumented aircraft	National Center for Atmospheric Research	Aircraft platform measurements of meteorological parameters; concentrations of CO, SO_2, O_3 and NOx; aerosol concentrations and size distribution; surface temperature, incident and reflected solar radiation
Automated air quality monitoring network	Secretariat of Social Development	Multi-station network monitoring meteorology, O_3, CO, SO_2, NO_x, and NO_2
SO_2 DIAL	Mexican Electric Research Institute	Lidar for range-resolved remote measurements of atmospheric SO_2 concentrations
Rawinsondes	National Meteorological Service	Free flying weather balloons launched at a schedule of 7 per day from the airport. Returns atmospheric meteorological parameters via telemetry
Solar radiation	UNAM Institute of Geophysics	Global, diffuse, direct, UV, longwave, and spectral (OG1, RG2, and RG8 filters)
Total suspended particulates (TSP)	UNAM Institute of Geophysics	High volume samplers; one used with a 5-stage cascade impactor
TSP and PM-10	National Institute of Nuclear Research	Particulate concentrations followed by PIXE analysis for airborne metals
	Other ongoing air quality activities in Mexico City	
Viable particles	UNAM Center of Atmospheric Sciences	Sampling of biological aerosols using Burkards spore traps
Biomonitoring		Long-term sampling of atmospheric metals through uptake by lichens
Doppler sodar	Secretariat of Social Development	Atmospheric structure and winds by sound reflection (under development during this time period)
Visibility	National Meteorological Service	Human observation of visual range along several sight paths

contains four thermoelectrically cooled, lead selenide sensors, each equipped with a specific bandpass filter. The four filters isolate bands at 4.6, 4.3, 3.3 and 3.9 μm. These spectral regions are absorption bands for CO, CO_2 and HC, respectively, with the last being a non-absorbing region that serves as a reference. The instrument is computer-controlled for operation, data gathering and analysis. In addition, a computer-controlled video camera records a freeze-frame image of the back of each passing vehicle with date, time, and emissions measurements. License plates, which must be read manually at a later time, can provide information on vehicle make, model, and year form more detailed analysis of fleet emissions.

The absorption measured in the first three channels is ratioed to the reference in order to eliminate the effect of smoke and dust. The unit is calibrated daily with a certified gas mixture. The HC calibration gas

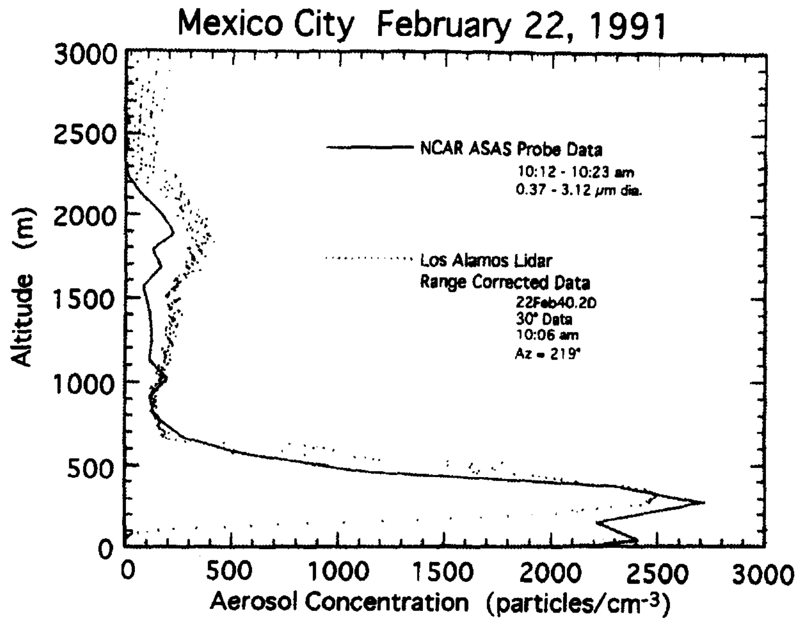

Fig. 4. Overlay of lidar and aircraft-based particulate data. The dropoff of the lidar signal below 300 m is an instrumental artifact.

