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Megacities and Atmospheric Pollution

Judith C. Chow and John G. Watson
Desert Research Institute, Reno, NV

Jitendra J. Shah
The World Bank, Washington, DC

C.S. Kiang
Peking University, Beijing, China

Christine Loh
Civic Exchange, Hong Kong

Miriam Lev-On
The LEVON Group, Thousand Oaks, CA

James M. Lents
University of California at Riverside, Riverside, CA

Mario J. Molina and Luisa T. Molina
Massachusetts Institute of Technology, Cambridge, MA

INTRODUCTION

The following is a discussion of the 2004 A&WMA Critical Review[1,2,3] of megacities and their effects on air quality and pollution-control policies. In the Review, Drs. Mario J. Molina and Luisa T. Molina examined nine large metropolitan areas to identify similarities and differences that affect pollution and its adverse effects. They found that cities in developing nations have higher pollution levels than cities in wealthier nations, despite the greater use of public transportation by their residents. These cities do not have the infrastructure needed to deliver clean fuels to homes for cooking and heating, resulting in greater use of solid coal and biofuels. They also contain older vehicles with higher exhaust emissions and unpaved or poorly maintained roadways that suspend dust. Roadways and public transportation systems are congested and misuse of fuels is common. Cities in developing countries are concerned about loss of employment and economic benefits associated with polluting industries. The Review recommends the use of integrated assessment tools to evaluate emission reduction measures in the world's megacities. These include accurate emission estimates, source and receptor models to identify pollution sources, and monitoring networks tailored to compliance, source assessment, forecasting, and tracking of reasonable progress. The Review concludes that pollution control efforts are often hindered by insufficient local expertise and resources, and by a lack of commitment to air quality management and control. Trained experts, working with local stakeholders, politicians, and the population at large, must take the initiative to institute changes. With appropriate planning, megacities can efficiently address their air pollution problems through integrated control strategies that are effectively implemented and embraced by the public.

The discussions presented here agree and disagree with points made in the Review and add information relevant to the topic. Each discussion is self-contained, and joint authorship of this article does not imply that a discussant subscribes to the opinions expressed by others. This discussion was compiled from written submissions and presentation transcripts with revisions for conciseness and to minimize redundancy. Substantial deviations from the intent of a discussant are unintentional and can be addressed in a follow-up letter to the *Journal*. Invited discussants are:

- Dr. Jitendra (Jitu) Shah, Lead Environmental Specialist for the World Bank in Washington, DC, who has more than 25 years of U.S. and international research and environmental project management experience. At the World Bank for the past 12 years, his work has spanned conceptualization to implementation of regional air quality programs to address acid deposition and urban air quality management in Asia. He manages environmental investment projects and reviews environmental impact assessments of Bank-financed projects.

- Dr. C.S. Kiang, Dean of the College of Environmental Sciences at Peking University in Beijing, China, who has designed and conducted large-scale air pollution studies for more than 34 years. Before joining Peking University in 2002, Dr. Kiang was a Professor and Director of the Office of Environmental Sciences and Technology, and the Director of Earth and Atmospheric Sciences at the Georgia Institute of Technology. He is a member of the steering committee of the Global Water Partnership.
- Dr. Christine Loh, founder and CEO of Civic Exchange—a Hong Kong-based, nonprofit public policy think tank—who is a lawyer by training. She spent 15 years in the commercial world followed by 9 years as a member of the Hong Kong legislature. Since 2000, she has focused on developing a public policy culture in Hong Kong. Civic Exchange is managing a number of air quality projects related to South China.
- Dr. John G. Watson, Research Professor at the Desert Research Institute in Reno, NV, who became interested in developing economies and technology transfer as a member of the U.S. Peace Corps in Peru from 1970–72. He has since conducted air quality studies and training programs in Mexico, Chile, South Africa, China, Japan, Korea, and India. He specializes in the design and execution of air quality studies to optimize emission reduction strategies. Dr. Watson authored the 2002 A&WMA Critical Review on visibility.

Comments are also contributed by:

- Dr. Miriam Lev-On, executive director and co-founder of The LEVON Group, who has more than 25 years of professional experience, 15 of which were in the oil and gas industry. She held positions dealing with global corporate environmental strategies and policies with ARCO and BP. She has expertise in environmental management and compliance strategies, air quality and environmental impact assessments, technical data analysis, and environmental technology.
- Dr. James M. Lents, Director of the Environmental Policy, Atmospheric Processes and Modeling Laboratory at the University of California, Riverside, Center for Environmental Research and Technology, who is actively involved in research on the development of air quality management plans (AQMPs), emissions analysis, environmental sustainability and global warming, and market-based regulatory approaches. He has spent 27 years directing air quality improvement programs, including 12 years as Executive Officer of the South Coast Air Quality Management District (SCAQMD).

