Reducing Air Pollution from Urban Transport

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Foreword

Urban air pollution from road transport is a growing concern in a large number of developing country cities. With rising income, the use of motorized transport is expected to continue to increase in the coming years, potentially worsening air quality. Poor air quality in turn has been shown to have seriously adverse effects on public health. The World Health Organization estimated that 650,000 people died prematurely from urban air pollution in developing countries in 2000.

The need to tackle air pollution from transport is widely acknowledged. But the menu of options available is varied and can be daunting. Are there key questions that should be answered to guide policymaking? Under what conditions are the different mitigation measures likely to achieve pollution reduction? Are there key steps to be taken or underlying conditions that must be met, without which pollution reduction is unlikely? Which mitigation measures are "proven," which are more difficult to implement, and which are still in the realm of pilot-testing?

This report is intended to provide guidelines and principles for answering these and other related questions. The report does not attempt to provide a detailed road map applicable to all circumstances—given the varying nature of air pollution, pollution sources, and available resources, answers and even key policy questions will be different from country to country—but rather proposes a framework in which policy selection and implementation should occur, drawing lessons from international experience. It places a special emphasis on how to coordinate policies across three sectors most closely linked to the mitigation of air pollution from road transport—environment, transport, and energy—and how to reconcile the sometimes conflicting objectives and demands of these sectors to achieve environmental improvement.

We hope that this report will stimulate and contribute to a discussion on how best to coordinate policies across different sectors to their mutual benefit in an environmentally sustainable manner.

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List of Abbreviations, Acronyms, and Glossary

ACEA	Association des Constructeurs Européens d'Automobiles (Association of European Automobile Manufacturers)
AQIRP	Air Quality Improvement Research Program (U.S. auto/oil industry study)
ARPEL	Associacíon Regional de Empresas de Petróleo y Gas Natural en Latinoamérica y el Caribe (Regional Association of Oil and Natural Gas Companies in Latin America and the Caribbean)
ASTM	American Society of Testing and Materials
ATC	Area traffic control (systems)
BMTA	Bangkok Mass Transit Authority
BRT	Bus rapid transit
C_5	Hydrocarbons with five carbon atoms
CAA	Clean Air Act
CAFE	Corporate average fuel economy (U.S. standards, set by the Department of Transportation, on the actual sales-weighted average fuel economy of domestic and imported passenger cars and light-duty trucks)
CARB	California Air Resources Board
CBD	Central business district
CFC	Chlorofluorocarbons (refrigerants that have global warming impacts as well as having damaging effects on the stratospheric ozone layers)
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COI	Cost of illness
CR	Concentration-response
CUEDC	Composite Urban Emissions Drive Cycle
DALY	Disability-adjusted life-year
ECE	United Nations Economic Commission for Europe
ECMT	European Conference of Ministers of Transport
EEVs	Environmentally enhanced vehicles
EGR	Exhaust gas recirculation
ELR	European load response
EMA	Engine Manufacturers Association
EPEFE	European Programme on Emissions, Fuels and Engine Technologies (a European auto and oil industry study)
ERP	Electronic road pricing
ESC	European stationary cycle
EU	European Union
EUDC	(EU) Extra urban driving cycle
EWG	Environmental Working Group
FTP	(U.S.) Federal Test Procedure
GEF	Global Environment Facility
GHG	Greenhouse gas (gas that contributes to global warming effects)
GTZ	Deutsche Gesselschaft für Technische Zusammenarbeit (German Technical Cooperation)
GVWR	Gross vehicle weight rating
HC	Hydrocarbon
HCHO	(Molecular formula for) formaldehyde
HDDE	Heavy-duty diesel engine
IANGV	International Association for Natural Gas Vehicles
ICCT	International Council on Clean Transportation
I/M	Inspection and maintenance (systems)
IQ	Intelligence quotient
ITS	Intelligent transport systems (computer based real-time control systems of traffic or vehicles)
IU	In-vehicle unit
JAMA	Japan Automobile Manufacturers Association
JASO	Japanese Standards Organization
LDT	Light-duty truck
LDV	Light-duty vehicle
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MCMA	Mexico City Metropolitan Area
MON	Motor octane number (ability of gasoline to resist auto-ignition, or knocking, under highway driving conditions)
MTA	Metropolitan Transportation Authority
MTBE	Methyl tertiary-butyl ether (an oxygenate)
MY	Model year
NEPC	National Environment Protection Council (of Australia)
NG	Natural gas

NGO	Nongovernmental organization
NGV	Natural gas vehicle
NMHC	Nonmethane hydrocarbons
NMT	Nonmotorized transport
NO	Nitric oxide
N_2O	Nitrous oxide (a powerful greenhouse gas)
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
NPRA	(U.S.) National Petrochemicals and Refiners Association
NREL	National Renewable Energy Laboratory
NTE	(U.S.) Not to exceed
OBD	On-board diagnostic
OECD	Organisation for Economic Co-operation and Development (association of mainly industrial countries)
OEM	Original equipment manufacturer
OLADE	Organización Latinoamericana de Energía (Latin American Energy Organization)
PAH	Polyaromatic hydrocarbon (a hydrocarbon with more than one benzene ring)
PM	Particulate matter
$PM_{2.5}$	Particulate matter of size 2.5 microns or smaller in aerodynamic diameter, also referred to as respirable particulate matter or fine particulate matter
PM_{10}	Particulate matter of size 10 microns or smaller in aerodynamic diameter, also referred to as inhalable particulate matter
RAD	Restricted activity day
RFG	Reformulated gasoline
RON	Research octane number (ability of gasoline to resist auto-ignition, or knocking, under city driving conditions)
SAE	Society of Automotive Engineers
SET	(U.S.) Supplementary emission test
SFTP	(U.S.) Supplemental Federal Test Procedure
SO_2	Sulfur dioxide
SO_x	Oxides of sulfur
SPM	Suspended particulate matter
STAP	Science and Technology Advisory Panel
SUV	Sport utility vehicle
TSP	Total suspended particles
T_{90}, T_{95}	Temperature at which 90 percent or 95 percent of a fuel evaporates
UNECE	United Nations Economic Commission for Europe
URBAIR	Urban Air Quality Management Strategy in Asia
USDA	U.S. Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency
U.S. GAO	U.S. General Accounting Office
VOC	Volatile organic compound
VSL	Value of a statistical life
VLSY	Value of statistical life-years
WHO	World Health Organization
WTP	Willingness to pay

Units of Measure

B/d	Barrels per day
cc	Cubic centimeters (a unit of volume)
cSt	Centistokes, a unit of kinematic viscosity (viscosity divided by density)
€	Euros
g	Grams
g/km	Grams per kilometer
g/kWh	Grams per kilowatt-hour
g/l	Grams per liter
kg	Kilograms
kg/m^3	Kilograms per cubic meter (a unit of density)
km	Kilometers
km/h	Kilometers per hour
kPa	Kilopascals (a unit of pressure)
kW	Kilowatts
kWh	Kilowatt-hours (a unit of energy)
m	Meters
m^3	Cubic meters
ppb	Parts per billion
ppm	Parts per million
psi	Pounds per square inch (a unit of pressure; 1 psi is equal to 8.9 kPa)
rpm	Revolutions per minute
R$	Brazilian Real
vol%	Percent by volume
wt%	Percent by weight
wt ppm	Parts per million by weight. 10,000 wt ppm is 1 percent by weight, 1,000 wt ppm is 0.1 percent, and so on.
µg/m^3	Micrograms per cubic meter
µm	Microns

Preface

This report is intended to assist World Bank Group staff and client countries in the design of appropriate strategies for controlling the impacts of urban air pollution from mobile sources. The report considers only the direct air impacts of surface transport, excluding aviation, marine transport,[1] non-road vehicles (such as bulldozers and mining equipment), noise pollution, habitat fragmentation, and waste disposal of scrapped vehicles. It is aimed at World Bank Group staff as well as national and local government policymakers working in a number of sectors related to air pollution from mobile sources—transport, energy, and environment. ***Main guideline recommendations and observations appear in bold italics in the main text.***

The report is divided into eight chapters and is supplemented by nine technical annexes and an Executive Summary. The Executive Summary provides general guidelines to practitioners and policymakers on key policy themes, cross-references the relevant sections of the report and annexes where the topics are discussed, and is recommended for those readers who want an overview of the main messages in the report.

Chapter 1 describes the nature of the problem, the levels and trends of ambient air pollution in developing country cities, and the context within which transport-related air quality policy needs to be set. It emphasizes that the behavior of the many personal and corporate actors in the transport sector are fundamental in determining the effectiveness of policy efforts to reduce urban air pollution. Chapter 2 discusses the impacts of the principal urban air pollutants, and how to assess the contribution of transport to poor urban air quality. It concludes by identifying three principal transport aspects within which air quality improvement can be sought: through reducing the emission of pollutants per unit of fuel consumed, reducing the consumption of fuel per unit of transport services, and limiting the overall demand for motorized transport services.

Chapters 3 through 5 discuss, for each of these three aspects, the array of policy areas and instruments in which improvements can be sought, and identify the range of instruments that can be used. The annexes supplement these chapters by providing more detailed information on the physical and economic characteristics of technologies—both of some current commercially viable technologies and of some technologies that are still in development, and also how to ensure their proper maintenance—and on the economic valuation of health impacts of air pollution. The basis for the guidance and policy discussion in these chapters draws heavily on the experience of the World Bank in the urban transport, fuel, and environment sectors in developing countries. Emphasis is put on the need for solutions to be both affordable and sustainable.

Many of the technological and policy instruments discussed cannot be sustained, or will be less effective, unless introduced in the appropriately supporting fiscal framework, discussed in chapter 6, and institutional setting, discussed in chapter 7. Finally, chapter 8 discusses how to formulate a policy package appropriate for the many different situations found in developing countries. It identifies a range of instruments that grasp synergies between environmental and economic policy dimensions or that have been found to be cost-effective over a wide range of country circumstances. However, because technology is changing very rapidly, both in capability and in private and public cost, and because affordability varies

[1] Emissions in harbors, inland waterways, and airports can have a marked impact on urban air pollution.

by country, there is no "magic bullet" to solve all problems. Hence the report does not prescribe a "one-size-fits-all" list of technological imperatives, but rather concentrates on providing information and a strategy framework with which countries may design and adopt air pollution strategies appropriate to their own environmental, social, and economic circumstances.