is propane, so the exhaust HC fraction is reported as "propane equivalents". A data measurement cycle is initiated each time the infrared beam is blocked. Excess noise in the measurement or failure to record an exhaust plume, as happens when the beam is blocked by a pedestrian or bicyclist or the vehicle has a high-mounted exhaust pipe, causes an invalid measurement. For this study, only those measurements that were valid for all three channels were used. Over the course of this study, 31,838 acceptable measurements were made (approximately 1% of the vehicle fleet in Mexico City).

Of the nearly 32,000 valid records, it was possible to read the license plates of approximately 26,000, and of those, about 20,000 were registered in the Federal District Department. Table 2 lists the number of events, of "triggers", as well as the number of valid vehicular readings at each site. The column "DDF plates" lists the number of vehicles whose license plates could be read and which were registered in the DDF (since only this database was available). The final column lists the number of those DDF plates that were private vehicles. The difference between the final two columns represents

Table 2. Location and number of vehicles registered by the FEAT unit, Mexico City, February 1991

Sites	Triggers	Vehicles	DDF plates	Private cars
IMP	5667	4822	2716	1704
POL	9935	9164	6310	5590
UAM	4460	4026	2708	1815
PER1	9498	8922	6350	5733
PER2	5246	4904	3500	2879
Total	34,806	31,838	21,584	17,721

Site locations

IMP: North of the city; return lane at Eje Central Lázaro Cárdenas northbound to southbound at intersection with Av. Montevideo, north of the IMP.

POL: West of the city; eastbound L.G. Urbina at A. Dumas in Polanco.

UAM: East of the city; lane from southbound San Rafael St. into westbound Gavilán St., in front of Universidad Autónoma Metropolitana, Iztapalapa.

PER1: South of the city; ramp from eastbound Periférico to northbound Tlalpan.

PER2: South of the city; ramp from westbound Periférico to southbound Tlalpan.

commercial vehicles (delivery vans, trucks, buses, taxis, etc.).

The mean age of the cars observed in Mexico City was found to be 8–9 yr old. Taxis, however, averaged 11 yr old, significantly older than the private cars. The age for taxis should be considered a lower limit. Private car license plates always remain with the same vehicle until it is removed from circulation, but taxi license plate can be and are often sold separately from the vehicle and transferred to another vehicle. During the time that elapsed between the measurements and the processing of the license plate information, some of the taxis were sold and the plates affixed to new models. Thus, the registry information may show a new vehicle, whereas an old one was measured. Because there is an ongoing effort on the part of the government to renew the taxi fleet by granting loans to buy new vehicles and by restricting the maximum age of taxi vehicles, there were numerous instances of plate transfers in the months between the measurements and obtaining registry information.

The distribution of CO emissions is not surprisingly, quite different from distributions obtained in similar studies in Los Angeles, Denver and Chicago. In the U.S. studies, about 70% of all vehicles emit less than 1% CO while only 18% are in this category in Mexico City. This may be clearly attributed to the widespread use of catalytic converters in the U.S. With catalytic converters, most of the cars are clean, and only a small number of cars are the classic high emitters. The average CO emission for Mexico City (all 31,838 records) was 4.3% with a median of 3.8%. The average fleet in the U.S. emits 1% CO with a median of 0.4%, showing a greater domination by high emitters. The high emitter phenomenon is seen in U.S. measurements in that 10% of the fleet is responsible for 50% of the CO emissions, whereas in Mexico City, that 50% arises from 25% of the fleet. Thus, it would be easier to target high emitters in the U.S.

The HC emissions in Mexico City show a greater degree of skew than do the CO emissions. The fleet average is 0.21% with a median of 0.11%. Only 12% of the vehicles contribute 50% of the emissions, and a mere 4% contribute 30% of the emissions. In this case, a program to target high emitters would have greater payoff. In fact, 107 vehicles (0.3% of the fleet) contributed 5.6% of the HC emissions. These vehicles are clearly misfiring, so the potential fuel savings and pollution reduction from repair and maintenance are great.

