

Toward Cleaner Urban Air in South Asia: Tackling Transport Pollution, Understanding Sources

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(ESMAP)



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Abstract

This ESMAP study was undertaken to provide technical input to support the region-wide process of developing and adopting cost-effective and realistic policies and efficient enforcement mechanisms to reverse the deteriorating trend in urban air quality in South Asia. It focused mainly on fine particulate matter, estimated to account for most premature mortality and illnesses caused by outdoor air pollution. Through stakeholder feedback, the study examined two areas where more information and policy analysis could complement ongoing activities on air pollution control: making vehicle emissions inspection more effective and understanding sources of small particulate matter.

Poorly maintained older technology vehicles contribute disproportionately to total vehicular emissions. A common approach to identifying gross polluters and ensuring that they are repaired or retired is a vehicle inspection and maintenance (I/M) program. The analysis carried out in this study recommends that limited resources be concentrated on applying more robust (but also costly) test protocols to vehicle categories in large cities likely to contain a disproportionately large fraction of high annual-kilometer, gross polluters (for example, commercial diesel vehicles). The ultimate goal of I/M is to reduce human exposure to elevated concentrations of harmful pollutants. Where air pollution is not serious, the number of people exposed is not large, or for vehicles that are not driven many kilometers a year or do not pollute much (such as new gasoline vehicles), the benefit of testing vehicles would be much less limited, if not negligibly small.

At the heart of an effective I/M system are the steps taken to minimize corruption and measurement inaccuracy. A significant number of controls are needed to achieve these goals; a few developing country cities have demonstrated that these controls can be successfully implemented. These control measures increase the cost of each test, so that serious consideration should be given to limiting emissions tests to potential gross contributors to particulate air pollution. The alternative approach of testing every vehicle regularly makes simplicity and cost paramount criteria at the expense of program effectiveness. Where a universal system already exists, as in India, an enhanced program can be introduced for the targeted vehicles only.

The amount of information available on sources of fine particulate air pollution in South Asia is extremely small. This study carried out an analysis of ambient fine particulate matter in the three largest Indian cities. This represents one of the first detailed fine particulate matter source apportionment studies carried out in South Asia. The results indicate that there is no single dominant source, but rather three principal sources of particulate air pollution: vehicle exhaust, re-suspended road dust, and solid fuels, especially in cities with cold winters. This would suggest that vigorously pursuing control measures in the transport sector while leaving other

sectors essentially untouched is less likely to result in a marked improvement in urban air quality than if a multipronged approach addressing a number of sources is adopted.

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Abbreviations and Acronyms

AIHL	Air and Industrial Hygiene Laboratory
AirMac	Air Resource Management Center
CBD	central business district
Cl⁻	chloride ion
CNG	compressed natural gas
CO	carbon monoxide
CO₂	carbon dioxide
CR	concentration-response
CUEDC	Composite Urban Emissions Drive Cycle
ECE	(United Nations) Economic Commission for Europe
EF&EE	Engine, Fuel, and Emissions Engineering, Incorporated
ESMAP	Energy Sector Management Assistance Programme
EU	European Union
FTP	federal test procedure
GC-MS	gas chromatography–mass spectroscopy
GEF	Global Environment Facility
HC	hydrocarbons
HDIP	Hydrocarbon Development Institute of Pakistan
I/M	inspection and maintenance
INDOEX	Indian Ocean Experiment
INR	Indian rupees
JICA	Japan International Cooperation Agency
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MgO	magnesium oxide
NEERI	National Environmental Engineering Research Institute
NEPC	National Environment Protection Council (of Australia)
NGO	nongovernmental organization
NH₄⁺	ammonium ion
NO	nitric oxide
NO₂	nitrogen dioxide
NO₃⁻	nitrate ion
NO_x	oxides of nitrogen
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
OE	original equipment
PAH	polyaromatic hydrocarbons

PC	personal computer
PM	particulate matter
PM₁₀	particles with an aerodynamic diameter less than 10 microns
PM_{2.5}	particles with an aerodynamic diameter less than 2.5 microns
PM_{0.1}	particles with an aerodynamic diameter less than 0.1 microns
PTFE	polytetrafluoroethylene
PUC	Pollution Under Control
RAD	restricted activity days
SAE	Society of Automotive Engineers
RSPM	respirable suspended particulate matter
SMART	self-monitoring and reporting
SO₂	sulfur dioxide
SO₄²⁻	sulfate ion
SO_x	oxides of sulfur
SPM	suspended particulate matter
TERI	The Energy and Resources Institute
TSP	total suspended particles (of all sizes)
UNDP	United Nations Development Programme
VSL	value of statistical life
WHO	World Health Organization
WTP	willingness to pay
XRF	X-ray fluorescence

Units of Measure

°C	degrees Celsius
cm²	square centimeters
INR	Indian rupees
km	kilometers
lpm	liters per minute
m	meters
m⁻¹	inverse meters
mm	millimeters
ppm	parts per million
rpm	revolutions per minute
wt%	percent by weight
wt ppm	parts per million by weight
µg	micrograms
µg/dl	micrograms per deciliter
µg/m³	micrograms per cubic meter
µm	micron (one-thousandth of a millimeter)

Executive Summary

1 This ESMAP study, called South Asia Urban Air Quality Management, was undertaken to provide technical input to support the region-wide process of developing and adopting cost-effective and realistic policies and efficient enforcement mechanisms to reverse the deteriorating trend in urban air quality in South Asia. It focused mainly on fine particulate matter, which is estimated to account for the majority of premature mortality and illnesses caused by outdoor air pollution. On the basis of feedback from stakeholders, the study examined two areas where more information and policy analysis could complement the ongoing activities on air pollution control: how to construct an effective mitigation package to address transport-related air pollution with a focus on exhaust emissions inspection programs, and understanding the sources of small particulate matter. The study disseminated the findings of the studies as well as lessons from regional and international experience for use by policymakers, non-governmental organizations (NGOs), industry, academics, and researchers, highlighting main policy considerations and the issues that would need to be addressed to formulate a policy approach.

2 Available air quality data suggest that the pollutant of most concern from the point of view of environmental health risk in South Asia is airborne particulate matter. Where measurements are available, alarmingly high concentrations have been recorded in Bangladesh (Dhaka), India (large cities), Nepal (Kathmandu), and Pakistan (Karachi, Lahore, and Rawalpindi). The ambient particulate concentrations are moderately elevated in Sri Lanka (Colombo), and although measurements are not available, air pollution is not considered a concern in Bhutan and the Maldives. The strongest evidence for adverse health impact is linked to the so-called fine particles, those smaller than 2.5 microns also known as PM_{2.5}.

3 The governments in South Asia, especially those with heavily polluted cities with large populations, have been implementing a range of policy responses. Most have concerned mitigating transport-related emissions.

?? *Fuel and lubricant quality improvement* One significant achievement in South Asia is complete elimination of lead in gasoline throughout the region by mid-2002, the first developing region of the world to do so. Lead has been historically used to boost gasoline octane, but has been shown in the last two decades to be extremely toxic, even at levels previously considered safe. Gasoline lead removal should provide significant health benefits, especially among poor, malnourished children who have been shown to retain more lead. Aside from lead elimination, fuel quality standards are being progressively tightened in India following extensive consultation and work carried out by the

Expert Committee on Auto Fuel Policy. Sri Lanka has been steadily decreasing sulfur in diesel. To address the public's concerns about fuel adulteration and marketing of sub-standard quality fuels, some oil marketing companies in India and Pakistan have begun to guarantee gasoline and diesel fuel quality at their retail stations. Recognizing that the addition of inferior-quality lubricants contributes disproportionately to particulate emissions from two-stroke engine gasoline two- and three-wheelers, India and Bangladesh have banned the sale of sub-standard lubricants.

?? *Controlling emissions from in-use vehicles* An inspection program to enforce exhaust emission standards for in-use vehicles is in place in Kathmandu, Nepal, and in India. The governments of Bangladesh and Sri Lanka are in the process of establishing an inspection program for the first time. There are voluntary emissions inspection centers in Pakistan. A city-wide ban on all existing two-stroke engine three-wheelers was imposed in Dhaka effective January 2003. Age limits on in-use commercial vehicles are imposed in some cities in India and in Kathmandu.

?? *Alternative automotive fuels* There is an active program to promote vehicles powered by compressed natural gas (CNG) in India and Pakistan, including mandatory conversion from diesel to CNG in certain vehicle categories in Delhi, India.

?? *Stationary sources* Polluting industries have been relocated by court order in Delhi. The government of Pakistan is aggressively pursuing fuel switching from fuel oil to natural gas in industry. The environment ministry in Pakistan has launched voluntary self-monitoring and reporting of emissions and discharges by industry.

4 Given the large amount of efforts devoted to controlling emissions from vehicles, this study explored how to mitigate emissions from in-use vehicles through an emissions inspection program. At the same time, there is not sufficient evidence to conclude that vehicles are the majority contributors to particulate air pollution. Sources of fine particulate matter include large industrial sources such as power plants, small industrial sources and commercial establishments, households, refuse burning, road dust thrown into the air, and exhaust emissions from vehicles. To better understand contributions of different sources, a source apportionment study for fine particulate matter was conducted.

Vehicle Emissions Inspection Program

5 Poorly maintained older technology vehicles contribute disproportionately to total vehicular emissions. A common approach to identifying gross polluters and ensuring that they are repaired or retired is a vehicle inspection and maintenance (I/M) program. There are plenty of examples of ineffective I/M programs worldwide, but only a handful of successful ones. To be effective, I/M programs must meet certain key requirements. An up-to-date and

accurate vehicle registration record is a first prerequisite for identifying gross polluters and getting them to the inspection centers. A requirement to display a visible sticker certifying that the vehicle has been inspected and passed, under penalty of a fine large enough to deter evasion, is one way of tackling this problem. Test protocols should be designed to minimize false passes and false failures (making it difficult to cheat or avoid inspection), minimize measurement differences among test centers as well as among testers at a given test station, and maximize reproducibility and accuracy. In particular, the testing technology has to be able to prevent the use of temporary “tuning” that enables a vehicle to pass the test even though it cannot sustain that level of emissions for regular driving. Unfortunately, the test protocols used in Kathmandu and India, and those proposed in Bangladesh and Sri Lanka, can be fairly easily defeated by temporary tuning.

6 The analysis carried out in this study recommends that limited resources be concentrated on applying more robust (but also costly) test protocols to those vehicle categories in large cities likely to contain a disproportionately large fraction of high annual-kilometer, gross polluters (for example, commercial diesel vehicles). The ultimate goal of I/M is to reduce human exposure to elevated concentrations of harmful pollutants. Where air pollution is not a serious problem, where the number of people exposed is not large, or for vehicles that are not driven many kilometers a year or do not pollute much (such as new gasoline vehicles), the benefit of testing vehicles would be much less limited, if not negligibly small. The alternative approach of testing every vehicle regularly makes simplicity and cost paramount criteria at the expense of program effectiveness. Where a universal system already exists, as in India, an enhanced program can be introduced for the targeted vehicles only.

7 Such a selective approach to inspection should be accompanied by far more control measures to ensure that instruments are regularly and properly calibrated; test procedures are automatically controlled by computer rather than left to the discretion of each individual tester; data entry, storage, and transmission are computerized; and pass certificates are also controlled by computer with digital signatures to prevent forgery and fraudulent certificate generation. Minimizing corruption and measurement inaccuracy is at the heart of a successful I/M program.

8 There is much discussion in South Asia about the benefits of outsourcing inspection to the private sector. Even if the entire I/M system is outsourced to the private sector, it needs to be recognized that there is a cost to the government: the government must be willing and able to provide the resources for auditing and supervising the program (even if the supervision in turn is outsourced) that are needed to guarantee the system’s objectivity and transparency. All testing centers should be subject to equally rigorous implementation of protocols and inspection of their procedures by independent bodies. The legal framework should include penalties for failure to carry out the testing protocols correctly, including revocation of the license to operate.

Other Policy Considerations for Air Pollution from Road Transport

9 A number of factors, and not just technology-specific issues, are responsible for high emissions in road transport as well as in other sectors. An effective strategy for controlling air pollution will require an appropriate mix of technology, policy, and institutions. Some policy instruments, such as setting emission standards for new and in-use vehicles, are directly aimed at reducing air pollution. Other policy measures are indirect policy tools with primary objectives other than air quality improvement, but can give sizeable collateral air quality benefits. They have long “gestation” periods, but can derail air quality management in the long run if poorly handled. Several policy considerations are discussed below.

10 *Traffic management?* traffic system management to improve speeds of existing traffic volumes? has been shown to improve traffic conditions and lower emissions significantly by reducing the number and duration of stops and permitting higher travel speeds. Traffic management measures can be relatively cheap and quick acting. They can, however, induce additional travel that may have to be restrained by introducing traffic demand management steps to ensure the sustainability of the traffic and pollution benefits. Traffic management strategies need a high and continuing degree of political, institutional, and human resource commitment to ensure that their benefits are sustained. The establishment of traffic management units with appropriate authority and ability to plan and implement traffic management measures is essential. The involvement of police authorities working in concert with traffic management units is critical to successful traffic management.

11 *Substitution of diesel by CNG*, if it can be carried out in a sustainable manner, can reduce particulate emissions from diesel vehicles considerably. However, the much higher retail price of gasoline compared to diesel on account of differentiated taxation in South Asia, as in most other developing regions of the world, promotes fuel switching between gasoline and CNG, and not between diesel and CNG. Moreover, diesel technology is robust, and experience with heavy-duty vehicles (buses being the most common example) switching to CNG is that maintenance costs tend to increase. The greater maintenance difficulties of CNG vehicles compared to diesel means that fleet operators must be strongly committed to CNG, provide the necessary staff training, and cover the incremental costs.

12 *Increasing the price of diesel to better reflect its marginal social damage* is a sensible policy but encounters much political opposition. Throughout South Asia, diesel costs 30 to 40 percent less than gasoline. This has resulted in vehicles as small as three-wheelers running on diesel in India. Lower fuel prices discourage efforts at improving fuel economy, many of which can also reduce exhaust emissions. Studies in Pakistan and Sri Lanka show that the welfare impact of a large increase in the price of diesel is rather modest. Whatever the adverse impact on the poor can be further mitigated if the tax on diesel is rebated to intermediate users of diesel, such as rail transport. The studies also show that relying only or primarily on fuel taxation to promote fuel switching from diesel to gasoline is sub-optimal, and differentiated vehicle taxation needs to be an integral component.

13 *Transport and downstream petroleum sector reforms* are two examples of indirect policy tools. The twin goal of public transport policy should be to make public transport vehicles clean, and to draw passengers away from private vehicles to high-occupation public transport vehicles by making public transport attractive. A critical requirement is to provide incentives to improve efficiency, the most effective of which is some competitive threat. Well-designed competition for the market overcomes the disadvantages of unregulated competition and can strengthen environmental discipline.

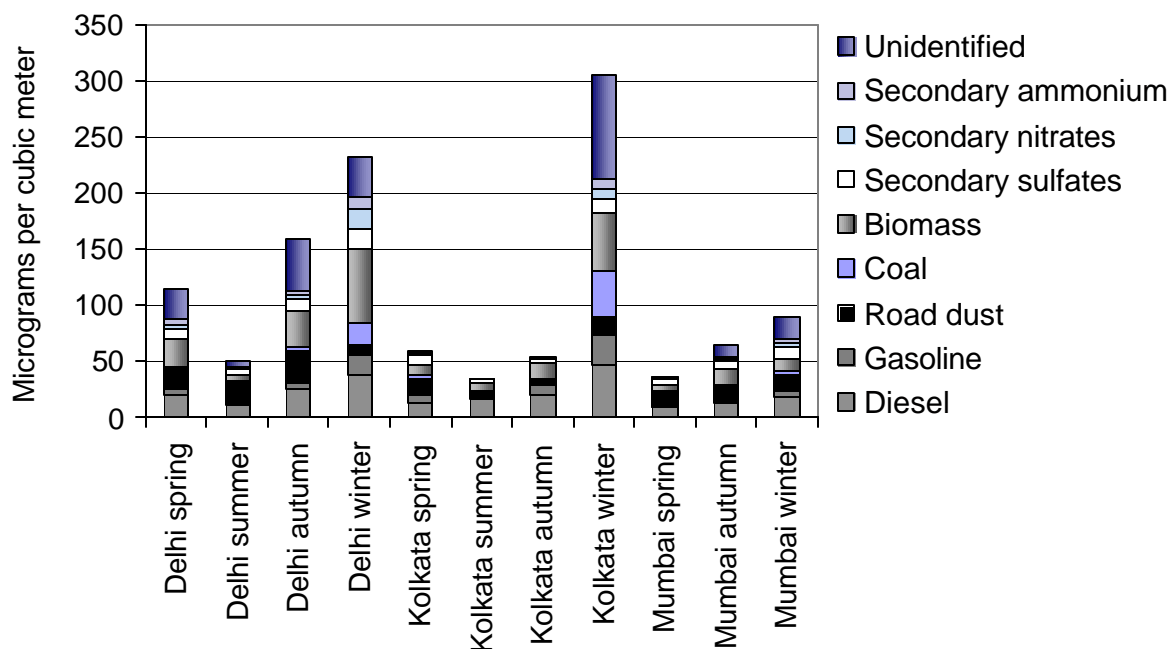
14 One important requirement for fuel-quality improvement and adequate fuel supply is an efficient downstream petroleum sector. Where there are serious distortions in the sector, unsustainable subsidies, gross inefficiencies, and a serious shortage of investment, coupled with sector protection, it is difficult to realize significant fuel quality improvement or meet demand for cleaner fuels. Countries with refineries—Bangladesh, India, Pakistan, and Sri Lanka—can be especially prone to shielding the domestic oil sector from outside competition. Bangladesh and Pakistan have lagged considerably behind in fuel quality standards for historical reasons, although in recent years Pakistan has been carrying out substantial sector reform.

Sources of Fine Particulate Air Pollution

15 The amount of information available on sources of fine particulate air pollution in South Asia is extremely small. This study carried out an analysis of ambient $PM_{2.5}$ in the three largest Indian cities using a technique called chemical mass balance receptor modeling. The particles were analyzed for organic carbon, elemental carbon, metals, and ions, and the hydrocarbons found in organic carbon were further subjected to detailed speciation. This work represents one of the first detailed $PM_{2.5}$ source apportionment studies carried out in South Asia. It should be stressed, however, that the results carry large uncertainties and should be considered *semi-quantitative*.

16 The results indicate that there are three principal sources of particulate air pollution: vehicle exhaust, re-suspended road dust, and solid fuels, especially in cities with cold winters. The results, representing averages of $PM_{2.5}$ collected in each season at one sampling site in each city, are shown in Figure E.1. The sources are shown as fuels (gasoline, diesel, coal, and biomass), road dust, particulate matter formed through atmospheric reactions (the so-called secondary nitrates and sulfates, which are formed from emissions from various combustion sources, and secondary ammonium, which can be from agricultural sources in addition to combustion sources), and unidentified (the difference between measured $PM_{2.5}$ concentrations and the sum of identified particulate matter). The results are shown by season because fuel combustion requirements vary from season to season.

**Figure E.1 Receptor Modeling of PM_{2.5} in India:
Delhi, Kolkata, and Mumbai**



Note: Insufficient sample was collected in summer in Mumbai to carry out hydrocarbon speciation.

17 The results show that there is no single dominant source but rather a number of sources contribute to PM_{2.5}. Gasoline is exclusively from mobile sources, but diesel contribution is from both stationary and mobile sources, although mobile sources contribute far more than stationary sources per unit of fuel consumed because internal combustion engines are much more polluting. It is not possible to attribute secondary sulfates, nitrates, and ammonium to specific primary sources. Broadly, mobile sources and biomass combustion appear to contribute substantially and in several cases approximately in equal proportions (Delhi spring, Delhi autumn, and Mumbai autumn). Road dust contribution can also be significant (Delhi summer, Mumbai spring, and Mumbai autumn). Predictably the combined contribution of biomass and coal, presumably used for heating, is high in winter in Delhi and Kolkata.

Policy Implications

18 Understandably, much policy attention has been concentrated on vehicle exhaust to date in the region. However, the source apportionment study presented here points to the importance of addressing several sources of air pollution in parallel. In particular, fuel combustion for heating can become a significant contributor to ambient particulate concentrations in cities with cold winters that require heating—mainly in northern India, Nepal, and Pakistan—precisely in the season when ambient concentrations from all sources are

elevated on account of thermal inversion. These and other sources, although not dealt with in this study, would need to be tackled for effective air quality management.

19 There is no simple or universal strategy for improving air quality. It is necessary for decisionmakers to consider policies within their own technical, economic, political, and institutional circumstances. While the specific actions for reducing air pollution will vary from city to city, there are several underlying principles that can guide the construction of an effective policy package.

- ?? Target gross polluters, and design and institute monitoring and enforcement mechanisms that ensure that high emitters are identified with reasonable accuracy and their operators take action to reduce emission levels.
- ?? Raise awareness among policymakers and the general public about urban air pollution levels and damages and specify and promote the role that different sectors play.
- ?? Press for sector reform that increases sector efficiency, benefits society at large by providing goods and services at lower cost, and at the same time reduces emissions.
- ?? Raise awareness about “best practice” in business as well as among consumers that is also likely to bring about environmental benefits to society.
- ?? Work with, not against, the economic incentives of various actors.

20 With respect to mobile sources, the governments in South Asia are at different stages in setting and tightening fuel quality and vehicle emission standards. In countries where there is no immediate prospect of tightening fuel standards, such as with the content of sulfur in diesel in Bangladesh and Pakistan, supplying large cities with cleaner fuels might be considered as an interim solution. As regards controlling emissions from in-use vehicles, this study suggests that, given the widespread lack of effectiveness of “traditional” I/M systems in South Asia and elsewhere, a much more rigorous approach incorporating far greater control on the test protocols, data collection, storage, transfer, and analysis be adopted in a targeted system, perhaps confined to commercial diesel vehicles in large cities in the first instance.

21 Traffic management can reduce emissions arising from frequent stop-and-start operations. In the long run, totally segregated busways may be given serious consideration. Properly implemented, experience in other regions shows that a bus rapid transit system can maintain the share of public transport in the face of rising income, reduce congestion, and markedly lower both accidents and emissions.

22 Re-suspended road dust can be addressed by urban designs and landscaping. They can be implemented at a small incremental cost in many road projects, bringing significant environmental benefits. Whenever possible, road projects should include provision for paving all sections of the road including sidewalks, and where paving is not practical, landscaping with trees that require no watering.

23 Solid fuels are much more polluting than liquid or gaseous fuels but are also cheaper, and their low cost is the main driver for their extensive use, especially when large quantities of fuels are needed, such as for space heating in winter in cold climate regions. In the long run, switching out of solid fuels to liquid and gaseous fuels is the most effective mitigation measure for small fuel users, and installing emission control devices with high efficiency in the absence of fuel change is the most effective measure for large industrial users.

24 In Bangladesh and Pakistan which have abundant domestic reserves of natural gas, expansion of natural gas pipelines in large cities can help in the medium to long term to reduce dependence on solid fuels. In Nepal and Sri Lanka, as well as cities in other countries without natural gas, cleaner alternative fuels are kerosene, liquefied petroleum gas (LPG), and electricity, although kerosene can be polluting if not burned efficiently. Fuel switching for cooking is easier than for space-heating which requires much more energy, but even so, switching out of solid fuels is not an immediate option for many users for the foreseeable future. In some cases, biomass briquettes may be a viable cleaner alternative. Different modes of ignition and combustion to reduce particulate emissions need to be understood more and the findings disseminated.

25 Different stakeholders have different roles to play in air quality management. Government sets regulations, enforces them, and provides financing for certain activities. Civil society not only pays for and benefits from air quality improvement, but can also influence government policy through votes and other means. NGOs can raise awareness and act as advocacy as well as pressure groups. The involvement of the private sector through consultation in standard-setting and fostering market-based approaches to air pollution control can be beneficial.

26 Air quality management requires sustained and cooperative actions over a long period. Forging cross-sectoral coordination is essential. An example of successful coordination across different stakeholders and government agencies is the case of lead phaseout in Sri Lanka, where cooperation among environmental, transport, and petroleum sectors helped to bring forward the target date for lead removal by eight years, from 2010 to 2002. At the same time, no city can implement a large number of measures all at once, however desirable. Different and typically increasingly more stringent mitigation measures are inevitably phased in stages. As new measures are implemented, it is helpful to monitor progress, and assess and discuss the perceived benefits and costs at each stage.

1

Tackling Air Pollution in South Asia

1.1 High levels of urban air pollution have attracted growing attention from government, civil society, and industry in the countries of South Asia. Poor air quality threatens human health and causes other forms of environmental damage. With continuing migration from rural to urban areas, urban air pollution will affect an increasing percentage of the population in the coming years.

1.2 The cities and countries in South Asia differ in the level of air pollution, level of urbanization, size of the population exposed, fiscal regime, fuel and other supply infrastructure, availability of natural gas (a clean fuel), and the resources and institutions available to carry out air quality management. It is therefore understandable that South Asian governments have followed different paths in addressing air pollution. India leads the region in tackling local air pollution for a number of reasons: it has a number of large population cities with high levels of air pollution, a significant presence of refining and vehicle manufacturing industries, a long history of air quality monitoring, and a number of very active and well informed environmental non-governmental organizations (NGOs) raising public awareness, collecting and analyzing data, and challenging government to play a more active role. It is the only country in the region with an emissions laboratory that is certified to measure mass emissions for vehicle certification. At the opposite end are Bhutan and the Maldives where local air pollution is not a policy concern.

1.3 Costs to society arising from urban air pollution include damage to human health, buildings, and vegetation; lowered visibility; and heightened greenhouse gas emissions. Of these, increased premature mortality and morbidity are generally considered to be the most serious consequences of air pollution, both on account of their human and economic impacts. It is common and appropriate, therefore, to use damage to human health as the primary indicator of the seriousness of air pollution.

Estimating and Valuing the Health Impacts of Air Pollution

1.4 The health damage from urban air pollution depends upon the toxicity of different pollutants, the impact of ambient levels on health, and the number of people exposed.

The World Health Organization (WHO) classifies sulfur dioxide (SO₂), nitrogen dioxide (NO₂), carbon monoxide (CO), ozone (O₃), suspended particulate matter (SPM), and lead as key or “classical” pollutants. Their health effects are briefly described in Table 1.1. The same pollutants are called “criteria” pollutants by the U.S. Environmental Protection Agency (EPA). Health-based ambient air quality standards are normally set for the classical pollutants first, and their measurements are examined to judge the magnitude of the air pollution problem.

Table 1.1 Key Pollutants and Their Significance

<i>Pollutant</i>	<i>Significance</i>
Lead	Lead retards the intellectual development of children and adversely affects their behavior. At high levels, lead increases incidence of miscarriages in women, impairs renal function, and increases blood pressure. More lead is absorbed when dietary intake of calcium or iron is low, when the stomach is empty, and by children. Young and poor malnourished children are particularly susceptible to lead poisoning.
Particulate matter (PM)	The most significant health effects of air pollution in South Asia are associated with exposure to particulate matter: premature death from heart and lung disease, and chronic bronchitis, asthma attacks, and other forms of respiratory illness. The impact of PM increases with decreasing particle size, with studies increasingly focusing on particles smaller than 2.5 microns (µm) and even 0.1 µm (called <i>ultrafines</i>).
Ozone	Ozone has been associated with lung function decrements, asthma attacks, and other forms of respiratory illness, as well as premature death, and is also responsible for photochemical smog. Ozone is not emitted directly, but is formed in the atmosphere through photochemical reactions of oxides of nitrogen and reactive hydrocarbons.
Oxides of sulfur (SO _x)	SO _x causes changes in lung function in persons with asthma and exacerbates respiratory symptoms in sensitive individuals. SO _x also contributes to acid rain and to the formation of small particles through atmospheric reactions, called secondary particles.
Oxides of nitrogen (NO _x)	NO _x causes changes in lung function in persons with asthma, contributes to acid rain and secondary particulate formation, and is a precursor of ground level ozone.
Carbon monoxide	CO inhibits the capacity of blood to carry oxygen to organs and tissues. People with chronic heart disease may experience chest pain when CO levels are high. At very high levels, CO impairs vision, manual dexterity, and learning ability, and can cause death.

1.5 WHO provides health-based air quality guidelines for the classical pollutants except for SPM. WHO does not provide numerical guidelines as acceptable limits for SPM because the existing epidemiological studies have not been able to establish a threshold below which no adverse effects occur (WHO 2000). The size distribution of airborne particles matters for health impact, and WHO places special emphasis on suspended particles smaller than 10 microns (µm) in diameter (PM₁₀), also called *inhalable* particulate matter, and those smaller than 2.5 µm (PM_{2.5}), called *fine* or *respirable* particulate matter.

1.6 How to estimate health effects in developing countries is discussed in detail in annex 1. The analysis of the health benefits associated with air pollution reduction has made great progress over the past 10–15 years. Estimates of the health impact of air pollution are generally obtained from epidemiological studies that are designed to determine relationships—referred to as concentration-response (CR) functions—between air pollution and health effects in human populations.

1.7 Of the pollutants listed in Table 1.1, the most extensive body of evidence for adverse health effects at ambient concentrations that the general public is typically exposed to (as opposed to occupational exposure) exists for particulate matter. Although quantification of health impact is testing, the consistent findings across a wide array of cities, including those in developing countries with diverse population and possibly diverse particle characteristics, strongly indicate that the health gains indeed result from PM pollution reductions. Emerging scientific evidence points to increasing damage with decreasing particle diameter. Particles larger than about 10 μ m are deposited almost exclusively in the nose and throat, whereas particles smaller than 1 μ m are able to reach the lower regions of the lungs. The intermediate size range gets deposited in between these two extremes of the respiratory tract. A statistically significant association has been found between adverse health effects and ambient PM₁₀ concentrations, and recent studies using PM_{2.5} data have shown an even stronger association between health outcomes and particles in this size range.

1.8 Although WHO no longer provides numerical guidelines for particulate matter, a number of national governments have set health-based ambient air quality standards for PM₁₀ and PM_{2.5}. Often quoted are the U.S. and European Union (EU) ambient PM standards, shown in Table 1.2. The target date for compliance with the EU PM₁₀ standards, which are much more stringent than the U.S. standards, is January 2005. In South Asia, PM₁₀ and PM_{2.5} standards are still in the process of being developed for the most part, with the exception of India where the standards for respirable suspended particulate matter (RSPM) exist. Although the definition of the cut-point for sampling particulate matter is not the same as that for PM₁₀ in North America and Europe, the Indian RSPM standards can be considered to be comparable to PM₁₀ standards elsewhere.

Table 1.2 Ambient Air Quality Standards for Particulate Matter (μ g/m³)

<i>Country</i>	<i>PM₁₀</i>	<i>PM₁₀</i>	<i>PM_{2.5}</i>	<i>PM_{2.5}</i>
	<i>24-hour average</i>	<i>annual average</i>	<i>24-hour average</i>	<i>annual average</i>
United States	150	50	65	15
European Union	50	40	—	—
India	150/100/75	120/60/50	—	—

— No standard.

Notes: The 24-hour U.S. limit refers to the 98th percentile. EU standard compliance is to be achieved by January 2005, with 35 exceedances for the 24-hour average limit allowed per year. The three numbers in the India standards are for RSPM and apply to industrial/residential/sensitive areas.

1.9 To convert the health impacts into monetary terms that can be compared with the resource costs of remedial policies, economists have customarily placed a value on avoided morbidity on the basis of the amount that a person is estimated to be willing to pay to avoid the illness. Where estimates of willingness to pay (WTP) are not available, it is customary to use the avoided medical costs and productivity losses arising as a consequence of the illness. This “cost-of-illness” approach, which does not include the value of pain and suffering and lost leisure time, is usually a lower bound to the WTP. For premature mortality, economists have tried to measure what people would be willing to pay to reduce the risk of dying, usually expressed in terms of the value of a statistical life (VSL). That has been controversial. When estimates of the VSL are unavailable, forgone earnings (including adjustments for labor market distortions) are often used to place a lower bound on the VSL. Annex 1 describes various options and discusses how these calculations may be carried out in South Asia.

Measuring Airborne Particulate Matter

1.10 Historically, all cities around the world were measuring total suspended particles (TSP), which do not have a well-defined cut-off point for the particle diameter and include many large particles. In response to the emerging scientific evidence that small particles are especially damaging to health, environmental agencies in industrial countries began requiring monitoring of smaller particles, first with a cut-point of 10 μ m and more recently 2.5 μ m.

1.11 It is worth remembering that different measuring techniques and instruments can give a wide range of ambient concentrations at the same location for the same PM, and for this reason regulatory agencies in industrial countries define particles to be monitored very precisely. For example, the U.S. EPA requires that only measurements using U.S. EPA-designated instruments and methods may be referred to as “PM_{2.5}.” The apparatus must have a 50 percent cut-point of 2.5 \pm 0.2 μ m and sampling bias for PM_{2.5} concentrations less than \pm 5 percent. The scientific definition of PM_{2.5} is based on the particle size-selection characteristics of the so-called Well Impactor Ninety-Six impactor used in the second stage separator. The U.S. EPA has set strict performance criteria, including the flow rate through the instrument, the precision and accuracy of the flow controller, frequency of flow rate recording, filter temperature control, the temperature range over which the entire apparatus must provide accurate performance, and frequency of barometric pressure, ambient temperature, and filter temperature measurements. Such precise procedures and definitions have not yet been adopted in South Asia.