INVITED COMMENTS BY DR. JITENDRA SHAH

The Review covers many topics with a large number of useful references. Although results are listed for several cities, the Review would be more useful if it provided guidance regarding what these examples mean and what is recommended for other cities. The Review identified leapfrogging and learning from the mistakes of others as valuable methods, but concrete examples of leapfrogging (Kuznet's curve) should have been more specific (e.g., not adding lead to gasoline, two-stroke to four-stroke engines, and clean coal).

The Review does not sufficiently address differences in air quality management for developed *versus* developing countries. There is a tendency in developing countries to either copy or recommend what has been applied in developed countries. This approach has not always succeeded, as is shown in the Review. Most of the current megacities are, and most of the future megacities will be, in developing countries (primarily in Asia). Some of the failures in developing countries occur because local issues related to capacity (e.g., human, infrastructure, and financial) and enforcement are not understood. Most developing countries have reasonable legislation, but the laws are poorly implemented. Much can be accomplished without new laws or large expenditures. In spite of difficulties and obstacles, politicians, academics, nongovernmental organizations (NGOs), and ordinary people have championed simple but effective practices that have improved the environment. A clean environment is good politics for these champions (many of whom have been re-elected by good margins); this needs to be better acknowledged, recognized, and promoted. Many corporations are also following environmental protection practices, not out of altruism, but because it is good business.

Most cities need to focus on a few pollutants and sources at a time. In most Asian megacities, suspended particulate matter (PM) levels most often exceed local and global guidelines (sulfur dioxide [SO_2] is still an issue in China). As noted in the Review, a large fraction of emissions comes from a small fraction of the emitters (e.g., on-road measurements show that most of the mobile source emissions derived from 10–20% of the vehicles). Environmental champions lose credibility when they expend valuable resources to monitor and control sources while achieving no perceptible improvements. This has been shown in a public perception survey in Manila, Philippines.

Looking at control options from only a technical viewpoint may not deliver the expected benefits. Economic analysis should be added to the list of assessment tools. Assigning a monetary value to the impacts of air quality degradation (negative value) or to improvements (positive value) is one of the major motivators and justifications for decision-makers in developing countries.[4,5] Some countries and cities began to address air quality problems only when adverse impacts (morbidity and mortality) were identified and valued to be millions of dollars. The concepts of "polluter pays" and "targeting gross polluters" have been successful Asian strategies. Nontechnical issues that should be considered when developing air quality improvement strategies include:

- Compatibility with other sector objectives. To what extent do environmental objectives go against, or reinforce, objectives of other sectors?
- Political feasibility. Which interest groups oppose the proposed measures?
- Cost of implementation. Which strategies provide the greatest reduction in human exposure for the least cost?
- Ease of enforcement. How can strategies be implemented and enforced?

The Review emphasizes that transportation emissions may be a large contributor to elevated air pollution levels in megacities, but transportation is only part of the problem. Uncontrolled heavy industrial emissions and nontraditional area sources such as burning (e.g., garbage, slash and burn, and rice paddies) and resuspended road dust are also important contributors. The Review suggests that ultra-low sulfur fuels are needed to reduce vehicular emissions, but this may not be the most cost-effective approach at this stage in many developing countries. Replacing old diesel buses with new buses along with better maintenance might provide a better first step, as is being implemented in Bangkok, Thailand.

INVITED COMMENTS BY DR. C.S. KIANG

The Review covers extensive information on a wide range of topics, from scientific issues of air pollution—including sources, sinks, and transformation and transport of precursors of air pollutants—to land-use and urban planning, energy, transportation systems, public health, quality of life, policy implementation, and accountability.

Air pollution problems in megacities involve systems engineering and require systems management. Such problems require holistic solutions, and the training for such solutions is not always available in highly specialized societies. More human resource development in systems sciences, systems engineering, and systems management is needed to address the complexities of megacity management.

Addressing air pollution requires regional planning. For example, China has 1.4 billion people, 400 million of whom live in urban areas. There are 600 million to 800 million people considered to be "excess labor," and many of them are moving from rural areas to live as migrants in megacities. Some Chinese megacities have nonresident populations that exceed several million. Garbage burning by these migrants can be a large emission source of air pollution. Urban and regional planning is needed to deal with this situation. In China and in megacities elsewhere in the world, addressing air pollution without looking at water, solid waste, and other media does not provide a comprehensive picture of the environmental problem.

Reducing megacity air pollution requires teamwork. Reward systems of the current system encourage only the individual. A strategic alliance between public, private, and government entities is essential for addressing the issue of policy implementation. China lacks a conflict-and-resolution process in its operational system. The process of conflict and resolution is needed to address the issue of megacity air pollution. Recently, in the process of developing mid-term (2010) and long-term (2020) economic development plans, a task force was established to address environmental issues that will arise during future economic development. Experts in the task force have asked specific questions about how to address the complexities of environmental pollution problems, including: (1) how to collect quality data; (2) how to manage the collected data; (3) how to analyze the data; and (4) how to establish policy based on the findings of the analyses. The leadership of China has accepted that the policy must be scientifically based. Environmental policies should be based on a balance of economic, scientific, and social issues.