Given the rapid changes in vehicle and pollution control technology, one caveat should be noted. The recommendations and observations concerning vehicle technology, fuel quality, and corresponding standards should be interpreted in the light of the circumstances prevailing at the time of report publication. Different recommendations and observations related to technology and standards will undoubtedly become more appropriate in the future. In contrast, recommendations and observations concerning sector and fiscal policies change much less with time. Indeed, setting appropriate sector and fiscal policies can create an enabling environment that facilitates advances in standards and technology.

Executive Summary

Background

Air pollution is a serious problem in many developing country cities. Ambient concentrations of fine particulate matter, which is one of the most damaging air pollutants, are often several times higher in developing country cities compared to those in industrial countries. The largest human and economic impacts of air pollution are the increased incidence of illness and premature death that result from human exposure to elevated levels of harmful pollutants. Using damage to human health as the primary indicator of the seriousness of air pollution, the most important urban air pollutants to control in developing countries are lead, fine particulate matter, and, in some cities, ozone. Air pollution impacts in developing countries often fall disproportionately on the poor, compounding the effects of other environmental problems such as the lack of clean water and sanitation.

While the impacts of urban air pollution have been documented in both industrial and developing countries, for policymaking purposes it is important to know the relative contribution of mobile sources (cars, trucks, buses, motorcycles), stationary sources (power plants, industry, households), and other sources (construction, re-suspended road dust, biomass burning, dust storms). In the transport and transport fuel-supply sectors, many actors must be part of an effective strategy for reducing mobile-source emissions. To be effective and sustainable over the long term, regulatory and policy instruments for reducing transport emissions must provide incentives for individuals and firms to limit the pollution from existing vehicles and to avoid delay in adopting new and cleaner technologies and fuels. Public and private institutions must be equipped with the resources and the skills necessary to support measures to control transport emissions and to evaluate the effectiveness of such measures. Above all, interventions must be cost-effective and affordable in light of the myriad of other pressing needs in developing country cities.

This report discusses policy, technological, administrative, and economic issues surrounding interventions for air quality improvement in developing countries, and provides examples of both successful and unsuccessful actions and approaches to air quality management. The purpose of the report is to assist national and local government policymakers and professionals identify the roles that the transport, energy, environment, and other related sectors play in urban air quality management in their particular contexts and to help design cost-effective strategies to control the impact of mobile-source emissions. It complements the World Bank's *Pollution Prevention and Abatement Handbook* (World Bank 1999), which provides general policy advice on pollution management and detailed recommendations for addressing pollution from stationary sources.

A Framework for Decisionmaking[1]

In order to design effective approaches to pollution management from mobile sources, it is important to diagnose urban air pollution problems, determine the impact of mobile sources, and identify affordable and sustainable solutions. The first step is to ask how serious outdoor air pollution is in a given city and the nature of the pollution problem. This entails monitoring air quality and comparing ambient concentrations with national air quality standards or, in their absence, internationally recognized health-based air quality guidelines. Pollution reduction measures should focus on the most damaging pollutants, based on the combined impact of high ambient concentra-

[1]Chapter 2.

tions, toxicity, and human exposure. Once the most damaging pollutants have been identified, the relative contribution of mobile sources to the problem should be determined (chapter 2). For some pollutants, such as lead and carbon monoxide, the transport sector is often a major contributor, while for fine particulate matter the transport sector is typically one of several sources of emissions. Where transport activities are a major contributor to a specific air pollution problem, it is important to determine in what ways these activities can be reduced (chapters 3–5). The instruments by which emissions can be reduced need to be identified (chapters 3–6), the effectiveness of different policy instruments assessed, and institutional arrangements developed and strengthened (chapter 7) to construct an overall policy package (chapter 8).

Policy Instruments for Reducing Transport Emissions and Reducing Human Exposure

The contribution of transport to air pollution can be viewed broadly as the product of three factors.[2]

Air pollution from mobile sources can be decreased by reducing emissions per unit of fuel,[3] consuming less fuel per passenger- or freight-kilometer traveled,[4] or requiring fewer passenger- or freight-kilometers.[5]

Effective interventions for reducing transport-related emissions range from general improvements in sector efficiency to specific regulatory, policy, and institutional development, and technical measures. Transport emission reduction strategies target either the transport system as a whole or individual vehicles, and they can affect both at the same time. For example, changing fuel prices can have an immediate impact on the use of individual vehicles and, over time, affect the overall composition of the vehicle fleet.

Many measures taken to reduce transport-related air pollution will be suboptimal or ineffective over the longer term without policy changes in the transport and fuel sectors. While such policy changes will rarely be made based on environmental concerns alone, it is important to recognize that reforms in the urban transport sector or the oil and gas industry can have an enormous positive effect on reducing transport-related air pollution. Some reforms, such as import liberalization for clean fuels, will be national in scope, whereas others, such as urban transport sector reform, will be local. In both cases, they are likely to have significant economic and social benefits aside from their environmental benefits, and in this sense should be seen as "no regret" measures.

Reducing Emissions through Transport System Improvement

Transport sector emissions can be reduced through a variety of changes to the overall transport system: efficiency improvements in the urban transport system, changes in modal shares through infrastructure investments or land use policy, or through fiscal policies that can affect fuel and vehicle technology choice, fuel consumption, and vehicle use.

Traffic management[6] and land use[7]

Traffic system management is intended to smooth the flow of traffic and enhance mobility, but can also have the added benefit of reducing emissions and fuel consumption. Traffic signal control systems are the most common traffic management instruments to secure traffic flow objectives. 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

[2] The three factors were selected for ease of discussing different dimensions of transport emissions and are not intended to imply that fuels and vehicles should be treated separately and in isolation from each other. An important objective remains reducing emissions per passenger- or freight-kilometer traveled, which requires treating fuels and vehicles as a joint system.

[3] Chapter 3.

[4] Chapter 4.

[5] Chapter 5.

[6] Chapter 4, Traffic Management.

[7] Chapter 5, Land Use Policy.

FIGURE E. 1

Factors Contributing to Transport Emissions

Transport emissions = Emissions per unit of fuel × Total transport services demanded × Fuel consumption per unit of transport service

passenger-kilometer. One weakness associated with simply improving traffic flow is that faster traffic flow often invites more traffic. Thus if traffic demand is not controlled in parallel, congestion may be little relieved and total emissions may even increase.

Options for traffic demand management include promoting appropriate land use planning to reduce trip lengths, placing restraints on vehicle movements through parking policies, and location- and time-specific charges or bans on certain categories of vehicles. For the structure of land use, high-population density and the concentration of employment and retail in a centrally located central business district is likely to encourage public transport and reduce trip length. Traffic management is essential to realizing the potential benefits of good land use planning.

Influencing modal choice[8]

Positive actions to promote alternatives to private motorization are important and have been notably successful in recent years in Bogotá, Colombia, and other cities. These include encouraging nonmotorized transport by building and protecting pedestrian and bicycle paths, as well as policies to promote public transport. Bus sector reform warrants special attention. Buses are much cheaper than rail mass transit and will continue to play an important role in public transport in developing countries. Bus transport policy affects urban air pollution both *directly* through its effects on bus vehicle emissions and *indirectly* through its effects on the use of smaller vehicles. Without an effective bus system, mobility is provided by numerous small vehicles—three-wheelers, minibuses, or private cars—contributing to congestion and reducing average traffic speeds. Policy must therefore aim *simultaneously* to minimize the direct air pollution impacts of buses by making them clean and to maximize their indirect benefits by making them sufficiently attractive to draw passengers from small vehicles to high-occupancy transport vehicles.

Higher standards (for emissions as well as quality of service) for buses need to be introduced in the context of a general policy framework that makes the provision of clean bus services financially viable for the supplier and affordable to the user. Otherwise, higher standards may raise costs and inadvertently reduce service, causing adverse social and environmental consequences. The usual effect is the market entry of informal operators using smaller, often very old and polluting, vehicles. During the last decade,

Mixing motorized and nonmotorized transport, as well as public transport vehicles with cars and other vehicle types, reduces the average speed of traffic and makes it difficult to establish an effective bus system.

[8] Chapter 4, Encouraging Nonmotorized Transport, Regulation and Control of Public Road Passenger Transport, and The Role of Mass Transit.

conventional bus systems have failed in many countries in Africa, Central Asia, and elsewhere as a result of keeping fares low while attempting to mandate socially desirable service quality. When this happens, bus operators face increasing costs and decreasing profits on account of growing traffic congestion and competition from weakly regulated paratransit vehicles.

General Guidelines for Improving the Transport System

Any intervention in the transport sector needs to be part of a favorable transport planning and management policy framework. That framework should consider the following:

- Formulating transit-oriented development strategies to reduce trip lengths and concentrate movements on efficient public transport axial routes.
- Conducting air quality audits of all new major transport infrastructure projects as a required part of the environmental impact assessment to determine if the projects will lead to or worsen exceedances of air quality standards.
- Giving priority to buses in the use of road infrastructure, and particularly the creation of segregated busway systems, in order to improve and sustain environmental standards for buses.
- Improving the efficiency of bus operation through the design of more efficient route networks, better cost control, and creation of incentives for improvement through commercialization and competition.
- Promoting competitive bidding for transport franchises based on performance-based criteria, including emission characteristics of vehicles.
- Establishing adequate and safe pedestrian and bicycle facilities in order to promote nonmotorized options for short distance trips.
- Establishing and implementing protocols for traffic signal system settings that result in reduced exhaust emissions.
- Establishing urban traffic management centers and involving police in traffic management system design and training.
- Establishing a municipal department or agency with comprehensive responsibility for integrated land use and transport planning, including environmental protection issues.

Fiscal policies[9]

It is typically more efficient and cost-effective to tax polluting vehicles and fuels than to subsidize cleaner alternatives. This would mean that, ideally, taxes on more polluting fuels such as conventional diesel should be raised rather than subsidies given to cleaner fuels such as compressed natural gas (CNG). One successful application of differential fuel tax is levying a higher tax on leaded gasoline than on unleaded gasoline. Subsidies given to public transport fares are generally not cost-effective as an environmental policy. There is strong evidence that up to half of the subsidy "leaks" to benefit transport industry interests rather than passengers. Moreover, private car owners are only marginally sensitive to public transport fare levels so that the subsidy is not particularly effective in shifting travelers from private to public transport.