Particulate Air Pollution in South Asian Cities

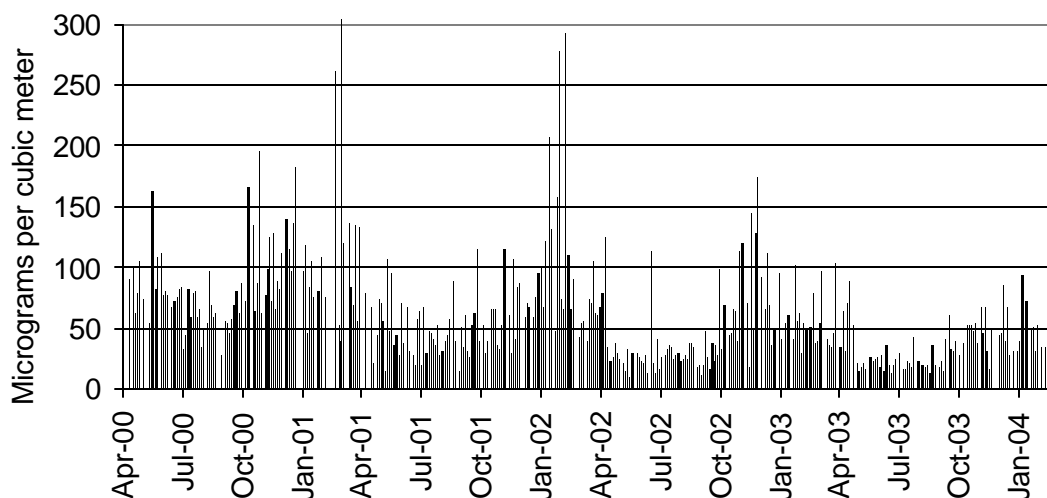
1.12 Historically measured TSP levels in a number of South Asian cities have been high. In comparison, the ambient concentrations of NO₂, SO₂, CO, and ozone have been relatively low, typically not exceeding the WHO health-based guidelines. CO, NO₂, and SO₂ can be elevated in mega cities, especially CO (predominantly from gasoline vehicles) at busy traffic intersections and corridors, but the exceedances above internationally recognized air quality standards are not of the magnitude observed for particulate matter. Airborne lead was a

concern but the phaseout of lead in gasoline implemented throughout South Asia in the early 2000s has contributed greatly to reducing lead concentrations in ambient air.

1.13 The pollutant of concern in South Asia is particulate matter. Large cities in India and Pakistan appear to have very high concentrations of small particles. Outside of these countries, Dhaka in Bangladesh (and possibly other large cities but data are not available) and Kathmandu in Nepal suffer from serious particulate air pollution, the latter in part because of its topography (being located in a valley which traps polluted air). The largest city in Sri Lanka, Colombo, has recorded lower levels of air pollution than other South Asian mega cities although particulate levels are still moderately elevated. Outdoor air pollution is not a concern in Bhutan and Maldives.

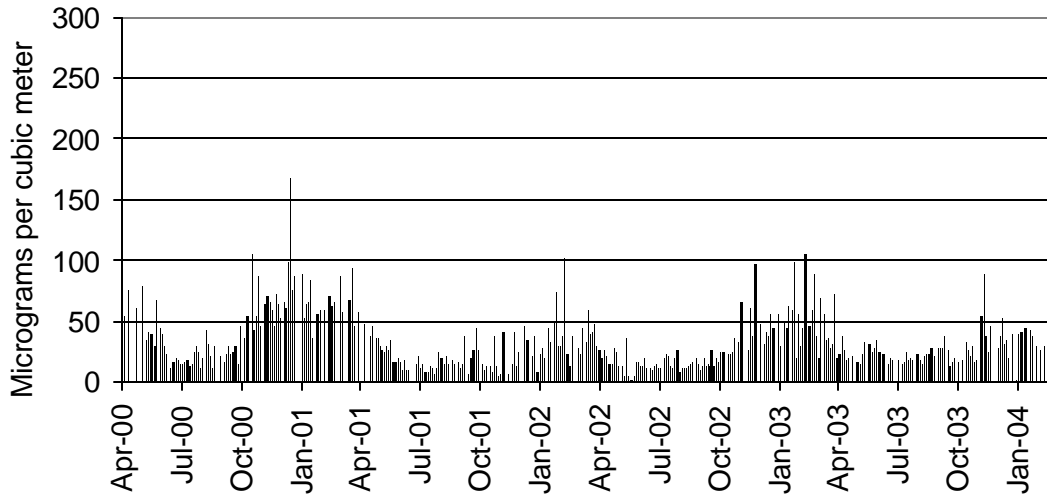
1.14 Recently, several large cities have begun monitoring PM_{10} and $PM_{2.5}$. Consistent with high ambient TSP levels, the recorded levels of PM_{10} and $PM_{2.5}$ have been found to be elevated. Available data from Bangladesh, India, Pakistan, and Sri Lanka are shown in Figure 1.2–Figure 1.6. $PM_{2.5}$ data are shown for Dhaka, Delhi, Kolkata, Mumbai, and Colombo, and PM_{10} for Lahore. The Farm Gate in Dhaka, the Fort Railway Station in Colombo, and all the sampling sites in Lahore are urban traffic “hot spots,” where major contributors are likely to be vehicular emissions. The ambient concentrations in Lahore are much higher: first, because PM_{10} rather than $PM_{2.5}$ is measured. $PM_{2.5}$ is typically one-half or less of PM_{10} in mass, and second, because busy traffic intersections were selected as sampling sites. The average of the PM_{10} measurements in Lahore is 900 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), which is extremely high by any standard, and correspondingly $PM_{2.5}$ concentrations at the Lahore sites are also likely to be highly elevated. The three sampling sites in India were carefully selected to avoid influence from emissions coming from heavy city traffic or industries, and at the same time enable the city plume to be captured.

Figure 1.2 24-Hour Average $PM_{2.5}$ Data at Farm Gate, Dhaka, Bangladesh



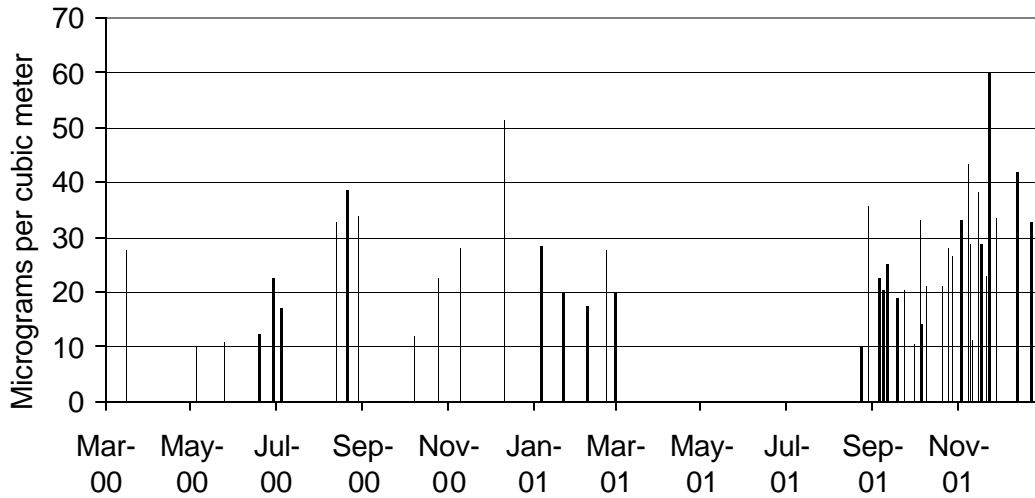
Source: Bangladesh Atomic Energy Commission

Figure 1.3 24-Hour Average PM_{2.5} Data at Semi-Residential Area, Dhaka, Bangladesh



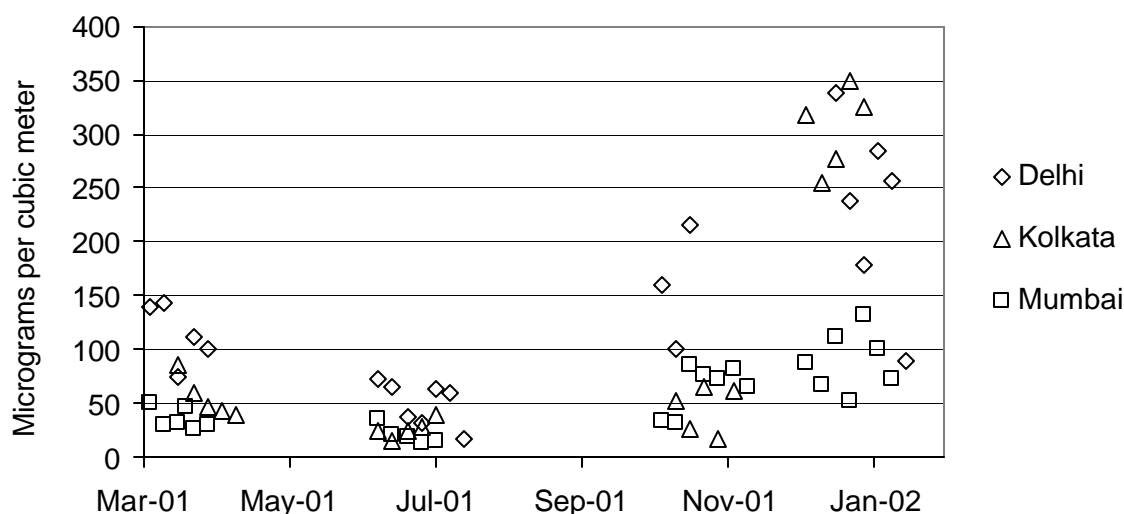
Source: Bangladesh Atomic Energy Commission

Figure 1.4 24-Hour Average PM_{2.5} Data at Fort Railway Station, Colombo, Sri Lanka

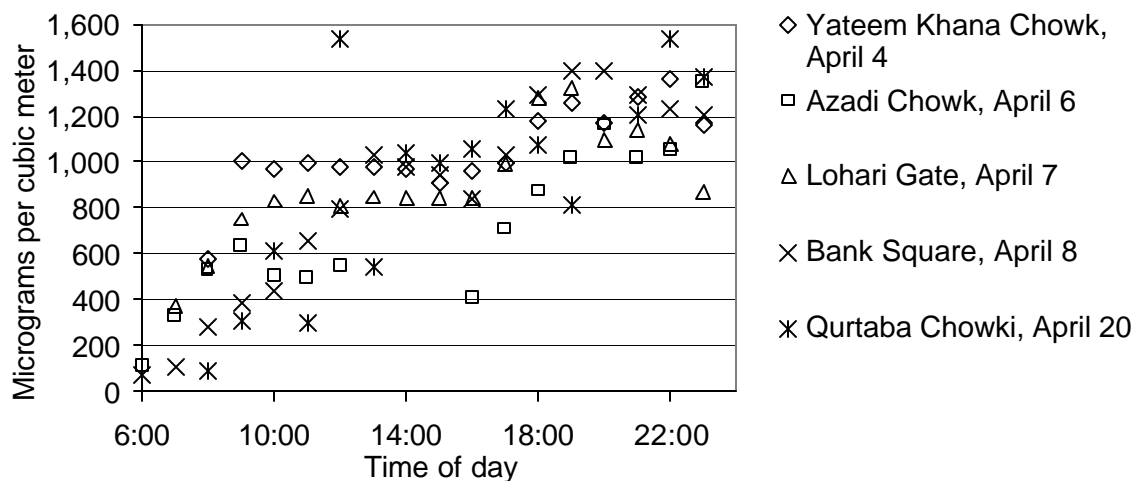


Source: Central Environmental Authority

Note: Data are missing for several months at a time.

Figure 1.5 24-Hour Average PM_{2.5} Data in Delhi, Kolkata, and Mumbai, India

Source: Georgia Institute of Technology

Figure 1.6 Hourly PM₁₀ Data at Traffic Intersections in Lahore, Pakistan in 2000

Source: JICA (2000)

1.15 The most extensive time-series data for PM_{2.5} in South Asia are available in Dhaka, Bangladesh. The data have been collected at two sampling sites: Farm Gate (Figure 1.2) which faces an intersection of several major roads, and a semi-residential site located about 50 meters (m) from a road with moderate traffic (Figure 1.3). These figures show the seasonal pattern observed throughout the region: high particulate concentrations in winter when it is dry and when low temperatures cause thermal inversion whereby pollutants are trapped near ground level, and low concentrations during the rainy season. There is a considerable fall in PM_{2.5} concentrations at the Farm Gate between 2002 and 2003. As discussed below, this could be in part due to the ban on all existing two-stroke engine three-wheelers that went into effect on

January 1, 2003. In contrast, no decrease in PM_{2.5} concentrations is observed at the semi-residential site. The concentrations are high even at this site when compared to U.S. EPA's standards for PM_{2.5}.

Government Response

1.16 In response to growing concerns about the adverse impact of deteriorating air quality, governments over the years have implemented a number of policy measures and initiatives to curb urban air pollution. One of the most successful policy interventions in this regard is the history of gasoline lead elimination in South Asia. This and a few examples of other measures are briefly reviewed below.

Gasoline lead elimination

1.17 Historically, lead has been added to gasoline worldwide as an inexpensive octane booster. However, lead is a potent toxin. High lead concentration in the bloodstream may increase incidence of miscarriages, impair renal function, and increase blood pressure. Most significantly, lead retards the intellectual development of children and adversely affects their behavior. These effects are known to occur even at levels previously considered safe. Equally troubling, more lead is absorbed when dietary calcium or iron intake is low, when the stomach is empty, and when one is very young. For these reasons, poor, malnourished children are particularly susceptible to lead poisoning. The combustion of leaded gasoline can give rise to as much as 80–90 percent of atmospheric lead in cities where leaded gasoline is still used. Lead in gasoline also contributes to fine particulate emissions.

1.18 The above findings have led to a worldwide move to phase lead out of gasoline. In the absence of other significant sources of lead, eliminating lead in gasoline can reduce the level of lead in blood to less than 5 micrograms per deciliter (µg/dl). Many international health organizations consider 10 µg/dl to be the threshold above which action is called for. Because gasoline lead elimination involves refinery modification with accompanying capital expenditure, lead phaseout is often easier in countries that import gasoline. In South Asia, all countries but India and Pakistan rely to varying degrees on gasoline imports.

1.19 In June 1999, Bangladesh became the first country in South Asia to stop the addition of lead to gasoline altogether. Bangladesh was able to do so by importing high-octane unleaded gasoline and blending it with domestically produced low-octane gasoline. This step was made easier by the low average octane pool in the country. India banned the use of lead in gasoline in February 2000. Nepal, which imports all of its gasoline from India, became lead-free around that time. Pakistan and Sri Lanka followed in 2002. In the case of both Pakistan and Sri Lanka, lead was phased out of gasoline years ahead of schedule following extensive stakeholder consultation.

1.20 Lead acts as a lubricant, and in old cars with soft valve seats, lead elimination can result in the so-called valve-seat recession, the only vehicle performance concern in gasoline lead elimination. The vast majority of vehicle owners in South Asia have not experienced valve-

seat recession, and there have been essentially no reports of such incidents. The rapid phaseout schedule followed in South Asia has a number of advantages. First, an extensive dual distribution system, one for leaded and the other for unleaded gasoline, did not have to be set up. Second, shortening the transition period minimized the chances of misfueling whereby vehicles that should not be fueled with leaded gasoline are exposed to lead because of cross-contamination during gasoline storage and distribution, or because the vehicle owner intentionally or inadvertently purchased leaded gasoline. Third, by not having to provide fiscal incentives to promote unleaded gasoline over leaded to motorists over a prolonged period of time, this move avoided posing a fiscal burden on the treasury.

1.21 The benefits of lead phaseout include not only the direct health benefits, but indirect health benefits through enabling the adoption of catalytic converters in new vehicles. Catalytic converters are by far the most effective means of controlling exhaust emissions from gasoline vehicles, but are permanently poisoned by the presence of lead in gasoline. Complete lead removal ensures that catalysts are not poisoned in this way.

1.22 Lead phaseout, if it is complete, is unique in that it stops lead emissions from *all* vehicles running on gasoline. More specifically, the effectiveness of lead removal does not depend on the state of vehicle repair or the vehicle driving pattern. Other policy measures are not so straightforward: the effectiveness depends to a large extent on the behavior of the stakeholders, such as how well they operate, maintain, and service the equipment emitting pollutants, or whether they actually shift to less-polluting modes of operation. Some of these issues are discussed in the country examples below.

Bangladesh

1.23 Air quality management efforts in Bangladesh have so far focused mainly on Dhaka, a city with a population of more than 10 million. Vehicles are believed to constitute the dominant source of air pollution in Dhaka. There are no power stations, significant industrial sources of emissions, or nearby deserts to cause dust pollution. Therefore, much of the government interventions to date have concentrated on vehicular emission control.

1.24 Two pollutants of concern in the 1990s were lead and particulate matter. Eliminating lead in gasoline was identified as a top priority and, as mentioned earlier, the addition of lead to gasoline was terminated in 1999. With respect to particulate matter, the government has been active in addressing one of the two categories of vehicles making significant contributions: two-stroke engine three-wheelers. The other category is diesel vehicles. Particulate emissions from two-stroke engine three-wheelers were exacerbated by the use of inferior-quality (the so-called straight mineral oil) and excess lubricant. It is important to note that straight mineral oil is intended for use in stationary engines, but not motor vehicles. There were an estimated 50,000 three-wheelers in Dhaka in the early 2000s, providing useful point-to-point transportation but emitting significant smoke and hydrocarbons. A number of steps have been taken to address emissions from these three-wheelers.

1.25 In 2000, training of 427 mechanics who service two-stroke engine three-wheelers was conducted (ESMAP 2002). The purpose was to provide training on how to properly tune and repair vehicles to reduce emissions. In 2000 and in 2001-2002, a series of auto-clinics were conducted whereby three-wheelers were checked for emissions free of charge, drivers were given a simple health examination, and information was given to the drivers on how to operate vehicles to minimize emissions.

1.26 Following workshops and consultation, a notification, approved by the Ministry of Energy and Mineral Resources and issued by the Bangladesh Petroleum Corporation, was published in January 2001. The notification, explicitly setting as its objective mitigating smoke emissions from vehicles, prohibited production, blending, import, and marketing of straight mineral oil without additives, and set minimal standards for lubricants for two-stroke and four-stroke engine vehicles. These regulations are applicable throughout Bangladesh.

1.27 In Dhaka, the government implemented phased retirement of existing two-stroke engine three-wheelers with the last phaseout occurring on December 31, 2002. An estimated 86,000 drivers, 10,000 owners, 600 workshop owners, 2,600 mechanics and helpers, and 500,000 dependents were affected in the process. Consultation with the stakeholders began in 1996, and continued throughout the process. Strong public support mitigated the adverse impact of this large-scale phaseout. The government stopped registering two-stroke engine three-wheelers in Dhaka in July 1999. In July 2000, the government imposed a 200 percent supplementary duty on imported two-stroke engine three-wheelers, effectively stopping imports. By the time of the final phaseout, no new two-stroke engine three-wheelers had been added to the fleet population for two and a half years.

1.28 There were protests from three-wheeler owners and drivers, including a three-day strike. Despite anticipated disruptions to public transport, support from the public and press for the phaseout remained strong throughout. The retired vehicles were permitted to be registered outside of Dhaka. The supplementary duty on three-wheelers fueled by compressed natural gas (CNG) was lowered to 10 percent in July 2002, facilitating their imports. Immediately following the final phaseout, there was serious disruption to public transport. Mitigation measures were planned and implemented, but only partially. The impact on air quality was marked and measurable. The average $PM_{2.5}$ concentrations for the month of January in 2001 and 2002 were 87 and 136 $\mu g/m^3$ (before the phaseout), respectively, compared to 55 and 54 $\mu g/m^3$ in 2003 and 2004, respectively (after the phaseout). The monthly concentrations were 125, 75, and 74 $\mu g/m^3$ in December for 2000, 2001, and 2002 (before the phaseout), and 44 $\mu g/m^3$ in 2003 (after the phaseout).

1.29 The government is currently in the process of establishing a network of air quality monitoring units and a vehicle exhaust emissions inspection program. An earlier program to set up a centralized inspection center was not implemented. There is also a plan to expand the use of CNG in vehicles with support from the Asian Development Bank. Because Bangladesh has ample natural gas reserves, natural gas can be an attractive fuel option if a suitable fuel fiscal regime is set up.

1.30 Until recently, there was essentially no air quality management system in place in Bangladesh to tackle air pollution. The government has begun to set up regulatory and institutional frameworks only in the last several years to address urban air. The activities undertaken to date include reviewing and revising ambient air quality standards and emission standards for imported and in-use vehicles. With outside support, the government is learning about options and developing components of urban air quality management by means of pilot activities and institutional strengthening.

India

1.31 The first systematic air quality monitoring in India was started in 1967 by the National Environmental Engineering Research Institute (NEERI, then named Central Public Health Engineering Research Institute) in 10 cities with three monitoring stations in each city. The Central Pollution Control Board (CPCB) established nationwide air quality monitoring in 1984. By March 1999, there were 290 stations covering more than 90 towns and cities in 24 states and four Union Territories, monitoring SO₂, NO₂, and TSP. All 30 stations operated by NEERI and a number of other stations monitor RSPM.

1.32 CPCB reports that the data collected in Ahmedabad, Bangalore, Chennai, Delhi, Hyderabad, Kolkata, and Mumbai in 2001 show high ambient NO₂ concentrations in Kolkata but low or moderate concentrations in the other cities, and low SO₂ levels in all seven cities. In contrast, RSPM was high or critical in the residential areas of all seven cities (see the CPCB website).

1.33 As Figure 1.5 shows, fine particulate air pollution differs significantly from city to city. Mumbai, the largest city in India, is located on the Arabian Sea. Because ocean air is typically cleaner than continental air, proximity to the ocean and the influence of diurnal land and sea breezes aid the dilution of PM_{2.5} concentration. In contrast, Delhi is located inland. Analysis of backwind trajectories (tracing where winds are coming from) between January 1995 and December 1999 by the National Oceanic and Atmospheric Administration (NOAA) shows that 62 percent of all trajectories arriving in Delhi during that period experienced stagnation. Air stagnation in turn keeps particles suspended over the city for an extended period of time and worsens air quality. In addition, lower temperatures in the winter months lead to atmospheric inversion where pollutants are trapped close to the ground in all three cities, and this, combined with low rainfall, increases PM_{2.5} concentrations further. Kolkata falls in between the two cities, with ambient concentrations being lower than in Delhi except in winter in the set of data shown.

1.34 In terms of priority, the government has targeted four largest metros—Chennai, Delhi, Kolkata, Mumbai—for air pollution control. More broadly, there are 11 cities with a population greater than 2.5 million in India, of which six (the four metros above plus Bangalore and Hyderabad) have a population exceeding 5 million. Since economic costs of air pollution are a function of the number of people exposed and the ambient concentration levels to which they are exposed, large polluted cities should be given high priority.

1.35 The intervention of the Supreme Court in addressing air quality in Delhi has received worldwide attention. The Supreme Court ordered relocation of polluting industries to outside the city and a series of fuel, lubricant, and vehicle technology measures targeting vehicular emissions, including conversion of the entire city bus fleet to run on CNG by the end of March 2001. While there has been a tendency to focus on mandatory conversion from diesel to CNG, it is important to bear in mind that a number of parallel steps have been taken in the past several years, resulting in air that is visibly cleaner. Among other steps directed at vehicular pollution control are banning the sale and purchase of loose lubricant for use in two-stroke engine vehicles and requiring that the lubricant be pre-mixed with gasoline to ensure correct quantity, progressively lowering sulfur and benzene in gasoline and sulfur in diesel, eliminating lead in gasoline in 1998, and mandating Bharat Stage II emission standards (equivalent to Euro II, see annex 2 for Euro I and Euro II) in 2000 for passenger vehicles and in 2001 for heavier vehicles.

1.36 At the national level, one notable recent development is the auto fuel policy issued in August 2002. Aimed at formulating a comprehensive and integrated approach, this policy was developed by an expert committee constituted by the government in September 2001. The committee included representatives of various ministries including environment, transport, industry, agriculture, petroleum and natural gas, non-conventional energy, and consumer affairs; research institutions; the oil industry; and the auto industry. The committee reviewed air quality data and trends, vehicle population growth and characteristics, supply and demand for auto fuels, options for gasoline and diesel reformulation and their associated costs, alternative fuels, vehicle technologies, emission standards, fuel quality specifications, control of emissions from in-use vehicles, public transport systems, economic instruments for mitigating exhaust emissions, and institutional issues. The final report proposed a road map to 2010, including specific standards for emissions and fuel quality, a recommendation for a single body entrusted with the task of enforcing these standards, and rationalization of fuel taxes.

1.37 India has the longest history of urban air quality management in South Asia. The presence of significant manufacturing capacity, including a number of large and sophisticated refineries and vehicle manufacturers, enables a greater variety of policy options to be considered in India than in other countries that rely to a significant extent on imports, and there is technical expertise to guide that decisionmaking. The size and diversity of the country has also led to different cities and states pursuing their own policies. This can be cost-effective, but sometimes results in lack of harmonization. The developments in Delhi are especially carefully watched, with a number of cities adopting master plans similar to those in Delhi.

Nepal

1.38 Air quality management in Nepal has concentrated on the Kathmandu valley. Because of its topography and wind conditions, Kathmandu, as many other valleys, is subject to poor dispersion, especially in winter, which is also a dry season. This leads to thermal inversion and serious particulate air pollution in winter. A study conducted by Nepal Environmental and Scientific Services in 1999 and 2000 reports 24-hour average PM₁₀ concentrations ranging

from 49 to 495 $\mu\text{g}/\text{m}^3$, with average values of 225, 135, and 126 $\mu\text{g}/\text{m}^3$ in the core, sub-core, and remote part of the valley, respectively (Shrestha and Raut 2002). In contrast, SO_2 , NO_x , and CO have been found to be well below international health-based guidelines. Particulate emission sources have historically included vehicles; brick and cement industries burning coal; small industries burning fuel oil, diesel, and agricultural waste; and refuse burning. PM_{10} and $\text{PM}_{2.5}$ are being monitored at six sites.

1.39 In response, the government has banned new three-wheelers except those running on electricity or liquefied petroleum gas (LPG). In 1999, the government banned the import of new two-stroke engine vehicles. In the latter half of 2000, the government announced a ban on all public vehicles older than 20 years, and all two-stroke three-wheelers in Kathmandu effective from November 2001, but these bans have not been implemented.

1.40 The government issued emission standards for in-use vehicles effective October 2000, limiting CO and hydrocarbon (HC) emissions for spark ignition vehicles and smoke emissions for diesel vehicles. Two sets of standards are set for each vehicle category depending on the vehicle model year. A vehicle emissions inspection program has been in place in Kathmandu since then. Analysis of the collected data shows that the failure rate increased from one fiscal year to the next for spark ignition vehicles, while it fluctuated from calendar 2000 to calendar 2002 with no decreasing or increasing trend in the case of diesel vehicles. As long as emission standards remain unchanged (as was the case here), an effective inspection and maintenance program should show a declining failure rate as vehicle owners and mechanics learn to maintain and repair vehicles properly.

1.41 The decision announced in December 2001 to close Himal Cement factory, the most polluting industry in the valley, was driven in part by environmental concerns. After the factory's closure, brick kilns, numbering some 125, have been the main industrial source of pollution. Ambient concentrations of PM_{10} during the brick-making season have been reported to exceed 500 $\mu\text{g}/\text{m}^3$ (Shrestha and Raut 2002).

1.42 From the institutional point of view, the situation in Kathmandu is comparable to that in Bangladesh. There is limited capacity to manage air pollution and outside support provided by the government of Denmark has been helpful in strengthening capacity and setting up instruments in place to carry out monitoring activities. The Danish program has focused on controlling emissions from in-use vehicles, air quality monitoring, and adoption of simple but cleaner technology or practice in industry, including good housekeeping.

Pakistan

1.43 Ambient air quality monitoring carried out recently by the Pakistan Environmental Protection Agency, with support from the Japan International Cooperation Agency (JICA), in Islamabad, Lahore, and Rawalpindi showed alarmingly elevated levels of particulate matter, but SO_2 , NO_x , and CO levels below the WHO health-based guidelines. Declining rainfall in recent years has exacerbated particulate air pollution. Sources of particulate

emissions include vehicles, cement factories, brick kilns, fertilizer plants, and stone crushers (A.S. Khan undated).

1.44 Pakistan has natural gas reserves equivalent to about 25 years of production at the current production rates. The government has been actively promoting the use of natural gas. An important program is one under the leadership of the Hydrocarbon Development Institute of Pakistan (HDIP) to promote the use of CNG as a clean transportation fuel. The government has provided a number of incentives to facilitate conversion to CNG, including priority given to CNG filling stations for natural gas connection and exemption of import duties and sales tax on the imports of equipment, CNG conversion kits, and CNG cylinders. By 2003, there were 450 filling stations and more than 400,000 vehicles running on CNG (N.S. Khan 2003), making the CNG vehicle population in Pakistan the third highest in the world.

1.45 Fuel cost savings are the main driver for fuel substitution. Because gasoline is taxed much more than diesel, resulting in a much higher retail price for gasoline than diesel, CNG has displaced gasoline rather than diesel. Until 2002 when leaded gasoline was widely used, substituting gasoline with CNG had one significant environmental benefit: stopping lead emissions. With respect to PM, while CNG leads to lower emissions compared to old carburetor-technology gasoline vehicles not equipped with catalytic converters, significant emission benefits are achieved when CNG replaces conventional diesel. As in nearly all other countries with large CNG vehicle populations, most prominently Argentina, substitution of diesel with CNG has not occurred to any sizeable extent in Pakistan because the tax on diesel, and hence the end-user price of diesel, is too low to make switching from diesel to CNG economical.

1.46 An important outcome of the government's policy on natural gas is the substitution of fuel oil by gas. Pakistan imported 4.6 million and 4.4 million metric tons of fuel oil, mainly for power generation, in fiscal 2002 and fiscal 2003, respectively. The sulfur content of the imported fuel oil was high, about 3.5 percent, raising concerns about particulate and SO₂ emissions. As a result of much greater production and use of natural gas, fuel oil imports ceased in August 2003, with the differential volume being displaced entirely by natural gas. While the primary driver for this move was foreign exchange savings, elimination of fuel oil imports has considerable collateral environmental benefits.

1.47 Pakistan is in the very early stages of pilot testing an emissions inspection system for in-use vehicles. As part of the UNDP/GEF-funded Fuel Efficiency in Road Transport Sector Project, 30 tune-up demonstration and training centers have been set up, and a revolving loan has been provided to encourage purchase of equipment and installation of additional tune-up stations in the private sector. One lesson learned relates to the complicated system of financial recoveries required to deal with the repossession of equipment from owners who default on payments, a problem that was not envisaged in the design of the project (Pinto 2002).

1.48 In 2000, Pakistan EPA started a system of self-monitoring and reporting by industry (SMART). SMART is a result of a consultative process among the government, industry, and other stakeholders spanning several years. As the name implies, the system is

designed to let the industry regulate itself by systematically monitoring and reporting emission and discharge levels at specified time intervals, thereby reducing the need for EPA inspectors to monitor individual industrial units. Although SMART is voluntary at this stage, it has the potential to become an effective instrument.

1.49 Air quality monitoring is limited in Pakistan, and, as with Bangladesh and Nepal, virtually all major initiatives on air quality management have depended on financial support from donors, thereby raising questions about sustainability. Two key questions are priority and budget allocation: to what extent urban air pollution is a policy priority and, should priority ranking indicate a need for greater budgetary allocation, whether the government is willing to set aside a greater share of the budget in the long run for air quality management.

Sri Lanka

1.50 Sri Lanka is the least polluted among the five countries discussed in this section. Air quality monitoring in Colombo shows moderately elevated levels of PM_{2.5} and PM₁₀ at Fort Station, but this is not surprising given that this monitoring site is an urban hot spot. Colombo is a coastal city, and as with Mumbai, ambient pollutants are diluted with cleaner air from the ocean.

1.51 In 1993, the cabinet of ministers approved the Clean Air 2000 Action Plan. The objective of Clean Air 2000 was to reduce, from estimated 1990 ambient levels by the year 2000, PM and CO by 40 percent, NO_x and lead by 30 percent, SO_x by 75 percent, and hydrocarbons by 20 percent. To this end, seven areas of intervention involving 49 specific actions were recommended. A Clean Air 2000 Action Plan Implementation Committee was set up, and the Central Environment Authority, the legal body empowered with the enforcement of rules and regulations to mitigate air pollution under the National Environmental Act, has been acting as the secretariat for this committee. While several recommended actions have been completed, Clean Air 2000 proved to be too ambitious and its implementation encountered numerous problems, ranging from lack of funds to enforcement problems. The absence of a clear policy on air quality management hampered its progress further. These lessons have been incorporated in the development of the Clean Air 2005 Action Plan.

1.52 Recently, Air Resource Management Center (AirMac), a body under the Ministry of Environment and Natural Resources, was established for more effective coordination among various agencies and stakeholders, better integration of abatement programs, public awareness-raising and education, policy formulation and review, data collection, capacity building, and research. AirMac commissioned three studies: a refinery analysis of gasoline and diesel reformulation, an economic analysis of fuel and vehicle taxation measures to control emissions, and a technical assessment of in-use vehicle emissions control through emissions inspection and appropriate emission standards. The government is currently in the process of launching a nationwide vehicle emissions inspection system.

1.53 AirMac's involvement facilitated inter-agency coordination, and wide consultation of a range of stakeholders—environment and transport ministries and their

agencies, finance ministry, the Colombo Municipal Council, traffic police, the Ceylon Petroleum Corporation, research institutes, and universities—has taken place. Following consultation, the Ceylon Petroleum Corporation stopped the use of lead in gasoline in 2002 eight years ahead of schedule, and the government gazetted revised fuel standards and vehicle exhaust emission standards for imported vehicles in June 2003. Another significant move in fuel quality improvement was lowering the limit on sulfur in diesel from 1 percent to 0.5 percent in 2003, and the limit is scheduled to be lowered further to 0.3 percent in 2005.