Other critical methodological questions posed by the experts are (1) how to implement policy, and (2) how to evaluate the impact of policy implementation. One of the key issues for policy implementation in air pollution management is the knowledge of the emission inventory. Due to rapid double-digit growth, emission inventories are out of date the moment they are taken. Without knowing the emissions, it is difficult to know "where we are" and to implement a policy that leads to "where we are going to be." It has been suggested in China that monitoring stations' observed data and inverse modeling should be used to identify possible major emission sources. By using the operational mode of an air quality forecast system, a dynamic emission inventory in time and space can be established. If this proposed new approach could be established in China, it would also be applicable everywhere in the world. Furthermore, it is recognized by China and elsewhere in the world that three-dimensional spatial air chemistry measurements are needed for a better understanding of air pollution problems in megacities and their nearby regions.

The air pollution in Hong Kong and the Pearl River Delta cities cluster is more complex due to the issue of "one country, two systems." There is no regional air quality management board to address this regional problem. It has been recommended at a workshop in Guangzhou that a Regional Air Quality Management Board be established. This proposed organization can lead to the development of (1) a regional data management system; (2) a regional emission inventory in time and space; and (3) a validation accountability system. It was also proposed to establish the critical loading for the Pearl River Delta Region. Critical loading is the concept that anything added to economic development, such as new automobile plants, must be offset by the replacement of some of the old industries with more efficient technologies. Future economic development requires the development of offset technology and new economics to sustain the environment.

Scientific research and discovery are still urgently needed for better management of urban and regional air quality. Fine and ultrafine particles in heavily polluted Beijing and their possible impacts on environmental health and atmospheric chemistry are examples of the need for continuous research and discovery. New products are generated daily. The possible new impacts on the environment of these new products need to be evaluated and assessed accordingly. The air pollution problem is going to be extant as long as there is a need for economic development under current existing development paradigms.

INVITED COMMENTS BY DR. CHRISTINE LOH

The Review provides a useful discussion of the general issues related to urbanization and air quality. It touches on many aspects of the causes and consequences of urban growth and its impact on air quality. The extensive reference section will be useful to students and experts alike. The Review is done broadly, and in choosing to do so, the authors addressed some of the more challenging problems with general terms, rather than specific actions. The real challenges are political, institutional, and systemic. Another approach to such a review would analyze the political economy of developing countries and the implications for environmental improvement.

In many developing countries, governments of different political persuasions target economic growth ahead of public and environmental health. Governments believe that for them to stay in power, they must continue to facilitate rapid growth. Some scholars have argued that growth so generated is often "growth without development." The fast pace of growth has turned many regions into ecological wastelands. Because economic growth is the key political goal, economists are regarded with greater respect than are experts from other disciplines. This is unfortunate, as achieving sustainable development requires the integration of many disciplines. Another common problem in developing countries is that many of the largest state-owned enterprises are major polluters, but they are not closed because politicians feel they need to protect these interests.

The World Bank ranks 16 Chinese cities among the world's 20 most polluted. Beijing's traffic emits more carbon monoxide (CO) than Tokyo and Los Angeles (LA) combined. Recent studies done by Peking University also indicate that PM levels are exceptionally high, which may have a devastating impact on health. The challenge of controlling vehicular emissions is colossal. The authorities would have to raise prices to revamp refining industries to produce cleaner gasoline and diesel fuels or import cleaner fuels; eliminate polluting vehicles and invest in new ones (which is being done); train a new group of vehicle mechanics; and have vehicle owners who understand basic car maintenance well enough to maximize the benefits of the fleet upgrade. Among Chinese cities, Beijing has to force the pace of change because of the 2008 Olympics. As for air pollution that comes from the surrounding region, China may have to shut down many activities for a period of time to ensure reasonable air quality for the Olympics.

China presents another characteristic not discussed in the Review: a lack of information and data for top leaders to make the best decisions possible. While the Review highlights the need for collecting and analyzing data on a systematic basis, it does not address the culture of official secrecy. China's air quality data are officially secret. While China is now investing in air quality research, the data that is officially released may not be reliable. For cities of the Pearl River Delta in Guangdong Province (China's top export province), obtainable air quality data indicates that standards are not being exceeded in some cities, but complementary data from nearby areas suggest that the standards have in fact been breached. If the figures are being manipulated to show that environmental conditions are more favorable than they really are, then decision-makers may be acting without the benefit of correct information. This phenomenon has to be understood within the overall political context that local authorities, while they are being asked to improve environmental conditions, are also expected to produce high growth.

INVITED COMMENTS BY DR. JOHN G. WATSON

The Review makes several statements that are not completely supported by the evidence given. These statements are summarized as follows, with added qualifications.