Fuel taxation is the most common tax on transport activity. It is popular not only because of its ease of collection and income-generating properties, but also because of its role as a proxy for road user and environmental charges. Fuel taxes are effective both in reducing motorized travel and encouraging fuel-efficient vehicles. Unfortunately, a fuel tax is a relatively weak proxy for local pollutant emission charges because it fails to reflect the location of emissions as well

[9] Chapter 6.

as the amount of emissions per unit of fuel consumed. For that reason, more precisely targeted alternatives to fuel taxes should be considered in parallel.

Taxes for petroleum fuels should take careful account of, and minimize, the possibilities for fuel adulteration and socially undesirable inter-fuel substitution. There is a strong case for setting the gasoline tax above the general tax rate on commodities on distributional grounds as well as to direct efficient allocation of resources in developing countries. There is also a strong case for a diesel tax as the principal means of charging heavy vehicles for wear and tear on the road and capturing the marginal social damage from diesel emissions. Because of the significant impact of higher taxation on non-automotive uses of diesel—in rail transport, agriculture, and industry, for example—it may be sensible to give rebates on the higher diesel tax to non-road users.

General Guidelines for Fiscal Policies

The economic ideal would be a system of direct taxation on emissions, combined with trading of emission certificates among fuel and vehicle manufacturers, but the complexity of such a system makes it necessary to devise alternatives. Among the fiscal policies that can be used to reduce transport sector emissions are the following:

- In those countries where taxes on diesel fuel for transport use are very low, raising them to compensate for environmental damages, pay for road wear and tear, and encourage fuel-efficient vehicles and the use of cleaner fuels.
- In addition to fuel taxes, considering separate vehicle charges based on vehicle weight, axle loadings, and annual mileage.
- Introducing direct charges for the use of urban road space, including congestion charges.
- Introducing or raising taxes, import duties, and vehicle licensing disincentives for polluting vehicles and engines.
- Giving serious consideration to eliminating subsidies to public off-street parking as well as not permitting free on-street parking, especially where they increase congestion by generating private transport trips to congested locations, or where on-street parking increases congestion by reducing available road space.

Reducing Emissions at the Vehicle Level[10]

Improved fuels and vehicle technology have enormous potential for reducing vehicle emissions, and fuel and vehicle standards are often the most widely discussed policy options for tackling mobile source emissions. In this context it is very important to treat fuels and vehicles as a joint system, since cleaner vehicle technology generally requires improved fuel quality. The ultimate objective is to adopt a fuel and vehicle system embodying high standards and best practice technology that have been proven cost-effective in the industrial countries. The question is not *whether* to adopt these standards in developing countries, but *how* and *when* to adopt them. The pace of that transition will be determined by the cost-effectiveness of such measures to improve air quality compared with other measures (including those in other sectors), given the constraints in human and financial resources.

Improving vehicle technology is not sufficient to ensure that emissions will remain low over the lifetime of the vehicle. The state of vehicle repair is known to have a great impact on the amount of pollution generated and of fuel consumed. Fuel and vehicle technology measures will be most effective in reducing emissions if vehicles are routinely repaired

[10] Chapter 3; chapter 4, Improving Fuel Efficiency through Vehicle Technology, Increasing Fuel Efficiency through Vehicle Operation; and annexes 1–7 .

and serviced, if cheaper but lower-quality counterfeit spare parts are avoided, and if exhaust control devices and other parts of the vehicle affecting emissions are properly maintained. Fostering a system of regular and proper preventive vehicle maintenance among both public and private vehicle owners is an essential element of urban air quality management. Driving behavior, particularly the avoidance of excessive acceleration, is also important to fuel consumption and emissions.

Inspection and maintenance[11]

Vehicle inspection and maintenance (I/M) programs can help improve vehicle maintenance behavior and enforce emission standards for in-use vehicles. The primary objective of I/M 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. The I/M system in Mexico City is an example of a successful program on a large scale. Experience in Mexico has shown that high volume, centralized test-only centers are more effective than decentralized test-and-repair garages. Given limited resources available, it may be advisable to concentrate resources on categories of vehicles likely to contain a large fraction of high annual-kilometer, gross polluters (for example, commercial diesel vehicles), rather than test every vehicle each year.

[11]Chapter 3, Vehicle Technology; and annex 7.

General Guidelines for Inspection and Maintenance

An effective vehicle inspection program can help enforce emission standards for in-use vehicles. International experience suggests the following advice on establishment of an I/M system:

- 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.
- Centralized, test-only private sector centers with modern instrumentation, maximum automation, and "blind test" procedures are easier to control for quality; all centers should be subject to independent monitoring.
- An up-to-date and accurate vehicle registration record is necessary coupled with 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, to ensure that all vehicles in the designated categories report for testing.
- Education campaigns and clinics to improve vehicle maintenance, especially for two-stroke engine maintenance and lubrication, can be helpful complements to I/M.

Fuel quality[12]

Conventional liquid transportation fuels will remain the primary focus of fuel quality improvements for the foreseeable future. Improving gasoline by reformulating it can involve eliminating lead and reducing benzene, sulfur, vapor pressure, and total aromatics, while reformulating diesel properties (including lowering density, sulfur content, and polycylic hydrocarbons) can result in a reduction in particulate emissions.

Some fuel quality improvements reduce emissions from all vehicles immediately using the improved fuel. For example, discontinuing the addition of lead to gasoline instantly eliminates lead emissions from all gasoline-fueled vehicles, regardless of their age or

[12]Chapter 3, Cleaner Fuels, Maintaining Fuel Standards; and annexes 1–4.

state of repair. Similarly, reducing fuel sulfur levels lowers the emissions of oxides of sulfur (SO_x). Other measures, such as the use of ultralow[13] sulfur and the so-called sulfur-free[14] gasoline and diesel fuels, are slated to be mandated in industrial countries and a few developing countries during the latter half of this decade primarily to enable the use of sulfur-intolerant exhaust control devices that can dramatically reduce emissions of pollutants, especially particulate matter and oxides of nitrogen (NO_x). Because they are a system, it is important to consider fuel quality and vehicular emission standards together. Aside from significant investment in oil refining capacity that is typically required to produce fuels with very low sulfur levels, there is also a greater need than is the typical practice in developing countries for proper vehicle maintenance and operation in order for the exhaust control devices to be effective.

[13]In this report, ultralow refers to 50 parts per million (ppm) or lower.

[14]"Sulfur-free" fuels contain a maximum of 10 ppm sulfur. EU member states are required to make sulfur-free gasoline and diesel beginning January 2005, and sell only sulfur-free gasoline and diesel effective January 2009.

General Guidelines for Fuel Quality

The appropriate standards for fuel will depend on country circumstances, including the level of air pollution and the costs of upgrading. But some general guidelines can be stated:

- Moving to unleaded gasoline as a first priority while ensuring that benzene and total aromatics do not rise to unacceptable levels.
- Progressively implementing steps to reduce the sulfur content of both gasoline and diesel fuels to very low levels, taking into account the initial situation and human and financial resource constraints:
  - Where the sulfur content of gasoline is high, reducing it to 500 parts per million (ppm) and preferably lower as soon as possible, to ensure efficient operation of catalytic converters (following lead removal).
  - Where sulfur content in diesel is very high, identifying and implementing a strategy to reduce it to 500 ppm or lower.
  - Where moving to 500 ppm for diesel is very difficult in the near term but lowering it to 2,000–3,000 ppm is relatively inexpensive, immediately moving to this level.
  - In countries with current or potentially high levels of air pollution from mobile sources, especially those that have already taken steps toward 500 ppm, or where new or significantly renovated oil refining capacity is being invested in, examining the cost-effectiveness of moving to ultralow sulfur standards, taking into account maintenance capability and the concomitant investments in the necessary emission control technologies to exploit lower sulfur fuels.
- Where the resource and infrastructure conditions for natural gas are favorable and those for clean diesel technology are much less so, giving consideration to shifting high mileage public transport fleets from diesel to CNG.
- Taking steps to prevent fuel adulteration and the smuggling of low-quality fuels from neighboring countries, and giving consideration to holding fuel marketers legally responsible for quality of fuels sold.

Vehicle technology[15]

Vehicle technology improvements, including emission control devices such as catalytic converters and exhaust gas recirculation, are driven to a large extent by emission standards for new vehicles in industrial countries. A common policy question for developing countries is where to set standards for new additions to their vehicle fleet population (either through imports or domestic vehicle manufacture). Countries importing fuels and vehicles find it easier to impose tighter standards than do manufacturing countries. It is also important to balance standards for new vehicles with those for in-use vehicles. If standards for new vehicles are very stringent and those for in-use vehicles lax, the result is that vehicle renewal becomes expensive and the retirement of old vehicles may be delayed. Since old and heavily polluting in-use vehicles tend to contribute disproportionately to air pollution from mobile sources, it is thus important from an air quality perspective to focus on tightening standards for in-use vehicles and to get them repaired or retired.

[15]Chapter 3, Vehicle Technology; chapter 4, Improving Fuel Efficiency through Vehicle Technology; and annexes 2 and 3.

General Guidelines for Vehicle Technology

The setting of appropriate vehicle standards complemented by adequate fuel standards is very important for emission reduction over time. General guidelines for setting these standards include the following:

- Setting emission standards for in-use vehicles at levels that are achievable by a majority of vehicles with good maintenance, and tightened over time.
- Progressively tightening vehicle emission standards for new vehicles to levels consistent with improving fuel quality.
- Setting emission standards that require the installation and continued maintenance of catalytic converters for all new gasoline-powered vehicles in countries where lead in gasoline has been eliminated.
- Giving consideration to the introduction of particulate filters (traps) and other devices to reduce end-of-pipe emissions from diesel vehicles where ultralow sulfur diesel is available. As trap and other device technology develops and prices fall, and as ultralow sulfur fuels become more widely available, this strategy will become more robust.
- Establishing regulatory measures to prevent the import of grossly polluting vehicles.
- Establishing institutions for administering and enforcing vehicle emission standards with a primary task of identifying and removing gross polluting vehicles from the road.