Common regional concerns

1.54 The first step in urban air quality management is collecting ambient air quality data. Data quality control is a problem at most monitoring sites. Discussions with practitioners in air quality monitoring suggest that quality assurance and quality control need considerable strengthening. The areas that call for attention include not only the accuracy and reproducibility of the measurements but also data analysis; timely publication of, and access to, raw data; re-examination of site selection in light of changes in land use patterns; the actual (as opposed to stipulated) monitoring frequency; and the positioning of the instruments at a given site. While automated instruments can give real-time data, their effective use is hampered by much higher costs of maintenance and operation. It is common not to calibrate instruments for a long time because of the expenses involved in proper instrument calibration, casting serious doubt on the accuracy of the measurements. Equally common is to cannibalize one instrument in order to repair another instrument, so that the number of operating instruments falls with increasing time. Even with manual instruments, flow rate control, which is crucial for PM measurements, is often inadequate. Filter clogging adds to the problem.

1.55 One crucial question for formulating policy to combat urban air pollution is which sector activities are contributing significantly to airborne particulate matter. This information is not available in most cities in South Asia. The popular perception is that vehicle exhaust contributes significantly. As a result, much of the governments' efforts have historically focused on controlling emissions from vehicles. This has ranged from tightening fuel quality and emission standards and promoting CNG to establishing a vehicle inspection system. All the five countries discussed are either in the process of establishing, or have already established and been operating, an emissions inspection system. Yet in India, which has the longest history of such an inspection system, it is widely acknowledged to be making little contribution to air quality improvement. The gaps and needs in these two areas—how to overcome the shortcomings of the current vehicle emissions inspection systems and gaining a better understanding particulate source apportionment—were dealt with at some length in this study.

Reducing Emissions from Gross Polluters

1.56 Vehicle inspection programs can help improve vehicle maintenance behavior and enforce emission standards for in-use vehicles. The governments of Bangladesh and Sri Lanka are in the process of setting up an emissions inspection system, India has been running inspection centers since 1991, and Nepal in the Kathmandu valley for the last few years. Yet

where such a system is in place, such as India, it is widely acknowledged to be ineffectual on account of faulty measurements and fraud, resulting in false passes and false failures.

1.57 The primary objective of inspection systems is to identify gross polluters and ensure that they are repaired or retired. Test protocols should be designed to minimize false passes or false failures, make it difficult to cheat or avoid inspection, minimize measurement differences among test centers, and maximize reproducibility and accuracy. There are a number of lessons from international experience, many of them directly applicable to South Asia. At the heart of an emissions inspection program is the question of which test protocols and administrative controls would be least likely to be bypassed or defeated and assure reasonable chances of identifying gross polluters. The test center ownership structure, vehicle testing methodology, and equipment and computer specifications are all important, and discussed in detail in this report. Equally important, the government must be willing and able to provide the resources for auditing and supervising the program (even if the supervision is outsourced) that are needed to guarantee its objectivity and transparency

Approaches to Source Apportionment

1.58 Which sources are contributing to elevated ambient particulate concentrations is an important but one of the most difficult questions to answer. In some cities, such as Dhaka, where only a handful of emission and fugitive sources are apparent, it is probably safe to assign one or two sources (mobile sources in the case of Dhaka) as dominant sources of air pollution. In other cities, the situation is more complex, and very few source apportionment studies are available. This makes cost-effective policy formulation difficult. Ambient pollution can be attributed to specific sources in two ways: (1) dispersion modeling, which starts with emission sources; and (2) receptor modeling, which starts with where air pollution is measured.

1.59 *Dispersion modeling* starts with the estimated emissions from different sources (called an “emissions inventory”) and, on the basis of a model of how those emissions are dispersed, calculates the expected ambient concentrations at particular “receptor” sites where ambient concentrations are measured. Ambient concentrations can be used to calibrate the dispersion models for running future scenarios. Each pollutant considered a significant hazard should be modeled in this way.

1.60 Often, emissions inventories are constructed without carrying out dispersion modeling. Emissions inventories are useful in and of themselves, but their limitations should be recognized. What ultimately should drive policy is not which source is emitting more, but which source is likely to lead to greater exposure to health-damaging pollutants and at what cost that source of emissions can be mitigated. A coal-fired power plant with a tall stack that is located at the edge of a city may be the largest emitter of particles in terms of absolute tonnage, but may be contributing less—from the point of view of overall human exposure—than all the households burning biomass. That is, the height at which pollutants are emitted, and where they are emitted, matter a great deal. An emissions inventory, however accurate, should not be the sole basis of policy formulation.

1.61 A mistake that has often been made in South Asia as elsewhere is to tabulate primary emissions in tons of CO, NO_x, SO_x, and PM from different sources, add them up, and then examine percentage contributions of different sources to the total. This almost inevitably points to CO as constituting the largest fraction of the total weight of primary emissions, and transport (primarily gasoline vehicles) as the greatest contributor to CO and hence to the summed pollutants. This approach has often resulted in statements such as “Transport is responsible for 70 percent of air pollution.” But the toxicity of CO is much lower on a weight basis than the toxicities of other pollutants, so that these results cannot be directly correlated with health effects. Different pollutants with varying toxicities should not be added together on a weight basis.

1.62 Another point to bear in mind is that data availability can, but should not, bias source contributions. Typically more data on emission factors as well as the number of operating units tend to be available for vehicles than for such informal sources as refuse burning, diesel power generation by small shops, and combustion of solid fuels by cottage industries and households. As a result, mobile sources are often ranked higher in importance than they would be if the necessary data were fully available.

1.63 *Receptor modeling* uses detailed chemical analysis of particles in the atmosphere to match their characteristics at given receptor (that is, where the pollutants are sampled) and source (where primary pollutants are emitted) locations (“fingerprinting”). A chemical mass balance receptor model expresses each receptor concentration of a chemical species as a linear sum of products of source profiles and source contributions. Unfortunately, it is rare for one compound or element to be exclusive to a single source and hence to act as an unambiguous tracer for that source. More commonly, similar sources may have dissimilar profiles, while different source categories may have similar profiles. Detailed speciation of particles conducted in properly executed studies is time-consuming and resource-intensive. Nevertheless, even rudimentary carbon and other chemical analyses of particles can give a broadbrush picture of contributions from different sources.

1.64 It is worth remembering that source contributions are a strong function of the size range of particles being considered. Geological matter is a major component if particles of all sizes are considered, but the contribution of transport rises sharply if ultrafine particles are targeted. A study in the United Kingdom (Airborne Particle Group 1999) reported that road traffic nationally contributed 25 percent of primary PM₁₀ emissions, but the relative importance of road traffic emissions increased with decreasing particle size, amounting to 31 percent if PM_{2.5} was considered, and 60 percent for PM_{0.1}. Given the current scientific understanding of health impacts of particulate matter, it would make more sense to concentrate policy formulation on sources known to be significant contributors to very small particles than on sources that contribute generally to particles of all sizes, and in this regard the attention given to vehicle exhaust in South Asia seems sensible provided that policy interventions do not exclude other sources of pollution.

Study Description

1.65 As the foregoing paragraphs show, there are numerous ongoing efforts to tackle urban air pollution in South Asia, especially in large cities. This ESMAP study was undertaken to support the region-wide process of developing and adopting cost-effective and realistic policies and efficient enforcement mechanisms to reverse the deteriorating trend in urban air quality in South Asia. The study concerned mainly the reduction of ambient concentrations of inhalable and fine particles, the most serious threat from urban air pollution to public health in the region. The activities in the study included:

- ?? Preparing concise briefing notes for use by policymakers, non-governmental organizations (NGOs), industry, academics, and researchers, highlighting main policy considerations and the issues that would need to be addressed to formulate a policy approach. These notes were targeted to address current debates in the region and highlight lessons from international experience: various aspects of transport-related air pollution, economic valuation of air pollution, urban planning, science of particulate air pollution, and current state of air pollution analysis.
- ?? Commissioning reviews and studies to evaluate the current state of knowledge and practice, and to make recommendations for improvement. Two topics selected were PM_{2.5} source apportionment and steps for making a vehicle emissions inspection system more effective.

The publications and other activities are detailed in annex 3.

1.66 The study draws upon past and ongoing work in Bangladesh, India, Nepal, Pakistan, and Sri Lanka. In particular, it has complemented and contributed to other World Bank-supported programs: the Bangladesh Air Quality Management Learning and Innovation Loan; the India Environmental Management Capacity Building Project; the Mumbai Urban Transport Project; and the Institutional and Policy Framework for Urban Air and Fuel Quality Improvement program supported by the Institutional Development Fund in Sri Lanka.

1.67 The intention of the study was not to draw up a road map that can be systematically followed by cities in South Asia for air quality improvement. Rather, one important objective was to fill in the existing gaps to contribute to the ongoing programs in urban air quality management in the region. Another objective was to distill lessons from international experience and consider how they might be applied in South Asia. Yet another objective was to bring to the attention of those engaged in air quality management a wide range of activities seemingly outside of environment that directly or indirectly affect urban air quality, broad policy issues and regulations in other sectors that are driven by considerations other than environment that nevertheless have an important impact on urban air, and how inter-sectoral coordination can be effectively leveraged to reduce air pollution. A number of specific issues in this regard were described and disseminated in briefing notes.

1.68 Chapter 2 of this report discusses why many vehicle emissions inspection systems have failed in the past, what are some of the key contributing factors to that failure, and how they can be redesigned to make inspection more effective. Chapter 3 describes other issues that need to be considered in controlling air pollution from road transport.

1.69 Chapter 4 summarizes the findings of two studies, both of which focused on understanding sources of particulate air pollution. The first was a review of past and ongoing air pollution studies in India conducted by The Energy and Resources Institute (TERI). The second was a source apportionment study of PM_{2.5} samples collected in Delhi, Kolkata, and Mumbai, jointly carried out by the Georgia Institute of Technology, the National Physical Laboratory (NPL) in Delhi, the Indian Institute of Technology in Mumbai, and the National Environmental Engineering Research Institute (NEERI) in Kolkata and Mumbai. It was the first study to make use of speciated hydrocarbons as tracers in identifying sources for PM_{2.5} in South Asia. Chapter 5 outlines the policy implications of the findings of the studies presented in this report.

2

Controlling Emissions from In-Use Vehicles

2.1 Vehicle fleets in South Asia usually consist predominantly of older, earlier-generation vehicles with correspondingly high emissions. Lack of regular preventive maintenance and proper tuning increases emission levels further. As will be shown in chapter 4, mobile sources are important contributors to elevated concentrations of $PM_{2.5}$. With a growing economy in South Asia, motorization will inevitably accompany economic gains. Therefore, addressing mobile sources of air pollution is expected to be a priority in the large cities of South Asia in the coming years.

Maintaining Technology

2.2 Emission standards from fixed and mobile sources are being increasingly tightened worldwide, and South Asia is no exception. Significant investments have been made in South Asia to achieve tighter emission standards. However, tightening emission standards and investing in the necessary hardware is only half the story. The challenge is to maintain the technology so that the more stringent emission standards continue to be met.

2.3 This study examined how vehicles are maintained in Delhi, Mumbai, and Pune, India. The findings are applicable to other cities and countries in the region. The market for truck engine and transmission parts in India reported in the study (Rogers 2002) provides an informative illustration of how vehicles are serviced in South Asia today.

2.4 The truck spare parts market in India is divided basically into four segments: genuine original equipment (OE) parts, grade 2 parts, grade 3 parts, and spurious parts, with quality and price differences between each category. For engine and transmission parts, the price structure is given in Table 2.1. Most vehicle owners try, within their economic means, to use “closer to genuine” parts for critical assemblies such as engines and transmissions and lower-cost components for “non-critical” areas such as brakes and electrics.

Table 2.1 Different Quality and Price Categories for Truck Engine and Transmission Parts

<i>Category</i>	<i>Price scale</i>	<i>Quality</i>
Genuine (OE)	100	Original equipment
Grade 2	70	Parts from the OE suppliers and parallel market through their own distribution channels. Includes parts surplus to OE requirements and parts with minor quality problems
Grade 3	50	Parts mainly from the OE suppliers that were rejected by the OE for unacceptable quality and lower quality parallel parts
Spurious	<40	Will-fit parts from non-OE approved suppliers. Usually of dubious quality

2.5 For engine and transmission components, the main volume sales are grade 2 parts. However, for other components the breakdown is different. In electrical components, the price differential is far greater because their standardized design makes this market more attractive to the spurious supplier. One alternator regulator, for example, has an OE price of 3,500 Indian rupees (INR) while an equivalent “will-fit” component can be obtained from spurious suppliers at INR 150. Most trucks still use hydraulic brakes, and parts used come mainly from spurious suppliers.

2.6 The engine components that affect emissions the most are probably fuel injection pumps, fuel injectors, and turbochargers. Because of the high cost of these components, only 20–25 percent of spare fuel injection pumps are through genuine channels. Approximately 70 percent of this market is supplied from alternative sources, many of which probably buy their parts from the original equipment manufacturer. The remaining 5–10 percent are rebuilt and reconditioned. For fuel injectors, the market is divided between genuine and rebuilt assemblies.

2.7 Turbochargers are another high-cost assembly costing approximately INR 25,000 new. As a result, about one-half are rebuilt at a cost of INR 5,000. In Europe and the United States this would entail changing a core assembly that includes the bearing housing and bearings together with the complete turbine, shaft, and compressor wheel-assembly because of the critical balance of these components. The practice in India is to change only the bearing and the compressor wheel.

2.8 Many component suppliers are Indian companies historically operating in a closed economy with a reputation for quality of somewhat less than international standards. This, however, is slowly changing since original equipment manufacturers are now able to source components from foreign suppliers. This has yet to influence the spares market.

2.9 Poorer truck owners (and fleets) tend to own older vehicles and use cheaper spare parts. Thus, as the trucks get older, their emissions increase even more by the use of lower-cost and quality components. The better-off fleets with newer vehicles that use original

parts in their repairs report that they have to send a manager or the owner to stand over the mechanic while the mechanic is rebuilding the engine or transmission assembly to ensure that components are not switched for lower-quality, lower-priced ones.

2.10 Much of the state-of-the-art diesel equipment requires sophisticated maintenance for which it takes years to develop the necessary skills. Mirroring the preference shown by vehicle owners for two-stroke engine two- and three-wheelers rather than their four-stroke equivalents, mechanically governed diesel vehicles are much more suitable to self-diagnosis and self-repair than modern engines with electronic controls. The latter are robust, but require a different type of mechanical skills, and once a fault is identified, all too often the mechanic or the vehicle owner cannot repair the part but has to buy a (rather expensive) replacement part. All this adds to maintenance costs compared to where most cities in South Asia are today.

2.11 In this regard, it is informative to bear in mind that Europe, Japan, and North America have undergone incremental tightening of standards. This has given fleet owners and mechanics in these regions many years to move from working with wrenches to computer-code diagnosis of vehicles. It is worth noting that when natural gas buses were introduced in the United States, despite the sophisticated level of maintenance skills available, lack of familiarity of mechanics with natural gas bus maintenance was a major issue. In many cities in South Asia there are very few established companies that have reasonably equipped workshops and trained mechanics, and the vast majority of vehicles are serviced by roadside establishments with few tools, virtually no diagnostic equipment, little training, and essentially no capital.

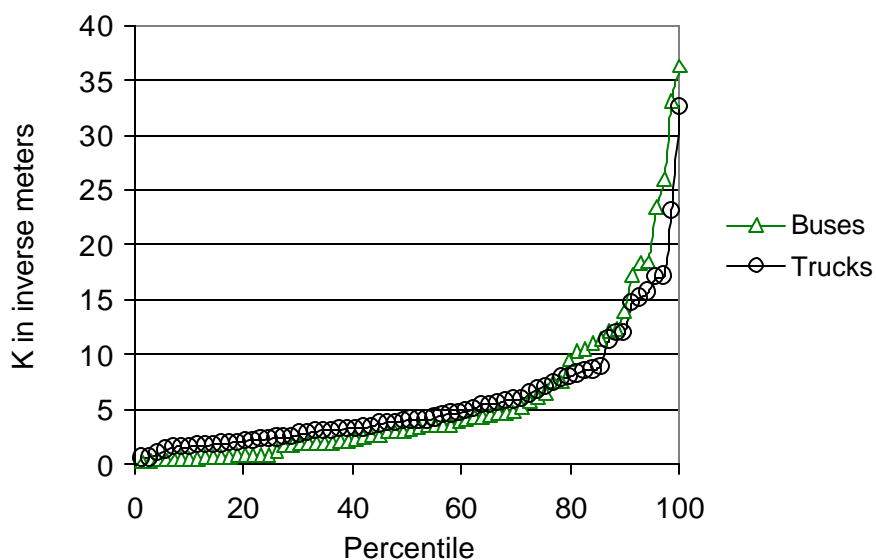
2.12 An important step in creating a wider market demand for service and repair facilities with good diagnostic equipment and qualified technicians is enforcing emission standards for in-use vehicles more rigorously and requiring that vehicles that fail be repaired and retested. This chapter addresses key components of an effective vehicle inspection and maintenance (I/M) program.

Emissions from In-Use Vehicles

2.13 Worldwide, where emissions from in-use vehicles have been measured and the emissions profile examined, a small fraction of the fleet population has typically been found to contribute disproportionately to the total emissions from vehicles. For example, an extensive study conducted jointly by the auto and oil industry in the United States between 1989 and 1995 found that poorly maintained vehicles, representing 20 percent of all vehicles on the road, contributed about 80 percent of total vehicular emissions (*Auto/Oil Air Quality Improvement Research Program 1997*). A limited study conducted in Colombo, Sri Lanka showed a similar trend (EF&EE 2003). Figure 2.1 presents data from the study conducted in Colombo showing smoke emissions from buses and trucks measured in a test procedure called snap acceleration.

About 20 percent of vehicles tested recorded an absorption coefficient (smoke density), K ,¹ higher than 10 inverse meters (m^{-1}). The path length (the distance traveled in an optical system by light) in this study was 12.7 centimeters (5 inches). A K value of $10 m^{-1}$ would therefore be equivalent to 72 percent opacity, high by any measure. A 50 percent opacity would correspond to $5.5 m^{-1}$, and a 35 percent opacity to $3.4 m^{-1}$.

Figure 2.1 Cumulative Distribution of Snap Acceleration Smoke Emissions from Buses and Trucks in Colombo, Sri Lanka



2.14 Repairing gross polluters to lower vehicular emissions is potentially one of the most effective means of addressing transport-related air pollution. Establishing fuel and vehicle-emission standards is an important first step, but such standards need to be effectively enforced. If in-use vehicles are poorly maintained and many are high emitters, then the environmental benefits will be much smaller. For controlling emissions from in-use vehicles by means of proper vehicle maintenance, governments rely on I/M programs. The underlying principle of I/M programs is to identify vehicles that are not in compliance with emission standards and get them repaired or replaced.

2.15 Poor maintenance of gasoline-fueled vehicles can increase CO emissions by two orders of magnitude. Incorrect injection timing in diesel engines can increase NO_x emissions as much as three-fold. A plugged air filter can increase particulate and CO emissions in both gasoline and diesel engines. Turbochargers and injectors in diesel trucks are often not replaced when they should be because these replacements are costly for the owner, but emissions increase markedly if replacements are not carried out. Old, poorly maintained vehicles may have leakage past rings and crankcase vents open to the atmosphere, increasing crankcase emissions.

¹ The relationship between percent opacity and K is given by the following equation: percent opacity = $100 \times [1 - \exp(-K \times \text{path length})]$.

These considerations inevitably put the main emphasis on improved behavior in the maintenance and operation of in-service vehicles. In this regard, while very strict emission standards for in-use vehicles are theoretically attractive, stringent standards that are not enforced are likely to discredit the regulatory framework while achieving little air quality improvement. It is better to have realistic standards that are vigorously enforced than very stringent standards that cannot be effectively enforced.

Criteria for Effective I/M

2.16 There are several essential requirements for successful implementation of vehicle I/M.

- ?? *Targeted vehicles must be made to show up at test centers.* Gross polluters that would be costly (in terms of repair costs or vehicle downtime or both) to repair have a large incentive not to show up for testing. But if gross polluters do not report to inspection centers, then the authorities do not know which vehicles are high emitters and cannot require that they be repaired. Therefore, the program needs to be mandatory for the vehicle categories selected and well enforced. An up-to-date and accurate vehicle registration record is a first prerequisite. A requirement to display a visible sticker certifying that the vehicle has been inspected and passed, under penalty of a fine large enough to deter evasion, is needed for tackling this problem.
- ?? *Emission levels need to be accurately measured, and vehicle testing procedures should be devised to discourage temporary, “pass-the-test” adjustment of engine settings.* If gross polluters pass the test because their measured emission levels are low, or if clean vehicles fail because they are falsely identified as gross polluters, then the credibility of the system is called into question, public acceptance falls, and most importantly, the system will do little to improve air quality. Avoiding this situation requires choosing a test protocol that is difficult to cheat on or to bypass and implementing rigorous audit and supervision schemes from the very beginning. It also requires well-trained technical staff who are given equipment in good condition. Lack of proper equipment maintenance, inadequate calibration, and unsuitable test procedures are three common problems leading to inaccurate or no measurements. Tampering of the test results by the I/M staff for financial gain is another serious problem. Independent auditing of adherence to the established testing procedures is important.
- ?? *Identified gross polluters need to be repaired or scrapped.* Even if gross polluters are correctly identified, if there is no follow-up, the system will not contribute to air quality improvement. This requires adequate infrastructure for vehicle servicing with good diagnostic equipment and qualified technicians. If adequately equipped and staffed service and repair facilities that provide quality

service are not readily available, a rigorous inspection program may well prove to be little more than a mechanism for collecting fines. In the absence of effective enforcement of emission standards, the market for service and repair facilities is limited, focusing on a vehicle's drivability but not that it be repaired to be less polluting. Under these circumstances, as discussed above, much cheaper and inferior counterfeit spare parts are often widely used in vehicle repair. As the authorities start enforcing standards, given the right policy framework, the market will respond by expanding service and repair facilities.

The various steps needed to meet the above criteria are discussed in the sections below.

Merits of Selectivity

2.17 Selectively targeting vehicles—both in terms of vehicle categories as well as geographical areas in which they are registered or operate—for emission testing to make maximum use of limited resources is likely to lead to much higher chances of success than an all-inclusive program requiring every vehicle to be tested with the same regularity. Proper implementation of rigorous quality control carries a cost. For emissions inspection, it is almost certain that the necessary control measures will not be adopted if every vehicle is required to be inspected. The government therefore effectively faces the choice of (1) mounting a universal program at the expense of necessary administrative control, thereby compromising the program's effectiveness, *or* (2) selecting that fraction of the total vehicle population considered to be major contributors to transport-related air pollution, and testing them properly.

2.18 Taking India as an example, there are an estimated 4,000 centers for testing private vehicles operating under "Pollution Under Control" (PUC), a system of vehicle exhaust emissions testing, widely acknowledged to be ineffectual. Attempting to upgrade them all at once is a daunting task which is unlikely to be practical or successful. In taking steps to revamp PUC, it is important to bear in mind that the objective of I/M is to improve air quality. Where air pollution is not serious, there is little point in devoting significant resources to carry out rigorous testing. It is informative that nationwide emissions inspection requiring every vehicle to be tested regularly is not mandated even in much more motorized countries. For example, in the United States, inspection is mandatory only in cities with serious air pollution and a population exceeding a certain size. Similarly, concentrating efforts on large metropolitan areas in South Asia would be a logical approach.

2.19 Because fine particulate matter is by far the most damaging air pollutant in South Asian cities at present, it would make sense to focus the emissions inspection program on gross contributors to particulate air pollution, namely diesel and two-stroke engine gasoline vehicles. Greater benefits are likely to be achieved by identifying and repairing gross particulate emitters than by spreading resources thin to test relatively clean (for example, new four-stroke engine gasoline) vehicles as rigorously and frequently as potential gross polluters.

2.20 Because resources are limited, there are tradeoffs to be made between the number of vehicles that can be tested, the frequency of testing, and the rigor of the test

procedure. As a near-term objective, it may make sense to target a relatively small number of vehicles in large metropolitan areas (for example, both the U.S. Auto/Oil Program and the study in Colombo, Sri Lanka, cited above found that about 20 percent of vehicles are gross polluters) using test procedures that are more expensive but are also much more effective in identifying gross polluters than the commonly used static procedures.

Test Protocols

2.21 Much has been learned in other countries about which test protocols are suitable for I/M. Test protocols that allow large variations and differences across different test centers are not only unhelpful for the purpose of identifying high emitters, but also decrease the credibility of the I/M system and reduce public acceptance. The elimination of measurement differences must be a high priority. This has to be taken into account when defining the equipment and test protocols to be used in the programs along with calibration audits and other activities.

Dilution of exhaust gas

2.22 In emission tests, concentrations of various pollutants in the exhaust gas are typically measured. These concentrations can be easily lowered by entraining clean air. Therefore, monitoring the dilution of the exhaust gas must be one of the integral elements of any test protocol. Otherwise, it would be too easy to pass by partially withdrawing the sample probe from the exhaust pipe to allow sample dilution to reduce the gas concentrations. Controlling for this in turn requires oxygen (O₂) and carbon dioxide (CO₂) measurements in addition to the pollutants of concern. The establishment of dilution threshold values, outside of which the test is automatically aborted, is also required. Unfortunately, measuring and recording O₂ and CO₂ is not required in India and Nepal and hence is not carried out.

Preventing “late-and-lean” tuning in gasoline engines

2.23 It is easy to reduce the carbon monoxide (CO) and hydrocarbon (HC) emissions from an older gasoline vehicle by delaying the ignition timing and increasing the air-to-fuel ratio. This “late-and-lean” approach reduces CO and HC, but it also reduces engine power and increases NO_x. Without testing vehicles under load or measuring nitric oxide (NO), it is not possible to detect if the engine has been tuned “late and lean” just to pass the test. Vehicles that have been tuned in this way to pass the test are usually retuned immediately afterward to regain this lost power. This practice allows the “clean-for-a-day” brigade to tune the engine temporarily just to pass without fundamentally lowering the vehicle’s emission levels, thereby having no positive impact on air quality. Testing under load and measuring NO requires a dynamometer. In South Asia, there is no regularly conducted dynamometer-based testing, leaving the door open for the loophole of tuning “late and lean.”

Identifying high particulate emitters

2.24 Ideally, diesel vehicles that emit disproportionately high levels of fine particulate matter should be identified and required to be repaired. Identifying those diesel vehicles that are high particulate emitters, however, is problematic, because the test procedures currently used in the emissions inspection test centers worldwide do not readily identify mass particulate emissions.

Snap acceleration smoke tests

2.25 The most common procedure for testing emissions from in-use diesel vehicles is the “snap” (also called “free”) acceleration test defined according to the Society of Automotive Engineers’ (SAE) J1667 (in North America) or ECE R24 (in Europe) standards. The test specifies that, with the transmission in neutral, the throttle pedal should be pushed rapidly but not abruptly to its full-throttle position, accelerating the engine from low idle to its maximum governed speed. This is repeated several times and the average of the maximum exhaust gas opacity in each test is computed.

2.26 Reproducibility is poor when this test procedure is utilized by a large number of testers using different equipment, especially in an environment where financial incentives are offered to testers to pass smoking vehicles. In July 2002 in Mexico City, a test was mounted in which simultaneous free-acceleration tests were conducted using the ECE R24 procedure on four makes of opacity meter with different operators. All were taking simultaneous samples from a Mercedes Benz L1217. On any particular run, the difference between the lowest and highest reading was as much as 700 percent. Even the two closest readings differed by 30 percent. With this level of discrepancy, the results obtained in an emission test can be said to be effectively arbitrary.

2.27 Slight differences in the time taken to accelerate the engine from low idle to maximum governed speed can lead to very different exhaust opacity readings. Therefore, the rate of acceleration for each engine type needs to be more precisely defined. Each instantaneous reading should be corrected for gas temperature, pressure, humidity, and altitude, as required in the SAE J1667 standard. Any dilution of the exhaust gases with clean air will lower smoke readings. Furthermore, it is difficult to get readings on engine speed, revolutions per minute (rpm), from diesel engines, particularly the older ones, yet accurate rpm readings are essential to add to the controls. Finally, the ECE R24 procedure, but not SAE J1667, checks if the engine cylinders’ combustion chambers have reached their normal operating conditions by detecting decreasing opacity readings in consecutive tests and reports results only after stable conditions have been met.

2.28 Carefully defined test protocols need to be followed strictly to have acceptable reproducibility across different operators and instruments at different test centers. Otherwise, a conscientious vehicle fleet owner regularly checking emissions by conducting in-house smoke tests may find that properly maintained vehicles routinely fail in the mandatory emission tests. This and the resulting driver harassment were among the complaints voiced in the assessment of

the emissions inspection program in India (Rogers 2002). Further procedural improvements can be introduced to reduce the opposite kind of error, by which grossly emitting vehicles are allowed to pass the test.

Shortcomings of smoke tests

2.29 Even when properly administered, snap acceleration smoke tests, which are the tests used in South Asia, still have two distinct problems. One set of concerns can be addressed by using a more reproducible (and more expensive) form of opacity testing using a dynamometer, which can also simulate real-world driving conditions much better than snap acceleration. The second problem is much more difficult to address, as it underscores the fundamental shortcoming of measuring smoke.

2.30 The snap acceleration test is not representative of normal operating conditions. More specifically, it is easier to prepare a vehicle to pass a snap acceleration test than a test under load using a dynamometer, especially if a transient (as opposed to steady-state) loaded test is used. In Hong Kong, for example, the environment officials found that diesel vehicle owners temporarily adjusted the fuel injection pump, enabling high smokers to pass the snap acceleration smoke test. The officials closed this loophole by introducing the so-called lug-down dynamometer test (test conducted at full throttle, with the dynamometer load gradually increased to slow down the engine speed so that the engine is laboring, or “lugging”). Immediately after this change, the pass rate fell dramatically (Mok 2001).

2.31 Smoke measurements also depend heavily on the driving cycle for a given vehicle-fuel combination. One study (Vipac Engineers & Scientists Ltd. 2001) shows that smoke opacity measurements using different driving cycles on a loaded dynamometer were poorly correlated with each other for light-duty vehicles. The lowest correlation coefficient was -0.16 , the highest 0.73 . The correlation coefficients for heavy-duty vehicles were higher, with the lowest coefficient being 0.20 and the highest 0.92 . This implies that the same vehicle may have quite low readings under one driving cycle and high ones on another.

2.32 A smoke test procedure, however well carried out, cannot be used for controlling anything other than visible smoke. An important question is then whether visible smoke can act as a proxy for particulate matter, the pollutant with demonstrated health effects.

Correlation between smoke opacity and mass particulate emissions

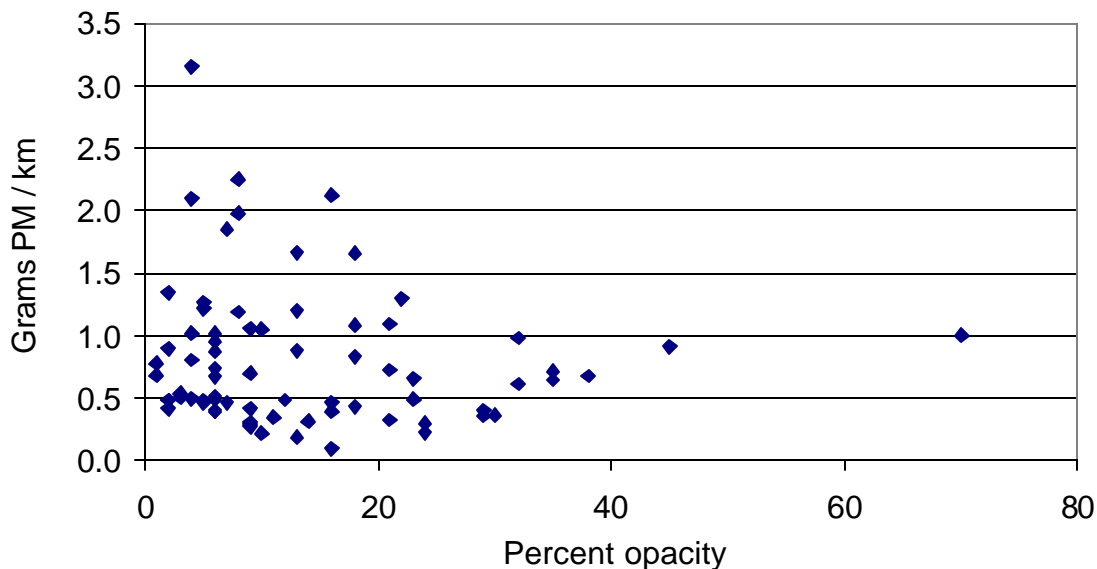
2.33 If a diesel vehicle testing program does not lead to the reduction of fine particulate emissions, then it has failed in its ultimate objective, namely, the reduction of pollutants that damage public health. The question immediately arises, therefore, as to how closely correlated “smoke” is with fine particulate matter.

2.34 To answer this and other related questions, the National Environment Protection Council (NEPC) of Australia commissioned eight projects to collect data on the diesel vehicle fleet and emission characteristics with the objective of developing cost-effective emission

management measures (see the series of reports available online at the website for the Environment Protection and Heritage Council).