Economic growth creates the means to improve the environment. Although growth can create more income from taxes and fees, it usually creates demands on basic city services (e.g., water, sanitation, roads, schools, and law enforcement) that may outstrip revenue increases, leaving little funding for environmental control. Impact fees need to be assessed on developers to compensate. These should include the value of environmental degradation or the cost of improvements.

Transportation is the main source of city pollution. On-road cars, trucks, and buses will always be important emitters in cities, but they are not the only ones. Combustion of residential fuels for heating and cooking, construction and renovation, surface coatings and solvents (e.g., VOC [volatile organic compound] sources), nonroad engines (for construction, lawn maintenance, and electrical generation) and windblown dust are often of equal or greater importance. Small- to medium-sized commercial enterprises (e.g., dry cleaning, brick manufacturing, metal fabrication, and plating) are often unregulated and uninventoried, but may be important emitters. Poorly controlled heavy industries are often located within or near megacities. Even distant industrial sources in rural areas create high regional ozone (O_3) and PM sulfate levels to which urban contributions are added.

Some pollution decisions are easy to make. This is a true statement, but elaboration is needed on which options are truly "no regrets" and provide benefits beyond improved air quality. Table 1 lists several solutions that are widely accepted as beneficial. The ways in which they are implemented, however, may differ among megacities depending on their resources, economic pressures, and cultures.

Table 1. Examples of "no-regret" actions for air pollution control in cities (compiled from delegates at the 2004 International Urban Air Quality Forum in Indianapolis, IN).

Policy initiatives	Produce and distribute unleaded gasoline
	Phase-in improved technology vehicles and engines through tighter standards
	Remove fuel subsidies
	Abolish burning of garbage and other biomass
	Lower taxes on clean products
Institutional measures	Identify and encourage champions for change
	Formulate a Clean Air Group that includes industry, fuel providers and nongovernmental organizations
Road, transport, and traffic management	Make public transportation affordable or even free for downtown destinations
	Train bus drivers about pollution and fuel use
	Promote fuel efficiency for cars and industry
	Establish one-way traffic with synchronized signals
	Pave roads, including access roads
Awareness, media, educational, and social	Publish and broadcast Air Quality Indices
	Promote a regular media outlet for air quality stories to keep up interest
	Offer environmental education in primary schools and agricultural extension services
Technical measures	Eliminate refueling leaks, establish primary VOCs recovery, as a minimum
	Reduce sulfur content of diesel fuel and gasoline to 500 ppm or lower
	Require new gasoline-powered vehicles to have operational catalytic converters
	Mandate inspection and maintenance for commercial vehicles
	Design and disseminate better stoves for coal briquettes, wood pellets, and other solid fuels
	Focus on less-polluting, better-ventilated kitchens
	Promote more efficient agricultural burning methods
Enforcement initiatives	Identify and target gross polluters
	Provide complaint phone or text message numbers for visual sighting of polluters

Special studies are needed to understand causes of excessive concentrations and to monitor progress. Most of the "no regrets" measures in Table 1 require no additional studies to justify their implementation. Long-term monitoring is needed to evaluate their effectiveness and determine the need for additional measures, but this doesn't necessarily require the newest, most complex, or most expensive instrumentation. It requires a long-term commitment that is usually lacking in special, short-term studies. In many cases, simple, relatively inexpensive instrumentation, such as battery-powered Minivol filter samplers[6] and continuous monitors developed for personal exposure[7] can provide sufficient information at a reasonable cost (Figure 1). Low cost, durability, ease of repair, large spatial coverage, and portability can offset the lower accuracy and precision of these measurement systems. As noted by Dr. Loh, quality assurance and traceability are needed for measurements to be useful. Eliminating the high values just to demonstrate compliance with standards is worse than dishonest. It defeats the whole purpose of the monitoring effort.