Alternative fuels[16]

Alternative transport fuels are those other than gasoline and diesel, and include gaseous fuels, biofuels, and electricity. Although they can be more expensive for the final consumer than conventional fuels, alternative fuels can reduce emissions significantly, especially when gaseous fuels replace conventional diesel. Other advantages of alternative fuels include diversification of energy sources and, particularly in the case of biofuels, reductions of lifecycle greenhouse gas emissions. The factors needed for successful conversion to gas in developing countries include the existence of a gas distribution pipeline for other users of natural gas in the case of CNG, close proximity to the supply of natural gas or liquefied petroleum gas (LPG), and inter-fuel taxation policy that eliminates or reduces the potential financial burden of the substitution of gas for diesel fuel to acceptable limits. Because

[16]Chapter 3, Alternative Fuels; and annex 6.

diesel is taxed much less than gasoline in many developing countries, it is often difficult to stimulate substitution of diesel with a gaseous fuel through tax policy alone. When used in conventional vehicles, biofuels such as ethanol and biodiesel can have emission benefits compared to conventional fuels. The main barrier to biofuels development has been their higher production costs compared to conventional petroleum fuels, which has meant that, to date, all biofuels programs worldwide have required significant explicit or implicit subsidies.

Making technical instruments effective[17]

Technical solutions cannot be viewed in isolation from their policy and institutional context. Where there are serious sector distortions, it becomes much more difficult to implement technical measures. Protection of a domestic auto or oil industry—that is otherwise not able to withstand competition from the international market—tends to cause technologies and standards to lag. If subsidies are given to the industry or to its products (for example, fuel subsidies), it becomes even more difficult to tighten standards. An example is a state oil company selling subsidized fuels that finds it difficult to take even the first step of moving to unleaded gasoline.

Institutional capacity, both public and private, is also a necessary component for the successful introduction of new vehicles, fuels, and emission control technologies. Industrial countries have spent decades putting in place the necessary technical expertise and infrastructure for proper and regularly conducted vehicle maintenance, both in the public and private sectors. While developing countries can shorten the time frame, significant time and resources will be needed to establish effective institutions for inspection and markets for vehicle repair, without which the benefits of advanced technologies will be greatly reduced.

Conclusions

There is no simple or universal strategy for reducing transport sector emissions. While the specific actions for reducing transport emissions will vary from city to city, there are several underlying principles that this report seeks to emphasize for building an effective policy package:

- Raise awareness among policymakers and the general public about urban air pollution levels and damages and specify and promote the role that transport plays.
- 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 in business and with consumers about business "best practice" that is also likely to bring about environmental benefits to society.
- Work with, not against, the economic incentives of various transport actors.

The most aggressive and bold actions to control transport-related emissions should be undertaken in those cities with the most serious air quality problems and where the transport sector is a major contributor. Given the increase in transport emissions that has accompanied economic growth in virtually every municipality worldwide, it is important for all cities to begin putting in place systems for monitoring and controlling emissions from the transport sector. However, even where the transport sector's contribution is not currently high, such as in major coal-consuming countries or in low-income cities with a high percentage of solid fuel use, many of the measures outlined above can be appropriate where they have other social and economic benefits.

[17]Chapter 3, Cleaner Fuels, Downstream petroleum sector reform; chapter 4, Regulation and Control of Public Road Passenger Transport, Improving internal efficiency of operations; chapter 4, Regulation and Control of Public Road Passenger Transport, Public transport franchising; and chapter 7.

CHAPTER 1

The Context of the Problem

The Air Quality Problem in Developing Countries

The costs of air pollution in terms of damage to human health, vegetation, and buildings and of reduced visibility are perceived as a serious problem in many developing country cities. Air quality is poorer than that in most industrial country cities of equivalent size. The adverse effects of air pollution often fall disproportionately on the poor, compounding the impacts from other environmental problems in developing countries such as the lack of clean water and sanitation.

Transport as a Source of Pollution

Transport is a known source of many air pollutants. The first six listed below are termed "classic" air pollutants by the World Health Organization (WHO):

- **Lead** from the combustion of leaded gasoline is the best-known toxin in this context. 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 may occur even at levels previously considered safe. 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.
- **Total suspended particles (TSP)**, also referred to as suspended particulate matter (SPM), is not a single pollutant, but rather a mixture of many subclasses of pollutants that occur in both solid and liquid forms. Each subclass contains many different chemical species. Particulate matter (PM) may be classified as primary or secondary. Primary particles are emitted directly by emission sources, whereas secondary particles are formed through the atmospheric reaction of gases, such as the reactions between ammonia and oxides of nitrogen or sulfur that lead to the formation of particles. TSP have historically been monitored and continue to be measured in developing countries. The size distribution of airborne particles matters for health impact. The WHO places special emphasis on suspended particles smaller than 10 microns (µm) in diameter (PM_{10}), also called *inhalable* particulate matter, and those smaller than 2.5 µm ($PM_{2.5}$), called *fine* or *respirable* particulate matter. Emerging scientific evidence points to increasing damage with decreasing particle diameter. Particles larger than about 10 µm are deposited almost exclusively in the nose and throat, whereas particles smaller than 1 µm 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 PM_{10} concentrations, and recent studies using $PM_{2.5}$ data have shown an even stronger association between health outcomes and particles in this size range. In response, industrial countries have switched from monitoring TSP, which is not directly correlated with health effects, to PM_{10}, and increasingly to $PM_{2.5}$.
- **Ozone** (O_3) has been associated with transient effects on the human respiratory system, especially decreased pulmonary function in individuals taking light-to-heavy exercise. Several recent studies have linked ozone to premature

mortality.[1] Ozone also reduces visibility, damages vegetation, and contributes to photochemical smog. Oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) that are photochemically reactive (such as aromatics with two or more alkyl groups and olefins) are the two main precursors of ozone. NO_x is emitted by gasoline- and diesel-powered vehicles, while VOCs are emitted in most significant quantities by gasoline-fueled vehicles. Ambient concentrations of ozone are not necessarily lowered by reducing the two main contributors to ozone formation, hydrocarbons and NO_x. Depending on the ratio of these two components, decreasing one may even increase ambient ozone concentrations. Therefore, it is important to understand if the atmospheric chemistry in the city falls in the so-called NO_x-limited category (where reducing VOC concentrations may have little or even adverse impact on ambient ozone concentrations) or VOC-limited category (where reducing NO_x may have little or adverse impact on ambient ozone concentrations). Mexico City, in part by virtue of its altitude and geography, has historically suffered from high ambient concentrations of ozone, with levels exceeding the ozone standards on about 80 percent of the days a year. The government has been imposing increasingly stringent emission standards on its 3 million gasoline-fueled vehicles aided by a strictly enforced emissions inspection program (see annex 7).

- **Carbon monoxide (CO)**, the largest contributors to which are typically gasoline-fueled vehicles, inhibits the capacity of blood to carry oxygen to organs and tissues. People with chronic heart disease may experience chest pains when CO levels are high. At very high levels CO impairs vision and manual dexterity, and can cause death.
- **Sulfur dioxide (SO_2)**, which is emitted in direct proportion to the amount of sulfur in fuel, causes changes in lung function in persons with asthma and exacerbates respiratory symptoms in sensitive individuals. Through a series of chemical reactions, SO_2 can be transformed to sulfuric acid, which contributes to acid rain and to the formation of secondary (sulfate-based) particulate matter.
- **Nitrogen dioxide (NO_2)** also causes changes in lung function in asthmatics. Like SO_2, NO_2 can react to form nitric acid and thereby contribute to acid rain and secondary (nitrate-based) particulate formation. In addition, nitric oxide (NO) and NO_2, or NO_x as they are commonly called, are precursors of ground-level ozone. Both diesel- and gasoline-fueled vehicles contribute to NO_x emissions.
- **Other air toxin emissions** of primary concern in vehicle exhaust include benzene and poly-aromatic hydrocarbons (PAHs), both well-known carcinogens. Air toxin emissions such as benzene depend mostly on fuel composition and catalyst performance. Exhaust PAHs are due primarily to the presence of PAHs in the fuel itself; in the case of gasoline, they are also formed by fuel combustion in the engine.

Aside from fuel quality, the amounts of pollutants emitted depend on such factors as the air-to-fuel ratio, engine speed, engine load, operating temperatures, whether the vehicle is equipped with a catalytic converter, and the condition of the catalyst.

Air Pollution Levels and Trends

While all of these emissions are potentially damaging, their incidence and health impacts differ substantially, both among pollutants and from region to region. In cities with serious air pollution, the three most damaging pollutants tend to be lead, particulate matter, and ozone. The strongest evidence linking air pollution to health outcomes is the impact of small particles on premature mortality and morbidity. The consistent findings across a wide array of cities, including some in developing countries with diverse popula-

[1]Recent studies have found a significant independent effect on premature mortality for ozone if the important nonlinear effects of temperature (and humidity) are taken into account (Thurston and Ito 1990).

tions and possibly diverse particle characteristics, indicate that this association is robust. Particles are even more damaging if they contain lead. Ozone is a growing problem in developing country cities and a serious problem in many industrial countries.

WHO studies of megacities show that, although health-based guidelines of pollutants can be widely exceeded, the significance of the problem varies considerably. Lead excesses over norm are serious where leaded gasoline is used, but not usually elsewhere. Excess of CO is typically not nearly as great as that of small particulate matter, especially in countries where the consumption of gasoline is relatively low compared with that of diesel.[2] Significantly elevated levels of ambient SO_2 tend to come from the combustion of coal much more than from the transport sector. Marine engines may also contribute disproportionately to the local SO_2 inventory in port cities because marine fuel tends to be high in sulfur.

However, the situation is not static. Ambient NO_2 concentrations are often below the WHO guidelines but are on the increase, as are those of ozone. As in the industrial countries, it is expected that the relative importance of mobile source air pollution will increase in developing countries as incomes grow and other gross polluters either disappear naturally (domestic wood burning), or are suppressed at source (industrial pollution).

In designing measures to improve air quality, it is therefore necessary to take into consideration both the current pollutants of concern and likely future trends. If ozone is within air quality limits but on the rise and the gasoline vehicle population is growing rapidly due to rising household income, ozone is likely to be a serious problem in the future unless steps are taken. The suitability of different measures should also take into account the climatic conditions, topography of the city, altitude, dispersion profiles, and other defining characteristics of the airshed, all of which affect ambient pollutant concentrations in addition to sources and levels of emissions.