2.35 Figure 2.2, taken from a project report (Anyon and others 2000) prepared for the Australian NEPC, indicates a very poor correlation between visible smoke measured using SAE J1667 snap acceleration and mass particulate emissions measured in a dynamometer test using a driving cycle for estimating “real-world” emissions from vehicles in urban areas, called the Composite Urban Emissions Drive Cycle (CUEDC). CUEDC consists of four segments: congested, minor roads, arterial roads, and highway driving. The figure illustrates that a number of high particulate emitters have quite low scores on smoke emissions registered during the free acceleration test, while some of the high “smokers” have relatively low particulate emissions compared to the true gross polluters. That is to say, snap acceleration smoke tests run the danger of classifying gross polluters as relatively clean and of classifying low polluters as high emitters.

Figure 2.2 Correlation Between Average Smoke Opacity in Snap Acceleration and Mass Particulate Emissions in CUEDC



2.36 The report also compares the results of the so-called 10-second smoke test? used in enforcing Australia’s national standard for smoke emissions? to smoke opacity and mass particulate emissions measured in transient dynamometer tests. In a test specifically conducted on an incline, 32 percent of those that were identified as smoky vehicles were also found to be high particulate emitters in the CUEDC, but 68 percent of smoky vehicles were found to be low particulate emitters. Overall, the on-road smoke checks classified a higher number of vehicles as high emitters than mass particulate measurements.

2.37 An unfortunate scenario, from the point of view of managing a vehicle I/M maintenance program, would be one in which vehicle repair lowers particulate emissions but

increases smoke. Such a case was indeed confirmed in the NEPC's diesel program whereby for two vehicle categories (1996–2000 diesel buses heavier than 5 tons and goods vehicles between 12 and 15 tons for the first, and 1996–2000 goods vehicles heavier than 25 tons for the second), particulate emissions decreased by 38 percent and 14 percent, respectively, on average after repair, but opacity readings increased by 29 percent and 10 percent, respectively (Parsons 2001).

2.38 In light of the above, snap acceleration smoke tests cannot be viewed as a means of identifying high particulate emitters, but rather as diagnostic tests to identify malfunctioning and defects among older engine vehicles with mechanically controlled fuel systems. For this category of vehicles, these smoke tests may be especially helpful for identifying tampering to increase power by overfueling. However, given the poor correlation between smoke and particulate emissions, and the poor correlation among the results of smoke tests on the same vehicle using different driving cycles, it would make sense to set relatively lenient standards to identify the most serious smoke emitters so as to minimize chances of false failures.

2.39 Snap acceleration smoke tests are not at all effective for modern, electronically controlled engines or turbocharged engines with boost control. For these vehicle categories, an alternative test procedure has to be identified. Studies to date suggest that at a minimum dynamometer-based loaded tests are needed, but they are expensive to set up for heavy-duty diesel vehicles. Dynamometers for testing light-duty vehicles in steady state or lug down tests are of the order of US\$15,000, for single drive axle heavy-duty vehicles US\$19,000, and for dual drive axle heavy-duty vehicles US\$42,000 in North America. The costs will be somewhat higher in South Asia. The series of studies in Australia recommend a short dynamometer-based test with transient acceleration segments using a laser light scattering photometer to measure mass particulate emissions. However, this test is still at the pilot stage with no wide application. Dynamometers required for transient tests are much more expensive.

2.40 Finally, it is important to view the limitations of smoke tests in broader perspective. Smoke is a public nuisance and harms public health. High smoke emissions, even if particulate emissions prove to be relatively low, suggest that there is something wrong with the vehicle settings or parts. The value of the smoke test as something that the public can understand should also not be underestimated. Given the technical problems associated with measuring particulate emissions in a garage setting, smoke tests will continue to play an important role in emission testing programs for the foreseeable future.

Remote sensing

2.41 Remote-sensing technology for vehicle emissions is a tool for testing a large number of vehicles rapidly under potentially realistic conditions. Remote sensing utilizes the principles of infrared spectroscopy to measure concentrations of HC, CO, CO₂, and NO_x in the exhaust plume of a vehicle while it is being driven on a street or highway. Recently the ability to measure smoke has been added. The speed and acceleration of the passing vehicle can be recorded simultaneously with an image of the license plate, making it possible to identify vehicles

and determine the conditions under which the measurement was taken. Existing systems can measure more than 4,000 cars per hour on a continuous basis, potentially providing a powerful tool for characterizing the emissions from the on-road vehicle fleet. Remote sensing has been used as a component of I/M programs in North America, either to identify high-emitting vehicles and call them back for repair or to identify clean vehicles and exempt them from regularly scheduled measurement at I/M stations.

2.42 Existing remote-sensing systems have a number of technical limitations:

- ?? Smoke has been added only recently. Until smoke was added, remote sensing could be used only for gasoline vehicles.
- ?? Measurements are limited to a single lane of traffic.
- ?? Heavy-duty vehicles may have exhaust locations that make them inaccessible to a remote-sensing device set up for passenger cars.

2.43 The reason for the single-lane limitation is that the beam traversing the road at exhaust height must see the emissions from one vehicle at a time for unique identification. This condition can be met by placing the remote-sensing device on highway entry and exit ramps. However, such ramps may not see all vehicles, or even a representative sample. Furthermore, like exhaust measurements at idle, emissions of vehicles on entry and exit ramps do not show the best correlation with emissions over a whole trip. To channel part of the traffic on heavily traveled roadways to a special measurement lane is not generally considered a viable option. Another mode of operating a remote-sensing device as an I/M tool would be to ask drivers to drive past an off-road station at a given speed instead of stopping to complete exhaust measurements at idle or on a chassis dynamometer.

2.44 At present, remote sensing can be considered proven technology for light-duty gasoline vehicles. For heavy-duty gasoline vehicles or diesel vehicles, promising advances have occurred in remote-sensing research and development, but their operational effectiveness needs to be demonstrated in field trials. Effective remote sensing must cause vehicles to behave in some reasonable representative manner, such as accelerating lightly or climbing a hill at some speed. Emissions vary substantially with load and transient behavior, so that a careful design is needed to limit variations in the results to an acceptable level.

Administrative Control

2.45 Even when the test centers are entirely in the hands of the private sector, I/M is not “cost-free” to the government: the local authorities must dedicate significant resources, personnel, and effort in supervising and controlling I/M programs. An important aspect is enabling automation to control and check test procedures, equipment calibration, data capture, and results as much as possible.

Centralized software development

2.46 Developing one software to be used by all inspection centers merits serious consideration. The computer software package should contemplate ensuring compliance with test protocols, proper operation and maintenance of equipment, data security, data capture, data analysis, and administrative functions.

Brief history of computer control in emission test development

2.47 In considering software development, it is instructive to review the history of vehicle inspection programs with particular reference to exhaust gas measuring instruments. The first specifications for vehicle exhaust gas analyzers were published around 1970. Since these initial attempts, many subsequent specifications have been published to resolve problems that were found. Each generation of analyzers has been more reliable, accurate, and complex. The first analyzers measured only HC and CO. Models one decade later were substantially more accurate because of improvements in the design of the infrared optical bench, rudimentary self-diagnostics, and the use of an on-board calibration gas cylinder, but they still exhibited many operational problems.

2.48 Diesel smoke meters were first introduced in the late 1960s to measure the engine's exhaust gas opacity both under load on a dynamometer and in the snap acceleration road-side test. The smoke meter specifications and snap acceleration test protocol were finalized in 1973 and have undergone little modification over the last 30 years. Because of its simplicity, the snap acceleration test was later adopted in many countries as the standard test for checking diesel smoke opacity.

2.49 Around 1985, the analyzers became computerized. This enabled the analyzer to make the pass/fail decision automatically and allowed a number of other features to detect analyzer tampering and to ensure that they were calibrated once every seven days or otherwise prevented from further testing. The computer instructions that carried out these functions were programmed onto chips connected to the analyzers circuitry. These had limited capacity, programming power, and development flexibility.

2.50 In the early 1990s, in-use vehicle emissions analyzers started to be designed around a personal computer (PC) system. This gave the analyzers the ability to greatly refine the test procedures and inspection-center controls, allowing them to perform more uniform and consistent tests. The computer could

- ?? control when and how the emissions should be measured
- ?? calculate and control for exhaust gas dilution based on CO₂ and O₂ measurements
- ?? ensure that the vehicle is operating at the specified rpm
- ?? print out the inspection report on a dedicated printer automatically.

For diesel exhaust smoke readings, the computer allowed statistical filters to be used to generate better consistency in the test results. The computer also allowed the data on vehicles'

owners to be captured and entered into a database together with the test results, which were stored on a disc and could be automatically transmitted to a central database for analysis and governmental control.

2.51 Since the computer took charge of some of the controls required to get uniform and consistent results, the tests became easier for technicians with relatively low level of training to perform correctly and these specifications were soon adopted by many countries (such as Canada, Germany, Mexico, Sweden, and the United States) to perform no-load, two-speed emission tests on in-use vehicles.

2.52 By the mid-1990s it was found that these measures had not succeeded in reducing tailpipe emissions sufficiently in several of the most polluted cities. Unscrupulous mechanics had discovered ways of cheating and obtaining a pass certificate fraudulently for an otherwise failing vehicle. Where false passes could be obtained, it was often easier and cheaper to cheat on the test than to repair the vehicle properly to reduce emissions. Owners of polluting vehicles were being offered the option of “buying” a certificate instead of conducting more costly repairs. Predictably, the greatest incentive to cheat was for the most polluting vehicles—whose repair cost was the highest.

Merits of centralized software development

2.53 In South Asia, only India has a nationwide emissions inspection system. The current inspection centers in India are equipped with manually operated analyzers from more than 20 different manufacturers. This diversity of suppliers should ensure competitive pricing and good after-sales support. At the same time, the absence of complete standardization and consistency across the different manufacturers makes reproducibility more difficult. As computer systems are introduced and become more complex, there is a need to ensure that automation does not adversely affect the equipment suppliers or the test-center operating base.

2.54 There are a number of advantages to having a single centrally developed and controlled software package. Taking India as an example, should each of the 20 manufacturers be required to develop this software package independently, international experience has shown that problems will occur in several critical areas:

?? Because the software requirements are complex, it will be very difficult to achieve the same detailed level of functionality and control from all the equipment manufacturers. Thus the test centers with some makes of equipment would enjoy unfair advantages over the other makes while some centers would have unfair restrictions imposed by their unknowing choice of supplier.

?? If different local governments were to adopt their own version of the software, they would each be faced with the technically daunting and extremely costly prospect of having to test and certify the compliance of up to 20 suppliers to the required specifications at the start of operations and every time the specifications are modified. Detailed modifications could be expected on an annual basis.

- ?? Not all the suppliers would be able to react to changes required by the government within the same timeframe. Thus the changes would either have to be delayed until the last supplier is in compliance, or test centers with different makes of equipment could be working to different standards.
- ?? The cost of developing and maintaining up to 20 sets of identical software would substantially increase the equipment suppliers' costs and hence prices.
- ?? The high cost of developing and maintaining the software would favor large international suppliers over national companies since they would be in a better position to defray expenses via sales in other countries and regions. This would lead to an oligarchic supplier situation which would hinder future vehicle emission testing development in South Asia.

2.55 It is more beneficial to have one computer software package developed and controlled by the central government for use with all makes of equipment. The equipment-specific interface layer that connects to this unified software package would be developed together with each manufacturer based on a standardized design. Fortunately, little development will be required by each manufacturer, enabling it to bring its equipment to market in a timely manner and the functions that need to be enabled by this interface layer are not prone to frequent modification.

Test protocol control

2.56 Running the test protocol under computer control allows many of the test variables to be dynamically verified under real-time second-by-second conditions and allows multiple readings to be obtained under precise repeatable conditions to eliminate instantaneous inconsistencies. The recorded second-by-second data are useful for statistical analyses designed to detect fraudulent practices during the test. In the snap acceleration test to measure smoke opacity in diesel exhaust, for example, the adoption of computer control of the test procedure allows many variables that are otherwise uncontrolled to be managed: the software is able to determine the characteristics of the diesel engine, particularly its low idle speed, its rated maximum speed, and the time it should take to accelerate between the two, if these have been included in a master reference table within the program. With this information the software is able to validate if the test has been correctly performed. Without computer control the technician is able to start the test at a higher-than-low-idle speed, end the test at a lower-than-maximum speed, and accelerate at a slower rate—all of which reduce the smoke emission readings from a high smoke emitter.

2.57 Dynamic validation of the key test protocols enabled by computer include exhaust gas dilution, engine or vehicle speed, engine load, and other factors. Every second the computer performs checks to see if these parameters are within limits, if the test equipment is not in a low-flow condition, and if the equipment is being tampered with. Should any of these parameters be found to be out of bounds, messages are given to the tester (and logged in the computer database) to correct this situation and requires that the test be restarted.

2.58 Reliable and consistent vehicle identification and test data in centralized databases is essential for performing the statistical analyses required to define differentiated emission limits and to modify non-differentiated limits. Different vehicles may require different emission standards depending on their design and size, and this can be accommodated only when the vehicle can be reliably and consistently identified through a database. An example of this is oxygen. For most gasoline and gas-fueled vehicles, a high oxygen reading in the exhaust shows that the vehicle is not in an adequate mechanical condition (very high air-to-fuel ratio or leaks in the exhaust pipe) or that the test has not been performed correctly. However a few vehicles equipped with three-way catalysts have air injection into the center of the catalytic converter to promote the oxidation process, and these have higher oxygen readings in the exhaust gas. The use of a computer-controlled test allows suitable oxygen limits to be applied to both types of vehicle.

2.59 Automatic, computer-controlled calibration audits are needed to ensure that the instruments are within their correct specifications, and this is made possible by the use of software. The software can also improve the measurement accuracy by automatically calibrating the equipment at intervals that depend on each specific instrument's proven stability and usage pattern. For extensively used I/M equipment, the gas and opacity meters need to be calibrated with reference gases and filters at least once per day when the equipment is started up and should be referenced to zero between every test. Computer-controlled testing allows the instrument's calibration to be verified and corrected at predefined and modifiable periods. For example, an optical gas analyzer should be routinely auto-calibrated with reference gases every day before testing commences. On days when the work load is particularly intensive, a more frequent recalibration is highly beneficial. Recalibrations should also be considered after high emitters have been tested since there is a tendency to saturate the measuring circuits and this can cause the next vehicle tested to fail. The calibration history of each instrument can be used to determine the frequency of calibration it requires. A new optical gas analyzer that generates stable and consistent readings can be calibrated less frequently (with considerable savings in reference gases and time) than an older, less stable instrument.

Data capture and analysis

2.60 The identification of the specific vehicle and its owner can be improved by using computerized data entry software that automatically consults look-up tables to verify that the information is correctly entered and the correct test procedure is applied. Great care needs to be taken in the data entry to ensure that the data are entered every time without errors. Centralized databases allow the software to check for consistency and correct errors at source. This ensures that the correct test procedure, limits, and follow-up actions are chosen for that vehicle. Only when each vehicle is correctly and consistently identified can different test protocols be reliably applied to different vehicle types with corresponding differentiated emission standards. The alternative of applying the same standards to all vehicle types is sub-optimal because the standards are likely to be too lenient for those with newer technology and yet very stringent for other vehicle types.

2.61 When the centralized databases contain tests for a specific vehicle, registering the previous test certificate's barcode with a bar-code scanner allows the captured and validated data for that vehicle and its owner to be accessed. Thus the test technician has to enter and validate only those changes that might have taken place against other official documents. These include changes of vehicle ownership and of the owner's address.

2.62 Automatic real-time electronic transmission of the vehicle information, test data, and certification status to a central host computer system serves to minimize tampering of captured data and enables stringent automatic quality assurance procedures with auditing of test results and inspection equipment status by the central host computer system. Statistical analyses and other techniques need to be incorporated into the software on the central host computer system that continuously monitors the test results, calibration results, and maintenance requirements of each test center and each tester-lane combination. Common make/model and model-year vehicles, for example, should generate similar emission distributions in all test centers and with all test technicians. If one center is found to have emission results for that particular type of vehicle that are substantially lower than those registered in the other test centers, it is probable that it is using some technique to artificially modify the test results. Such findings, if confirmed, should lead to the temporary or permanent suspension of that center or stricter vigilance by the controlling authority.

Security measures

2.63 Improved equipment security measures and electronic detection of tampering attempts are an important aspect of administrative control. If the test technician or center operator were allowed to modify the characteristics of the measuring instruments (which are partly defined in each instrument's computer code) or the characteristics of the test equipment or the analog-to-digital conversion of the measurements made or many other conditions, false readings can be obtained that would help a polluting vehicle to obtain a pass certificate. Some of the measures used to prevent such modifications include:

- ?? Individual password codes that allow only authorized individuals to access specific areas according to governmentally-defined guidelines (for example, a test technician should not have access to maintenance functions and maintenance personnel should not be allowed to perform official emission tests)
- ?? Electronic locks on the equipment cabinets that can be opened only when an activated and authorized password code is entered
- ?? Automatic diagnostic checks every time a cabinet is closed to ensure that unauthorized modifications have not been performed
- ?? Electronic entry and exit logs transmitted to the central server of all activities that could have resulted in undue adjustments.

2.64 As controls become stricter it will become increasingly difficult to obtain a pass certificate fraudulently, and unscrupulous center owners will look for more technical and sophisticated means of supplying their clientele with fraudulent certificates. Elements such as

digital signatures then need to be included in the certificates to identify forgeries and to identify fraudulently generated certificates. A digital signature is a set of characters that have been generated by high security code that takes into account the contents of the certificate in such a way that if any of the certificate's contents were modified they would no longer match the signature and the modification can be easily detected. Thus no two certificates could have identical digital signatures. These are used in conjunction with digital fingerprints that offer a synopsis of the signature in a form that is easy to enter into the computer. This allows the computer to validate, for example, when a vehicle is presented for a test that its previous certificate has not been fraudulently generated or modified.

2.65 The electronic information also needs to be protected. This can require encryption (where the information cannot be read or deciphered without a specific key), per-register and per-table² digital signatures, fingerprints (where the information can be read, but not modified without detection), and protected operating systems and database structures.

Administrative measures

2.66 Remote lock-out of test and inspection equipment when inconsistencies or malpractice are found should be the first line of defense against fraudulent practices at test centers. There should be automatic certificate accounting and control procedures applied to test centers and end-users to verify tests performed and results obtained. An onerous part of the controlling authorities' test-center supervisory process is keeping track of the test certificates issued to each center, and of those issued to end-users, which were returned to the authority for technical or other reasons and which have not been accounted for. The software needs to validate the certificates' reported use against the centralized test databases to ensure that certificates are not just printed out with a spreadsheet program to issue false passes to dirty vehicles, bypassing the technical emission test altogether.

2.67 Vehicular enforcement procedures need to be strengthened to ensure that all vehicles do satisfactorily complete their designated inspection and certification requirements within the allotted time period. Once a centralized and comprehensive database has been established, information can be generated by the computer system on those vehicles that have not turned up for testing within their allotted time period or have not returned for re-testing after having obtained a fail certificate. This information greatly helps the vehicle enforcement process.

2.68 It is difficult for a salaried on-site inspector to adequately control an authorized testing station that is making a lot of money fraudulently. I/M programs should make use of remote auditing to distance their staff from the temptation of turning a blind eye to fraudulent practices in exchange for financial gains. The local authority needs to invest in remote computer-

² Two things need protection in the database: (i) one needs to ensure that data in a specific test record is not modified (for example, that the emissions readings that were reported by the test equipment have not been manually changed in the database); and (ii) one needs to ensure that records in the database are not deleted and that new records are not added, bypassing the test equipment. This requires protecting the contents of each record (per-register) and ensuring that records are not added or deleted from the database (per-table).

based auditing of all centers. The national government could develop such computer programs cost-effectively, since the same requirement will exist in every city that adopts such a system. Automatic and immediate electronic data transmission is essential. Unless fresh data from all tests performed are readily available, it will be very difficult to supervise and audit test operations effectively.

2.69 Calibration audits play a very important role in ensuring that the test equipment is correctly maintained and eliminating the perennial problem of the same vehicle producing different test results in different centers. Gas, opacity-filter, and dynamometer calibration audits should be performed by independent accredited materials standard laboratories on each test lane regularly. The gases used should be traceable to international standards and certified in accordance with internationally recognized protocols. Similarly, a set of internationally traceable neutral filters should be used to evaluate the linearity of the opacity meters.

Structure and Ownership of Test Centers

2.70 In South Asia, vehicles are tested for emissions both at private garages (India, Pakistan) and government centers (Kathmandu, Nepal). No city in South Asia yet has centralized test-only centers in operation.

Test-only versus test-and-repair centers

2.71 The evolution of I/M in Mexico City (ESMAP 2001a, Kojima and Bacon 2001), which is among the most extensively developed in developing country cities, allows a direct comparison of decentralized test-and-repair garages and centralized test-only centers. Annual inspections, made mandatory in 1988 for certain age vehicles, were initially conducted in the test-only centers operated by the city government, but soon afterwards independent test-and-repair garages were authorized. In 1991, a proposal was made to create independent, multi-lane, test-only “macro-centers” in which some of the lanes would be equipped with dynamometers, enabling dynamic loaded-mode testing. By 1993, there were 500 test-and-repair centers and 24 macro-centers in full operation, all privately owned. At the same time, strong lobbying by the independent garages forced the city government to close their own test-only centers. For a period there was side-by-side operation of test-and-repair and test-only macro-centers, enabling lessons to be drawn on their merits and shortcomings.

2.72 The test-and-repair centers were convenient for vehicle owners in that they provided a one-stop solution and eliminated the “ping-pong” effect of the vehicle owner being caught between a garage that argued that it had correctly repaired and tuned up the vehicle, and the macro-center that reported the vehicle out of limits. As a result, most private vehicles went to the test-and-repair garages, whereas all vehicles that were not privately owned had to go to the macro-centers for the dynamometer test, which was unavailable at the test-and-repair centers.

2.73 On the other hand, the test-only macro-centers were far easier for the government inspectors to supervise, and allowed better technical and administrative control to

be enforced. The ownership of these centers was concentrated in a few industrial groups specializing in emissions inspection, facilitating the adoption of new technology and generating more uniform results among centers.

2.74 Over time, the quality of testing from the test-and-repair centers degenerated. The garages soon found that they could make more money by cutting back on the cost of the repair services performed if they cheated on the emission testing. In a market with surplus capacity, the desire to increase profits by increasing the volume of business was strong, and the chances of being caught were small. Hence, although the test-and-repair garages were convenient to the end-user, their impact on reducing emissions was considerably less than that of the test-only centers. It finally reached the stage where an estimated 50 percent of the vehicles that went through the test-and-repair centers obtained their approval certificate fraudulently. Public opinion was that it was a highly faulted emission control program, and indeed it was very close to being shut down permanently.

2.75 These problems led to the program being completely restructured in the mid-1990s. Despite the political implications, the licenses were withdrawn from all the 600 test-and-repair centers, while the number of test-only macro-centers was increased from 26 to 33, for a total of 180 test lanes. A series of stringent quality assurance controls and technical changes were added to the multi-lane center operation and a new public identity was generated, repositioning them as test-only “verificenters.”

Reducing false passes

2.76 In addition to making some technical adjustments to the testing procedures, the verificenters introduced elaborate precautions to prevent individual testers giving “false passes.” These included the use of “blind” test lanes where the tester did not see the results of the test, which were available only at the exit from the station; central computer and video monitoring of testing; and technical audits of centers by government inspectors. Because of these actions, the proportions of failing tests increased substantially: whereas during the second six months of 1995 the test-and-repair centers had reported a reject rate of 5.8 percent and the macro-centers a reject rate of 10.3 percent, during the first six months of 1996, under these new operating rules, the rejection percentage from the verificenters in Mexico City was 22.5 percent.

2.77 It was estimated that, during the first half of 1997, although 73 percent of all vehicles obtained their emission certificates correctly, 8 percent of vehicles obtained a false approval because of incorrect practices in the test process in the verificenter, and an additional 19 percent of vehicles obtained their certificate through incorrect practices by the garage that tuned the vehicle prior to the test. Here, tuning the vehicle “late and lean” became a common practice, as did disconnecting air hoses from the inlet manifold. Although these percentages are high, they compare very favorably with the more than 50 percent figure of “false passes” estimated to have emanated from the test-and-repair centers.

2.78 It is worth noting that the number of center owners could also affect the performance of I/M. The competition for customers between privately operated centers, which

could lead to “automatic passes” being offered in the absence of effective monitoring and enforcement of test protocols, could be greater if each center had a different private owner than if all the centers were owned by a small number of industrial groups.

2.79 It is clear that whatever the structure and ownership, government needs to dedicate substantial resources for monitoring and supervision of the test centers, even if these activities in turn are outsourced. In this respect, the question of who should run inspection centers (that is, public or private entities) is not as much about who is a more efficient operator as about who would create a more enabling environment for supervision and monitoring. Strong government supervision and monitoring are considerably easier if test station operators are privately operated. It would be very difficult, if not impossible in practice, for one government agency to apply sanctions to another government agency in the form of suspension of license or firing of staff caught in corrupt acts.

Useful Role of Pilot Programs

2.80 Moving from the current situation of static testing with little quality control to a well-monitored and supervised targeted I/M system with adequate control measures, many involving automation, and more rigorous test protocols to minimize false passes and failures entails a large number of steps. Pilot programs are useful for answering critical questions and enabling policymakers to make suitable adjustments in response to unforeseen consequences of the proposed program design.

2.81 Questions that the government may want to answer in a pilot program include the following:

- ?? How much training is needed for testers to be able to perform static tests (for example, snap acceleration smoke tests) correctly and reproducibly? How much training for steady-state loaded tests?
- ?? How much variation is there from tester to tester, from equipment make to equipment make, and from test center to test center when the same test protocol is nominally followed?
- ?? Do third-party audits of test centers seem to be working? What type of problems do auditors and test center operators report?
- ?? Are there complaints about frequent breakdowns of equipment (opacity meters, optical gas analyzers, dynamometers, computers), or reports of problems with equipment calibration and equipment operation? If so, what seem to be major causes of these problems?
- ?? Do vehicle owners and the public at large perceive a marked decrease in false passes and false failures?
- ?? Do vehicles that fail report to be tested again? What are the results of repeat tests?

- ?? Does there seem to be reasonable evidence that most vehicles in the specified categories are reporting for testing?
- ?? Do the data collected indicate that targeting could be made even more selective, for example on the basis of vehicle age or further sub-division of categories?
- ?? What is the net incremental cost of implementing an improved system?
- ?? What additional steps would be needed to iron out the problems reported or identified?

2.82 A pilot program would be especially helpful for establishing initial cut-points for emission standards. The only effective procedure for defining cut-points is to take a sample of in-use vehicles and measure emissions using the testing procedure that is proposed to be implemented in the inspection program. The sample selection needs to satisfy the following criteria:

- ?? The vehicles selected should be representative of the vehicle population for that given category and include the entire range of emissions, from very low to very high. These vehicles should represent varying age, technology, and maintenance practice.
- ?? The number of vehicles selected should be sufficiently large to yield statistically meaningful results.

Ideally, once the test procedure has been defined, a pilot program should be implemented where all vehicles are required to test. The pilot should start with no predefined limits and no failed vehicles, but just as a data collection project.

2.83 After three months or so, there should be sufficient data to be able to define initial cut-points. These cut-points are likely to be high because they are based on a distribution of vehicles whose owners are not yet in the habit of maintaining and operating vehicles properly to minimize emissions. They should be implemented as pass/fail criteria, and emission data should continue to be collected. Given adequate enforcement, vehicle owners are likely to quickly adapt to the new requirement and start tuning for reduced emissions, changing the shape of the emission distribution curve. After about six months of operation a new analysis should almost certainly show that lower cut-points can be applied without increasing the rejection rate. New cut-points should then be implemented with pass/fail results and data should continue to be analyzed for the purpose of deciding when and how much to tighten the emission standards. By this time, if the authorities so wish and other essential components on I/M are more or less in place, the program can move from the pilot stage to full-scale implementation.

3

Other Policy Considerations for Air Pollution from Road Transport

3.1 Lowering ambient fine particulate concentrations is the first urban air quality management priority in South Asian cities. Given the considerable efforts devoted to addressing emissions from mobile sources in South Asia, this chapter discusses a range of topics for consideration in formulating a strategy for mitigating air pollution from road transport. They include direct policy tools—those policy instruments with air quality improvement as the primary goal—and indirect policy tools—those policies that do not have air quality as their primary objective, but have collateral benefits in air pollution reduction.

Traffic Management

3.2 Traffic management—comprising both supply-side and demand-side measures—has the potential to achieve rapid reductions in air pollution and to be affordable in South Asia. For any given vehicle and fuel combination, aggregate emission levels vary according to the distance traveled and the driving pattern. Broadly speaking, NO_x emissions increase, and CO, PM, and HC emissions decrease, with increasing engine temperature (or increasing vehicle speed). The most important influence on emission levels for a given vehicle is the driving cycle, with both fuel consumption and pollutant emissions many times higher per vehicle kilometer during acceleration and deceleration than during cruise. A number of devices, such as one-way street systems, linked traffic signal systems, and traffic control systems, can contribute to smoothing traffic flow.

3.3 From an environmental point of view, the critical features to address by traffic system management are the variability of traffic speed and the location of major traffic flows, particularly congested flows. Traffic management in industrial countries has been estimated to reduce emissions by 2 to 5 percent overall, but by much greater proportions in specific corridors or areas. Because of poor initial traffic conditions, there is considerable potential for traffic management to reduce fuel consumption in many South Asian cities.

3.4 Traffic signal control systems are the most common traffic management instruments to secure traffic flow and safety objectives. Linking of uncoordinated signals to create “green waves” can reduce travel times by 10 percent and emissions by a similar proportion in the controlled area. Allowing “near-side turn on red” (left turn where vehicles are driven on the left side of the road) gives another 1.5 percent improvement. Cycle lengths that minimize pollutant emissions are 50 percent longer than those that minimize delays, and in heavy traffic conditions these extended cycle times can reduce emissions by up to 3 percent.

3.5 Segregation of traffic, including bus priority systems (such as dedicated bus lanes), can decrease variability of traffic speed, enhance safety, and, equally important, increase the efficiency and attractiveness of public transport, resulting in significantly lower fuel consumption and emissions per passenger-kilometer. One very effective approach is to establish a totally segregated busway, or bus rapid transit system. Such systems have been developed as the core of a mass transit system in cities such as Curitiba, Brazil, and Bogotá, Colombia. These systems make it possible to replace four or five small vehicles with one larger vehicle that can then operate more rapidly and smoothly with shorter dwell times. When trunk lines are integrated, physically and in ticketing arrangements, with a system of feeder services, they have proved capable of maintaining or increasing the public transport share of trips even when incomes are increasing.

3.6 One interesting characteristic of these systems is that they have achieved their substantial environmental impacts without initial emphasis on advanced clean technology. For example, in TransMilenio, the bus rapid transit system in Bogotá, conventional diesel bus technology meeting Euro II emission standards has been used, although CNG buses are under consideration at the moment. The goal of the government in Bogotá is to supply 80 percent of bus transport with bus rapid transit by 2015, displacing medium-size and smaller buses in the process. Because emissions from these buses are much more effectively controlled than those from smaller buses owned by numerous operators and the public transport share of trips is steady or increasing, this is expected to bring significant environmental benefits.

3.7 Polluting buses are a concern in every large city in South Asia. Introduction of a bus rapid transit system could potentially bring about considerable reductions in both emissions and congestion. But such a move requires a very strong political commitment. In the case of TransMilenio, a mayor with a vision and strong commitment tirelessly pursued this scheme. Sufficient land must be set aside, and traffic flows substantially redirected. In Bogotá, some streets in the middle of the city are dedicated to TransMilenio buses and pedestrians only. TransMilenio enjoys support not only from bus riders, but also from private car drivers because of their speed, affordability, cleanliness, security, comfort, ease of use, and reduced congestion in other parts of the city.

3.8 The critical element in the success of these bus rapid transit systems has been that both involved a combination of public infrastructure planning with private operation that has made it profitable for the private sector. This experience has shown that good transport planning

and service integration is the essential prerequisite on which environmental improvement of bus services has been founded.

3.9 Some pollutants, such as CO, are within health-based air quality standards on average but can be extremely high at urban “hot spots,” such as heavily congested traffic corridors and intersections. For existing hot spots, traffic management can be used to minimize the impact of traffic on local air quality. For new infrastructure, roads should be carefully designed to minimize chances of creating hot spots.

3.10 There is one major drawback to smoothing traffic flow. As average traffic speed increases, so will trip lengths. Traffic management may induce more or longer trips to be made so that, in the long run, congestion is little relieved and total emissions may even increase. Traffic management is likely to realize its full potential to reduce air pollution only if supported by measures to restrain new traffic generation. Hence it is important that new traffic generated by improved traffic management be offset by the simultaneous introduction of demand management instruments.

3.11 In restraining demand for motorized transport, provision of additional infrastructure for comfortable walking and other forms of non-motorized transport is central. One aspect of restraint is particularly important. It is politically difficult to restrict the movement of private vehicles unless there is a viable alternative. Both theory and practical experience indicate that, at least in respect to trips to central areas, a coherent policy is likely to include a combination of car restraint and public transport improvement.

Compressed Natural Gas as a Cleaner Alternative Fuel

3.12 There is no question that in cities with serious particulate air pollution and a large number of vehicles running on conventional diesel, replacing diesel with CNG can go a long way in reducing exhaust particulate emissions. The impact is immediate, as the experience in Delhi along high-circulation traffic corridors has shown. That said, CNG worldwide has historically replaced gasoline, not diesel. It is important to understand the reasons for this trend.