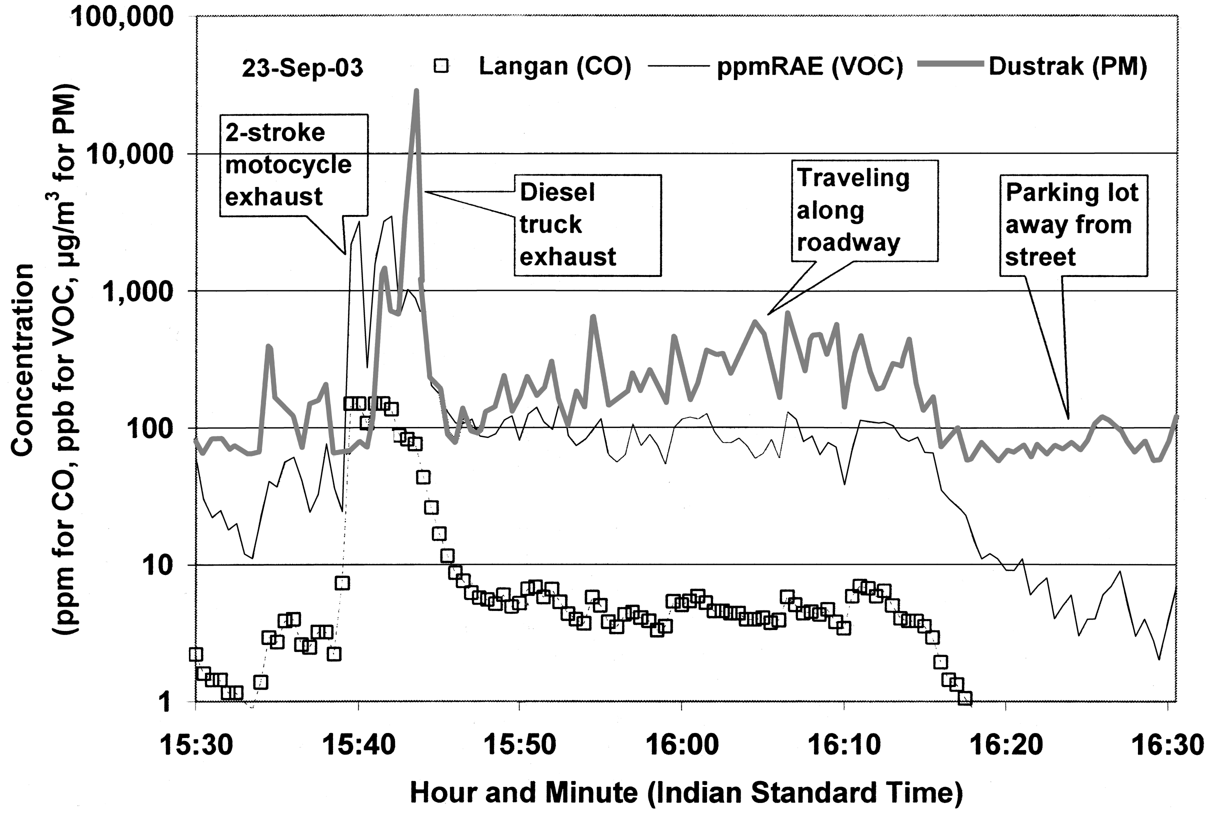

Figure 1. Example of continuous pollutant measurements obtained with battery-powered personal exposure monitors in Pune, India. These instruments were mounted into a briefcase and used to evaluate pollution gradients, zones of representation for fixed monitoring stations, and emissions compositions.[7] Particulate matter (PM) concentrations in $\mu g/m^3$ are estimated by a DustTrak 8520 (TSI, Shoreview, MN) that measures the forward scattering of 780 nm light. This instrument is factory calibrated with Arizona road dust and its readings are higher than actual mass concentrations typically found in urban atmospheres containing small particles from combustion sources. CO is measured with a Langan T15 (Langan Products, Inc., San Francisco, CA) by an electrochemical cell. Volatile organic compound (VOC) levels are estimated with the ppbRAE PGM-7240 (RAE Systems, Inc., Sunnyvale, CA) photionization detector. This is most sensitive to the aromatic fraction of VOCs. Note higher CO and VOC in motorcycle exhaust, higher PM in diesel exhaust, higher exposures during transit along the roadway, and lower concentrations in a parking lot several tens of meters from heavily traveled streets.

Pollutants should be considered together rather than individually. While this is a good idea in theory, it is difficult to implement in practice. As noted by Dr. Shah, it may be best to focus on a few pollutants at the outset, such as PM and O_3, to build up the assessment and planning infrastructure and to demonstrate effective progress. Benefits of different strategies for other pollutants should be considered, however. After-engine devices may reduce oxides of nitrogen (NO_x), VOC, and PM emissions, but reducing the quantity of fuel consumed through more efficient engines and public transit will also reduce carbon dioxide (CO_2) and other detrimental emissions.

Environmental policy is often left to chance rather than to careful planning. The city-specific examples given in the Review, and the additional examples provided by the discussants, indicate that policies on the atmospheric environment are being actively pursued in many cities. However, it seems that the concept of a megacity needs to be generalized beyond that of the 8–10 million people counted within a specific political or economic boundary (e.g., city limits and metropolitan statistical areas). Many urbanized areas are much larger, although they may overlap state, provincial, and international boundaries. NASA's City Lights[8] shows the extent of contiguous areas through a mosaic of nighttime satellite photographs. Isolated urban islands, such as Santiago de Chile, are rare. Continuous lighting is observed along the east coast of Japan, from Boston to Washington in the United States, along the shores of Lake Ontario from Toronto in Canada through Rochester in New York, and along the shores of the Pearl River Delta in southern China from Shenzen, Guangzhou through Macao, and Hong Kong. The examples given in the Review do not provide sufficient guidance on how these multinational urban centers might address contiguous, but cross-border, urbanization, possibly because such examples have not yet been successfully demonstrated.