Global Climate Change

Transport is a growing source of greenhouse gas (GHG) emissions, which are believed to be contributing to a change in the earth's climate. Major GHG emissions from mobile sources are carbon dioxide (CO_2), methane, nitrous oxide (N_2O), and chlorofluorocarbons (CFCs) or other refrigerants. Over a 100-year horizon, the global warming potential of methane and N_2O is estimated to be 23 and 296 times that of CO_2, respectively, on a weight basis. The potential of CFCs is thousands of times greater than that of CO_2. Recently, soot has been receiving increasing attention as a contributor to global warming. Some scientists say soot, such as from diesel engines, is causing as much as a quarter of all observed global warming by reducing the ability of snow and ice to reflect sunlight (Hansen and Nazarenko 2004). Oil and natural gas production can release a large amount of GHGs: one oil company reported that it burned one barrel of oil in its entire operation for every three extracted from its wells (Automotive Environment Analyst 2001). Flaring of associated natural gas is still common, releasing CO_2 and residual unburned methane. Worse still is the venting of natural gas, released in the form of methane, a much more powerful GHG than CO_2. Complete combustion of carbon-containing fuel in a vehicle produces CO_2, while N_2O has been found in recent years to be formed in significant quantities in vehicles equipped with aged three-way catalytic converters. Leaks of refrigerants used in air conditioning are another source of GHG emissions. Vehicles fueled by natural gas tend to have higher methane emissions.

In order to properly assess the contribution of particular transport fuels to GHG emissions, a full life-cycle analysis (not just an analysis of tailpipe emissions) is needed. That analysis should include emissions that occur during the preparation of the fuel supply and vehicle manufacture. Refining processes are energy-intensive, and energy intensity increases with increasing stringency in fuel specifications, especially with respect to sulfur reduction.[3] A

[2]Ambient CO concentrations can be high at certain "hot spots" such as traffic corridors and intersections.

[3]For example, to reduce sulfur levels in fuels in the refining process, a source of hydrogen is needed to bond with the sulfur

recent well-to-wheel analysis, jointly carried out by auto and oil companies in conjunction with the Argonne National Laboratory in the North American context, examined advanced fuel and vehicle systems that had reasonable chances of being commercialized in large volume—oil-based fuels, natural gas-based fuels, hybrid, hydrogen, and alcohols (General Motors and others 2001). The study showed that vehicles fueled by woody or herbaceous cellulose-based ethanol (as opposed to ethanol based on agricultural crops such as corn) had by far the lowest GHG emissions. This was followed by hydrogen fuel cell hybrid electric vehicles. Diesel hybrid electric vehicles had GHG emissions that were significantly lower than those of conventional gasoline vehicles.

Controlling CO_2 emissions from the transport sector has been found to be generally more difficult than controlling emissions from other sectors in industrial countries. A recent study by the Organisation for Economic Co-operation and Development (OECD) Working Group on Transport focused on policy instruments and strategies for achieving environmentally sustainable transport in Canada and eight European countries (Working Party on National Environmental Policy 2002). Because of the difficulty of stabilizing, let alone reducing, transport sector emissions, the contribution of the transport sector to total CO_2 emissions in OECD countries is forecast to increase from approximately 20 percent in 1997 to 30 percent in 2020 (Environment Directorate Environment Policy Committee 2002). In developing countries, with rising income and the rapidly rising mobilization that accompanies it, the increase in CO_2 emissions in the coming years will be even greater than in OECD countries in absolute tonnage.

Even more so than for local air pollutants, it is essential to identify interventions with multiple social and economic benefits for controlling GHG emissions in developing countries. According to the Science and Technology Advisory Panel (STAP) of the Global Environment Facility (GEF), measures that affect the long-term energy demand by the urban transport sector, such as modal choice and land use planning, are likely to have much greater effect on GHG emissions and be more cost-effective than incremental changes in fuels and vehicles (GEF 2002).

for removal. The higher the sulfur level of the crude oil, the more hydrogen and energy will be needed for sulfur reduction of refined products such as gasoline, diesel, and fuel oil.

Urban Transport Policy in Developing Countries

Environmental policy decisions cannot be separated from transport sector policy decisions. Urban air pollution from mobile sources is a by-product of the production of urban transport services. Those services are essential to the economic health of a city and to the welfare of all its inhabitants, including the poor. Environmental and ecological impacts are important, but are only one aspect of urban transport policy; economic, financial, social, and distributional concerns also come into play. The various dimensions of policy impact have to be balanced in the local and national political process.

The three dimensions of policy concern—those relating to economics, the environment, and equity—may sometimes be in harmony. For example, the cost of eliminating lead from gasoline is usually small in comparison to the large health benefits that typically accrue to some very vulnerable groups, particularly poor, undernourished children. Other urban air quality issues are not so straightforward. For example, the imposition of stringent fuel and vehicle emission standards can increase capital and operating costs for bus operators or transit systems. Where there are not compensating reductions in operating costs, fares may have to be raised, which in turn might make the service unaffordable by poor users. Transport policy must be designed to be *both* environmentally sensitive *and* consistent with public and private affordability.

Both on the supply and the demand sides, the urban transport sector is very fragmented. Moreover, most transport actors—individual and corporate users of transport services as well as transport suppliers—are motivated by private benefit or profit. Because air pollution impacts are typically external to the transport actors, and uncharged for in financial terms, they tend to be discounted or ignored in the private decisionmaking process of transport users or supply agencies. Whenever possible, therefore, strategies to reduce air pollution from mobile sources should be designed to be seen as in the private interests of the actors as well as in the social interest. For these reasons, fiscal measures are an essential support for environmental initiatives. Technological improvements and physical measures may therefore be seen not as substitutes for, but as complements to, fiscal measures such as taxes, penalties, and subsidies.

The Policy Stance

From all these considerations it may be expected that while the environmental goals will be largely shared among countries, the means of achieving these goals among different countries and cities within countries will vary according to their level of economic activity, air quality problems, and climatic and geographical conditions. Relatively wealthy developing country cities are likely to face problems and seek solutions similar to cities in industrial countries where the adoption of modern technologies has contributed significantly to the reduction of urban air pollution. In very poor countries with limited levels of motorization, there may be other environmental and social problems that are more pressing than urban air pollution. While state-of-the-art transport technologies will also play a role in limiting air pollution in these countries, resource limitations and competing priorities may make a different time scale of introduction appropriate.

To be effective and sustainable over the long term, regulatory and policy instruments for reducing transport emissions must provide incentives for individuals and firms to limit the pollution from existing vehicles and to avoid delay in adopting new and cleaner technologies and fuels. Public and private institutions must be equipped with the resources and the skills necessary to monitor transport emissions and take measures to reduce them. Above all, measures must be cost-effective and affordable in light of the myriad of other pressing needs in developing country cities.

The aim of this report is not to provide a "one-size-fits-all" prescription of what all countries should do immediately. Instead, it is intended to provide information and advice on air pollution control experiences in the transport sector from both industrial and developing countries that will assist the local formulation of policies towards urban air pollution in many different circumstances.

CHAPTER 2

A Systematic Approach to Controlling Urban Air Pollution from Mobile Sources

To assess the seriousness of transport-related air pollution and enable informed decisionmaking to combat air pollution, it is useful to have a systematic framework that can guide the process to evaluate issues and available data and to arrive at workable solutions. This chapter describes the type of questions to pose and methodologies that may be pursued in addressing mobile sources of air pollution.

A Framework for Analysis

Given the diversity of problems and situations, it is important to ask the right set of questions in order to diagnose urban air pollution problems, determine the role of the transport sector, and identify affordable and sustainable solutions. Figure 1 suggests a number of logical steps in developing a strategy for controlling air pollution from urban transport.

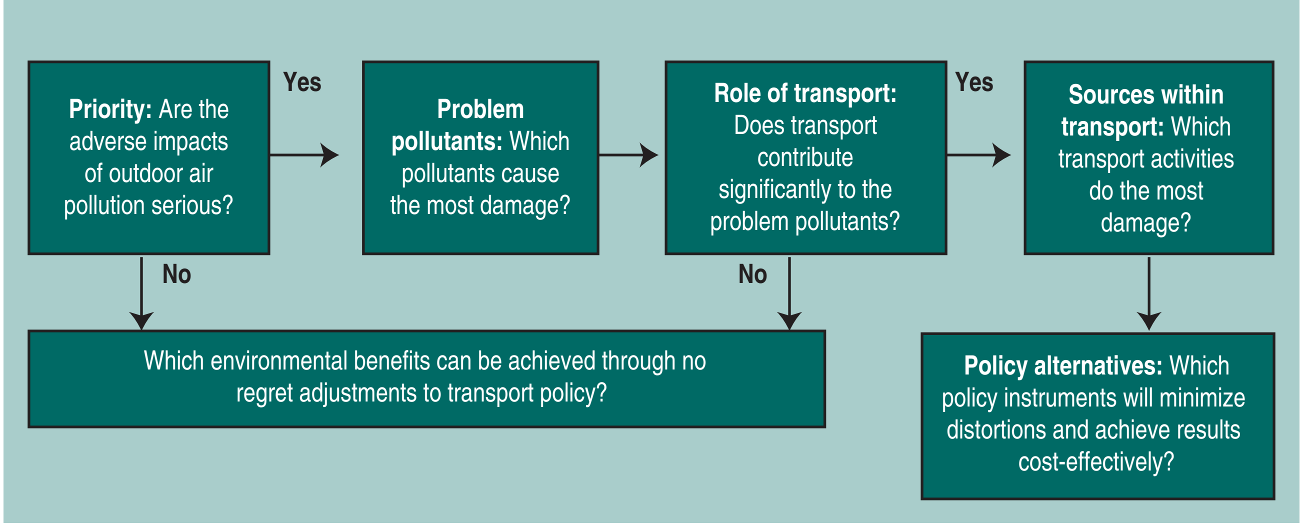
The first step is to establish the magnitude and nature of the ambient air quality problem in a particular city. The most damaging pollutants (on the basis of the combined impact of high ambient concentrations, toxicity, and exposure) then need to be identified. Thereafter it is necessary to determine the relative contribution of mobile sources (transport), and to establish which transport activities are the largest contributors of the most damaging air pollutants. Finally the ways these activities can be improved must be analyzed and the instruments by which the improvement could be achieved need to be identified. The effectiveness of different policy instruments should be assessed in order to construct the appropriate local policy package.

Air Quality Monitoring and Standards

The level and nature of air pollution varies substantially from city to city. Hence, the first requirement is the creation of an adequate knowledge base on local air quality on which to develop an air quality policy.