3.13 A switch to CNG can be achieved either by conversion of existing vehicles running on liquid fuels or by purchase of new vehicles manufactured to use CNG. Vehicles can be made to run on both liquid and gaseous fuels or only on a gaseous fuel. Engines converted or manufactured to operate only on CNG can be optimized for CNG for best performance and least emissions. If they have to be designed to operate on two fuels, their performance and emissions would be sub-optimal with regard to one or both of the fuels. From the point of view of reducing emissions, single-fuel (gaseous) vehicles are preferable to two-fuel vehicles.

3.14 Conversion of an existing vehicle may be cheaper for an operator than premature replacement of a polluting vehicle. However, the conversion process must be carried out properly. In the case of vehicles previously fueled by gasoline, conversion to CNG typically results in a power loss of about 10 percent, which can erode consumer acceptance. Poor conversions can increase, rather than decrease, emissions of some pollutants other than

particulate matter. When gasoline vehicles were converted to CNG, one of the unpleasant surprises in industrial countries was that the converted CNG vehicles were found to be more polluting when tested for emissions in cases where recent model year vehicles had been converted. In cities where ambient ozone concentrations are high, increased emissions of NO_x , an ozone precursor, resulting from conversion from diesel to CNG, could exacerbate the ozone problem. While ozone is not yet a serious problem in South Asia, it can become an emerging problem with growing motorization. Poor conversion can also lead to safety hazards, as demonstrated by bus and taxi fires in Delhi. It is necessary for the authorities to develop and enforce strict regulations to control the quality of conversion. There is a particular danger that a large number of small operators will enter the conversion business with little or no quality control. Programs to promote fuel switching to gas need to be implemented with a high degree of technical competence to avoid environmental and safety problems. International experience with conversion among heavy-duty vehicles to CNG has been poor.

3.15 Because the cost of vehicles designed for gaseous fuels is higher than that of conventional petroleum-derived fuel-driven vehicles, they will be attractive only if the incremental cost of higher vehicle acquisition cost can be recovered from lower maintenance and operational expenses. This is often not the case when switching from diesel to CNG.

3.16 There are several important considerations in deciding whether switching from CNG to diesel is a viable and cost-effective policy option for air quality improvement.

?? *Do diesel emissions contribute significantly to ambient particulate pollution in the city?* If so, then switching to gas could produce significant improvements in air quality. In many cities in South Asia, this seems to be the case.

?? *Are there sufficient supplies of natural gas that are available to the city?* This means a natural gas distribution pipeline for other uses of natural gas is in place. If so, CNG is a potentially viable option. If there are abundant domestic gas supplies—as in Bangladesh and Pakistan—natural gas may be an attractive option for use in the transport sector not only from the point of view of improved environment, but also in order to diversify energy sources. But having abundant reserves it not sufficient, because laying down a gas distribution network is very expensive and can be justified only if there are large industrial users of gas. If the country is short on natural gas and is importing liquefied natural gas (LNG), as the western part of India has recently begun to do, then CNG is likely to be markedly more expensive than diesel.

?? *Is there a realistic plan to match supply and demand during the initial phase?* Adequate refueling infrastructure for the number of CNG vehicles needs to be in operation, and a sufficient number of CNG vehicles, given the number of refueling stations, needs to be in existence or soon be established. However, dedicated CNG fleets, such as a downtown bus fleet with private refueling facilities, can be a success without an extensive network of refueling

infrastructure in the city, because buses in large fleets all “come home” to one refueling station at night, making fueling with CNG easier.

- ?? *Is diesel cheap?* Throughout South Asia, diesel is taxed less than gasoline. Under these circumstances, substantial subsidies would be needed to make switching from diesel to CNG close to financially neutral unless the tax on diesel is increased to make the end-user price comparable to that of gasoline. Otherwise, if CNG for all vehicle users is made cheap compared with diesel, the first result would be large-scale conversion of gasoline to CNG and not diesel to CNG, resulting in a significant loss of fuel tax revenue to the government. It is telling that Argentina, the largest CNG vehicle market in the world, has had virtually no fuel switching from diesel to CNG. In Delhi where CNG conversion was mandated for certain commercial diesel vehicles, large-scale conversion from gasoline to CNG among private cars created a shortage of CNG in the early days of the CNG conversion program.
- ?? *Are the potentially higher costs of CNG vehicle maintenance and the need for suitably trained technical staff taken into account in assessing conversion from diesel to CNG?* There is ample evidence from around the world that diesel vehicles are much more robust than CNG vehicles. The evidence is especially strong in the case of buses, which are otherwise ideally suited for alternative fuels. Managers of CNG fleets have to make a strong commitment to provide technical support to deal with CNG-related maintenance and operational problems not generally encountered with diesel vehicles. There are consistent reports that natural gas buses manufactured in the early 1990s were not only more expensive to purchase, but were also about 30 to 40 percent more expensive to maintain and had considerably reduced reliability. While many of these problems are being overcome, heavy-duty natural gas engine technologies are still being refined to achieve performance comparable to that of their diesel equivalents.
- ?? *Is fundamental reform in the transport sector needed to make the operation of vehicles being targeted financially viable?* If so, the reform issues should be tackled before saddling cash-strapped fleet operators with financially and technically challenging fuel switching from diesel to CNG. A classic example is bus sector reform. Transit buses in many cities are cash-strapped, partly on account of fare controls. As a result, buses are not properly maintained and operators are not in a position to purchase more expensive CNG buses, provide extensive training to all their staff on this new technology, and accept the possibility of more repairs to deal with greater frequency of bus breakdowns. High emissions from diesel buses are not merely a result of the choice of fuel. They are symptomatic of deeper problems, and the same problems may condemn CNG bus programs to failure if these underlying causes are not addressed.

3.17 In short, in countries with an abundant domestic supply of natural gas and reasonable fiscal policy toward diesel, fuel switching from diesel to CNG may be a good way of reducing air pollution. In other cases, the questions above should be carefully addressed before the decision is taken to promote fuel switching, especially if significant government support is needed.

Fiscal Instruments

3.18 In every country in South Asia, automotive diesel costs less than gasoline on a per-liter basis. Because diesel engines are inherently more efficient than gasoline engines, the effective cost difference is even greater on a per kilometer traveled basis. The lower price of automotive diesel is believed to have led to the “dieselization” of light-duty vehicles that would otherwise run on gasoline, and acts as a significant barrier to diesel substitution by CNG. The price difference between gasoline and automotive diesel was about 30 to 40 percent in January 2004, with the largest percentage difference found in Nepal (43 percent), closely followed by Sri Lanka (42 percent), and the smallest in Pakistan (33 percent).

Cause of dieselization

3.19 There is no question that the much lower end-user price of automotive diesel has historically contributed to the preference shown by many purchasers of light-duty vehicles for diesel rather than gasoline. For comparable vehicle size and age, diesel vehicles are more expensive than gasoline vehicles, so buying diesel vehicles would make sense only if fuel cost savings can offset the higher vehicle purchase price. The greater the price difference between gasoline and diesel, the lower the break-even annual km traveled above which it would be more economical to buy diesel vehicles.

3.20 A study was conducted in Sri Lanka to examine, amongst others, whether the fuel price difference was increasing the share of diesel vehicles in the light-duty category (Cambridge Economic Policy Associates 2002). The price difference at the time of the study was large: the retail price of gasoline was 49 Sri Lankan rupees per liter, of diesel only 26. The share of gasoline in the fuel used for transport fell from 30 percent in 1990 to 18 percent in 2002. Despite the large fuel price difference, a review of the historical vehicle population data showed that substitution of diesel by gasoline had not occurred among passenger cars. The proportion of diesel-powered cars imported fluctuated, not because of fluctuations in fuel price differences but most likely in response to the introduction and withdrawal of considerable import-duty concessions, independent of fuel choice, granted to civil servants and academics from time to time. The proportion of passenger cars running on diesel had remained small, about one-tenth of the total stock of cars in use.

3.21 During the same period, there was a rapid expansion of dual-purpose, light-duty vehicles using diesel. Car ownership grew at an annual rate of 5-6 percent and heavy trucks at 6 percent, in line with real growth of gross domestic product, but vans and dual purpose vehicles

grew at 8-9 percent, and vans and cars combined at 7 percent growth. There therefore appears to have been some substitution of cars by dual-purpose vehicles.

3.22 A series of analyses was carried out to compare the break-even points for sizes and types of cars and vans on the basis of annual km traveled under different tax scenarios. The objective was to explore whether the taxes prevailing in 2002 were promoting efficient choices of vehicles. The study found that the incentive to buy diesel-powered cars created by the lower tax on diesel was offset by higher vehicle taxes on diesel cars. However, at least in some cases, the existing fuel and vehicle taxes encouraged diesel dual-purpose vehicles (vans) when gasoline would be more efficient. In addition the study found the lower age limit on imported second-hand cars (three years) than vans (five years) encouraged the substitution of diesel-powered vans for petrol cars. As the import duties are ad valorem, cheaper vehicles, particularly vans and dual-purpose vehicles, were unduly encouraged, despite the higher rates of import duty on diesel vehicles. In the absence of taxes, or with equal fuel taxes with or without an extra pollution tax, gasoline vans would be cheaper. The study concluded that unless the import age restrictions were changed, vans might continue to be inefficiently substituted for cars.

3.23 This analysis shows that it is not sufficient to focus only on fuel taxation when examining underlying reasons for fuel choice. Vehicle taxation in Sri Lanka has been set up to discourage diesel vehicles. But the determining factor was the differential age limit on cars versus vans, so that it became cheaper to buy diesel vans than gasoline cars.

Impact on households

3.24 The general consensus in South Asia appears to be that the tax on automotive diesel does not sufficiently capture the marginal social damage of diesel use, especially wear and tear on the road and pollution. However, the prospect of raising tax on automotive diesel is opposed by heavy users of diesel (such as the trucking industry) as well as concerns about the adverse impact on the poor. Two recent studies have examined the impact of raising diesel prices on households in South Asia.

3.25 One study examined the impact of narrowing the price difference between gasoline and diesel in Pakistan (ESMAP 2001b). Two scenarios were studied, one in which the price of diesel was raised by 67 percent and the price of gasoline reduced by 10 percent, and the other in which the price of diesel was raised by 10 percent and gasoline reduced by 29 percent. The price difference as of March 2001 was substantial, 30.00 Pakistani rupees per liter for regular gasoline versus 15.40 for automotive diesel. It is the first scenario that raises concerns about impact on the poor.

3.26 The impact of changes in fuel prices on household expenditures was examined by means of input-output analysis and using household expenditure survey results. The first scenario was found to increase the cost of living of households by 1.4 percent of income on average. The impact was higher for urban households (1.5 percent) than rural (1.3 percent). The impact was regressive, with the increase in household expenditure falling from 1.9 percent for the bottom income quartile to 1 percent for the top income quartile in rural areas, and from

1.9 percent to 1.2 percent for the corresponding income groups in urban areas, assuming zero price elasticity. This scenario generated substantial additional revenues (thereby reducing the budget deficit) and reduced imports significantly (thereby improving the balance of payments) at the cost of somewhat lower growth (due primarily to contraction of the road transport sector), significantly higher short-run inflation, and some deterioration in unemployment.

3.27 The second scenario benefits the richer car users considerably, and encourages rather than discourages urban private car use. As such, it is not a desirable policy option. It does have more limited macroeconomic implications than the first scenario, achieving the same desired inter-fuel indifference but causing much smaller dislocation to the economy. There are some minor revenue losses and a small worsening in the balance of payments, but it impacts marginally on the poorer sections of society while conferring some benefits to car owners.

4.28 The second study is the previously mentioned study on fuel and vehicle taxation in Sri Lanka (Cambridge Economic Policy Associates 2002). The share of expenditure on all fuels is a rather small percentage of total household expenditure, averaging 5 percent for the top expenditure decile and 3.5 percent for all households. These percentages include the direct consumption of fuels and the indirect consumption through purchases of other goods and services. While direct consumption of diesel is concentrated at the top of the distribution, the indirect effect is more important for each expenditure decile group because diesel is an important input to many goods and services. The indirect effect is most important at the bottom of the distribution and progressively less important higher in the distribution.

3.29 In this study, the total household expenditure was held constant, and the impact of price increases was expressed as the percentage change in volume consumption. When a price elasticity of demand for diesel of -0.1 was assumed, the bottom and the top of the distribution were those least affected, with an average impact of 1.4 percent for doubling of the price of diesel. However, with increasing elasticity the fact that the top of the distribution has more direct consumption of diesel began to make a larger difference. For an elasticity of -0.8 , the impact of the price change was progressive, with the top decile having a welfare change 40 percent higher than the bottom decile. The impact varied from 1.3 percent from the bottom decile to 1.9 percent for the top decile, averaging 1.7 percent.

3.30 What these two studies suggest is that the impact of a large increase in the retail price of diesel is rather modest. Whatever the adverse impact on the poor can be further mitigated if the tax on diesel is rebated to intermediate users of diesel, such as rail transport. The study in Pakistan also points to the limitations of using just one fiscal instrument, in this case fuel taxation. While the second scenario may have negligible economy-wide consequences, the transport sector in Pakistan is plagued by urban congestion and inadequate provision for road maintenance. A move that will certainly encourage greater urban private car use will further exacerbate the problems facing the transport sector, even if environmental gains can potentially be made in the short to medium term.

Indirect Policy Tools

3.31 There are indirect policy tools that can have positive or negative effects on urban air, depending on how they are managed. These policy tools are not driven primarily by concerns about air quality improvement, and their effects often become evident only in the medium to long run. If they are poorly managed, however, their adverse impact on the environment can be felt for a long time. Examples include urban planning, transport sector reform, and petroleum sector reform.

Urban Planning

3.32 The role of urban planning is to manage the spatial organization of cities for efficient allocation of urban infrastructure and land use. Depending on how it is applied, urban planning can improve air quality in the long run by strategic location of polluting sources and exposed population, and encouraging a city structure that would minimize pollution emissions and build-up. Unfortunately, urban regulations in South Asia have historically contributed to misallocation of land use and growth of urban shapes that are not necessarily conducive to economic development or air quality improvement. For example, there is a tendency in South Asia to limit the floor space index—ratio of the maximum total floor area permitted to the area of the plot of land—far below what is common in the rest of Asia. This results in demand for land far outstripping supply, pushing up the price of land and making the development of commercial real estate financially uneconomic. The resulting lower investment by the private sector in turn reduces government revenue in taxes and user fees as well as job creation.

3.33 Increasing or maintaining population densities and maintaining a dominant central business district can make it easier to operate an efficient public transport system and reduce the number and length of trips. That said, higher densities require much better traffic management, stricter enforcement of parking laws, and capital investments in sidewalks and pedestrian overpasses. If these measures are not taken, not only heavy congestion and resulting high emissions can ensue, but also highly polluting two- and three-wheelers can end up dominating the urban centers because of their maneuverability.

3.34 In the interest of environmental improvement, there is a drive to earmark zones for all industry away from metropolitan areas. While strict enforcement of such zoning would improve air quality, such a policy points to conflicts between different sector objectives. Banning new industries in metropolitan areas exacerbates the phenomenon of increasing number of under- or unemployed workers forced into the informal sector. Urban-based workers may have to be transported to and from their homes to far-flung industrial sites. Small- and medium-sized industries, which need urban locations to maintain profitability, are often forced to operate illegally, making it more difficult to control them for labor, safety, and environmental (including emission and discharge) standards.

3.35 Effective urban planning requires careful balancing of divergent, and sometimes incompatible, objectives. Urban planners have to weigh the benefits of such socioeconomic considerations as creating employment opportunities in cities by allowing new industries, and

their potential adverse effects on air quality and traffic. There is scope in South Asia for allowing market forces to play a greater role in shaping cities, but it is crucial to coordinate policies across key sectors, such as urban and transport, to realize air quality improvement.

Impact of Policy and Sector Reform

3.36 Many of the measures needed to improve air quality will be sub-optimal or ineffective over the longer term without the reform of the transport and fuel sectors. The oversupply of heavily polluting bus and taxi fleets or a shortage of cleaner fuels such as natural gas for household use can be symptoms of market distortions or regulated inefficiencies. Therefore, prior to or in parallel with instituting regulatory and administrative measures for reducing emissions, cities and countries should ensure that transport and fuel sectors are efficiently (and equitably) organized.

Policy for public transport

3.37 Policy to increase use of public transport is a complement to restraint of private vehicles. Its aim should be to minimize the direct air pollution impacts of public transport by making it clean, and to maximize its indirect benefits by making it sufficiently attractive to draw passengers away from private vehicles to high-occupation public transport vehicles. The danger is that empty buses can contribute more to particulate air pollution than full cars, particularly where the buses use diesel and the cars gasoline. If the imposition of stringent emission standards makes formal public services more expensive and passengers are lost, or reduces the financial viability of the operators so that vehicle maintenance is prejudiced, their purpose will not be served. Hence it is important to ensure that policies for public transport combine measures to make it less directly polluting with measures to maintain its attractiveness relative to private automobile use.

3.38 The internal efficiency of formal bus operating companies in South Asian cities can often be improved by more efficient design of route networks, better cost control, and better control of performance on the road. Some of these involve relatively modern technology (such as automatic vehicle location) that is likely to be employed only by large, possibly area-monopoly, companies. There are some scale economies in staff training, supply procurement, and management information systems. But unless monopoly franchises are competitively tendered for limited temporal duration, international experience indicates that these potential benefits are not of a magnitude to justify monopoly operation of large urban systems because of the losses of efficiency inherent in monopoly operation that does not have to face competition. The advantages of integrated systems planning, also frequently considered to justify monopoly, can be equally well achieved by separation of planning from the operation of services, which can be competitively procured by the planning agency. The most critical requirement is usually the need for internal incentives to efficiency, the most effective of which is some competitive threat. Competition in urban public transport is a critical stimulant to operating efficiency.

3.39 Most public sector operations of public transport are politically controlled and inefficient. Yet allowing small informal sector operators to enter the market to supplement or

compete with the existing operator has often been associated with excessive supply (as in Santiago, Chile, until the early 1990s), the use of old, polluting vehicles (as in Lima, Peru today), or dangerous operating practices (as in Delhi). Unregulated competition can clearly be dangerous, inefficient, and environmentally damaging.

3.40 But this is not inevitable. Several countries, including Denmark, Sweden, and the United Kingdom, have awarded monopoly franchises of limited duration and scope on the basis of a competitively bid tender. This “competition for the market” allows the authority to control the main policy sensitive variables, such as fares and service structures, while mobilizing competition to get the desired level of service at the lowest possible cost. It has shown reductions in cost per bus kilometer between 20 percent and 40 percent and is now the preferred form of competition in large cities (Halcrow Fox 2000). The replacement of competition “in the market” by competition “for the market” in the central area of Santiago allowed the authorities to get the economic benefits of competition without environmental damage by the simple device of setting minimal pollutant emission standards as a condition for holding any franchise, as well as by using environmental quality above the minimum as one of the criteria on which competitively tendered franchises are awarded. Well-designed competition for the market overcomes the disadvantages of unregulated competition and can strengthen environmental discipline.

3.41 For competitive tendering to be effective, a franchising authority must be technically and administratively able to design and award franchises with sensible environmental conditions and to monitor performance, including vehicle emissions, effectively. There is now a wealth of experience in doing this, both in industrial countries (for example, in Copenhagen and London) and developing countries (in such cities as Santiago and Bogotá). Furthermore, effective competition, either in the market or for the market, is dependent on the commercialization or full privatization of the incumbent parastatal operator, as private operators are understandably reluctant to compete with an agency that can rely on deficit finance from its owner to ensure that it retains its position in the market. The cities that have most satisfactorily reconciled efficient and clean operations with low budget burden are those that have confronted the need to develop effective competition.

Downstream petroleum sector

3.42 One of the important requirements for fuel-quality improvement and adequate fuel supply is an efficient downstream petroleum sector. Where there are serious distortions in the sector, unsustainable subsidies, gross inefficiencies, a serious shortage of investment, or even lack of maintenance of the existing assets, coupled with sector protection, it is very difficult to realize significant fuel quality improvement or meet demand for cleaner fuels.

3.43 Countries with refineries are especially prone to sector distortions. In South Asia, Bangladesh, India, Pakistan, and Sri Lanka have refineries. Some are completely government owned. Historically, they have been protected through the combined use of import restrictions, quotas, and high tariffs. Unsustainable and mounting government subsidy and inability to attract the capital needed for investment in the sector are typically the two primary

drivers for sector reform. Environmental considerations play a minor role. While environmental degradation may not drive sector reform, fuel-quality improvement cannot be divorced from it, and sector reform is in fact often a prerequisite for fuel quality improvement.

3.44 In countries with inefficiently operated or small-scale domestic refineries, a further consequence of refinery protection is that consumers are denied access to cleaner fuels that are available on the world market and are often cheaper than dirtier, domestically produced fuels. In Bangladesh and Pakistan, diesel containing as much as 1 percent sulfur is permitted to this day. For comparison, it is worth noting that North America, Europe, and Japan are moving from about 0.035 percent sulfur in diesel to 0.001–0.005 percent in the next few years. In South Asia, only India is set to move to 0.05 percent by 2005. Establishing fair, healthy, and transparent competition in the supply of fuels to the domestic market and market-based fuel pricing is thus an integral element of the policy for making cleaner fuels available and affordable.

4

Understanding Sources of Airborne Particles

4.1 The current policy emphasis on tackling vehicular emissions rests on the assumption that these emissions are the largest contributors to particulate air pollution. But if they are not, the effectiveness of the policy efforts will be compromised. Therefore, it is important to examine what the major contributors to air pollution might be. To gain a better understanding of sources of particulate pollution, two studies were commissioned and their findings are presented in this chapter. The first (TERI 2001) reviewed the past and ongoing work on urban air quality in India, focusing primarily on particulate matter. The second (Chowdhury and others 2003) carried out chemical analysis of fine particles collected in Chandigarh, Delhi, Kolkata, and Mumbai with the objective of identifying source contributions using chemical mass balance receptor modeling.

Review of Particulate Analysis in India

4.2 TERI's review suggests that most of the published work has concentrated on heavy metals, particularly lead during the time leaded gasoline was used. Lead levels have been observed to decrease only along dense traffic corridors and not necessarily in other parts of urban areas. Re-suspension of dust is also an important source of airborne lead. The levels of different elements have been found to be correlated with the characteristics of the site and anthropogenic activities taking place in its vicinity. Soil has been cited as a significant component in several studies. Incineration has been cited as an important source of lead in addition to vehicular sources.

4.3 Very few studies have examined the size distribution of particles. These studies have been mostly of short duration, small sample size, and have not adequately documented seasonal variation. There are indications from data from the National Ambient Air Quality Monitoring Program that PM_{10} makes up one-third to two-thirds of TSP. $PM_{2.5}$ has been found to constitute about one-half of PM_{10} . One recent study that analyzed total and elemental carbon in PM_{10} (Mayol-Bracero 2001) found that total carbon accounted for approximately one-third of PM_{10} , which is similar to the results reported in other countries. (For the definition of

elemental carbon, see annex 4.) The ratio of elemental carbon to total carbon was comparable to those found in the Indian Ocean Experiment (INDOEX) in February and March of 1999 at altitudes ranging from 0 to 6.5 kilometers (km) over the Indian Ocean region. The authors (Mayol-Bracero and others 2002) proposed that these results suggested significant contributions from the combustion of fossil fuels rather than biomass (such as wood and leaf burning). Given the small sample sizes in the studies, however, these findings need to be investigated more. There is essentially no information on background particulate concentrations or the characteristics of particulate matter in background areas. The definition of “background area” relevant to Indian cities is itself lacking.

4.4 Emission factors representing typical sources in India are not available for the most part. The emission factors used in studies contain large uncertainties as a result. The data needed for computing total emissions using emission factors? such as the total number of vehicles operating on the road by vehicle type and age; annual distance traveled and fuel economy; amount of leaf and garbage burned; the number of cottage industries, their processes, and fuels consumed; and the efficiency of exhaust treatment devices? are also scarce. There are no reliable emissions inventories for PM_{10} . Where PM_{10} emissions inventories have been compiled for the same city, the results have differed considerably from study to study.

4.5 There are very few source apportionment studies in India and most of them are more than ten years old. All studies but two to date have looked at TSP. Only one study has examined PM_{10} , and another, size-fractionated particles. Only one study, on TSP, has explicitly quantified source contributions. None of the studies has analyzed particles for carbon, seriously limiting the ability to examine the combustion of fossil fuels and biomass in detail. Most studies have confirmed that natural dust is the predominant source of TSP. The one study examining PM_{10} found natural dust to be the predominant source. Vehicular sources have typically been lumped together with all other fossil fuel combustion sources. Wood and refuse burning have also been identified as important sources of particulate matter.

4.6 Most studies have chosen industrial locations. Typical downtown or residential areas have so far not been examined. Seasonal variations in source contributions have not yet been studied. A couple of studies have identified small stationary sources of combustion as being important. Agricultural sources have not been considered.

Source Apportionment of Fine Particles in Delhi, Kolkata, and Mumbai

4.7 The source apportionment study by the Georgia Institute of Technology and several Indian institutions employed a chemical mass balance receptor model (see 1.63 for a description of chemical mass balance receptor modeling) using organic tracers as molecular markers for several key primary sources. Receptor modeling has been widely used as a technique in air pollution source apportionment studies. Chemical mass balance receptor models make use of chemical concentrations in the ambient data and source profile data to estimate the contributions of different source types to ambient pollutant concentrations. Elemental analysis of $PM_{2.5}$ has been performed in Bangladesh in the past, followed by chemical mass balance

receptor modeling, but as annex 4 shows, this approach without detailed organic carbon analysis is limited. Hydrocarbon speciation, although laborious and expensive, yields much valuable information and insights into potential sources because they capture fossil fuel and biomass combustion much more precisely.

4.8 Molecular markers can be highly specific for distinct sources and there exists a good understanding of tracers for a wide range of sources in industrial countries. Spatial and temporal distribution can also help validate capturing of information on source contributions by examining tracers. That said, detailed source profiles are expensive to generate and are available mostly in industrial countries. While markers are sufficiently specific to different sources and are not expected to vary from region to region, the precise composition (for example, the relative ratio of a given marker to other components, including total particulate mass) has been shown to vary depending on the mode of operation (of vehicles or machinery), location (especially for road dust), weather conditions, and other parameters. Therefore, chemical mass balance receptor modeling should be regarded as a tool that provides a *semi-quantitative* understanding of the importance of different sources.

4.9 The three largest cities in India were selected as monitoring sites in this study. In addition, Chandigarh, a small city with a population of 0.8 million located in northern India, was selected as a suitable background site upwind of Delhi. Unfortunately, only five samples during the summer season were obtained in Chandigarh following the data collection protocols. Therefore, only limited results from Chandigarh are given in this report.

4.10 One urban residential site was selected in each city. Care was taken to avoid undue influence from heavy city traffic or industrial emissions, and at the same time enable the city plume to be captured. $PM_{2.5}$ samples were collected over consecutive 24-hour periods in Delhi, Kolkata, and Mumbai between March 2001 and January 2002. Samples were collected in Chandigarh in June and July 2001. The total number of days yielding useful results was 5 in Chandigarh, 21 in Delhi, 20 in Kolkata, and 25 in Mumbai. The details on when samples were collected (Table A4.2), the experimental setup, and how the data were analyzed are given in annex 4. The particles deposited on the filters were subjected to chemical speciation of sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), and other water-soluble inorganic compounds; determination of carbon and organic compounds by weight; and chemical speciation of the organic compounds by gas chromatography–mass spectroscopy (GC-MS).

Data

4.11 Seasonal averages of $PM_{2.5}$, carbon, and sulfate measurements in Delhi, Kolkata, and Mumbai are shown in Table 4.1. Delhi recorded the highest $PM_{2.5}$ concentrations except in winter when Kolkata was higher. Averaged over all the days when samples generating useful data were collected, $PM_{2.5}$ concentrations were $132 \mu\text{g}/\text{m}^3$ in Delhi, $56 \mu\text{g}/\text{m}^3$ in Mumbai, and $108 \mu\text{g}/\text{m}^3$ in Kolkata. When these numbers are compared with the U.S. standard of $65 \mu\text{g}/\text{m}^3$ for the 24-hour average (daily 98th percentile) and $15 \mu\text{g}/\text{m}^3$ for the annual average, it is

clear that the concentrations in these cities are alarmingly high. Carbon constituted about one-half of $PM_{2.5}$ in the three cities. Sulfates made up about 10 percent of $PM_{2.5}$.

Table 4.1 Seasonal Average Concentrations of $PM_{2.5}$, Carbon, and Sulfate

<i>Season</i>	<i>Component</i>	<i>Units</i>	<i>Delhi</i>	<i>Kolkata</i>	<i>Mumbai</i>
Spring	$PM_{2.5}$? g/m ³	114	55	36
	Elemental carbon	? g/m ³	9.1	6.1	3.7
	Organic carbon	? g/m ³	38	19	9.5
	Percent total carbon	wt% (weight percent)	41	44	37
	SO ₄ ²⁻ (sulfate ion)	? g/m ³	9.6	8.7	5.6
	Percent SO ₄ ²⁻	wt%	8.7	17	15
Summer	$PM_{2.5}$? g/m ³	49	26	21
	Elemental carbon	? g/m ³	4.0	6.6	1.1
	Organic carbon	? g/m ³	16	7.8	1.6
	Percent total carbon	wt%	40	55	13
	SO ₄ ²⁻	? g/m ³	5.2	3.0	3.1
	Percent SO ₄ ²⁻	wt%	11	11	14
Autumn	$PM_{2.5}$? g/m ³	159	45	64
	Elemental carbon	? g/m ³	11	9.1	5.6
	Organic carbon	? g/m ³	57	18	20
	Percent total carbon	wt%	44	62	38
	SO ₄ ²⁻	? g/m ³	10	4.0	7.9
	Percent SO ₄ ²⁻	wt%	6.7	7.6	12
Winter	$PM_{2.5}$? g/m ³	231	305	89
	Elemental carbon	? g/m ³	17	27	8.2
	Organic carbon	? g/m ³	96	147	34
	Percent total carbon	wt%	46	57	48
	SO ₄ ²⁻	? g/m ³	19	13	11
	Percent SO ₄ ²⁻	wt%	8.8	4.5	12

Note: All averages shown are averages of daily values. In the modeling results, an average percentage for component X in season Y is calculated as the percentage of the average weight of component X in season Y divided by the average weight of $PM_{2.5}$ in the same season. Here, daily percentage figures for component X are averaged over season Y.

4.12 It is important to emphasize that the definition of elemental and organic carbon is procedural. There are at least 15 international methods for determining elemental and organic carbon by combustion, none of which is free of artifacts. The numbers in this study are not directly comparable to those in other studies using different methods. With this limitation in mind,

the ratio of elemental carbon to organic carbon was low throughout the year in Delhi, about 0.2 to 0.3. Fine particles found in diesel engine exhaust and fuel oil combustion products tend to have a high elemental carbon to organic carbon ratio, exceeding 1.0 (using the method employed in this study for elemental and organic carbon determination), while gasoline cars not equipped with catalysts, biomass, and road dust tend to have a low ratio, of the order of 0.1. In Kolkata and Mumbai, this ratio rose in summer to 0.8–0.9 and declined in winter to 0.2. The summer and spring samples from Kolkata contained a disproportionately high percentage of elemental carbon, more than two-fold greater than in other samples. It is not clear if the samples were not representative or if this trend is typical of Kolkata in these two seasons. This merits further examination through more sample collection and analysis.

4.13 It is interesting to compare sulfate levels with changes in diesel sulfur that took place during sample collection in this study. While diesel sulfur was 500 parts per million by weight (wt ppm) during all the four seasons in Delhi, they changed in Mumbai and Kolkata. The details are given in Table 4.2. Kolkata is the only city where diesel sulfur was at 2,500 wt ppm for spring and summer. In Mumbai, diesel sulfur was already at 500 wt ppm for private vehicles, and changed from 2,500 to 500 wt ppm for commercial vehicles beginning with autumn sampling.

Table 4.2 Diesel Sulfur Specifications in Delhi, Kolkata, and Mumbai

<i>City</i>	<i>Private diesel vehicles</i>	<i>All diesel vehicles</i>
Delhi	2500 wt ppm until April 2000, 500 wt ppm thereafter	2500 wt ppm until March 2001, 500 wt ppm thereafter
Kolkata	2500 wt ppm until July 2001, 500 wt ppm thereafter	2500 wt ppm until October 2001, 500 wt ppm thereafter
Mumbai	2500 wt ppm until January 2001, 500 wt ppm thereafter	2500 wt ppm until October 2001, 500 wt ppm thereafter

4.14 There is no clear trend when ambient sulfate concentrations are examined, with the highest sulfate concentration in Kolkata occurring in winter, the only season when diesel sulfur was at 500 wt ppm for all vehicle categories. In terms of percent contribution of sulfates, there is a downward trend in Kolkata, but this includes from spring to summer, when there was no change in diesel sulfur. The number of samples collected is probably too small and the timing of sample collection was also sub-optimal to judge whether diesel sulfur reduction had a measurable impact on ambient sulfate concentrations. Larger numbers of samples collected before any diesel with 500 wt ppm sulfur was introduced and after all diesel had switched to 500 wt ppm, and compared in the same seasons, would have given more conclusive results.

Source contributions

4.15 Based on the results of chemical analysis and comparing them with chemical profiles of some of the important sources, estimates of contributions of different sources were made. The markers used in this study are described in annex 4 and included hopanes and

steranes, found in lubricating oil in gasoline and diesel vehicles and stationary diesel. The chemical mass balance model used in this study quantifies sources according to primary organic carbon from primary emissions (as opposed to secondary organic carbon formed in the atmosphere). After extensive analysis, five primary source profiles were retained in this work: gasoline, diesel, road dust, coal, and biomass. Of the five, regional source profiles were available only for biomass: coconut leaves, rice straw, cow dung, biomass briquette, and jackfruit branches, all from Bangladesh (Sheesley and others 2003). Source profiles for gasoline, diesel, and road dust obtained in the United States, and that for coal in Beijing were used for the remaining four sources. The absence of local source profiles is an important source of modeling uncertainties.