Much of the difference between average emissions measured in Mexico City and in the U.S. can be attributed to the lack of catalytic converters in Mexico City. However, beginning with the 1991 model year, converters were required on new vehicles in Mexico. It would be extremely interesting to repeat these measurements when a significant number of converter-equipped vehicles have entered the fleet. However, it is also clear that maintenance and tuning practices could have a dramatic effect on emissions from the current fleet. The problem of misfiring was mentioned above. Over 50% of the vehicles emit from 3–9% CO. Peak power tuning is achieved in the 3–6% CO range, so it seems that tune-ups in Mexico are deliberately in this range. If the industry could be persuaded to tune to 2% CO (readily achievable in cars without catalytic converters), CO (and probably HC) emissions could be cut in half.

In March 1992 a smaller measurements campaign was conducted by LANL, the IMP and the U.S. EPA. Part of the campaign focused on ambient hydrocarbon measurements; information which was vital to the photochemical modeling effort. A portable photoionization detector was used by LANL to measure ambient total hydrocarbon concentrations and to detect time varying concentration trends. Data are somewhat difficult to interpret, but it confirmed high ambient concentrations and established that there was a distinct concentration increase from 7 a.m. to 10 a.m. (Streit, 1992). The U.S. EPA, with assistance and support from SEDESOL, DDF and IMP, conducted a canister whole air sampling campaign throughout the month of March at several different city locations. The canisters were returned to Research Triangle park and analyzed for CO, CH_4, total NMOC and speciated hydrocarbons. Six a.m. to 9 a.m. measurements at a northern industrial site (samples on 14 different days) and downtown (samples on 15 different days) showed mean NMOC concentrations of 4.5 and 3.8 ppmC, respectively. (Seila *et al.*, 1993) These are very high levels; approximately twice the *peak* levels currently experienced in southern California. These measurements, and others taken in October 1991 and January 1992, together with the analysis of gasoline sold in Mexico City, show that the distribution of hydrocarbon species and fuel composition was similar to that found in U.S. cities. High hydrocarbon levels were measured citywide which indicates that the automotive fleet is a major contributor, but the highest concentrations were noted in an industrial region of the city, pointing to significant contributions by industry.

The other objective of the March 1992 campaign was to measure and gain better understanding of the wind flows at the lower end of the mountain slopes. For this purpose a new miniaturized elastic scattering lidar developed by LANL was deployed at the Asociación Nacional de Charros in the southwest of the City. Measurement of the dynamics of the aerosol layers was coupled with improved cross-correlation techniques to determine wind velocities in three dimensions (Quick *et al.*, 1993b). A Doppler sodar (acoustic radar) was also used at the site to obtain vertical profiles of wind velocities and temperature to assist in interpreting the lidar data.

STRATEGIC EVALUATION: TASK THREE

There are many options under consideration for improving the air quality of Mexico City. Each option

Table 3. Examples of cost and environmental data for linear programming model

Option description	Cost ($ Millions)	Emissions reductions (t yr^{-1})				
		NO_x	HC	CO	SO_2	PM-10
Require catalytic converters on cars (1993 and following)	2570	21,000	98,400	1,300,000	4000	2500
Construct line 8 of the Metro	562	1100	2400	23,820		
Produce gasoline conforming to international standards	975		33,000	461,000		
Prohibit open burning	1.1	700	6400	20,350		3200
Install control equipment on commercial boilers	33.5	11,400	150	270	1960	2000