Emerging economies can leapfrog developed economies with emission reduction strategies. This is probably true for many, but not for all, emission reduction strategies. The

Review points out the advantages of on-road emissions evaluation by remote sensing and makes a good argument that this technology might be used to replace fixed-point testing under artificial conditions. The Review does not, however, recognize the unintended consequences of many emission reduction strategies. These are largely anecdotal, but they illustrate a basic human ingenuity to avoid impositions that are seen to be disadvantageous. Several of these unintended consequences include:

- Price differentials encourage misfueling. In India, kerosene for cooking is less costly than diesel fuel, which in turn is lower than the price of gasoline. This has reputedly led to less costly mixtures for two-stroke engines that allow the vehicles to function, but at much higher emission levels.
- Beltways, freeways, and metro extensions do not always reduce congestion. More often than not these reduce travel times for a short period as they encourage urban sprawl and longer distance commutes, thereby increasing emissions.
- NO_x reductions in cities without VOC reductions may increase O_3. O_3 levels are not linearly related to their precursors. Recent analyses of weekend O_3 levels[9] show them to be consistently higher, even though NO_x emissions are lower.
- No-drive days encourage purchases of older cars. Mexico City's no-drive day, based on the last number of the license plate, was believed to encourage the purchase of a second vehicle of older vintage (and higher emissions), with the prime requirement being eligibility for a no-drive day. This has since been rectified with a very strict emission inspection requirement for everyday driving.

The Review and this discussion point out the complexities of reducing the effects of megacities on atmospheric pollution. In the process, they reveal a large knowledge gap about what strategies are effective and how well they can be implemented. While these reports are useful steps, they are not the final word on this topic.

CONTRIBUTED COMMENTS BY DR. MIRIAM LEV-ON

Several issues raised by the Review resonated with participants in the 2004 International Urban Air Quality Forum, which took place after the Critical Review presentation. The Forum reflected the spirit of integration called for in the Review while examining in detail the challenges facing large cities in their quest for sustainability. Participants from 14 countries and five continents exchanged views on innovative strategies and shared experiences in implementing air quality control programs. They focused on themes expressed in the Review, which include: (1) integrated management; (2) reducing PM emission; (3) committing to sustainability; and (4) linking air quality to urban transportation and planning.

The phrase "integrated pollution management" depends on the framework and context for the actions proposed. It may mean integration of strategies across the pollutants to be controlled (e.g., PM, NO_x, CO, ammonia [NH_3], VOCs, air toxics, and CO_2). Integrated assessment is also needed for product life cycles (e.g., extraction, manufacturing, end use, and disposal); multiple effects (e.g., human health, visibility, climate, and ecology); economic sectors (e.g., agriculture, energy, transport, fuels, tourism, and trade); and political boundaries (e.g., towns, counties, states, countries, and continents).

Some cities and regions have been recognized for successful integrated management strategies, such as the Pacific Northwest in the United States; Cape Town, South Africa; Bogotá, Columbia; and Singapore. Examples of regional activities that deal with long-range transport include the Gothenburg Protocol—a European integrated strategy across pollutants and political boundaries—and the U.S. Interstate Air Quality Transport Rules, which deal with the impact of air pollution transport among 33 eastern U.S. states.

Excessive PM exposure was the most important air quality problem identified by Forum delegates. To develop workable PM control measures, there is a need to understand, identify, and quantify emission sources. The most successful strategies seem to combine air quality considerations with land use planning and control measures for all sectors, including mobile and stationary sources. In addition to reducing emissions from the transportation sector, special emphasis needs to be placed on traditional practices, such as biomass burning.

A crucial issue in developing countries seems to be how to best preserve and upgrade existing infrastructure while preventing the dumping of old technologies and products in other countries or regions. Local action plans can address such low-hanging fruit, while regional implementation programs will require more patience and a better understanding of the limitations of existing governmental institutions. Fuels and transportation options must be regionally harmonized.

Bus Rapid Transit (BRT) exemplifies a successful system that could become a lifeline for megacities in developing countries. Few cities have succeeded in public transport system improvement because too many competing interests are involved in the process. The key success factor is public awareness and support, which promotes civic pride in tangible improvements to the quality of life.

Decision-makers and financial agencies need to be educated about the benefits of interlinking air quality considerations with urban and transportation planning. Specific policies that could be used to promote such an approach include: (1) incorporating air pollution costs (externalities) into financial models; (2) discouraging private vehicle use by fuel pricing; and (3) supporting public transport with revenues from fuel taxes.

Successful strategies require more than technical acumen. They also require proper institutional arrangements for implementation; public and media awareness; and a legal system (and political will) to enforce requirements in an even-handed manner. A holistic approach is essential to garner the required support and resources to undertake action.