4.16 The profiles for gasoline, diesel, and coal can indicate the fuel used but not how or in which sector the fuel is combusted. For example, while virtually all gasoline can be safely attributed to mobile sources, it is not possible to distinguish between diesel burned in vehicles and diesel burned in stationary sources (such as small diesel power generators frequently used by shops in India). That said, external combustion engines emit much less particulate matter per unit of fuel burned than internal combustion engines. It should be mentioned that diesel in this study includes kerosene used in conjunction with lubricating oil (such as kerosene burned in engines, including vehicle engines) but not kerosene used in cooking because cook stoves do not use lubricant. Similarly, biomass burned by households is indistinguishable from biomass burned in bakeries and cottage industries. Nor is it possible to trace secondary sulfates, nitrates, and ammonium (obtained by subtracting calculated primary sulfates, nitrates, and ammonium from the total amounts measured in ambient samples) to different sources.

4.17 Of the 13 seasons examined (four seasons in three cities and one in Chandigarh), one season (summer in Mumbai) gave organic carbon that was below the detection limit for hydrocarbon speciation by GC-MS. The results from the remaining 12 seasons are shown by city and season in Table 4.3. The corresponding figures in $\mu\text{g}/\text{m}^3$ are given in Figure E.1.

Table 4.3 Percent Contributions of Different Sources to Ambient PM_{2.5}

<i>City and season</i>	<i>Diesel</i>	<i>Gasoline</i>	<i>Road dust</i>	<i>Coal</i>	<i>Biomass</i>	<i>Secondary sulfates</i>	<i>Secondary nitrates</i>	<i>Secondary ammonium</i>	<i>Total</i>
Chandigarh summer	7%	17%	32%	0%	9%	16%	2%	6%	90%
Delhi spring	18%	4%	16%	2%	22%	8%	2%	6%	77%
Delhi summer	23%	2%	41%	1%	10%	10%	3%	3%	91%
Delhi autumn	16%	3%	18%	2%	21%	6%	7%	2%	75%
Delhi winter	16%	7%	4%	9%	29%	8%	7%	5%	85%
Kolkata spring	24%	11%	28%	4%	19%	15%	2%	3%	107%
Kolkata summer	61%	8%	21%	1%	24%	10%	3%	1%	130%
Kolkata autumn	43%	21%	7%	5%	32%	8%	1%	2%	120%
Kolkata winter	15%	9%	5%	13%	17%	4%	3%	3%	70%
Mumbai spring	25%	3%	38%	0%	13%	15%	2%	2%	98%
Mumbai autumn	20%	2%	23%	1%	21%	12%	3%	3%	84%
Mumbai winter	21%	5%	16%	4%	13%	12%	3%	4%	78%

Note: Insufficient sample was collected in summer in Mumbai to carry out hydrocarbon speciation.

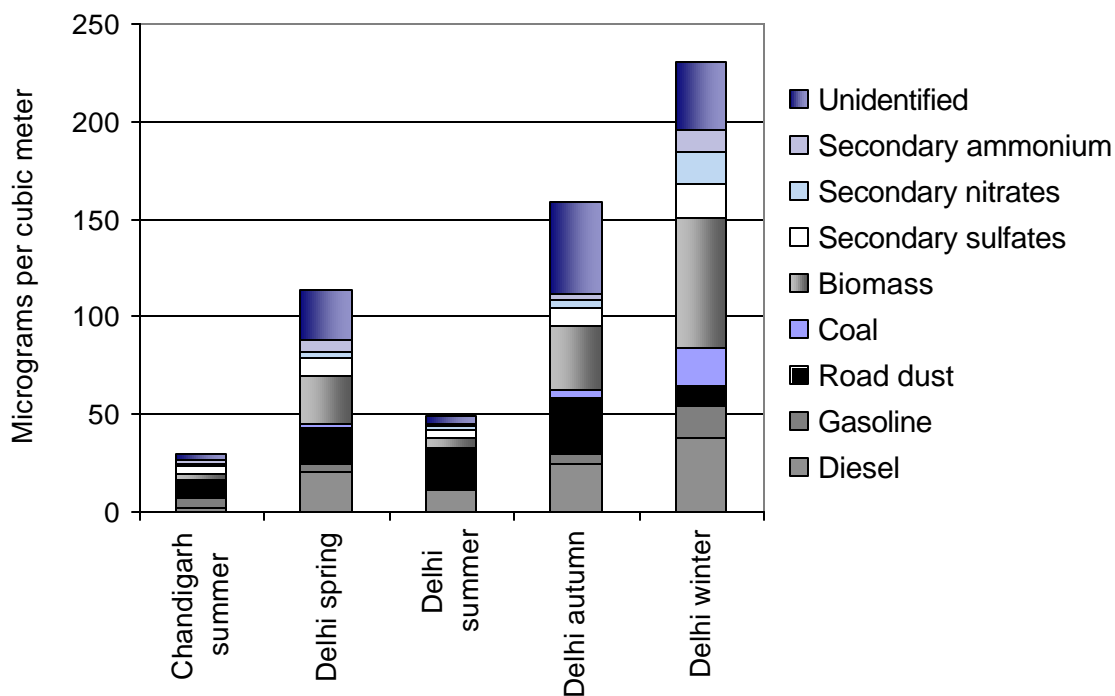
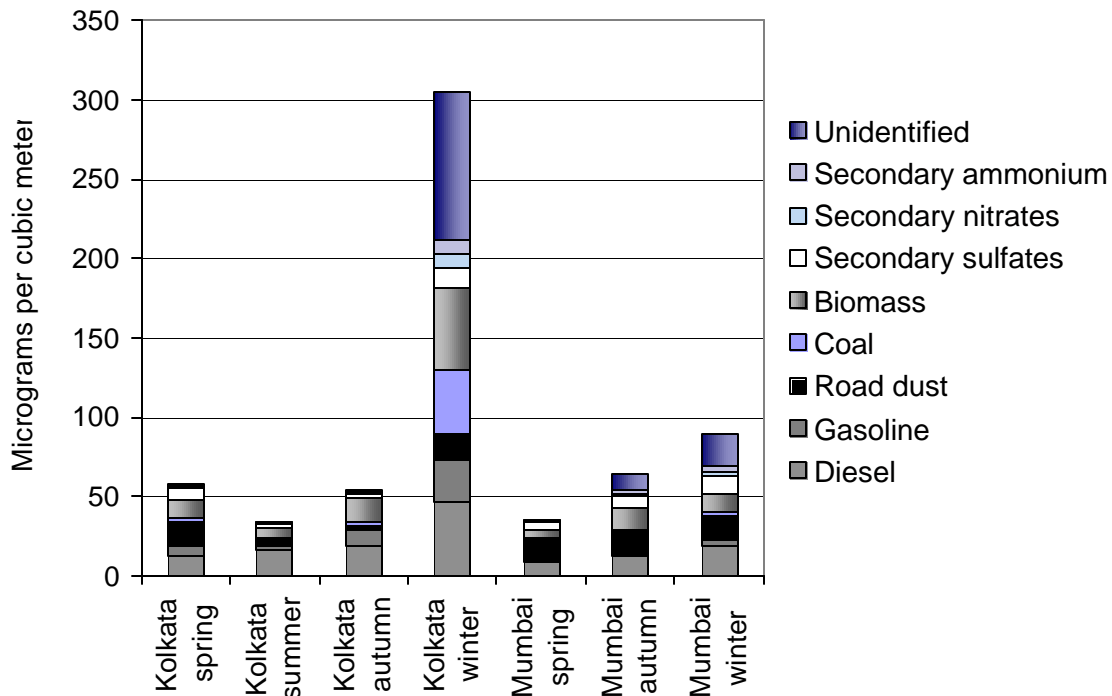
Figure 4.1 Estimates of PM_{2.5} Sources in Chandigarh and Delhi


Figure 4.2 Breakdown of PM_{2.5} Sources in Kolkata and Mumbai

4.18 “Unidentified” is the difference between the sum of components accounted for in source apportionment and the measured PM_{2.5} level. Unidentified organic species and water are some of the components making up the difference. One indication of the level of uncertainties that exist in this type of modeling is that for all but the winter season, the sum of the identified components exceeded 100 percent in Kolkata (and hence there were no unidentified components). It is clearly not possible for the sum of individual components to exceed the total, which is given by the measured ambient PM_{2.5} concentrations. This type of inconsistency is encountered in chemical mass balance modeling even in cities where much more detailed data are available, such as those in the United States.

4.19 There are several reasons why the sum of the contributions of identified sources can end up exceeding 100 percent. In fact, application of chemical mass balance receptor modeling often leads to apportioned mass greater than the measured value. Values ranging from 80 to 120 percent are considered acceptable (Watson and others 1990). As with all modeling based on measurements, errors in measurements will affect the modeling results, and measurement errors may be magnified if source profiles are similar. It can be shown that if two source profiles are similar, small variations in measurements can lead to large uncertainties in the source apportionment results. Omissions, variations, and errors in the source profiles affect the modeling results. The source profiles for vehicle emissions vary strongly as a function of the driving cycle, and this effect is much greater than those of fuel quality, vehicle technology, or the state of vehicle repair. If the driving cycle is markedly different, this could lead to greater

uncertainties. Road dust composition is likely to vary from region to region, with the result that the standard deviation can be as large as 100 percent or even greater. Quantification is based on contribution to primary organic carbon, and is scaled up to $PM_{2.5}$ by using the ratio of organic carbon to $PM_{2.5}$ (see Table A4.6). Underestimating this ratio can overestimate a source's contribution to $PM_{2.5}$, especially for those sources with low ratios of organic carbon to $PM_{2.5}$ such as road dust. Such overestimation in turn can result in summed contributions exceeding 100 percent of the measured ambient $PM_{2.5}$ concentrations.

4.20 Road dust was the largest contributor in three seasons, biomass combustion in two, and unidentified sources in the remaining three. That the diesel contribution exceeds that of gasoline in all cases appears reasonable given high consumption of diesel compared to gasoline in India. It is also interesting to note that despite the large number of two-stroke engine gasoline vehicles, which are known for high particulate emissions, diesel emissions appear to dominate. This would suggest that focusing on diesel vehicles should be given priority in air quality management. However, it can be difficult to separate gasoline and diesel contributions, so that the summed contribution of gasoline and diesel combustion is likely to be much more accurate than that of each individual fuel.

4.21 As mentioned earlier, it is not possible to distinguish between mobile and stationary sources of diesel combustion. If all of diesel is attributed to mobile sources, vehicle exhaust becomes the largest contributor in one season: Mumbai in winter at 26 percent. Secondary particulate formation comprised approximately one-tenth to one-fifth of $PM_{2.5}$. If all diesel, gasoline, secondary sulfates, and secondary nitrates are attributed to vehicle exhaust (an assumption that certainly does not hold, but gives an upper bound on the contribution from mobile sources) vehicle exhaust becomes the largest contributor in most seasons. Excluding those seasons where the sum of contributions from the identified sources exceeds 100 percent, the highest percentage contribution under this assumption is 44 percent, Mumbai in spring.

4.22 The contributions of secondary sulfates, nitrates, and ammonia are based on chemical analysis and assumptions about contributions from primary emissions, and are fairly robust. The markers for the five sources selected for examination in this study are reasonably easy to distinguish, but their quantification depends on a number of assumptions. Recent studies have shown that in the case of diesel vehicle exhaust, while vehicle technology, state of vehicle repair, operating conditions, and fuel quality all affect mass particulate emission levels, particulate composition is determined primarily by vehicle operating conditions and much less by fuel quality or vehicle technology (Kweon and others 2002). The contribution of road dust may carry large uncertainties. Sensitivity analysis using alternative source profiles in a recent study on $PM_{2.5}$ source apportionment in Hong Kong found that percent contributions of different sources could change two-fold or more (Zheng and others 2004b) depending on the source profile selected. The results presented above should therefore be interpreted with caution.

4.23 These limitations notwithstanding, the high carbon contents measured point to the importance of fossil fuel and biomass contribution to fine particulate air pollution in the three

Indian cities, and moreover suggest that a number of sources, rather than one dominant source, contribute to elevated ambient concentrations of fine particulate matter.

5

Policy Implications

5.1 This study has reviewed some of the broad principles for policy formulation and lessons from within South Asia as well as from other regions for urban air quality management. It has explored what specific measures can be taken to make one of the direct policy tools—vehicle emissions inspection—cost-effective. The study has also highlighted that, although smoky vehicles may be visible and numerous, other sources of air pollution can be equally important. Chemical mass balance receptor modeling using hydrocarbons as molecular markers showed that, at least in Delhi, Kolkata, and Mumbai, there appear to be three major sources of fine particulate pollution: vehicles, road dust, and solid fuels. This would suggest that vigorously pursuing control measures in one sector while leaving other sectors essentially untouched is less likely to result in a marked improvement in urban air quality than if a multipronged approach addressing a number of sources is adopted.

Policy Implications of the Findings of this Study

5.2 There is no simple or universal strategy for improving air quality. It is necessary for decisionmakers to consider policies within their own technical, economic, political, and institutional circumstances. While the specific actions for reducing air pollution will vary from city to city, there are several underlying principles that can guide the construction of an effective policy package.

- ?? Target gross polluters, and design and institute monitoring and enforcement mechanisms that ensure that high emitters are identified with reasonable accuracy and their operators take action to reduce emission levels.
- ?? Raise awareness among policymakers and the general public about urban air pollution levels and damages and specify and promote the role that different sectors play.
- ?? Press for sector reform that increases sector efficiency, benefits society at large by providing goods and services at lower cost, and at the same time reduces emissions.

?? Raise awareness about “best practice” in business as well as among consumers that is also likely to bring about environmental benefits to society.

?? Work with, not against, the economic incentives of various actors.

5.3 Different policy options can be ranked according to criteria that include the speed of response, ease of enforcement, and estimates of likely impact. A measure that requires a large number of individuals and firms to pay more or buy something extra for normal operation and maintenance of routinely used items has a smaller chance of success than if incremental operation costs are extremely small or if the incremental cost is incurred only once (for example, at the time of equipment purchase). Indirect policy tools have longer “gestation” periods with little immediate impact, but can also derail urban air quality management in the long run if poorly managed.

5.4 Given limited financial and human resources, selectivity has a number of significant advantages. Implementing a few policies rigorously is likely to be more effective than implementing a wide range of policy instruments with limited or no enforcement. Standards and regulations that are seldom enforced discredit the environmental policy framework and contribute little to air pollution reduction. It may also be easier to enforce standards and regulations among a smaller number of heavy users than across the entire population or industry because of the ease of monitoring. This is one of the reasons monitoring and enforcement among large industrial plants is often more successful than among small cottage industries. This also suggests that one of the first steps is to reduce emissions from large industrial sources.

5.5 That said, selectivity needs to be balanced against the risk of “leakage” when not everyone is covered. For example, if certain users are mandated to use more expensive emission control devices or more expensive but cleaner fuels, and others are exempted from such requirements, cheaper (and less clean) fuels can be diverted to those who should be purchasing cleaner fuels, or the expensive devices simply not installed (or maintained). If cleaner fuels are sold in urban centers while cheaper (and dirtier) fuels are sold just outside the city, users may travel to areas selling cheaper fuels and stock up, or large-scale clandestine distribution and sale of cheaper fuels inside the city may occur.

5.6 Observations and recommendations that can be made concerning the three principal sources of particulate air pollution identified in the PM_{2.5} source apportionment study are discussed below. It is worth noting in this respect that, as income levels in the large cities of South Asia rise, certain sources will decline in relative importance while others will likely contribute more to particulate air pollution. The latter include mobile sources because motorization inevitably accompanies economic growth in developing countries. In contrast, the use of solid fuels in cities is expected to decline over time.

Vehicle Exhaust Emissions

5.7 Setting increasingly tighter fuel quality and emission standards for new vehicles that can be realistically enforced, for example through extensive consultation with stakeholders in formulating the auto fuel policy in India, is an important step. Since lead is no longer used in

gasoline, it would make a great deal of sense to set gasoline emission standards at a level that would require three-way catalytic converters. They are by far the most effective means of controlling exhaust emissions from spark-ignition vehicles. The incremental cost of a converter is relatively small compared to the price of a new vehicle, and the emissions reduction effect is large and immediate. Data collected in California show that gasoline-fueled vehicles without functioning catalytic converters can be gross particulate polluters (Durbin and others 1999). Catalytic converters have been shown to lower CO and hydrocarbon emissions by more than 90 percent and NO_x emissions by 60–70 percent or higher. Particulate emission levels are so low that standards are not set for gasoline-fueled vehicles equipped with catalytic converters.

5.8 For new diesel vehicles, it would be extremely helpful to take the first step up the “diesel technology ladder” by moving from mechanical injection to electronic fuel injection. While the latter requires greater technical skills to maintain, there are significant fuel economy savings. Equally important, electronic fuel injection is a pre-requisite for a number of exhaust control devices. It is possible to meet Euro II emission standards (see annex 2 for a description of Euro II standards) by keeping mechanical injection and retarding ignition timing, but at a noticeable cost to fuel economy. Vehicles with mechanical injection, in turn, smoke when laboring under load no matter how well they are maintained.

5.9 With respect to diesel fuel quality, India has already announced that it will lower sulfur in diesel to 0.05 percent throughout the country by 2005, and several large cities have already done so. A maximum sulfur level of 0.05 percent is required for meeting Euro II emission standards (which went into effect in Europe in 1996). Because Nepal imports fuels exclusively from India, Nepal will follow the Indian fuel quality standards. Sri Lanka plans to move to 0.3 percent in 2005, but there are not yet firm plans for 0.05 percent sulfur. Bangladesh and Pakistan, on the other hand, have no plans to move away from the current limit for the domestically produced diesel sulfur level of 1 percent (with the actual level averaging about 0.6 to 0.7 percent). Such diesel sulfur levels are high by any standard. At these levels, it would not be possible to mandate even Euro I emission standards (see annex 2). It would be useful to start developing a concrete plan to lower diesel sulfur with a clearly defined time table. One short- to medium-term option is to have regionally differentiated fuel standards so that heavily polluted metro cities are supplied with cleaner fuels.

5.10 For the purpose of reducing emissions from individual vehicles, both technology-based solutions (cleaner fuels and vehicles) and enforcing proper maintenance through an effective I/M system are needed. The vast majority of emissions in transport are from poorly maintained, old technology vehicles. This study suggests that, given the widespread lack of effectiveness of “traditional” I/M systems in South Asia as elsewhere, a much more rigorous approach incorporating far greater control on the test protocols, data collection, storage, transfer, and analysis in a targeted system is likely to be required for I/M to contribute measurably to air pollution reduction. One option is to mount rigorous I/M for commercial diesel vehicles in large cities with serious particulate air pollution.

5.11 The situation is aggravated when traffic congestion forces vehicles to stop and start frequently, resulting in rapid acceleration and deceleration each time. This not only wastes fuel, but also increases particulate emissions markedly. Traffic system management and demand management are important components of mitigation measures for transport-related air pollution. Traffic management measures are relatively cheap and quick-acting, but they are not a guaranteed, one-shot cure for traffic congestion. They need effective planning, implementation, and enforcement skills and a high and continuing degree of political, institutional, and human resource commitment, all of which tend to be in short supply in South Asia.

5.12 Fundamental to the successful implementation of traffic management measures is the establishment of a traffic management unit at the local government level with the consolidated authority and ability to plan and implement suitable traffic management schemes. The role of the police in complementary enforcement activities is also essential. The traffic management system implemented in Mumbai in the 1980s is now largely out of commission because of institutional failures. Institutional factors are critical to the success of traffic management. In particular, it is important to make the environmental effects of urban transport one of the responsibilities of urban transport and land-use institutions even where there is a parallel institutional responsibility for air quality protection.

5.13 The adulteration of gasoline with kerosene, which is documented to occur in Bangladesh and India, is damaging to air quality. It is especially problematic in India where kerosene for household use is heavily subsidized. One market-based approach to tackling fuel adulteration is to encourage oil marketing firms to guarantee product quality. The incentive for the firm is that retail outlets known not to engage in adulteration and other abuses might be able to expand their market shares and drive out unscrupulous competitors. This is occurring in India and Pakistan. An example is the Enhanced Fuel Proposition program launched by Bharat Petroleum in India (see the Bharat Petroleum website), a nationwide voluntary effort to dispense standard-compliant quality and correct quantity of fuel. The retail outlets covered under this program display the “Pure for Sure” sign. At retail outlets displaying this sign, Bharat Petroleum guarantees that the correct quality and quantity are dispensed, for which the firm assures that it has put in place strict quality control and tracking measures at every point in the supply chain, from the depot to the customer’s fuel tank. If voluntary efforts are not enough, government may consider making oil marketing companies legally responsible for the quality of the fuels sold by their franchisees.

Re-suspended Road Dust

5.14 Some of what is classified as re-suspended road dust, which is geological matter, is dust that is transported over a long range. Locally generated re-suspended road dust, however, is something that can be directly addressed by simple urban designs and landscaping. Whenever these urban design features have been implemented, local air quality improves markedly as a result of smoother traffic flows and dramatically lower dust re-suspension. They can be implemented at a small incremental cost in many road projects, bringing significant environmental benefits. Whenever possible, road projects should include provision for paving all

sections of the road including sidewalks, and where paving is not practical, landscaping with trees that require no watering.

5.15 An example from India of successful integration of transport and urban planning policies and involvement of the private sector illustrates what can be achieved. Along the five-kilometer-long C.G. Road in Ahmedabad, a very simple road cross section design has dramatically improved through-traffic flows by separating through-traffic and service lanes. At the same time, the amount of managed parking space was increased, and simple paving and landscaping reduced dust re-suspension (see the Best Practice Database). All this was funded by a consortium of private firms that were given advertising rights in return.

Solid Fuels

5.16 Solid fuels are much more polluting than liquid or gaseous fuels but are also cheaper, and their low cost becomes an important consideration especially when large quantities of fuels are needed, such as for space heating in winter in cold climate regions. In the long run, switching out of solid fuels to liquid and gaseous fuels is the most effective mitigation measure for small fuel users, and installing emission control devices with high efficiency in the absence of fuel change is the most effective measure for large industrial users.

5.17 In Bangladesh and Pakistan, which have abundant domestic reserves of natural gas, expansion of natural gas pipelines in large cities can help in the medium and long term to reduce dependence on solid fuels. An important policy question here is how to charge households and other small users for the cost of initial gas connection, which can be high. In Pakistan, a sizeable fraction of urban households pay more to purchase biomass than those who use only natural gas for all their household energy needs. In some cases this is because it is not economic to connect the household to gas (because the neighborhood or the town lacks economies of scale). In other cases, however, the reason is that the household cannot afford the connection fee. It is sobering to note that even in much higher-income, gas-abundant South American countries, many poor urban households continue to use LPG when the operating cost is much lower for natural gas because they cannot afford the gas connection fee. An alternative to charging each individual user is to roll a large portion of the connection cost into gas tariffs, thereby spreading it across more users and even future generations of users. Connection fees for small low-income users can also be cross-subsidized by larger industrial users. Another option is an outright subsidy by the government. In any scheme involving implicit or explicit subsidies, if recipients can be selected through a means test, the burden on other users and government can be reduced, but means testing has been difficult in South Asia. The pros and cons of the different options should be carefully considered.

5.18 Nepal and Sri Lanka have no natural gas. In these countries as well as cities in other countries without natural gas, cleaner alternative fuels for small users are kerosene, LPG, and electricity, although kerosene can be polluting if not burned efficiently. Heating with LPG or electricity would be very expensive. Fuel switching is not an immediate option for many users, and solid fuels will continue to be used for the foreseeable future, especially for space heating.

From a technical point of view, a critical question is how to decrease the extent of incomplete combustion. This is a separate issue from overall stove efficiency. An improved stove can increase the overall stove efficiency *and* particulate emissions at the same time (Edwards and others 2004). This is an area that needs to be understood more. In some cases, biomass briquettes may be a viable cleaner alternative.

Roles of Different Stakeholders

5.19 In formulating and implementing a policy package, divergent stakeholders play different roles. Government sets regulations, enforces them, and provides financing for certain activities. Civil society not only pays for and benefits from air quality improvement, but can also influence government policy through votes and other means. NGOs can raise awareness and act as advocacy as well as pressure groups. The involvement of the private sector through consultation in standard-setting and fostering market-based approaches to air pollution control can be especially beneficial.

National Government

5.20 National government is usually the only agency that is commissioned to set policy and standards for ambient air and fuel quality, and limit emission and discharge levels; define what constitutes noncompliance; and stipulate the consequences of noncompliance. National government also sets fiscal policy, although individual states or provinces and cities may impose additional taxes and fines.

5.21 There may also be a range of direct expenditures that, because of their public-good characteristics, are likely to be undertaken only if centrally financed. These may include expenditures on air quality monitoring, environmental research, central laboratory facilities, and environmental education and information programs. National government should accept the responsibility for encouraging clean air by having a policy on clean air-related public expenditures.

5.22 The level and structure of taxation, which is usually a national government prerogative, is very important as an inducement to environmentally sensitive decisionmaking on the choice of technology as well as on the amount of energy and transport demanded. It is important that taxation powers be exercised with environmental as well as revenue-generation considerations in mind. Increasing the efficiency of tax collection can play an important role in South Asia. The ability to tax all final goods can be especially helpful, because it enables efficient allocation of resources reflecting social and environmental damage. But this presumes that most individuals and firms pay taxes and differentiated taxation can be effectively enforced. This is not yet the case in South Asia. As a result, differentiated vehicle taxation—for example, annual registration fees that include fuel choice as a criterion for light- and medium-duty vehicles to discourage the purchase of more polluting diesel vehicles—is not yet considered practical in countries such as Pakistan. But as chapter 3 shows, relying primarily on fuel taxation to discourage diesel vehicle use is very much suboptimal.

5.23 Concerted action within and among actors in different sectors is important for optimal policy formulation. Environment, industry, finance, transport, oil and gas, and urban planning are principal sectors that have a stake in, as well as a direct influence on, mitigation measures to control air pollution. In some cases the problem is simply a matter of lack of coordination; in others, there may be clear conflicts of interest among different ministries or agencies. At the national level, for example, the environment ministry may want a low tax on CNG, whereas the finance ministry may not want transport fuels to carry a low tax, especially if a low tax on CNG means large-scale switching from high-tax gasoline to CNG. It is important to encourage close collaboration among the national ministries of environment, industry, transport, finance, and energy on air pollution strategy.

5.24 Which ministry sets which standards and is responsible for monitoring is an important question. In South Asia, environment ministries tend to be underfunded, making it difficult for them to monitor and enforce compliance. They may even lack the expertise to establish standards and defend them before other ministries. But if fuel quality standards are brought under the auspices of the petroleum ministry, or vehicle emission standards under transport, there may be a conflict of interest. For example, the petroleum ministry may be more concerned to minimize price fluctuations and increases, thereby not wishing to see rapid tightening of fuel specifications even if they are warranted in some cities with heavy pollution. This is especially true if there is a large domestic refining sector, or if some refineries are state-owned. In the extreme, if there is a refinery that is guaranteed a minimum return on capital investment by the government, as in Pakistan, even the finance ministry may be reluctant to see tightening of fuel standards and support the position of the petroleum ministry. On the other hand, if the environment ministry is empowered with the responsibility to set fuel quality standards and announces tighter fuel specifications, only to watch the implementation dates slip time and again as has happened in other countries such as Colombia, setting more stringent fuel quality standards does little to improve air quality and discredits environmental policy. These considerations point all the more to the importance of close and frequent communication and negotiation among different sectors, and of paying explicit regard to air pollution impacts of different sector policies.

5.25 While government may consult industry and civil society about standards, it should not outsource responsibility for policy development and standard setting. For anything that requires major capital investments, such as refinery revamps, a lead time of several years is necessary. New investment may be difficult to attract if there is a great deal of uncertainty about how rapidly tighter standards would be adopted in the future or if government decisions are reversed from time to time. What is especially important in this respect is the establishment of a *predictable* and *consistent* policy and regulatory framework that will help attract the private sector financing needed to implement cleaner production, technology, and fuels.

State or Provincial and Municipal Governments

5.26 Air pollution problems are location-specific. Once standards are set, particularly if there is geographic differentiation, it is state or provincial and municipal governments that act

to implement them. Governments at these levels monitor air quality, emission and discharge levels, and fuel and lubricant quality; integrate air quality considerations into overall city development plans; develop traffic flow, demand management, and other strategies for mitigating traffic congestion and emissions; and, where appropriate and fiscally possible, offer financial and other incentives to facilitate cleaner technology and fuels, retirement of old equipment and vehicles, and other means of mitigating air pollution.

5.27 That powers should be devolved to the level in the hierarchy of government at which they can be most effectively implemented is a generally sensible principle. This may require granting some powers to local authorities to levy surcharges as part of local environmental policy or to be able to retain a portion of fees collected. Where responsibility for air pollution control is decentralized, appropriate fiscal arrangements need to be made to facilitate local ability to meet those responsibilities. All too often, a lack of funds is the most critical factor hampering air quality monitoring and enforcing environmental rules and regulations. Under these circumstances, it would be better to be ruthlessly selective about standards to be enforced and how often and what will be monitored, focusing only on those subgroups most likely to contain a disproportionate fraction of gross polluters. But this decision often rests with national government, and hence the need for frequent discussion between national and municipal governments. In air quality monitoring, source apportionment studies, and analysis of emissions data, close collaboration with universities and research institutions that already have the requisite technical expertise, if not scientific instruments, can be very helpful.

5.28 Fragmentation of responsibility between hierarchies of government can also cause problems. If different cities and provinces or states with comparable air pollution and population exposure allocate varying amounts of funds for air quality monitoring and mitigation measures with the result that some large cities lack even basic data on ambient air quality, it would be difficult for the national government to formulate a sensible air quality management strategy. Another example is different states pursuing their own version of vehicle I/M, as is happening in India today. As chapter 2 argues, there are considerable merits to centralized software development and standardizing test protocols and equipment specifications. Having the same air quality monitoring equipment specifications and procedures is yet another example of where standardizing across the country makes much more sense.

5.29 Problems arising from different objectives in different ministries and departments need to be addressed. At the national level such conflicts may be aired and find their resolution in high-level cabinet decisions. At the municipal level, the police, city planning, environment, transport, and other agencies are frequently less well coordinated. As an illustration, the police may wish to give priority to cars at junctions to keep traffic moving while the transport department may wish to give priority to buses to attract passengers to public transport. This conflict will be accentuated if the police report directly to a central ministry rather than through the local authority structure. The paucity of adequate technical advice and the absence of an effective political representation of some sector interests in mayoral decisions may also result in sub-optimal resolution of such conflicts.

5.30 At the municipal or city level the solution may be to establish a specific responsibility for urban air quality within the municipal government structure. Taking transport as an example, most U.S. and European cities with well-integrated urban transport policies have agencies with comprehensive responsibility for establishing a transport and land-use plan, with air quality as one of its objectives, to which contributory technical functions (traffic management, public transport policy, and road investment) must conform.

Nongovernmental Organizations and Civil Society

5.31 Nearly all of civil society is affected by air quality management. Tighter standards usually mean high prices of goods purchased. Poor air quality management, on the other hand, means low visibility, breathing in smoke, more illnesses, and even premature mortality among some residents. A ban on two-stroke engine three-wheelers or diesel buses may mean a severe shortage of public transport vehicles in the months following the ban, substantially reducing mobility.

5.32 Lack of information is one critical factor hampering the introduction and implementation of good air pollution control policies. Residents may notice black smoke, but may not recognize the toxicity of invisible pollutants. Or some may note that smoke from biomass combustion causes their eyes to water, but not link smoke to much more damaging health effects. Government can do more to inform civil society about why it is taking certain unpopular actions to reduce air pollution. Conversely, civil society, and particularly NGOs, can bring pressure on government to take more action by raising public awareness and conducting campaigns.

5.33 Information dissemination is one of the most important roles that NGOs and the media can play. For example, the decision to increase the tax on diesel to better reflect its externality (road, congestion, and environmental damage caused by the use of diesel not paid for by the diesel user), a useful step in every country in South Asia, may be sound but is almost universally politically unpopular. It would be helpful to inform the public about the downside of *not* increasing the price of diesel so that residents are fully informed about the costs as well as the benefits of having cheap diesel. More generally, NGOs and the media can be especially helpful in raising public awareness about the costs and benefits of measures to improve air quality, especially where behavioral changes are involved. In South Asia, NGOs and the media campaigned tirelessly for a ban on lead in gasoline by raising public awareness about the serious damage to public health caused by airborne lead and supporting acceleration of lead phasedown. NGOs and the media can urge and help the government implement new policy measures by playing an advocacy role.

5.34 NGOs in South Asia have collected data and published them to raise public awareness and to argue for more rigorous monitoring, enforcement, or tighter standards. This type of additional information is especially powerful when collected and presented by well-respected research institutions, universities, and environmental NGOs. “Naming and shaming,”

whereby those in flagrant violation of environmental regulations are published by name, can be another effective strategy, as is public listing of “green” companies and products.

5.35 Sector reforms are often prevented because a small number of vested interest groups stand to benefit from the existing system. Informing the public about the advantages of sector reforms, including environmental benefits, can create public pressure on the government to press on with the reform measures. This is especially relevant when environmental improvement is lagging behind because of protection of domestic industries that are inefficient or are so powerful that the government refrains from taking steps that will not bring about commercial benefits for them. Tremendous public pressure can make it easier for the segment of the government wanting to move forward with tighter environmental standards to confront powerful lobbies defending their own interests.