has costs (of several different kinds), certain projected environmental benefits and then a wide array of less easily quantified social-political-institutional considerations. How does a policy maker, under pressure to achieve results and always with limited resources, decide where to start? The Initiative developed and demonstrated two decision analysis techniques that will provide support for rational decision making. The first is the use of linear programming to select a set of options which meet some objective. The options each have an air quality benefit *vis-a-vis* one or more pollutants and certain costs including implementation costs and annual operating costs. The cost factor used in the linear programming model was the total capital cost plus five years of operating costs. Cost and benefit information was gathered on about 70 options. An example of a few options, costs and projected emissions reductions is given in Table 3. The NO_x and HC emissions reductions were used in a photochemical model to project ozone reduction. The linear programming objective can specify one or more pollutant reduction objectives at minimum cost or, perhaps, maximum pollutant reduction at a fixed cost. The mathematical formulation for the linear programming model is given in Fig. 5.

Minimize:

$$\sum_{\text{All Options}}^{i=1} N_i \cdot C_i$$

Subject to:

$$\sum_{\text{All Options}}^{i=1} N_i \cdot E_{ij} > \mu_j$$

For all pollutants j

Where:

N_i is 0 or 1 depending on whether the option is implemented,

C_i is the cost of implementing an option,

E_{ij} is the air quality improvement for pollutant j for each option (in % of maximum value), and

μ_j is the total air quality improvement desired for pollutant j (in % of maximum value).
For the example this would be set to 50%.

Fig. 5. An example of the equations used for linear programming in which the total cost of obtaining pollutant reductions is minimized.

After certain strategies, or combinations of options, were formulated by use of the linear programming model, multi-attribute decision theory was used to evaluate the social-political-institutional factors in combination with environmental, economic and technical factors. This decision theory is a technique to achieve figures of merit for an option given objectives, weights and utility functions. Representatives of IMP, SEDESOL, PEMEX, DDF and CONADE met weekly for nearly a year to develop, refine and test the decision tree. The decision tree is shown in Fig. 6. More detail on the strategic evaluation process has been presented by Barrera-Roldán *et al.* (1995).

To demonstrate the utility and application of the entire simulation and decision analysis system, three strategies were developed, analyzed, and ranked. Strategies were defined as subsets of 37 options involving control or modification of fixed, mobile, and natural emissions sources.

The first strategy was selected by constraining the linear program model to the most cost-effective means to obtain moderate reductions in ozone and suspended particles while maintaining other monitored pollutants at levels that comply with the air quality standards. The second strategy constraint was to select the most cost-effective subset to reduce peak ozone 30% more than in strategy one. The third strategy sought the same ozone reduction as strategy two, but was constrained to emphasize control of industrial emissions. Strategy two earned the highest figure-of-merit with strategy one being least favored.

CONCLUSIONS

Mexico City has an active air-quality management program underway. Air-quality standards have been adopted and air-quality monitoring is extensive. As a result of this project, the emissions inventory for the MCMA has been significantly improved. Measurement and modeling showed that the hydrocarbon component of the initial emission inventory was severely underestimated. This drastically altered the