FIGURE 1

Sequence of Questions to Appraise Mitigation Options to Tackle Mobile Sources



Monitoring of ambient air quality is an important first step. It is especially important to measure small particulate matter. In a number of developing country cities, ambient concentrations of PM_{10} or $PM_{2.5}$ are not measured regularly, or not measured at all. The absence of ambient data on what is probably the most important pollutant of concern makes it difficult to quantify the seriousness of outdoor air pollution. Common obstacles to systematic monitoring of PM_{10} and $PM_{2.5}$ are a shortage of skilled staff and of funds to operate, maintain, and repair instruments. For ozone, oxides of sulfur (SO_x), NO_x, and CO, rapid assessment can be carried out using diffusion tubes, which are relatively inexpensive to deploy and are good for giving spatial distributions of pollutant concentrations (averaged over several days) when they exist at elevated levels. Seasonal variation also needs to be established. Quality assurance and quality control should be given adequate attention to ensure data reliability.

The measured concentrations can be compared to national air quality standards to see where standards are exceeded. Another useful guide is WHO's health-based air quality guidelines, which provide numerical limits for different averaging periods for all the classic pollutants except particulate matter (WHO 2000). In the case of PM_{10} and $PM_{2.5}$, WHO gives no numerical limits on the grounds that no threshold levels for morbidity and mortality exist. In their absence, many developing countries follow the U.S. or European standards for particulate matter.

In a number of developing country cities, ambient concentrations of PM_{10} are grossly in excess of the national air quality standards while other pollutant concentrations seldom exceed them. In a few higher-income developing country cities, ozone has become a serious problem, and this problem is on the increase. One of the best-known examples is Mexico City, where ozone exceedances are much more common than PM_{10} exceedances. In cities with extensive use of coal, PM_{10} and SO_2 are the main pollutants exceeding the national air quality standards by a large margin.

Air pollution becomes a problem of policy concern when ambient concentrations of harmful pollutants are elevated *and* when a large number of people are exposed. The latter—significant human exposure—is the rationale for relocating polluting industries outside of cities or supplying cleaner fuels to power plants near major cities. Because human exposure is an important factor, air quality monitoring should target large population centers first. Within a metropolitan area, monitoring should take place at a variety of locations: urban "hot spots" such as areas affected by vehicle or industrial emissions; city center pedestrian precincts, shopping areas, and residential areas representative of population exposure; and urban locations distanced from sources and therefore broadly representative of city-wide background conditions, such as elevated locations, parks, and urban residential areas.

The Determinants of Transport Emissions

Transport activity characteristics

The major source of ambient lead is combustion of leaded gasoline: ambient lead concentrations have always been reduced significantly when lead has been banned in gasoline. However, while many countries have now banned lead, use of leaded gasoline continues in some countries, including Indonesia, Venezuela, and a number of countries in Sub-Saharan Africa. It is especially problematic in two-stroke engines because some alkyl lead added to gasoline as an octane enhancer may be emitted uncombusted as organic lead, which is even more damaging to health than the inorganic lead formed as a result of combustion of alkyl lead.

Fine particles are emitted as a product of combustion, especially from diesel vehicles but even from natural gas-fueled vehicles as a result of combustion of lubricants. Particulate emissions can increase substantially where engines are underpowered or poorly maintained or adjusted. Black diesel smoke results from inadequate mixing of air and fuel in the cylinder, with locally over-rich zones in the combustion chamber caused by higher fuel injection rates, dirty injectors, and injection nozzle tip wear. Overfueling to increase power output, a common phenomenon worldwide, results in higher smoke emissions and somewhat lower fuel economy. Dirty injectors are common because injector maintenance is costly in terms of actual repair costs and of losses stemming from downtime. Adulteration with heavier fuels also increases in-cylinder deposits and fouls injectors. While most modern gasoline vehicles return the crankcase emissions to the engine intake and re-burn them in the cylinder, all diesel engines still vent to the atmosphere because, although it can be done, there are technology barriers to re-circulating the crankcase gases. These crankcase emissions consist mainly of unburned diesel, products of combustion, partially burned diesel, and products from the lubricating oil (oil mist and some products of thermal degradation of oil).

Particulate emissions from gasoline vehicles tend to be much lower in mass than those from diesel vehicles,[1] except in the case of two-stroke engine gasoline vehicles where "scavenging losses" and the direct introduction of lubricant along with the intake air-fuel mixture lead to high emission of "white smoke." White smoke mostly comprises fine oil mist and soluble hydrocarbons, whereas the black smoke emitted by diesel vehicles contains a large fraction of graphitic carbon. The health impact of white smoke is not well understood.

Non-exhaust particles can also contribute significantly to overall particulate emissions from the transport sector. The factors affecting the total level of non-exhaust particulate emissions include:

- Tires and their interaction with different road surfaces
- Brake pad/shoe dust
- The operating characteristics of vehicles (for example, speed, acceleration, and loading)
- Type of road (paved versus unpaved)
- Ambient weather conditions (for example, temperature, rain, and wind).

The health impact of some categories of non-exhaust particles is believed to be serious because they are typically very small, with an average aerodynamic diameter of just 1 micron for bitumen particles. There is growing evidence of a relationship between the incidence of asthma and the concentrations of natural latex protein particles in the atmosphere resulting from the abrasion of tires and roads. Tires use a blend of natural rubber (latex and dry sheet) and synthetic rubber. Since the early days of paved highway construction, rubber has also been added to modify asphalt. Its release following abrasion with vehicle tires increases the concentration of rubber particles in the atmosphere. Unpaved roads create a different problem: they are responsible for significant resuspension of road dust. It is difficult to quantify the impact of non-exhaust particles on overall ambient concentrations in developing countries. Most of the data collected so far are from high-income industrial countries. This area merits greater attention.

Particulate emissions, some of which exit the tailpipe as black smoke, increase significantly when vehicles are in poor state of repair or engines are improperly adjusted, such as this heavy-duty diesel-powered bus.

Gasoline vehicles are the dominant contributor to ambient concentrations of CO in most cities. They are also responsible for emissions of NO_x and photochemically reactive VOCs which, in the presence of sunlight, react together to form ozone. Secondary particles are formed from NO_x and SO_x, which are also responsible for acid rain with adverse effects on vegetation. In addition, sulfur acts as a poison for catalysts, although its adverse effects are partially reversible in conventional three-way catalysts. SO_x

[1]Emerging evidence suggests that both gasoline and diesel vehicles emit "nanoparticles." The perception of gasoline particulate emissions may change if mass is no longer the metric for particles.

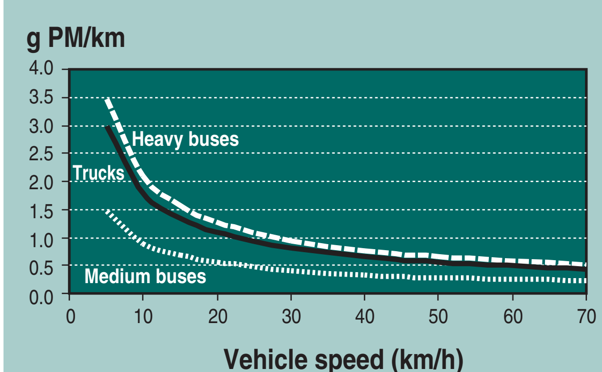
emissions are directly proportional to the fuel sulfur content. While gasoline sulfur levels tend to be low, as much as 1 percent (10,000 parts per million [ppm]) sulfur is still allowed in automotive diesel in some developing countries.

The transport operating characteristics determining the sector's contribution to urban air pollution are complex. For any given vehicle and fuel combination, aggregate emission levels vary according to the distance traveled and the driving pattern. The emissions of CO_2 and SO_x vary directly with fuel consumption. The tailpipe emissions of CO, NO_x, particulate matter, and hydrocarbons vary in addition with the air-to-fuel ratio, injection timing, and other settings. Figure 2 gives an illustration of particulate emissions from diesel vehicles as a function of vehicle speed. The optimum steady speed for emissions, which is usually in excess of 60 kilometers per hour (km/h), is rarely achievable in urban areas. Broadly speaking, engine-out NO_x emissions increase, and CO, particulate, and hydrocarbon emissions decrease, with increasing engine temperature or increasing vehicle speed.

The driving cycle has a significant influence on emission levels for a given vehicle; for example, both fuel consumption and pollutant emissions are many times higher per vehicle km during acceleration and deceleration than during cruise. Cold-start enrichment of gasoline engines increases CO emissions orders of magnitude more than in warm operation.

FIGURE 2

Particulate Emissions as a Function of Vehicle Speed



Source: Ntziachristos and Samaras 2000.

Moreover, as catalytic converters depend on heat for their effectiveness, they are least effective at cold start, further accentuating the influence of the driving cycle.

Human exposure

Costs to society arising from urban air pollution include damage to buildings and vegetation, lowered visibility, and heightened GHG emissions. However, increased premature mortality and morbidity are generally considered to be the most serious consequences, because of both 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. To assess this damage it is necessary to understand the toxicity of different pollutants, the ambient levels above which they begin to have health impacts (the threshold), and the number of people exposed to different levels of air pollution above that threshold.

The effect of any specific airborne pollutant depends on the location of the emissions with respect to the human population and the ways and extent to which emissions are dispersed. For example, even pollution from gross emitters may not be important on deserted roads where virtually no human beings are exposed, or in very windy locations from whence the emissions are rapidly dispersed. In practice, ***because urban vehicle emissions are emitted near ground level where people live and work, urban pollution from mobile sources merits the attention of policymakers in many cities.***

City size and income

Transport-related air pollution tends to be worst in large and densely populated cities, particularly those that are highly motorized, where there are high levels of congestion, and where there is a proliferation of older, more polluting vehicles.

For the highest-income cities in developing countries, as well as for cities in some of the transition economies of Eastern Europe that had already begun to develop car ownership before the transition, levels of motorization are high and equipment is sophisticated. In such cities the problems are likely to be similar to those in industrial countries where ozone is important, in addition to particulate matter.

Assessing Air Pollution Mitigation Measures

The "opportunity cost" approach

All commitments of public resources are implicitly economic decisions because they involve the diversion of resources from alternative uses. The goal of a cost-benefit analysis is to compare the monetized benefits of a policy—for example, a policy to reduce air pollution—with its costs. The value of the resources used in the best alternative use is called the "opportunity cost." The difference between benefits and costs is termed the net benefit of the policy. A cost-benefit analysis may be performed to determine whether a given policy yields positive net benefits, or to set local ambient air standards, or to help policymakers rank various pollution control policies.[2]

In the case of an air pollution control policy, the first step in the analysis of benefits is to predict emissions of the common air pollutants for all major polluting sectors, with and without the policy. The second step in the calculation of benefits is to translate the emissions predictions into ambient pollution concentrations with and without the policy. This allows the analyst to calculate the change in ambient PM or ozone concentrations attributable to the policy.