Private Sector

5.36 Many of the entities that implement activities that affect urban air quality are in the private sector. These include industrial and commercial firms, shops burning solid fuels or using diesel generators, fuel and vehicle manufacturers, public transport companies, households burning refuse and solid fuels, and individuals using private vehicles. For an air quality policy to be effective, all of these agents must have some incentive to behave in a way consistent with the policy.

5.37 Those incentives may be financial, where taxes are used to make socially desirable behavior individually attractive; legal, where penalties are attached to nonobservance of environmental standards; or moral, where antisocial behavior is sufficiently well identified and advertised for peer pressure to influence behavior. In all of these dimensions, but particularly in the last, the incentives are likely to be more powerful if the agents themselves have been involved in the formulation of the policies. For example, the formulation of India’s auto fuel policy closely involved vehicle and fuel manufacturers, greatly enhancing the chances of its effective implementation at the manufacturing level.

5.38 Where a certain decision is bound to have an adverse impact on the private sector, working closely with the affected parties prior to implementing the decision and possibly negotiating compensating measures could go a long way in minimizing social unrest. In Dhaka, Bangladesh, all two-stroke engine three-wheelers were banned effective January 2003. Given the large number of vehicle owners and drivers involved, numbering tens of thousands, this could have resulted in a large-scale general strike with serious economic and security consequences. However, years of consultation and negotiation prior to the implementation of the ban—so that the affected individuals had time to consider how the new policy would affect them and to seek alternative employment—helped smooth the transition.

5.39 Removing institutional and market barriers to the involvement of the private sector in areas such as monitoring, including self-monitoring as started in Pakistan, would be a useful step. The potential for the private sector and NGOs to take over from the government some monitoring and enforcement responsibilities should be explored. However, it is also

important to stress that outsourcing these functions does not mean that the cost to the government will fall dramatically. The experience with vehicle I/M in Mexico City demonstrates that the government must be committed to investing the resources, staff, and effort in auditing and supervising the environmentally driven programs to achieve high levels of objectivity and transparency.

5.40 Enforcing compliance is important not only from the point of view of air quality improvement, but more importantly, for promoting sector efficiency. Otherwise, a likely outcome is partial or total degradation of the market—an example of Gresham’s Law that the low-quality product drives out the high-quality product because of an inability to distinguish between the two. This applies not only to fuels, spare parts, and other items that consumers buy directly, but also whether a factory is equipped to meet emission and discharge standards, or a goods carrier can meet the safety and exhaust emission standards. The legitimate private sector can benefit from better standards of compliance. This may arise when the level of public awareness about fraud increases, so that those who guarantee quality can expand their market share. This underscores the importance of public education. Creating market conditions that would encourage private sector actors to police themselves for compliance with regulations and standards is a “no-regret” situation.

Cross-Sectoral Coordination

5.41 Air quality management is complex because a large number of stakeholders, often in different sectors driven by objectives and motives other than environmental improvement, are involved. In the case of vehicles and solid fuels, the sector is very fragmented both on the supply and demand sides, with most actors—individual and corporate users of transport services and transport suppliers, and household and small commercial or industrial users of biomass and coal and solid fuel sellers—motivated by private benefit or profit. For these reasons, whenever possible, strategies to reduce air pollution should be designed to be seen as in the private interests of the actors as well as in the social interest.

5.42 The three sources of particulate air pollution identified in this study—vehicles, road dust, and solid fuels—all have principal stakeholders outside of the environment ministry. Setting emission standards can easily involve four ministries simultaneously: environment, petroleum, industry (for stationary sources) or transport (for mobile sources), and finance (in charge of setting taxes, ranging from fuel taxes to duties on imported emissions control devices). Conflicting interests and lack of adequate communication have all too often led to delays in adopting policies that can improve air quality at a small incremental cost. Air quality management requires sustained and cooperative actions over a long period. Forging cross-sectoral coordination is essential. An example of successful coordination across different stakeholders and government agencies is the case of gasoline lead phaseout in Sri Lanka, where cooperation among environmental, transport, and petroleum sectors helped to bring forward the target date for lead removal by eight years, from 2010 to 2002. At the same time, no city can implement a large number of measures all at once, however desirable. Different and typically

increasingly stringent mitigation measures are inevitably phased in stages. As new measures are implemented, it is helpful to monitor progress, and assess and discuss the perceived benefits and costs at each stage.

Annex 1

Estimating and Valuing the Health Impacts of Air Pollution

A1.1 Air pollution has been associated with a variety of adverse health effects (see Table A1.1). These include impairments in lung function, increased incidence of chronic bronchitis, exacerbation of chronic respiratory disease (that is, asthma) or coronary disease (such as angina), and premature mortality from respiratory and cardiovascular disease. Less serious effects include increased incidence of acute respiratory illness (colds and sinus problems) and sub-clinical effects (itchy, watery eyes). This annex summarizes two briefing notes, No. 11 and No. 12, produced through this study.

A1.2 The most important health effects, in terms of economic damages that can be assigned monetary values, are premature mortality and increased incidence of chronic heart and lung disease. The air pollutants that have shown the strongest association with premature mortality and heart and lung disease are PM and airborne lead. PM has also been associated with hospital admissions, respiratory infections, and asthma attacks. Ozone has also been associated with mortality, hospital admissions, asthma attacks and respiratory restricted activity days (RADs), days on which a person cuts back on his or her normal activities, but does not necessarily miss work or stay in bed. SO₂ and NO_x do not have such significant direct effects, though they do have important health consequences because of secondary particulate formation: sulfates and nitrates react with ammonia and other substances in the atmosphere to form particulate matter, such as ammonium sulfate and ammonium nitrate.

Table A1.1 Human Health Effects of the Common Air Pollutants

<i>Pollutant</i>	<i>Quantified health effects</i>	<i>Unquantified health effects</i>	<i>Other possible effects</i>
Ozone	Mortality Morbidity: Respiratory symptoms Minor RADs Respiratory RADs Hospital admissions Asthma attacks Changes in pulmonary function Chronic sinusitis and hay fever	Increased airway responsiveness to stimuli Centroacinar fibrosis Inflammation in the lung	Immunologic changes Chronic respiratory diseases Extrapulmonary effects (changes in the structure or function of the organs)
Particulate matter / TSP/ Sulfates	Mortality Morbidity: Chronic and acute bronchitis Hospital admissions Lower respiratory illness Upper respiratory illness Chest illness Respiratory symptoms Minor RADs All RADs Days of work loss Moderate or worse asthma status (asthmatics)	Changes in pulmonary function	Chronic respiratory diseases other than chronic bronchitis Inflammation of the lung
Carbon monoxide	Morbidity: Hospital admissions— congestive heart failure Decreased time to onset of angina	Behavioral effects Other hospital admissions	Other cardiovascular effects Developmental effects
Nitrogen oxides	Morbidity: Respiratory illness	Increased airway responsiveness	Decreased pulmonary function Inflammation of the lung Immunological changes
Sulfur dioxide	Morbidity in exercising asthmatics: Changes in pulmonary function Respiratory symptoms		Respiratory symptoms in non-asthmatics Hospital admissions

<i>Pollutant</i>	<i>Quantified health effects</i>	<i>Unquantified health effects</i>	<i>Other possible effects</i>
Lead	Mortality Morbidity: Hypertension Nonfatal coronary heart disease Nonfatal strokes Intelligence quotient (IQ) loss effect on lifetime earnings IQ loss effects on special education needs	Health effects for individuals in age ranges other than those studied Neurobehavioral function Other cardiovascular diseases Reproductive effects Fetal effects from maternal exposure Delinquent and antisocial behavior in children	

Source: U.S. EPA (1997).

A1.3 This annex presents the methods used to estimate the health impacts of particulate air pollution, followed by those used to perform economic valuation of changes in illness and premature mortality, and discusses the appropriateness of transferring health benefit estimates from studies in other regions to developing countries. The annex gives sample calculations as well as illustrations of how the monetary value of health benefits associated with improvements in air pollution can be useful to policymakers.

Methodology for Estimating Health Effects

A1.4 Estimating the health impacts of air pollution reductions entails three steps. First, the demographic groups susceptible to air pollution and associated health outcomes are identified based almost exclusively on epidemiological studies. These studies determine relationships—referred to as concentration-response (CR) functions—between air pollution and health effects in human populations. CR functions empirically explain variations in the number of cases of illness or death observed in a population based on changes in the ambient concentrations of the air pollutants and other known explanatory factors. These other factors, called *confounding factors* (those that also affect health outcomes, making it difficult to attribute cause), include demographics (such as age, gender, marital status, diet, body mass, smoking, health habits, occupational exposure, education, and income), other pollutants, and time-varying factors (temperature, seasonality, day of week). CR functions may apply to the whole population or to specific demographic groups only. Virtually all CR functions assume that each unit decrease in the ambient concentration of a pollutant results in a fixed percentage change in the cases of illness or deaths avoided, independent of the initial pollution level. This assumption may not be valid when ambient concentration levels are several-fold higher than in cities where studies have been conducted, as is the case when applying CR functions estimated in industrial countries for fine particles to cities in developing countries.

A1.5 Ideally, cities considering significant policy changes to address air pollution problems should conduct an epidemiological study locally. In practice, the complexity and costs of undertaking these studies have limited the number of such studies. Instead, cities typically transfer information on health impacts of pollutants on the susceptible demographic groups from

existing studies conducted elsewhere. Figure A1.1 gives an example of a CR function transferred in a health impact estimation study of Mexico City (World Bank 2002). Similar functions are available for other health impacts from PM₁₀ as well as other pollutants such as ozone. The appropriateness of transferring these functions depends on whether the confounding factors for the city are similar to those for the cities included in the transferred epidemiological studies.

Figure A1.1 Sample Calculation from Mexico City—Estimating Impact of Lowering PM₁₀ Concentrations on Avoided Hospital Admissions for Respiratory Problems

Step 1: Epidemiological study (transferred)

Demographic groups: all

Concentration-response relationship: 0.139% change in hospital admissions for a change in the daily average PM₁₀ concentration of 1 $\mu\text{g}/\text{m}^3$

Step 2: Data from Mexico City

Population at risk: 18,787,934 persons

Baseline rate of hospital admissions for respiratory problems: 411 admissions per 100,000 persons

Baseline number of hospital admission: Population at risk \times 0.00411 admissions/person = 77,218 admissions

Current population-weighted annual average PM₁₀ concentration: 64 $\mu\text{g}/\text{m}^3$

Population-weighted annual PM₁₀ concentration after policy implementation: 51.2 $\mu\text{g}/\text{m}^3$

Change in PM₁₀ concentration in response to policy implementation: 64 $\mu\text{g}/\text{m}^3$ – 51.2 $\mu\text{g}/\text{m}^3$ = 12.8 $\mu\text{g}/\text{m}^3$

Step 3: Calculation of estimated avoided cases

Avoided hospital admissions: 77,218 admissions \times 0.00139 change/ $\mu\text{g}/\text{m}^3$ \times 12.8 $\mu\text{g}/\text{m}^3$ = 1,376 admissions.

Note: Reduced hospital admissions are only one of the health benefits of reducing PM₁₀ concentrations. Other impacts include premature death and less serious illnesses not requiring hospitalization.

A1.6 The second step in health impact estimation requires two pieces of information about the city: (1) the baseline cases of illness or death; and (2) the change in the population exposure to the pollutant. Baseline cases are typically estimated from the total population and the case incidence rate. The change in the population exposure is the difference between the current exposure level and estimates of population exposure levels after air pollution reductions are achieved.

A1.7 Pollutant exposure levels are difficult to estimate because of varying personal time-activity patterns. As a result, health impacts are generally based on the population-

weighted average ambient concentration of the pollutant across the city's susceptible residents. These ambient levels are estimated from the concentrations of the pollutants measured at fixed monitoring sites located in different parts of the city. It is important to ensure that the monitoring sites are representative of average exposure and are not unduly influenced by pollution "hot spots" such as inner-city transport corridors or industrial zones.

A1.8 The estimated burden of disease from air pollution, such as 800,000 deaths annually in the world reported in a recent publication (WHO 2002), provides a useful benchmark for comparing the relative magnitude of different health risk factors. However, these deaths and other health estimates are not an appropriate basis for comparing different air pollution reduction strategies. Burden-of-disease estimates are based on reducing air pollution to the theoretically minimum levels (for example, PM₁₀ concentration of 15 µg/m³). Pollution reductions to such low levels have not been achieved in many U.S. and European cities, and it would be unrealistic to assume that many heavily polluted developing country cities are in a position to reach these levels in the near future. Instead, health gain estimates should be determined for each pollution reduction strategy based on the expected population exposure reductions.

A1.9 The estimated avoided cases of illness or disease are calculated in the third step using the information collected in the first two steps. Figure A1.1 illustrates how the estimated avoided cases of hospital admissions for respiratory disease are calculated for Mexico City for a 20 percent reduction in population exposures to PM₁₀. The avoided cases provide a concrete measure of health gains understandable to a wide range of policymakers.

Results from Existing Epidemiological Studies

A1.10 Epidemiological studies can be grouped according to how exposure is measured (acute exposure studies and chronic exposure studies) and how health effects are measured (individual-based panel or cohort studies and population-based or ecological studies). Most studies in the scientific literature have examined acute, not chronic, health consequences.

Human health impacts of acute exposure to particulate air pollution

A1.11 Acute exposure studies examine the associations between short-term (daily or multiday average) variations in PM concentrations and short-term counts of total deaths, cause-specific deaths, or incidence of specific illness in an area (typically a city). The popularity of these studies stems from their minimal data requirement compared with other study designs. Problems associated with confounding are reduced in these studies because population characteristics (such as smoking and occupational exposures) do not change much over the study period for the study population. In addition to air pollution, temporal and meteorological conditions and the age of the individual are the main factors that are included in these studies. While these studies provide health impact estimates for the city being studied, the CR functions obtained are not readily transferable to cities with different population characteristics.

A1.12 However, the consistent findings across a wide array of cities, including those in developing countries with diverse population and possibly PM characteristics, strongly indicate that the health gains indeed result from PM pollution reductions. Meta-analysis—which pools results from several studies—of acute exposure studies provides health impact estimates that are more transferable than results from individual studies. These results indicate that every $10 \mu\text{g}/\text{m}^3$ increase in the daily or multiday average concentration of PM_{10} increases (1) non-trauma deaths by 0.8 percent; (2) hospital admissions for respiratory and cardiovascular diseases by 1.4 and 0.6 percent, respectively; (3) emergency room visits by 3.1 percent; (4) restricted activity days by 7.7 percent; and (5) cough with phlegm in children by 3.3 to 4.5 (Cohen and others 2003, Holgate and others 1999). The studies also indicate higher risk for the elderly with chronic heart and lung disease and for infants.

Human health impacts of chronic exposure to particulate air pollution

A1.13 Chronic exposure studies examine the impact of long-term exposure to PM air pollution as well as the cumulative effects of short-term elevated PM levels. These studies compare differences in health outcomes across several locations at a selected period in time. Some portion of the long-term impacts indicated by these studies corresponds to the impact of acute effects revealed in acute exposure studies. The remainder is caused by latent or chronic effects of cumulative exposure.

A1.14 Ecological studies, which use population-wide measures of health outcomes, have consistently found increased mortality rates in cities with higher PM levels. However, the inability to isolate the effects of PM from alternative explanatory factors (that is, confounding factors such as smoking, dietary habits, age, and income) that might vary among populations in different cities raises doubts about the reliability of these CR functions.

A1.15 Cohort design studies overcome these questions by following a sample of individuals, thereby making it easier to isolate the effects of confounding factors. These studies provide the most compelling evidence about mortality effects from chronic exposure to PM. The largest study to date (Pope and others 2002) indicates that a change in long-term exposure to $\text{PM}_{2.5}$ of $10 \mu\text{g}/\text{m}^3$ leads to a 4, 6, and 8 percent increase in the risk of all-cause mortality, cardiopulmonary mortality, and lung cancer mortality, respectively. The study did not find consistent relationships between long-term exposure to particles larger than $2.5 \mu\text{m}$ and premature death.

Estimating Health Effects in Developing Countries

A1.16 Only a few studies based on measured ambient concentrations of PM_{10} or $\text{PM}_{2.5}$ have been carried out in developing countries. Quantitative estimates of health gains in the immediate future will have to rely on the transfer of CR functions. Uncertainties about these transfers due to confounding need to be addressed through scenario-based sensitivity analysis.

A1.17 Because health risks from PM affect primarily the elderly with chronic heart and lung diseases and infants, transfer of cause- and age-specific CR functions is preferable. Use of

all-cause or all-age mortality is inappropriate when there are systematic differences in other health risks or the age distribution between the population in the city and those used in the epidemiological studies. For example, cardiovascular and respiratory diseases have been reported to account for a quarter of non-trauma deaths in Delhi, compared with half in the United States (Cropper and others 1997). If the cardiopulmonary-specific CR function from the study by Pope and others (2002) were transferred to Delhi, all-cause mortality would increase by 1.5 percent when $PM_{2.5}$ exposure is increased by $10 \mu g/m^3$, compared with a 4 percent increase if the all-cause CR function from the same study were applied.

A1.18 Three CR functions transferred to cities worldwide by WHO in one of its publications (Cohen and others 2003) can be a basis for CR function transfers to developing country cities. They include two separate CR functions for cardiopulmonary and lung cancer mortality for adults over 30 years of age from chronic exposure and a CR function for all-cause mortality in children from acute exposure. No morbidity CR functions were transferred because definitions of health outcomes differ across countries. The economic losses from the morbidity effects of PM pollution are so significant that excluding them would seriously underestimate the cost of air pollution. CR functions for morbidity can be transferred, provided that the differences in the confounding factors and definitions of health outcomes between the developing country cities and those in the epidemiological studies are properly accounted for.

A1.19 Uncertainty from three additional sources should be addressed through sensitivity analysis: lack of data on fine PM concentrations, lack of baseline health data and cases, and extrapolation of CR functions outside of the pollutant concentration ranges observed in the epidemiological studies. A number of developing country cities have historically monitored total suspended particles (TSP). Recently, a few cities have begun to monitor PM_{10} regularly, and some are monitoring $PM_{2.5}$. Because the size distribution of PM varies significantly depending on the sources of pollution and atmospheric conditions, estimating the concentration of fine particles in the absence of locally measured data is not straightforward. A World Bank study (Pandey and others 2003) found that after controlling for the fuel mix and local climatic factors, PM_{10} accounts for a smaller share of TSP as per capita income falls.

A1.20 Ambient PM concentrations are significantly higher in many developing country cities than those found in epidemiological studies in North America and Europe, requiring extrapolation of CR functions above the maximum PM concentrations found in the original epidemiological studies. If CR functions were linearly extrapolated, then at high particulate levels found in some developing country cities a significant proportion of health outcomes would be estimated to be from exposure to PM rather than from other competing factors such as smoking and high blood pressure. Since little collaborating evidence has been found to support such a conclusion, it would seem more reasonable to assume that, at these higher levels, the additional health impact per unit $\mu g/m^3$ increase in exposure would be smaller. Different assumptions about extrapolation can be used to estimate high, central, and low estimates of health effects, as shown in a recent WHO publication (Cohen and others 2003).

Valuing Reductions in Illness

What is being valued

A1.21 Improving air quality should reduce the number of episodes of acute illness (such as asthma attacks) as well as the number of cases of chronic respiratory illness that occur each year. To economists, the value of avoiding an illness episode, such as an asthma attack, consists of four components: (1) the value of the work time lost due to the attack (by the asthmatic or an unpaid caregiver or both); (2) the medical costs of treating the attack; (3) the amount an asthmatic (or, in the case of a child, the child's parents) would pay to avoid the pain and suffering associated with the attack; and (4) the value of the leisure time lost due to the attack (by the asthmatic or a caregiver).

A1.22 If the asthmatic were to bear all costs of the attack (including lost work time and medical costs) his or her stated willingness to pay should reflect all four components of value. If, in contrast, the asthmatic had health insurance and paid sick leave, he or she would not bear all medical costs and productivity losses. These are, however, legitimate economic costs that must be included in the value of an illness episode.

Calculating the value of avoided illness

A1.23 How are the four components of the value of avoiding illness measured? Medical costs and productivity losses are often estimated by asking about the type of treatment sought during an illness episode and by asking how long the episode lasted and for how many days the patient (or a family caregiver or both) were unable to perform their usual duties. Lost work time is then valued at the wage rate, and medical costs are imputed on the basis of the full social costs of providing the care, not just the costs to the patient. Economists usually estimate the value of pain and suffering avoided and the value of leisure time gained by direct questioning: that is, people are asked what they would pay to avoid the discomfort and inconvenience of an illness of a specific type and duration. This approach is referred to as the *contingent valuation method* (CVM) or the *stated preference* method.

A1.24 When estimates of the value of pain and suffering and lost leisure time are unavailable, medical costs and productivity losses are often used to provide a lower bound to the value of avoiding illness. This is referred to as the *cost-of-illness* (COI) approach to valuing morbidity. Medical costs are referred to as the *direct costs* of illness, and productivity losses as the *indirect costs* of illness. In the case of a serious but infrequent illness, such as a stroke, reducing air pollution reduces the risk of a person having a stroke. Thus what should be estimated is what a person would pay to reduce his or her risk of having a stroke. In practice, the COI approach is often used to value serious illnesses, such as a heart attack or stroke, since empirical estimates of what people are willing to pay to avoid the pain and discomfort of these conditions tend to be lacking.

Valuing Reductions in Premature Mortality

What is being valued

A1.25 Studies of the effects of air pollution on premature mortality predict how many fewer people are likely to die if air pollution is reduced. For example, a 10 percent reduction in PM₁₀ in Delhi, India, might result in 1,000 fewer deaths each year. We refer to the 1,000 fewer deaths as the number of *statistical lives* saved by improving air quality. This means that the risk of dying is reduced by a small amount for all people living in Delhi and that these risk reductions add up to 1,000 fewer deaths. To illustrate, if reducing air pollution in Delhi results in 1,000 fewer deaths in a population of 10 million, this is equivalent, on average, to reducing risk of death annually by 1 in 10,000 (0.0001) for each person in the population (calculated from dividing 1,000 deaths by 10 million people, or 0.0001).³

A1.26 Since reducing air pollution reduces risk of death by a small amount for each person in an exposed population, economists wish to estimate what each person in the population would pay for this small risk reduction. If this willingness to pay (WTP) were added across all 10 million residents of Delhi, it would represent the value of saving 1,000 statistical lives. Dividing the total willingness to pay by the number of statistical lives saved yields the average *value of a statistical life* (VSL). People's WTP for small risk reductions are usually stated in terms of the VSL—the sum of WTPs for risk reductions that save one statistical life.⁴

Calculating the value of a reduction in risk of death

A1.27 Economists realize that people trade money for safety every day. People are willing to work in riskier jobs if compensated for them, and people are willing to pay for safer vehicles or for helmets to protect themselves when riding two-wheelers. WTP for a reduction in risk of dying is usually estimated from studies on compensating wage differentials in the labor market, or expenditures to reduce risk of death. These studies are usually referred to as *revealed preference* studies because they are based on actual behavior. A second source of estimates are *stated preference* studies in which people are asked directly what they would pay for a reduction in their risk of dying (also called CVM and referred to above in the context of valuing morbidity).

A1.28 Studies of compensating wage differentials or expenditures on safety must determine what portion of the wage or what portion of the vehicle price represents payment for safety. This payment is then associated with the size of the risk differential to infer what people are willing to pay for it. For example, compensating wage studies empirically explain variations in the wage received by workers as a function of worker characteristics (age, education, skills) and job characteristics, including risk of fatal and nonfatal injury, in order to determine what

³ For simplicity, this example assumes that all people in Delhi benefit equally from the air pollution reduction. In reality, people with heart and lung disease are likely to benefit more than others.

⁴ The goal of calculating the VSL is to estimate what people themselves would pay for risk reductions. The VSL is not intended to estimate the intrinsic value of human life.

portion of wage represents compensation for risk of death. In theory, the impact of small changes in the risk of dying on wages should equal the amount a worker would have to be compensated to accept this risk.

A1.29 Compensating wage differential studies in the United States (U.S. EPA 1999) indicate that the VSL is approximately US\$5 million (1990 US\$). These studies may overstate the VSL for reductions in air pollution because people prematurely dying from air pollution in North America are much older than the workers in these studies, whose average age is about 40. Conversely, the VSL for environmental risks may be higher because these risks are involuntary.

A1.30 Unlike compensating wage differential studies, *contingent valuation* studies directly ask persons at risk what they are willing to pay for changes in life expectancy, and can be tailored to the age at which risk reductions occur and to the nature of the risks valued. They generally yield lower estimates of WTP than *wage differential* studies do. These studies often have difficulty eliciting consistent values for small probability changes that are difficult for respondents to perceive and value.

A1.31 When WTP estimates are not available, the *human capital* (“human capital” refers to knowledge and skills found in the labor force) approach can be used to obtain a lower bound to WTP. This approach values loss of life based on the forgone earnings associated with premature mortality. The notion is that people should be willing to pay at least as much as the value of the income they would lose by dying prematurely. This is not the theoretically correct approach to valuing a program that reduces the risk of dying, but does provide a useful lower bound to WTP (Freeman 2003). Labor market studies in the United States indicate the VSL is several times the value of forgone earnings. However, caution is urged in using these values for policy formulation: if the same VSL is used for reducing a number of different risks, adding up WTPs could result in an unrealistically large monetary sum that is out of proportion to the total household income for the majority of the population.

Valuing Health Benefits in Developing Countries

A1.32 Few studies have been published using data for developing countries that estimate WTP to reduce mortality or morbidity. This implies that monetization of health benefits must, in the immediate future, rely on transferring WTP estimates from one country to another or must calculate a lower bound to benefits based on forgone earnings (for mortality benefits) or the cost of illness (for morbidity benefits).

A1.33 The standard approach to benefits transfer assumes that preferences are the same in the two countries, including attitudes toward risk when estimates of the VSL are transferred. WTP is assumed to differ only as a result of differences in income between the two countries. If this is true, U.S. WTP can be transferred to a specific developing country after accounting for income differences as shown in equation (1):

$$WTP_{SA} = WTP_{US} [Income_{SA}/Income_{US}]^? \quad (1)$$

where Income_{SA} is the income in South Asia measured in U.S. dollars and η represents the income elasticity of WTP: the percentage change in WTP corresponding to a 1 percent change in income. There is considerable uncertainty regarding the income elasticity of WTP, even within a country. A conservative approach to benefits transfer is to use an income elasticity of 1.0, including smaller and larger values for sensitivity analysis. For example, the transfer of a U.S. VSL of US\$1 million to India using 1998 purchasing power parity⁵ income and an elasticity of 1.0 yields a VSL for India of US\$69,000. Using the nominal exchange rate to convert the income in India rather than purchasing power parity would give a lower estimate, and is typically not done on methodological grounds. Since the assumptions underlying benefits transfer may not be valid, it is always desirable to provide lower-bound estimates of the value of health benefits based on the COI approach for morbidity and the human capital approach for mortality and to compare these with higher values based on the WTP and VSL approaches.

The Policy Relevance of Health-Benefits Analysis—Example from Mexico City

A1.34 To illustrate the usefulness of computing the monetary value of health benefits, the results of a study in Mexico City (World Bank 2002) are given in Table A1.2. The study quantified the effect of 10 and 20 percent reductions in annual average population-weighted ozone and PM_{10} concentrations in metropolitan Mexico City in the year 2010. The impact of each pollutant reduction was first expressed in terms of cases of illness and premature death avoided; then dollar values were assigned to health benefits.

Table A1.2 Annual Health Benefits due to Ozone and PM_{10} Reductions in Mexico City (in million 1999 US\$)

<i>Methodology for calculation</i>		<i>Air pollution reduction</i>	
<i>Morbidity</i>	<i>Mortality</i>	<i>10%</i>	<i>20%</i>
Benefits from ozone reduction			
COI	Human capital	18	35
COI + WTP	Human capital	75	151
COI + WTP	VSL	116	232
Benefits from PM_{10} reduction			
COI	Human capital	96	191
COI + WTP	Human capital	644	1,289
COI + WTP	VSL	1,451	2,903

⁵ Purchasing power parity is a way to compare the costs of goods and services between countries. It is different from the official exchange rate and considers a rate of exchange that will give each currency the same purchasing power in its economy. In terms of purchasing power parity, local currencies in South Asia are worth much more than the official exchange rate.

A1.35 Three approaches were used to value reductions in illness and premature mortality. The most conservative, giving the “low estimate,” was to value mortality using forgone earnings and morbidity using productivity losses plus medical costs: that is, COI. This should be viewed as a lower bound to the value of health benefits. A less conservative approach, giving the “central case estimate,” was to add estimates of WTP to avoid the pain and suffering associated with illness to the COI used in computing the low estimate of benefits, but to use forgone earnings to value reduced mortality. The “high estimate” used the same method of valuing avoided morbidity as the central case estimate but uses WTP (that is, the VSL) in place of forgone earnings to value avoided mortality.

A1.36 WTP estimates were transferred from studies conducted in the United States and Europe, using an income elasticity of WTP of unity and purchasing power parity incomes. The resulting VSL for Mexico City was approximately US\$300,000 in 1999 US dollars.

A1.37 The values of reducing PM₁₀ and ozone by 10 percent and 20 percent appear in Table A1.2. Two features of the results warrant discussion. The first is that the dollar values of benefits associated with the 20 percent reduction scenario are exactly twice the values of the benefits of the 10 percent reduction scenario. In general, each additional 1 µg/m³ reduction in annual average population-weighted PM₁₀ will have approximately the same value, because the impact of a 1 µg/m³ change is assumed to be independent of baseline concentrations. In this case a reduction of 10 percent is equivalent to lowering PM₁₀ by 6.4 µg/m³. This implies that, using the study’s central case estimate, a 1 µg/m³ reduction in PM₁₀ is worth US\$100 million (1999 US dollars) annually (US\$644 million for COI+WTP divided by 6.4 µg/m³).

A1.38 The second point worth noting is that the value of the health benefits associated with a 10 percent reduction in ozone is much smaller than the value of the benefits of a 10 percent reduction in PM₁₀ regardless of the approach used to monetize benefits. This is primarily because there are, as yet, no studies relating reductions in long-term exposure to ozone to premature mortality. This does not imply, however, that programs to reduce the precursors of ozone (nitrogen oxides and volatile organic chemicals) yield few health benefits. In addition, NO_x and SO_x can convert to secondary particulate matter in the atmosphere. Programs to reduce oxides of nitrogen and sulfur are, therefore, likely to result in benefits from reduced particulate matter.

The Use of Benefit Estimates in Cost-Benefit Analyses

A1.39 The estimates of health benefits, such as those computed in the Mexico City study in Table A1.2, could be used as inputs to a cost-benefit analysis of air pollution control strategies. To analyze the benefit of an air pollution control strategy, one must first translate the control measures—for example, a program to convert diesel buses to CNG—into changes in emissions of the common air pollutants, and then use air quality models to predict the change in ambient pollution concentrations associated with the control strategy. Once the changes in ambient concentrations associated with the control strategy have been estimated, they can be quantified and valued using the unit values derived in the health-benefits analysis.

A1.40 The final step in a cost-benefit analysis is to subtract the costs of the program (such as the cost of replacing diesel buses with CNG buses) from its benefits to determine the net social benefits of the program. Economists typically argue that control strategies should be ranked according to their net social benefits; this assumes that what matters is the total benefits to society versus the total costs to society of a program, even if the people who pay for the program are not the same people as those who benefit from it. The distribution of benefits and costs is, however, important information that should also be presented to policymakers, in addition to total benefits and costs.

Conclusions

- ?? The health impacts of air pollution depend on the sensitivity and the exposure level of the susceptible population to the pollutant. The largest health impacts in most developing country cities result from exposure to fine particulate pollution. Elderly persons with cardiovascular and lung disease and infants are at greatest risk.
- ?? In performing health impact analyses for most developing country cities, reliance has to be placed on CR transfer in the immediate future. For mortality, this should be limited to CR functions for cause- and age-specific mortality developed from PM₁₀ and PM_{2.5} measurements. CR functions for morbidity can be transferred, provided that definitions of health outcomes are comparable and there are no large differences in confounding factors.
- ?? Uncertainties in transferring CR functions should be fully addressed by examining the sensitivity of results to alternative assumptions. The most significant uncertainties are baseline health data, estimations of PM_{2.5} and PM₁₀ needed in the CR function if no local data exist, and extrapolation of CR function outside of the PM concentration range in the original studies.
- ?? The economic benefits of reducing illness and premature mortality associated with air pollution are well defined, and empirical estimates of these benefits (for example, of the VSL) exist for industrial countries.
- ?? In performing health-benefits analyses for most developing countries, reliance will have to be placed on benefits transfer in the immediate future. In addition, it should be possible to calculate a lower bound to benefits using the cost of illness and human capital approaches. Policy interventions that can be justified on the basis of lower-bound estimates of benefits are likely to be robust and merit serious consideration.
- ?? Calculating the monetary value of health benefits associated with small (for example, 10 percent) changes in the common air pollutants is useful for two reasons: (1) it provides estimates of the value of a one-unit reduction in each pollutant that can serve as input into a cost-benefit analysis of air pollution

reduction strategies; and (2) it can indicate the relative benefits of controlling one pollutant versus another.

Annex 2

European Fuel and Vehicle Emission Standards

A2.1 The European Union has issued a series of emission standards for new vehicles, commonly known as Euro standards. Indian Bharat Stage I, II, III, and IV follow Euro I, II, III, and IV with minor differences in the driving cycle. The Euro emission standards are given in Table A2.1–Table A2.3.