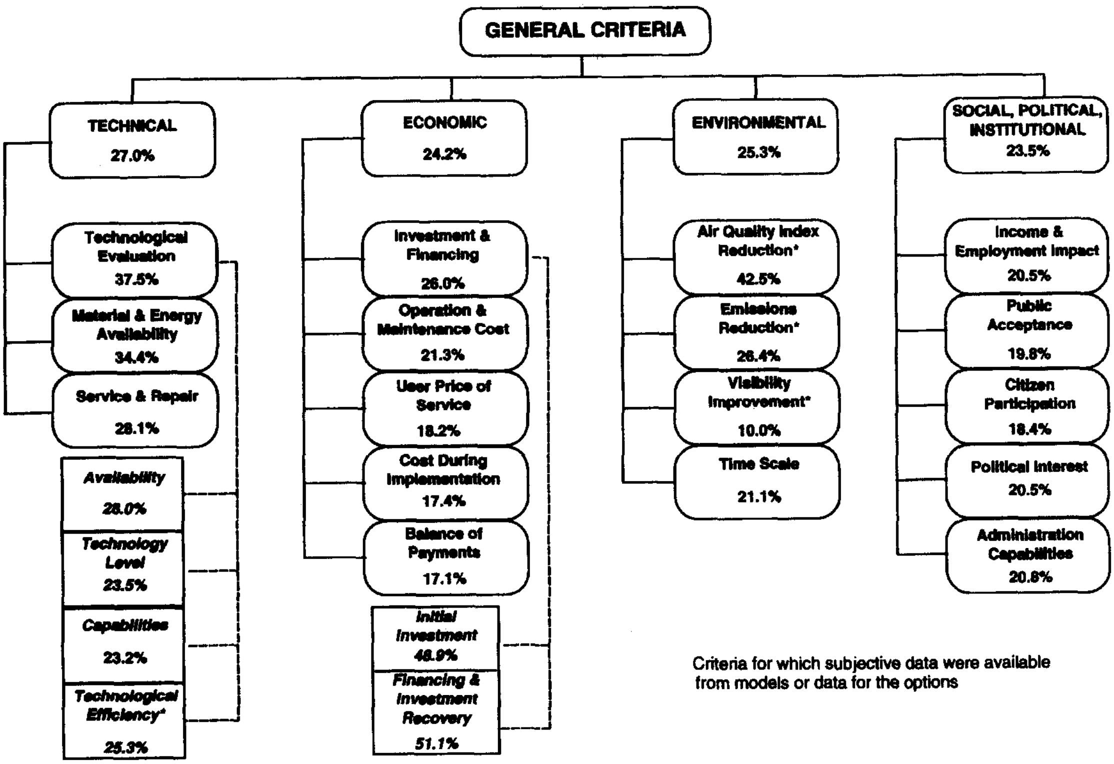

Fig. 6. Multiattribute decision tree designed for the evaluation of air pollution control options and strategies for the Valley of Mexico.

potential benefit and impact of certain options considered in the selection of strategies. Updating and refinement of the inventory will be a continuous process. Based on the experience of the South Coast Air Basin of California, this is a difficult task with the emissions database seemingly always underestimated.

In addition to a full suite of air quality models adapted to the Valley of Mexico airshed, the MARI project has developed the first and only (to date) significant database of three-dimensional meteorological and air quality parameters (including aerial measurements via remote sensing use of lidar, balloon soundings, specially instrumented aircraft, and routine meteorological instrumentation) for the MCMA. This database not only was essential for this project, but also will be of great value to the general air quality research community.

The methodology developed through the MARI project has provided a framework for communication between researchers and those responsible for making air pollution reduction policy. The criteria used in the decision tree have provided guidelines for the technical personnel in determining which aspects of the air pollution problem are deemed most important and time-critical by the decision makers.

The strategic evaluation analysis suggests that aggressive strategies should be pursued in setting future policy for improving air quality in the MCMA. These strategies will be broad-based and focused on overall cost-effectiveness rather than on singling out a particular sector such as industry or transportation. However, the transportation sector will naturally be subject to much of the control effort because it is the predominant contributor to the problem. To begin to mitigate the problem some control measures, such as catalytic converters on automobiles, have already been adopted. The evaluation tools developed through MARI are expected to become increasingly important as decisions pertaining to less obvious measures will be necessary to achieve incremental pollution reductions.

It is clear from the examples of other air quality programs (Streit, 1993) that education is a critical, component of an air quality management program. Education for the general populace is needed, for example, so that emissions reduction components on automobiles or filling station vapor recovery systems are used properly. But an even greater need is education leading to assent by the public that the air pollution problem is their responsibility and that individual actions contribute to the problem, or conversely, will help solve the problem. The pollution problem in Mexico City is very complex and will require the participation of all sectors—private citizens, commercial, industrial and government—to solve it.

MARI has been cited as a model for international cooperative projects in the areas of energy and environmental practices and technologies. A few of the key elements include researchers from both nations working side by side as peers, both nations investing resources and having an interest in the outcome of the project, and the objective being, not advocacy, but application of science to problem solving.

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