The damage function approach is then used to quantify the physical benefits associated with the policy and to value them. This entails translating changes in ambient concentrations into physical effects—for example, calculating the cases of illness and premature mortality avoided by the policy—and then valuing these physical effects. A similar approach is used to estimate the agricultural and aesthetic benefits associated with reducing air pollution. After benefits have been calculated, they can be compared with the costs of the policy.

[2]Policies are ranked according to the size of their net benefits (benefits minus costs) or, when budgets are limited, by the ratio of benefits to costs.

Attributing ambient pollution to specific sources

One of the most difficult and costly steps in the evaluation of an air quality regulation is to translate emissions with and without the regulation into ambient pollution concentrations. This is usually accomplished with air quality models that are demanding both in terms of the inputs they require (detailed meteorological and atmospheric data, in addition to emissions inventories) and in terms of the computer time they use (for example, four days of computer time to simulate a seven-day air pollution episode). In practice, the state of air quality modeling limits the number of regulatory options that can be evaluated in a cost-benefit analysis. This implies that it is important to screen possible regulatory options before performing a full-blown cost-benefit analysis.

Though the impacts of urban air pollution have been documented in both industrial and developing countries, a fundamental policy question is to what extent ambient air pollution is contributed by mobile sources (cars, trucks, buses, motorcycles) as opposed to stationary sources (power plants, industry, commercial establishments, households). Even more so than for stationary sources, there are multiple actors in the transport and transport fuel-supply sectors that must be made part of the strategy for reducing mobile-source emissions.

While measurements of ambient air quality provide information on the level of pollution, they say nothing directly about its sources. Broadly speaking, there are two approaches to quantifying the contributions of pollution sources to ambient concentrations:

- **Dispersion modeling** starts with the estimated emissions from different sources (called the "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. An example of this approach in developing countries can be found in the Urban Air Quality Management Strategy in Asia (URBAIR) reports (Grønskei 1996a and 1996b, Larssen 1996a and 1996b). Modeling of secondary particulate formation as well as contribution of distant sources adds significant complexity.

- **Receptor modeling** uses detailed chemical analysis of particles in the atmosphere to match their characteristics at given receptor and source locations ("fingerprinting"). 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. Recently, a $PM_{2.5}$ source apportionment study using receptor modeling was conducted in three Indian cities (ESMAP 2004). 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 broad-brush picture of contributions from different sources.

In carrying out source apportionment, identification of distant, contributing, upstream sources is also important. Over the longer term, significant investment is needed both in equipment and laboratory facilities and in human resources, which can be established at national or private research institutes or universities. Megacities may be able to carry out these activities, smaller cities may not. Depending on the extent of pollution damage in smaller cities, it may make sense to have a centrally funded facility to provide monitoring and analytical skills to smaller cities.

Several important lessons can be learned from experience in the attribution of pollution among sources.

- 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-

INTERNATIONAL EXPERIENCE 1

Source Apportionment: Lessons from the United States

Dispersion modeling and receptor modeling are two main approaches to quantifying the contributions of pollution sources to ambient concentrations. In principle, both approaches should give the same results. In practice, empirical studies comparing the results of the two approaches are rare, even in industrial country cities.

One of the most extensive comparisons of the two approaches is a study in Colorado (Watson and others 1998), which examined source contributions to $PM_{2.5}$. The available emissions inventory indicated that diesel accounted for two-thirds of on-road vehicle $PM_{2.5}$ emissions and gasoline the remaining one-third. However, the use of a receptor model suggested that diesel actually accounted for only one-third and gasoline two-thirds, and that $PM_{2.5}$ emissions from gasoline vehicles were seriously underestimated, not only with respect to diesel but also on an absolute basis. The discrepancy was caused primarily by the presence of gasoline "smokers" and high emissions during cold start.

A study conducted in southern California (Durbin and others 1999) found that some gasoline-fueled passenger cars emit as much as 1.5 grams per kilometer (g/km), an emission level normally associated with heavy-duty diesel vehicles. Comprising only 1–2 percent of the light-duty vehicle fleet, these gross polluters were estimated to contribute as much as one-third to the total light-duty particulate emissions. It is possible that the proportion of "smoking" gasoline vehicles is much larger in developing countries.

Source: World Bank 2002a.

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. The height at which pollutants are emitted, and where they are emitted, matters a great deal. ***An emissions inventory, which typically ranks pollution sources according to their absolute primary emissions, should not be the sole basis of air pollution control policy since it does not account for the contribution to ambient concentrations and the exposure of human populations.***

- Total weight of pollutants is also a poor indicator of impact. It is often concluded that road traffic is by far the largest contributor to urban air pollution, because in absolute tonnage, CO dominates all other pollutants, and the majority of CO is from gasoline vehicles. 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 as a way of indicating the seriousness or principal sources of air pollution.***

Vehicle exhaust's contributions to ambient concentrations of PM_{10} and $PM_{2.5}$ in different cities are shown in table 1.

Because of the particle size distribution of vehicular emissions, vehicle exhaust constitutes a larger fraction of $PM_{2.5}$ than of PM_{10} at any given location. Vehicle exhaust contributes little to ambient air in Qalabotjha in South Africa and Teplice in the Czech Republic where it is dominated by coal combustion, as has been the case in the majority of cities in China. The study in Denver, Colorado, is one of the most extensive undertaken to date (see International Experience 1). The study of 17 cities in the United Kingdom looked at the contribution of road traffic to PM_{10} in winter and summer as well as over the entire year. The contribution in winter was consistently higher than that in summer in every city. The contribution of vehicle exhaust varies significantly from site to site, ranging from a negligible percentage to more than half of the ambient particulate concentrations.

An accurate vehicle registration system is crucial for obtaining information on the vehicle population and fleet characteristics. This, together with estimates of annual vehicle distance traveled and the total sales of automotive fuels, can indicate which vehicle categories are likely to be major contributors to vehicular emissions. Having a reliable vehicle registration system is also a prerequisite for an effective vehicle emissions inspection system.

Analysis of the impacts of air pollution on health

The approach most commonly used to value health effects of air pollution is known as the "damage function approach." This involves estimating the impact of a change in level of air pollution on health and then attributing a monetary value to the change in health. The benefits of urban air quality improvements can then be evaluated in terms of the particular national situation and resource availability.

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 (see annex 8 for more detail). ***While many questions remain, the accumulation of studies over the years has yielded considerable consistency on the impacts of specific pollutants, especially the mortality impact of particulate matter.***

Valuing the health effects

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 based on the amount that a person is estimated to be willing to pay to avoid the illness (World Bank 2003b). 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

TABLE 1

Contribution of Vehicle Exhaust to Ambient Particulate Concentrations

City	PM contribution	Technique	Source
Mumbai, India	30% of ambient PM_{10}	Dispersion modeling	Larssen and others 1996b
Bangkok, Thailand	30% of annual and geographical average PM_{10} in 1996	Dispersion modeling	Radian 1998
Mexico City, Mexico	47% of ambient $PM_{2.5}$ (daytime) 40% of ambient $PM_{2.5}$ (nighttime) in 1989–90	Receptor modeling	Vega and others 1997
Teplice (industrial town), Czech Republic	Average 2.8% of $PM_{2.5}$ in winter 1993	Receptor modeling	Pinto and others 1998
Qalabotjha, South Africa (township south of Johannesburg)	0.1% of ambient $PM_{2.5}$ (study period winter 1997)	Receptor modeling	Englebrecht and Swanepoel 1998
Sihwa, Republic of Korea (residential area near heavy industrial complex)	8.6% of ambient $PM_{2.5}$ (4 intensive periods in 1998 and 1 intensive period in 1999, each of 10 days)	Receptor modeling	Park and others 2001
Denver, Colorado, USA	55% of ambient $PM_{2.5}$	Receptor modeling	Watson and others 1998
17 U.K. cities	Percentage of annual PM_{10} in 1996: London Kensington 33% Lowest contribution of road transport to PM_{10}—Swansea 17% Highest contribution—Wolverhampton 52%	Receptor modeling	Airborne Particles Expert Group 1999, table 5.1

"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). 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. In practice it has been difficult to obtain reliable estimates of the VSL, especially for developing countries. This is also true for estimates of the WTP to avoid morbidity. Annex 9 describes various options and discusses how these calculations may be carried out in developing countries. Despite the difficulties and large uncertainties associated with valuing avoiding morbidity and mortality, ***it is still advisable to apply the principles of cost-benefit analysis as a method of prioritizing intervention measures.***

Non-health impacts

Non-health impacts of urban air pollution include damage to property (for example, sooting or corrosion), damage to the local economy resulting from decisions to locate activities away from heavily populated areas, and the disutility to residents of unpleasant, albeit not necessarily health-threatening, conditions. Non-health impacts are usually more difficult to quantify and evaluate than are health impacts. What studies of air pollution have shown, however, is that the health impacts generally greatly exceed non-health impacts in socioeconomic terms. ***Health benefits may be a reasonably proxy for total benefits, particularly in comparisons between different air pollution instruments.***

The results: identifying the most damaging pollutants

When risk assessment of susceptibility to physical excesses is combined with evidence of health impacts from concentration-response (CR) analysis, studies in a number of cities (for example, Bangkok, Cairo, Mexico City, Quito, and Santiago) have indicated that the greatest damage to human health comes from exposure to small particulate matter. In some cities where a large amount of leaded gasoline is still consumed, airborne lead is another damaging pollutant. Depending on topographical and meteorological conditions, ozone can also be a serious health problem in large metropolitan regions, as it is in Mexico City, Santiago, and São Paulo. More detail is given in annex 8, including discussion of other pollutants.

Understanding the health impacts of air pollutants has been developing rapidly. Only within the past two or three decades have the health impacts of particulate matter and lead at even relatively low ambient concentrations attracted serious attention by researchers and policymakers. In recent years, the science of particulate air pollution has increasingly pointed to the importance of the number and size of particles (especially of ultrafine particles), rather than of aggregate mass (World Bank 2003c). The widely accepted notion that gasoline vehicles emit far less particulate matter than conventional diesel vehicles, based on total mass, may change if particle size and number come to be included in emission regulations. The Motor Vehicles Emissions Group of the European Commission is giving consideration to a proposal to limit the number of particles, in addition to mass, in vehicle exhaust.