Table A2.1 EU Exhaust Emission Standards for Passenger Cars, g/km

<i>Tier</i>	<i>Year</i>	<i>CO</i>	<i>HC</i>	<i>HC+NO_x</i>	<i>NO_x</i>	<i>PM</i>
Diesel						
Euro I	1992	2.72	? ?	0.97	? ?	0.14
Euro II – IDI	1996	1.0	? ?	0.7	? ?	0.08
Euro II – DI	1996-1999	1.0	? ?	0.9	? ?	0.10
Euro III	2000	0.64	? ?	0.56	0.5	0.05
Euro IV	2005	0.5	? ?	0.3	0.25	0.025
Gasoline						
Euro II	1996	2.2		0.5		
Euro III	2000	2.3	0.2	? ?	0.15	? ?
Euro IV	2005	1	0.1	? ?	0.08	? ?

IDI indirect injection; DI direct injection; ? Not applicable

Table A2.2 EU Emission Standards for Light Commercial Vehicles, g/km

<i>Class</i>	<i>Tier</i>	<i>Year</i>	<i>CO</i>	<i>HC</i>	<i>HC+NO_x</i>	<i>NO_x</i>	<i>PM</i>
Diesel							
N1	Euro I	1994	2.72	? ?	0.97	? ?	0.14
	Euro II	1998	1.0	? ?	0.6	? ?	0.10
	Euro III	2000	0.64	? ?	0.56	0.5	0.05
	Euro IV	2005	0.5	? ?	0.3	0.25	0.025
N2	Euro I	1994	5.17	? ?	1.4	? ?	0.19
	Euro II	1998	1.2	? ?	1.1	? ?	0.15
	Euro III	2002	0.8	? ?	0.72	0.65	0.07
	Euro IV	2006	0.63	? ?	0.39	0.33	0.04
N3	Euro I	1994	6.9	? ?	1.7	? ?	0.25
	Euro II	1998	1.35	? ?	1.3	? ?	0.2
	Euro III	2002	0.95	? ?	0.86	0.78	0.1
	Euro IV	2006	0.74	? ?	0.46	0.39	0.06
Gasoline							
N1	Euro I	1994	2.72	? ?	0.97	? ?	? ?
	Euro II	1998	2.2	? ?	0.5	? ?	? ?
	Euro III	2000	2.3	0.2	? ?	0.15	? ?
	Euro IV	2005	1.0	0.1	? ?	0.08	? ?
N2	Euro I	1994	5.17	? ?	1.4	? ?	? ?
	Euro II	1998	4.0	? ?	0.65	? ?	? ?
	Euro III	2002	4.17	0.25	? ?	0.18	? ?
	Euro IV	2006	1.81	0.13	? ?	0.1	? ?
N3	Euro I	1994	6.9	? ?	1.7	? ?	? ?
	Euro II	1998	5.0	? ?	0.8	? ?	? ?
	Euro III	2002	5.22	0.29	? ?	0.21	? ?
	Euro IV	2006	2.27	0.16	? ?	0.11	? ?

Note: For Euro I and II the weight classes were N1 (<1250 kg), N2 (1250-1700 kg), N3 (>1700 kg). For Euro III and IV, N1 < 1305 kg, N2 1305-1760 kg, and N3 > 1760 kg.

Table A2.3 EU Emission Standards for Heavy-Duty Diesel Engines, grams/kilowatt-hour (g/kWh), smoke in m⁻¹

<i>Tier</i>	<i>Date and category</i>	<i>Test cycle</i>	<i>CO</i>	<i>HC</i>	<i>NO_x</i>	<i>PM</i>	<i>Smoke</i>
Euro I	1992, <85 kW	ECE R-49	4.5	1.1	8	0.612	
	1992, >85 kW		4.5	1.1	8	0.36	
Euro II	1996.1		4	1.1	7	0.25	
	1998.1		4	1.1	7	0.15	
Euro III	1999.10, EEVs only	ESC and ELR	1.5	0.25	2	0.02	0.15
	2000.1	ESC and ELR	2.1	0.66	5	0.1	0.8
						0.13 ^a	
Euro IV	2005.1		1.5	0.46	3.5	0.02	0.5
Euro V	2008.1		1.5	0.46	2	0.02	0.5

EEV environmentally enhanced vehicle; ESC European stationary cycle; ELR European load response

^a For engines of less than 0.75 dm³ swept volume per cylinder and a rated power speed of more than 3000 min⁻¹.

A2.2 In order to comply with the Euro standards, gasoline and diesel need to meet certain fuel specifications. The European fuel specifications to the year 2005 are shown in Table A2.4 and Table A2.5 for gasoline and diesel, respectively.

Table A2.4 Automotive Gasoline Specifications in the EU

<i>Parameter</i>	<i>Units</i>	<i>1993^a</i>	<i>2000</i>	<i>2005</i>
Lead, maximum	grams/liter	0.013	0.005	0.005
Benzene, maximum	% by volume	5	1	1
Aromatics, maximum	% by volume	? ?	42	35
Olefins, maximum	% by volume	? ?	18	18
Oxygen, maximum	% by weight	2.7	2.7	2.7
Sulfur, maximum	wt ppm	500	150	50

^a Specifications for unleaded gasoline; ? No limits

Table A2.5 On-Road Diesel Specifications in the EU

<i>Parameter</i>	<i>Units</i>	<i>1993</i>	<i>October 1996</i>	<i>2000</i>	<i>2005</i>
Sulfur, maximum	wt ppm	2000	500	350	50
Cetane number, minimum		49	49	51	51
Cetane index, minimum		46	46	? ?	? ?
T95, maximum	°C	370	370	360	360
Polyaromatics, maximum	%	? ?	? ?	11	11
Density, maximum	kilograms/liter	0.860	0.860	0.845	0.845

T95 – temperature at which 95 percent of the fuel evaporates; ? Not applicable

Annex 3

Publications and Events

A3.1 The South Asia Urban Air Quality Management study published a series of policy briefing notes, commissioned studies, and held stakeholder meetings to discuss the findings of the studies and policy notes. The objective of the policy briefing notes was to summarize in four pages the key issues, criteria for selecting policy instruments, and examples of policy implementation as well as obstacles to urban air quality management from within and outside of South Asia.

A3.2 A total of 13 briefing notes were issued. They are listed in Table A3.1. Hard copies were circulated to government officials, researchers, academics, industry representatives, and NGOs. All the publications were also made available online at <http://www.worldbank.org/sarurbanair>. The briefing notes have invited questions and comments from stakeholders not only in South Asia, but also in other regions of the world, including government officials in Pretoria, Republic of South Africa, and Bogotá, Colombia.

Table A3.1 Briefing Notes

<i>No.</i>	<i>Title</i>	<i>Authors</i>	<i>Date</i>
1	Vehicular Air Pollution: Setting Priorities	Ken Gwilliam and Masami Kojima	October 2001
2	International Experience with CNG Vehicles	Masami Kojima	October 2001
3	How Can Urban Bus Policy Reduce Air Pollution?	Ken Gwilliam	December 2001
4	What Do We Know About Air Pollution?—India Case Study	Masami Kojima	March 2002
5	Impact of Better Traffic Management	Ken Gwilliam	April 2002
6	Urban Planning and Air Quality	Alain Bertaud	May 2002
7	Catching Gasoline and Diesel Adulteration	Ronald Tharby	July 2002
8	Can Vehicle Scrappage Programs Be Successful?	Ken Gwilliam	August 2002
9	Making Vehicle Emissions Inspection Effective—	John Rogers	November 2002

Learning from Experience in India

10	Tackling Diesel Emissions from In-Use Vehicles	John Rogers	November 2002
11	Health Impacts of Outdoor Air Pollution	Kiran Dev Pandey	February 2003
12	Economic Valuation of the Health Benefits of Reduction in Air Pollution	Maureen Cropper	February 2003
13	The Science of Health Impacts of Particulate Matter	Sameer Akbar	March 2003

A3.3 Three studies were commissioned. The first reviewed the past and current work on urban air quality in India with a special focus on particulate matter and its possible sources. The second reviewed Pollution Under Control (PUC) in India with a view to making recommendations for its improvement. The third collected PM_{2.5} samples in three Indian cities and analyzed them to identify the sources. The reports are listed in Table A3.2.

Table A3.2 Reports

<i>Title</i>	<i>Authors</i>	<i>Date</i>
Review of Past and On-Going Work on Urban Air Quality in India	Tata Energy Research Institute	December 2001
Assessment of the Pollution Under Control Program in India and Recommendations for Improvement	John Rogers, Trafalgar SA de CV	October 2002
Source Apportionment of the Ambient Fine Particles in Mumbai, Delhi, and Kolkata	Zohir Chowdhury, Mei Zheng, and Armistead Russell, Georgia Institute of Technology	December 2003

A3.4 In addition, two stakeholder meetings were held (Table A3.3). The first solicited feedback on the activities of this study with a special focus on the briefing notes published to date. The second was called by the Ministry of Road Transport and Highways, partially in response to the documents on vehicle inspection and certification issued under this study.

Table A3.3 Events

<i>Title</i>	<i>Participants</i>	<i>Location</i>	<i>Date</i>
Workshop on urban air quality management	Government, industry, NGOs, academics	Mumbai, India	May 14, 2002
Stakeholder meeting on inspection and maintenance system for motor vehicles in India	Government, industry, research institution	New Delhi, India	June 10, 2003

Annex 4

Experimental Setup and Methodology for Source Apportionment

A4.1 Between March 2001 and January 2002, PM_{2.5} samples were collected over consecutive 24-hour periods in Chandigarh, Delhi, Kolkata, and Mumbai. A description of the sampling sites and a schedule of sample collection are given in Table A4.1 and Table A4.2, respectively. The collection schedule covered periods of both low- ambient particulate concentrations (summer wet monsoon) and high concentrations (winter dry monsoon). Unfortunately, the sampling protocols could not be followed in Chandigarh except in summer and hence only the summer samples were analyzed. Gravimetric determination of PM_{2.5} was used in this work, enabling chemical analysis of the collected particles.

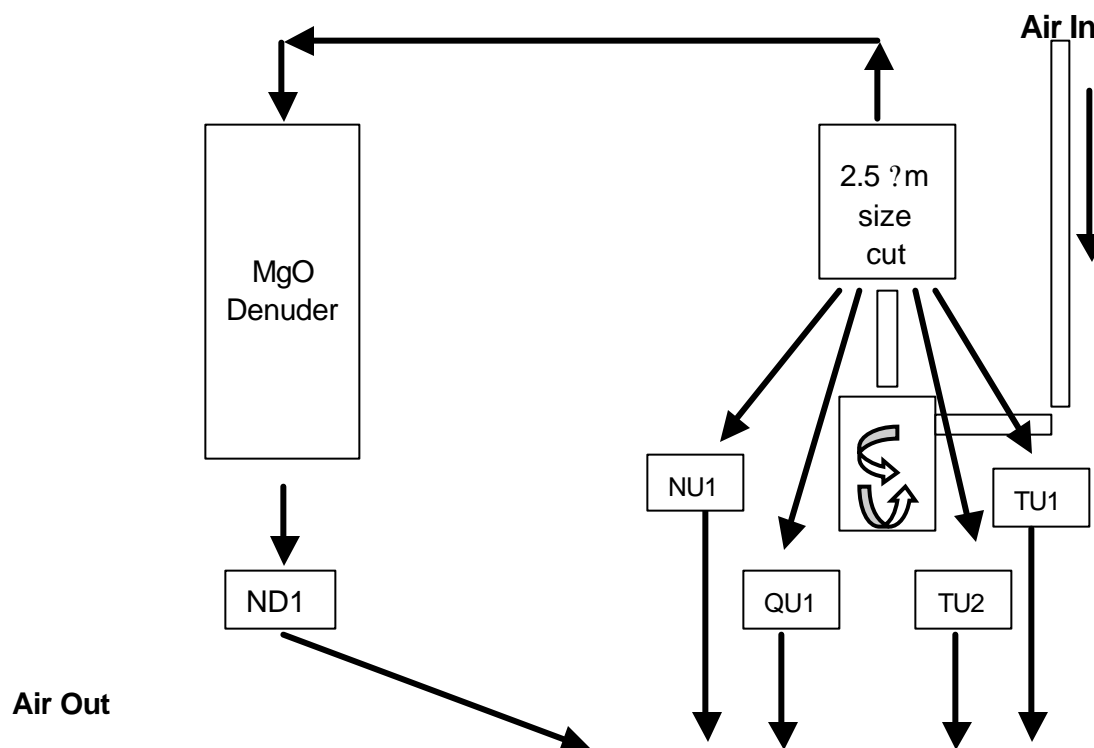
Table A4.1 Description of the Three Sites for PM_{2.5} Collection

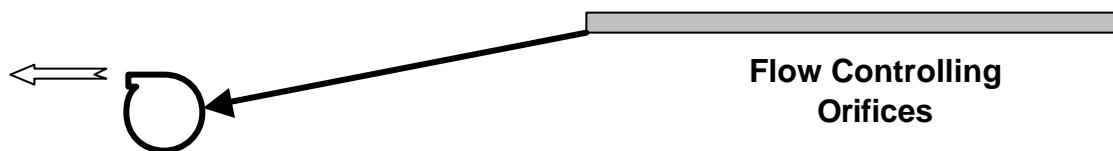
<i>City</i>	<i>Site address</i>	<i>Location type</i>	<i>Sampler position description</i>	<i>Source of pollution</i>
Delhi	National Physical Laboratory (NPL), Dr. K. S. Krishnan Marg	Urban residential	Sampler placed 5 m above ground on an office building rooftop in the NPL campus; unobstructed space around.	City traffic typically seen in residential and business areas, and cooking by slum dwellers
Kolkata	NEERI Zonal Laboratory, I-8, Sector-C, East Kolkata	Urban residential	Sampler on a 2 meter platform located in an open field, Ruby General Hospital and a diesel truck garage nearby	City traffic typically seen in residential and business areas, cooking by slum dwellers, and some emission from combustion from diesel trucks parked in a nearby garage

recommended. The different thermal combustion carbon methods vary in combustion atmospheres, temperature ramping rates, the position of the temperature monitor relative to the sample, temperature plateaus and residence time at each plateau, carrier gas flow through or across the sample, sample size, evolved carbon detection method, oxidation catalyst, and the optical monitoring configuration and wavelength. For proper interpretation of the results, it is crucial to document the analytical method used precisely.

A4.3 In this study, a $PM_{2.5}$ filter sampler built by the California Institute of Technology was used at each site. A schematic diagram of the sampling unit is given in Figure A4.1. Fine particles were collected simultaneously and in parallel on one quartz fiber filter, two pre-washed nylon filters, and two polytetrafluoroethylene (PTFE) membrane filters (Table A4.3). Different material filters were used for compatibility with subsequent chemical analysis. For collection of the fine particles, ambient air was drawn at approximately 22.5 liters per minute (lpm) through an acid-washed Pyrex glass inlet line to a Teflon-coated Air and Industrial Hygiene Laboratory (AIHL)-design cyclone separator (John and Reischl 1980) which removed large particles according to a collection efficiency curve having a 50 percent aerodynamic cutoff diameter at 2.5 μ m before the air passed through the fine particle collection filters. The nylon filter located downstream of the magnesium oxide (MgO)-coated diffusion denuder was used in conjunction with the nylon filter downstream of the cyclone alone to measure gas phase nitric acid, hydrochloric acid, and fine particle nitrate by the denuder difference method. The air flow rate through each filter was measured before and after each 24-hour sampling period with a calibrated rotameter.

Figure A4.1 Schematic Diagram of the Sampling Unit





Notes: TU1 and TU2 – PTFE membrane filters. NU1 and ND1 – nylon filters. QU1 –quartz fiber filter. The denuder removes nitric acid and permits particles to pass unattenuated, allowing the measurement of nitric acid and particulate nitrate with a minimum of removal artifacts caused by volatilization and condensation of ammonium nitrate.

Table A4.3 Characteristics of Filter Substrates Used for Collecting Samples

<i>Filter Type</i>	<i>Details</i>
Quartz fiber filter	Pallflex, 2500 QAO, 47 millimeter (mm) diameter
PTFE filter	Gelman Sciences, Teflo, 47 mm diameter, 1.0 μ m pore size
Nylon filter	Pall Gelman Nylasorb filters, 47 mm diameter

A4.4 Both unexposed filters and exposed samples were kept in individual Petri dishes and sealed with Teflon tape. To ship filters and samples by courier between the United States and India, ice coolers with blue-ice packets were used to ensure that the temperature of the filters during shipment would remain cool enough to prevent sample degradation. All PTFE filters were gravimetrically analyzed at the Georgia Institute of Technology by the same operator by repeated weighing before and after the sample collection on a Mettler Toledo microbalance maintained in a temperature- and humidity-controlled environment (20.5 \pm 0.2 degrees Celsius [$^{\circ}$ C], relative humidity 39 \pm 2 percent). Once weighing was completed, samples were stored in freezers until ready for chemical analysis. For each pair of PTFE filters, one was analyzed by ion chromatography (Dionex Corp, Model 2020i) for the anions NO_3^- , SO_4^{2-} , and chloride (Cl), and by an indophenol colorimetric procedure for NH_4^+ using an Alpkem rapid flow analyzer (Model RFA-300). The second PTFE filter was analyzed for trace elements using X-ray fluorescence (XRF).

A4.5 A 9.62 square centimeter (cm^2) punch was taken out of each quartz fiber filter and was analyzed for elemental and organic carbon content using the thermal-optical carbon analysis method of Huntzicker and others (1982) as modified by Birch and Cary (1996). Variations in elemental carbon values among alternative methods can arise on account of differences in the way alternative methods correct for charring of the samples during analysis. This report defines elemental carbon in accordance with the combustion method of Birch and Cary (1996). In their thermal evolution and combustion method, elemental carbon is defined as carbon that resists volatilization up to a temperature of 900 $^{\circ}$ C in an inert atmosphere (in a manner similar to graphite). The same quartz fiber filters without the punch area were then combined by season and analyzed by gas chromatography-mass spectroscopy (GC-MS) for hydrocarbon speciation. Mumbai summertime samples did not contain enough organic carbon for good GC-MS analysis and thus were not analyzed. In addition, filter blanks as well as

laboratory blanks were analyzed. Filter blanks were prepared, stored, and shipped in the same manner as the samples, and laboratory blanks were used to identify possible contaminants from handling samples in the laboratory. The results from both field and laboratory blanks were carefully analyzed and subtracted before reporting the final results. In total 23 samples were analyzed including field and laboratory quality assurance/quality control blanks. The nylon filters were analyzed to examine gas-to-particle conversion of nitric acid and hydrochloric acid.

Molecular Markers

A4.6 The following markers were used to identify sources:

- ?? Hopanes and steranes are present in heavy petroleum distillates (Simoneit 1985, 1999; Simoneit and others 1999) such as lubricating oil. In the southern California atmosphere, these compounds have been shown to be predominately from the exhaust emissions of gasoline and diesel-powered motor vehicles and result from the presence of lubricating oil in PM emissions (Rogge and others 1993a and 1993b, Rogge and others 1996, Schauer and Cass 2000, Schauer and others 2002). Wood smoke will contribute to carbonaceous aerosol concentrations but not to hopane and sterane concentrations. Diesel vehicles are important sources of both elemental carbon and hopanes and steranes, while gasoline-powered vehicles are important sources of hopanes and steranes and smaller contributors to elemental carbon concentrations.
- ?? Levoglucosan is a major component of wood smoke aerosol and has been shown to be a good tracer for wood burning (Schauer and Cass 2000, Simoneit and others 1999, Schauer and others 2001).
- ?? Picene is a marker for coal combustion.
- ?? Silicon and aluminum are markers for road dust.

A4.7 Inorganic elements have often been used as tracers in source-receptor models. Models using primarily inorganic elements have limitations when examining fine particulate mass, since a significant fraction of the fine particulate mass in the urban atmosphere is from combustion sources. These sources emit fine particles largely comprising carbon with only trace levels of inorganic elements. The trace elements present in the fine particle emissions from several important urban air pollution sources are not sufficient to provide unique fingerprints that can be used to properly distinguish the sources in a source-receptor model. The organic compounds present in fine particles emitted from cooking meat, burning wood, combusting of automotive fuels, and cigarette smoking are very different. These differences can be exploited by receptor models to determine their respective contributions to the atmospheric concentrations of fine particulate matter.

A4.8 It should be noted that, as with all other modeling of this nature, chemical mass balance receptor modeling makes a number of limiting assumptions. Compositions of source emissions are assumed to change little during transport from the point of emission, where the

source profile is defined, to the point of the receptor site where particles are collected for analysis. Chemical species are taken to add linearly and not react with each other. Source profiles are assumed to be linearly independent. Measurement uncertainties should be random, uncorrelated, and normally distributed. These assumptions are difficult, if not impossible, to satisfy in practice. Chemical mass balance modeling can tolerate deviations from these assumptions with some penalty in modeling uncertainty.

A4.9 An important aspect of molecular marker source apportionment is the selection of organic compounds that can be properly used as tracer species in the model. Fifty-five organic compounds have been quantified by using the methods described by Mazurek and others (1987) and further refined by Schauer and others (1996). These 57 compounds were selected carefully so that they can be used as tracer species in the chemical mass balance model. These species do not significantly react, are not formed, and are not selectively removed (for example, through volatilization) in the atmosphere. The compounds used as tracer compounds in this study are given in Table A4.4.

Table A4.4 Molecular Markers and Their Likely Sources Used in This Study

<i>Molecular type</i>	<i>Molecular marker</i>	<i>Major urban sources</i>
Alkanes	n-Pentacosane	Gasoline, diesel, fuel oil
Alkanes	n-Hexacosane	Gasoline, diesel, fuel oil
Alkanes	n-Heptacosane	Gasoline, diesel, fuel oil
Alkanes	n-Octacosane	Gasoline, diesel, fuel oil
Alkanes	n-Nonacosane	Vegetative detritus
Alkanes	n-Triacontane	Gasoline, diesel
Alkanes	n-Hentriacontane	Vegetative detritus, cigarette smoke
Alkanes	n-Dotriacontane	Variety
Alkanes	n-Tritriacontane	Vegetative detritus, cigarette smoke
Alkanes	n-Tetratriacontane	Tire wear debris
Alkanes	n-Pentatriacontane	Tire wear debris
Branched alkanes	anteiso-Triacontane	cigarette smoke
Branched alkanes	iso-Hentriacontane	cigarette smoke
Branched alkanes	anteiso-Hentriacontane	cigarette smoke
Branched alkanes	iso-Dotriacontane	cigarette smoke
Branched alkanes	anteiso-Dotriacontane	cigarette smoke
Branched alkanes	iso-Tritriacontane	cigarette smoke
Steranes	20S&R-5? (H), 14? (H), 17? (H)- Cholestanes	Gasoline, diesel, fuel oil
Steranes	20R-5? (H), 14? (H), 17? (H)-Cholestane	Gasoline, diesel, fuel oil
Steranes	20S&R-5? (H), 14? (H), 17? (H)-	Gasoline, diesel, fuel oil

<i>Molecular type</i>	<i>Molecular marker</i>	<i>Major urban sources</i>
	Ergostanes	
	20S&R-5? (H), 14? (H), 17? (H)-	
Steranes	Sitostanes	Gasoline, diesel, fuel oil
Hopanes	22, 29, 30-Trisnorneohopane (T m)	Gasoline, diesel, fuel oil
Hopanes	17? (H), 21? (H)-29-Norhopane	Gasoline, diesel, fuel oil
Hopanes	17? (H), 21? (H)-Hopane	Gasoline, diesel, fuel oil
Hopanes	22S-17? (H), 21? (H)-30-Homohopane	Gasoline, diesel, fuel oil
Hopanes	22R-17? (H), 21? (H)-30-Homohopane	Gasoline, diesel, fuel oil
Hopanes	22S-17? (H), 21? (H)-30-Bishomohopane	Gasoline, diesel, fuel oil
Hopanes	22R-17? (H), 21? (H)-30-Bishomohopane	Gasoline, diesel, fuel oil
Alkanoic acids	n-9-Hexadecanoic acid	Meat cooking
Alkanoic acids	Hexadecanamide	Biomass (cow dung)
Alkanoic acids	Octadecanamide	Biomass (cow dung)
Resin acids	Pimaric acid	Softwood Burning
Resin acids	Isopimaric acid	Softwood Burning
PAH	Benzo[b]fluoranthene	Gasoline, natural gas, coal, fuel oil
PAH	Benzo[k]fluoranthene	Gasoline, natural gas, coal, fuel oil
PAH	Benzo[e]pyrene	Gasoline, natural gas, coal, fuel oil
PAH	Indeno[1,2,3-cd]fluoranthene	Gasoline, natural gas, coal, fuel oil
PAH	Indeno[1,2,3-cd]pyrene/o-phenylenepyrene	Gasoline, natural gas, coal, fuel oil
PAH	Picene	coal
PAH	Coronene	Gasoline vehicles without catalyst
Other	beta-Tocopherol	Biomass
Other	Coprostanol	Biomass (cow dung)
Other	Stigmastan-3,5-dien	Biomass (cow dung)
Other	Vitamin E	Biomass
Other	Cholestanol	Biomass (cow dung)
Other	Campesterol	Biomass
Other	Stigmasterol	Biomass
Other	(3 beta, 5 beta) Stigmastan-3-ol	Biomass
Other	beta-Sitosterol	Biomass
Other	(3beta, 5alpha) Stigmastan-3-ol	Biomass
Other	Stigmasta-3,5-dien-7-one	Biomass
Other	Cholesterol	Meat cooking

<i>Molecular type</i>	<i>Molecular marker</i>	<i>Major urban sources</i>
Other	Levogluconan	Hardwood, softwood
Other	Galactosan	Biomass
Other	Mannosan	Biomass
Inorganic	Aluminum	Crustal material
Inorganic	Silicon	Crustal material

Note: The compounds actually used in modeling are highlighted in bold.

A4.10 In order to extract these compounds from ambient samples taken in India, the quartz fiber filters were combined by season for each of the three cities (Delhi, Kolkata, and Mumbai). Ideally, 1000 micrograms (μg) of organic carbon should be present in the composited sample for the GC–MS instrument to have excellent signal-to-noise ratios for the compounds of interest. All composite samples with at least 350 μg of organic carbon were analyzed in this study. Mumbai summertime samples did not meet our minimum requirement and thus was not analyzed.

Source Profiles

A4.11 The above compounds were identified for each season and used as inputs to the chemical mass balance model. Twenty source profiles were selected from a large database of source profiles available from the research group of Glen Cass at the California Institute of Technology. These source profiles were chosen because they contained large amounts of the 55 target compounds that were analyzed for in this study. The analytical procedures used in quantifying the organic compounds in this study were the same analytical procedures used in developing the selected source profiles. In the end, not all the 20 source profiles could be used for the reasons given below. Those that were retained were: medium-duty diesel trucks, gasoline vehicles with and without catalytic converters, road dust from three areas in California (Fresno, Bakersfield, and Kern Wildlife Refuge), Datong coal in China, coconut leaves from Bangladesh, rice straw from Bangladesh, cow dung from Bangladesh, biomass briquettes from Bangladesh, and jackfruit branches from Bangladesh. The five sources from Bangladesh are described in detail in Sheesley and others (2003). The selected source profiles covered the major urban sources: diesel, gasoline, dust, biomass, and coal. Retaining a large number of source profiles does not necessarily assist in converging the results of chemical mass balance modeling to the measured $\text{PM}_{2.5}$ mass, especially when the source profile is not from the region or the contribution to $\text{PM}_{2.5}$ from the source is negligible or both.

A4.12 Attempts were made to use source profiles for cigarette smoke, fuel oil combustion, meat-cooking, and natural gas combustion. Cholesterol, a marker for meat-cooking, was below the detection limit in all but two samples, and hence meat-cooking was dropped. Fuel oil and natural gas led to collinearity problems (these two parameters were too closely correlated without other sources being used to be distinguishable). For this reason, these two source profiles were not used in this study. Dropping them, however, made little change.

Branched alkanes were difficult to analyze because of inadequate signal-to-noise ratio, and hence cigarette smoke, which relies on quantification of branched alkanes, was not used in the model. With these omissions, 32 out of 55 molecular markers were retained and used to produce the final set of results.

A4.13 Assumptions were made about the contributions of identified sources to primary sulfate, nitrate, and ammonium emissions. The difference between the measured quantities and assumed primary emission contributions is designated as secondary sulfates, nitrates, and ammonium, respectively. The difference between the identified sources, including secondary particles, and the measured PM_{2.5} mass is indicated as “unidentified” in this report. Unidentified hydrocarbons and water are two potential sources of unidentified mass. When the spring, summer, and autumn samples from Kolkata were analyzed following the above procedures, the sum of the identified sources exceeded the measured mass of PM_{2.5}.

A4.14 Some of the key parameters from hydrocarbon speciation and carbon analysis are shown in Table A4.5. Kolkata summer and autumn, and spring to a lesser extent, stand out as having much higher ratios of elemental carbon to total fine particulate mass, of elemental carbon to organic carbon, and of hopanes and steranes to organic carbon as well as to total fine particulate matter, than other data sets. The reason for this unusual trend is not clear.

Table A4.5 Mass Ratios of Carbon Compounds

<i>City season</i>	<i>OC/PM_{2.5}</i>	<i>EC/PM_{2.5}</i>	<i>EC/OC</i>	<i>(H+S)/EC</i>	<i>(H+S)/OC</i>	<i>(H+S)/PM_{2.5}</i>	<i>Levo/OC</i>	<i>Picene/OC</i>
Chandigarh summer								
Delhi spring	0.33	0.080	0.24	0.0024	0.0006	0.0002	0.027	0.00003
Delhi summer	0.33	0.081	0.25	0.0021	0.0005	0.0002	0.013	0.00002
Delhi autumn	0.36	0.072	0.20	0.0033	0.0007	0.0002	0.031	0.00003
Delhi winter	0.41	0.075	0.18	0.0046	0.0008	0.0003	0.055	0.00005
Kolkata spring	0.34	0.11	0.32	0.0079	0.0025	0.0009	0.019	0.00003
Kolkata summer	0.29	0.25	0.85	0.0049	0.0041	0.0012	0.006	0.00004
Kolkata autumn	0.39	0.20	0.52	0.0056	0.0029	0.0011	0.027	0.00005
Kolkata winter	0.48	0.087	0.18	0.0041	0.0007	0.0004	0.037	0.00005
Mumbai spring	0.26	0.10	0.39	0.0018	0.0007	0.0002	0.008	0.00001
Mumbai autumn	0.31	0.088	0.28	0.0022	0.0006	0.0002	0.020	0.00002
Mumbai winter	0.38	0.092	0.24	0.0028	0.0007	0.0003	0.027	0.00003

Note: Insufficient sample was collected in summer in Mumbai to carry out hydrocarbon speciation.

OC – organic carbon; EC – elemental carbon; H+S – sum of hopanes and steranes; Lev – levoglucosan.

Quantification

A4.15 Quantification is based on contribution to *primary* organic carbon: those that are from primary emissions, and not secondary particulate formation in the atmosphere. All the

source profiles are for primary emissions. Ideally the source profiles should be representative of the local conditions, both in terms of fuel characteristics and operating conditions. Source profiles from South Asia were not available in this study except for five biomass samples from Bangladesh. The ratios of organic carbon to PM_{2.5} used and the references are given in Table A4.6.

Table A4.6 Ratio of Organic Carbon to PM_{2.5} Used in the Model

<i>Source</i>	<i>Ratio</i>	<i>Comments</i>	<i>Reference</i>
Diesel	0.304	Two 1995 model medium-duty trucks tested using the U.S. federal test procedure (FTP) using reformulated California diesel	Schauer and others (1999)
Gasoline	0.771	17% catalyst equipped, 83% no catalyst, gasoline cars of varying age running on California reformulated gasoline using the U.S. FTP	Schauer and others (2002)
Biomass	0.525	Average of five Bangladesh biomass sources	Sheesley and others (2003)
Road dust	0.126	Average of three California road dust sources	Schauer (1998)
Coal	0.409	Coal in Beijing, China	Zheng and others (2004a)

A4.16 The applicability of the ratios shown in Table A4.6 to the samples collected in India cannot be demonstrated without further data collection. Road dust composition in particular is likely to vary from region to region.

A4.17 The source profiles for vehicle emissions vary strongly as a function of the driving cycle, and this effect is much greater than those of fuel quality, vehicle technology, or the state of vehicle repair. Two studies have examined particulate composition in diesel exhaust as a function of engine speed, load, the air-to-fuel ratio, and fuel quality (Kweon and others 2003a, 2003b). Of particular relevance in South Asia is the finding that over-fueling vehicles emitted significantly more PM_{2.5} and elemental carbon, but not organic carbon.

A4.18 In the case of road dust, the profiles were generated by re-suspending a road dust sample and introducing a mixture of the road dust and air into the residence time chamber of the dilution source sampler at the California Institute of Technology. Samples were drawn through an AIHL-design cyclone to remove coarse particles, collected on quartz filters and Teflon filters, and analyzed for ions and organics. Organic analysis of road dust confirmed the presence of organic carbon species in the dust. The chemical mass balance model compares the aluminum-to-organic carbon and silicon-to-organic carbon ratios in the road dust profiles and in the ambient samples and attempts to find a match. Once the match is found, the model takes the organics from the road dust source profile and seeks them in the ambient samples. The amount of road dust in PM_{2.5} is back-calculated from the organic carbon species identified with road dust.

A4.19 It should be noted that although the source profile for diesel is from medium-duty diesel trucks, it is not possible to distinguish between diesel exhaust from vehicles and

diesel emissions from stationary sources. The use of diesel in small power generators is not insignificant in the Indian cities studied because of frequent power outage. Therefore, not all diesel-derived $PM_{2.5}$ is from mobile sources. Gasoline, in contrast, is used exclusively in vehicles, and all of gasoline can be attributed to mobile sources.

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