The 2004 International Urban Air Quality Forum recommendations cluster around six main themes:

1. Bold policies and political will are needed to promote change.
2. Institutional barriers should be removed or minimized by collaborative approaches.
3. Integrated transportation, land use, and urban planning is imperative for attaining air quality goals, as well as improving the quality of life for city residents.
4. Public awareness, understanding, and support engender the political will to endorse change and adopt equitable strategies that include all sectors of society.
5. Technical knowledge and information are needed to formulate scientifically sound control measures that are based on proper understanding of local conditions, enable the prioritization of resources, and track progress.
6. Strict enforcement of rules and regulations, including access to justice, is essential to instill confidence in the system and a "level playing field" for all entities.

Understanding emissions and constructing emission inventories has evolved with new computational tools and measurements. To make this useful globally, a clearinghouse is needed to establish consistency and quality. This would also require sound approaches for adaptation of available emissions information to local conditions.

Importing advanced technologies without the needed technical support and institutional infrastructure has proven many times to be a waste of money and effort. Local authorities, civil society, and industry need to tackle these issues collaboratively. They are best equipped to address local customs and culture, with the understanding that traditional practices might need to be changed (e.g., open agricultural burning, old farming techniques, or using traditional biomass for cooking and heating). Nevertheless, there are some proven strategies that are widely effective and have benefits beyond air quality improvements. Table 1 presents some examples of "no regrets" strategies that have been applied in areas around the world, that are cost effective, and that are adaptable to local circumstances.

CONTRIBUTED COMMENTS BY DR. JAMES LENTS

The Review includes a discussion of LA as one of the nine case study megacities, and a closer look at the history of air quality management efforts in LA provides useful insights. This history can be classified into three distinct eras. The first era was the initial recognition and handling of the problem between 1950 and 1977 with little actual air quality improvement. The second era was a reasonably successful focused effort based on a specified air quality planning and emission reduction program. The third era is the present 21st century effort that seems to be showing little progress, and possibly is contributing to air quality deterioration. This advance and retreat pattern offers instructive insights into the processes associated with effective air quality improvement in large cities.

Air quality became so bad in LA in the 1950s that citizens' eyes watered and lungs hurt when they breathed. Mountains only a few kilometers away disappeared into the choking haze. Health and welfare concerns resulted in the establishment of air quality monitoring systems and initiated pollution control actions. Professor Haagen-Schmidt of the California Institute of Technology provided important research in the 1950s to identify the chemical components and atmospheric processes leading to LA smog. Consequently, limited regulations were adopted to reduce evaporative vehicle emissions and to consider retrofitting vehicles with catalysts. However, these initial efforts seemed to have little effect on reducing air pollution levels.

The breakthrough finally came with the U.S. Clean Air Act (CAA) amendments in 1970 and 1977.[10] These amendments established a process for creating National Ambient Air Quality Standards, required a science-based air quality planning process, set penalties for not following the required planning process, allowed citizen groups to take the government to court for not meeting legal requirements, and required automobile emissions to be reduced by 90%. The planning process required an emission inventory, an advance determination of the emission reductions, and a set deadline for attaining those standards.

In 1977, California took an important step that placed the entire geographic region (air basin) around LA under one regulatory agency (SCAQMD) to eliminate intergovernmental wrangling.[11] The prime region of air pollution around LA was called the South Coast Air Basin (SoCAB). In 1988, California took a second important step in adopting state laws that gave the SCAQMD more authority and required a new AQMP every 3 yr that included all pollutants.[12]

These federal and state steps resulted in ~50% reduction in air pollution each decade between 1977 and 2000.[13] By 2000, air pollution levels that violated state or federal standards were occurring 40 days per year, a better performance than the 242 days of violation in 1977. Had the rate of improvement of the 1976–1987 period been maintained, there would be ~73 violations per year today and 46 violations in 2010. Using the 1988–1999 rate, the projection would be three violations per year today and no violations after 2005. However, this rate of improvement was not maintained, and the recent upturn in the number of air quality violations suggests that air quality could be back to 1992 levels by 2010.

The systematic planning process initiated by the 1970 CAA played a critical role leading to effective air quality management. Developing countries need to make an effort to establish a systematic planning process; otherwise, their programs are likely to fail. An effective planning process is made up of six elements:

1. Identify air quality problems. Ambient monitoring does not typically identify the sources of the air quality problem and therefore is not generally contested by any of the interest groups.
2. Identify pollution sources. Emission-reduction decisions are just guesses unless pollution sources are identified. This was the case in the early 1950s when LA banned backyard burning and forced a local tire plant to reduce its emissions. While these actions were valuable, the controlled sources likely represented only a few percent of the emissions at the time.
3. Determine amounts of emission reductions needed. With knowledge of the sources, rational decisions can be made about the most cost-effective ways to improve air quality. However, in LA, politics prevented some area-source emissions from being controlled and resulted in almost no controls on off-road mobile sources. When the SCAQMD attempted to regulate VOCs from charcoal lighter fluid and initiated hearings on hairspray, deodorants, and similar products, consumer product manufacturers were successful in moving regulatory authority away from the local agency.
4. Develop emission reduction regulations. In the SoCAB, point sources are regulated by SCAQMD and on-road mobile sources are regulated by the California Air Resources Board (ARB). In many areas where comprehensive AQMPs are drawn up, regulatory agencies fail to adopt meaningful regulations following initial planning efforts. In some cases the planning, regulatory, and enforcement agencies are in totally separate government agencies.
5. Implement and enforce emission reduction regulations. As the 1987 AQMP was adopted for the region, SCAQMD staffing was doubled to ensure that the regulations were enforced. Industries were notified of the emission reduction target and regular inspections were instituted. Total annual fines rose from ~$500,000 to ~$2,000,000 per year. Observed reductions in air pollution between 1987 and 2000 were apparent. However, business reacted angrily to the increase in fees. A recession in California in the early 1990s fueled business concerns and influenced politicians. Consequently, regulatory authority was pulled away from the SCAQMD and limits were placed on its ability to raise revenue. This resulted in a reduction in the work force and less enforcement.
6. Review air quality improvement progress and modify AQMP as needed. When air quality levels were not met, 1990 CAA amendments extended O_3 attainment deadlines to 2006 and 2010 depending upon the severity of the pollution problem in an area. The U.S. CAA has no provision for an area to routinely review and improve its AQMP. Areas adopted a single plan, submitted it to the federal government, and were not adequately called to task until deadlines were not met.

When supplemented with the California CAA,[14] California reported >75% reduction in public exposure to unacceptable air quality between 1977 and 2001. In the United States, almost no major city has attained all air quality standards over the past 30 yr in spite of federally mandated deadlines.[15] The most polluted cities may not meet the third attempt at setting attainment deadlines established in the 1990 CAA amendments. What needs to be done to continue air quality progress as population and economic activity continue to grow? A key conclusion of a National Research Council (NRC) panel[16] is that air quality management must involve more integrated planning.

Looking to the future, air quality appears to be deteriorating in the SoCAB since 2001 owing to several possible causes: (1) a reduction in aggressive enforcement and staffing by the SCAQMD; (2) removal of enforcement authority from the SCAQMD for rigorous driving reduction programs and for consumer solvent regulations; (3) an increase in the use of larger sport-utility vehicles (SUV) and an increase in truck traffic to move growing Asian imports; and (4) changes in the mixture, location, and timing of VOC and NO_x emissions as evidenced by higher O_3 levels on weekends compared with weekdays. The causes of recent air pollution increases must be clearly determined, which further argues for a well thought out science-based air quality management process to identify reasons for the problems and to mitigate them.

To continue with further progress, the six-step process must be continued with a serious commitment to enforcement. As identified in the Review, all air quality improvement needs should be considered together. This includes urban nonattainment problems along with acid deposition, stratospheric O_3 depletion, visibility reduction, and global warming. Integration among air quality, water quality, bio-complexity, and solid waste programs is also needed to achieve the most effective results.

RESPONSE FROM DR. MARIO J. MOLINA AND DR. LUISA T. MOLINA, CRITICAL REVIEW AUTHORS

We agree with most of the discussants' comments, many of which reinforce ideas presented in the Review; many of these are addressed in ref. 3. Several discussants emphasized the need to consider economic, social, and political issues in addition to science and technology for designing efficient emission control strategies. This is illustrated in the integrated assessment of Mexico City's air quality developed by Molina and Molina;[17] a similar integrated method is the optimal approach for any large urban center. Some discussants indicated that the role of the transportation sector as a source of pollutants might have been overemphasized. While this might be the case, we indicated that because of the broad scope of the subject, only a few selected measures and their consequences were discussed; further, we emphasized the need to develop appropriate emission inventories to evaluate the relative importance of the various sectors.

We agree with the "no regret" actions for air pollution control listed in Table 1, but note that the actions should be evaluated in the context of specific cities that might be at different stages of economic development. For example, inspection and maintenance should be mandated in some cities for all vehicles, not just commercial ones. The use of coal briquettes and other solid fuels might not be an issue everywhere. Similarly, the extent to which sulfur should be removed from fuel should be evaluated for each country. Dr. Shah suggests that approaches other than introducing ultra-low sulfur fuel are more cost-effective "at this stage" in developing countries. We agree, of course, that low-sulfur fuel is not a silver bullet and that other measures need to be taken simultaneously to drastically decrease emissions, and there are developing countries where other steps need to be taken first. However, there are a number of countries, such as Mexico, where an investment in the infrastructure to provide low-sulfur fuel is well justified, provided that other measures (e.g., renewing the vehicular fleet and tightening emission standards) are also effectively implemented. The point is that introduction of low-sulfur fuels needs to be planned with several years of lead time—possibly five or more—so that a long-term vision of truly clean air can materialize in due course. In the long run, it is more expensive for society to delay such measures, if the costs of health effects are taken into account.

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