Particulate emissions from the combustion of transport fuels and vehicle tire wear fall predominantly in the submicron range, raising serious health concerns. As a result, policy formulation has begun to focus on the contributions of combustion processes to the size fractions now considered most damaging to public health. A study in the United Kingdom reported that road traffic nationally contributed 25 percent of primary PM_{10} emissions, but the relative importance of road traffic emissions increased with decreasing particle size, and road transport accounted for an estimated 60 percent of $PM_{0.1}$ (particles smaller than 0.1 microns, also called ultrafines) (Airborne Particles Expert Group 1999). There is also a growing consensus that diesel exhaust poses a serious cancer risk (Lloyd and Cackette 2001), and diesel exhaust is classified as a probable human carcinogen by many governmental authorities, including the International Agency for Research on Cancer (part of WHO), the U.S. National Toxicology Program, and the U.S. Environmental Protection Agency (EPA). The impacts of some unregulated emissions, such as the so-called airborne toxics, are not as well understood because it is more difficult to estimate human exposure. ***The current understanding of pollution impacts shows that fine particulate matter should be a major focus of control efforts.***

Cost-Effectiveness Analysis

Given the difficulties of calculating the benefits of reducing morbidity and mortality, another option, discussed here, is to compare policies by their cost-effectiveness, for example by their cost per unit change in ambient pollutant concentrations.

The scope for cost-effectiveness analyses

Even if the monetary evaluation of the benefits of improved air quality may be elusive, the costs of the measures to obtain given physical improvements may not be. An alternative form of economic evaluation is that of cost-effectiveness analysis, which compares the costs of achieving different levels of improvement in physical conditions. ***Cost-effectiveness analysis can give strong guidance to decisionmakers on what are preferable instruments or packages of instruments to use.***

The simplest form of cost-effectiveness analysis computes the cost per ton of emissions reduced for various regulatory options. Even this approach gives estimates with large uncertainties because of the nature and number of assumptions that are necessarily involved. That said, cost-per-ton calculations provide a useful way to screen air pollution control policies. Because the height at which particles are emitted is essentially the same for all vehicle types, the impact on ambient air quality of reducing a ton of particulate emissions from different vehicles or of using different transport policy options is likely to be similar, provided that the temporal and geographical distribution of vehicle operation is also comparable.

Regulators typically face the problem of choosing among a set of regulatory options that vary in the size of the reduction in air pollution they deliver and in their expense. The purpose of a cost-effectiveness analysis of air pollution control policies is to compare the reductions in emissions achieved by various policies with their costs. In its simplest form, this entails computing the cost of each control strategy and dividing the cost by the (weighted) reduction in emissions achieved to yield a cost per ton of emissions reduced. The computation can indicate which options have the lowest cost per ton of pollution reduced and the size of the pollution reduction each option will achieve. ***Cost-effectiveness analysis can help by ranking policy options in order of their incremental cost.***

A more sophisticated approach computes cost per unit change in ambient pollutant concentrations, such as cost per change of 10 micrograms per cubic meter ($\mu g/m^3$) in ambient PM_{10} concentrations. This will involve modeling to estimate the impact of a reduction in emissions on ambient concentrations. This approach enables comparison of different measures for reducing emissions from stationary, mobile, and fugitive sources.

The above can be taken a step further to compute cost per life-year or disability-adjusted life-year (DALY) saved. A DALY is an indicator of the time lived with a disability and the time lost due to premature mortality. In principle, this can be carried out not only for air pollution reduction options but intervention measures in other sectors (such as supplying clean water to households), and results ranked in order of decreasing cost-effectiveness. This approach requires giving relative weights to disability and mortality, but avoids having to assign monetary values to human health and life, which many find controversial. The problems encountered in going from changes in ambient concentrations to DALYs are discussed in annex 8.

Typically a number of distinct mitigation measures can be pursued in parallel, and undertaking one would not affect the cost or the effectiveness of other options. For example, the Department of Buses of the Metropolitan Transportation Authority (MTA) New York City Transit, which runs more than 4,000 buses, has been testing three different options to reducing exhaust emissions simultaneously: CNG, diesel-electric hybrid, and "clean diesel" technology using ultralow[3] sulfur diesel and particulate filters. In other situations, for reasons of both cost and administration, it may not be possible to evaluate multiple options. For example, should new diesel trucks and buses in São Paulo remain with Euro III emission standards or should they move quickly to meet more stringent Euro IV standards, which will require that the sulfur content of diesel be significantly lowered? In this case, cost-effectiveness analysis can be used to compute the additional cost per ton of pollution reduced of moving from a less stringent to a more stringent standard. Policymakers can then compare the additional cost of moving from a less to a more stringent standard with perceived benefits to determine which policy to undertake.

Data requirements for cost-effectiveness analysis

Performing a cost-effectiveness analysis requires that the analyst predict emissions for all sectors affected by the policy with and without each policy.[4] The difficult step in a cost-effectiveness analysis comes in aggregating the emission reductions associated with each policy, assuming that the policy reduces the emissions of more than one pollutant as is typically the case. Calculating the cost per weighted ton of emissions reduced allows the analyst to rank pollution control options by their average or by their incremental cost. Ideally, the weights assigned to reductions in emissions of different pollutants should reflect the contribution of these emissions to some measure of ambient air quality (such as ambient $PM_{2.5}$ concentrations) or to monetized benefits (as in a full cost-benefit analysis). One of the greatest difficulties

[3]In this report, "ultralow" will be used to refer to sulfur levels lower than 50 parts per million by weight, corresponding to sulfur limits to comply with Euro IV emission standards.

[4]In a cost-benefit analysis, emissions with and without the policy must be predicted for *all* sources of the key air pollutants in order to produce the necessary inputs for air quality modeling.

lies in estimating weights to be assigned to different pollutants, especially if ozone reduction is desired.

If cost-effectiveness is expressed in cost per DALY, then emissions have to be linked to ambient concentrations and human exposure. The foregoing discussion on attributing sources to ambient concentrations and their associated difficulties applies in this case.

It is also important to note that the use of cost-effectiveness analysis to select instruments requires the prior specification of a constraint, either in the form of an available budget to be expended to obtain the greatest improvement in air quality or in the form of a target level of ambient air quality to be achieved at least cost. In either case, the determination of the constraint will require political judgments about the costs and benefits of alternative uses of national resources to which the principles of cost-benefit analysis, discussed earlier, will need to be applied.

Policy applications

Examples of the application of cost-effectiveness analysis to air quality policy assessment in developing countries include those carried out in Jakarta (Grønskei and others 1996a), Kathmandu (Grønskei and others 1996b), Manila (Larssen 1996a), and Mumbai (Larssen 1996b) under the regional program URBAIR (Urban Air Quality Management Strategy in Asia). In each city, an emissions inventory was built and rudimentary dispersion modeling carried out. Various mitigation measures for reducing PM_{10} were examined in terms of reductions in tons of PM_{10} emitted, the cost of implementation, the timeframe for implementation, and health benefits and their associated cost savings. Local stakeholders discussed and agreed on an action plan of abatement measures based on cost-benefit analysis, along with the identification of the lead agency, costs, time frame, and overall priority. The abatement measures that have been implemented include introduction of unleaded gasoline (and eventual elimination of lead in gasoline), tightening of standards, introduction of low-smoke lubricants for two-stroke engine vehicles, vehicle-exhaust emissions inspection to address gross polluters, and reduction of garbage burning. One of the associated benefits was the creation of cross-sectoral working groups that met regularly. In Jakarta and Manila, these meetings are continuing under the Clean Air Initiative–Asia.

Marginal analysis and the "overlay" approach

In many circumstances transport policies do not have air quality as their primary objective. But that does not mean that air quality should not be a consideration. In such cases an appropriate methodology would be first to identify the policy or investment selected as optimal from the point of view of the transport benefits being sought. From this starting point, one could explore the cost, either in terms of increased financial outlay or lost transport benefit, of a modified policy or investment to yield a better air quality outcome than the base investment. That would give an indicator of the cost-effectiveness of the adjustment to be compared with the costs at which those benefits could be achieved by an investment or policy oriented toward direct air quality improvement. This "overlay" approach has been worked out in some detail for the energy and forestry sectors in the analogous case of GHG reduction strategies. (For more information, see Halsnæs and others undated.) ***Countries would be well advised to institute a formal and systematic "air quality audit" of transport policy and investment initiatives to identify cost-effective adaptations of such initiatives to achieve collateral air quality benefits.***

The Results of Analysis of Air Pollution Control

An important indicator of the value of air pollution measures is the extent to which they can reduce mortality and morbidity impacts. The World Health Organization estimates that urban air pollution and lead exposure together in 2000 accounted for 84 percent of the premature deaths from environmental causes in industrial countries, but for fewer than 20 percent of deaths in developing countries as a whole and 10 percent for the low-income, high-mortality developing countries where half of the deaths are due to unsafe water, sanitation, and hygiene. These proportions fall further if DALYs, which take morbidity into account in addition to mortality, are used (WHO 2002). Transport is an important, but not the dominant, source of urban air pollution in many developing countries.

Intersectoral comparisons

It is informative to examine the health impact of outdoor air pollution in the context of overall environmental health risks. WHO's estimates indicate that, averaged across all developing countries, the impact of urban air pollution on premature mortality is about 15 percent of the total number of premature deaths from all environmental health risks. This is less than one-half of that from indoor air pollution and a little over one-third of that from unsafe water, sanitation, and hygiene. The relative importance of the health impact of urban air pollution diminishes in both low-mortality and high-mortality developing countries if DALYs are used as a metric rather than mortality. Focusing only on environmental health risks as before, urban air pollution accounts for 6 percent of total DALYs across all developing countries, 16 percent in low-mortality and 3 percent in high-mortality countries. But the importance of urban air pollution is increasing. In low-mortality developing countries, it is already the second highest environmental health risk in terms of mortality and third highest in terms of DALYs, and represents one-third of premature deaths. As countries take steps to increase access to safe water and sanitation and cleaner household fuels in the coming years, the relative importance of urban air pollution is expected to increase.

When the same approach is applied to appraisal of options for tackling urban air pollution, the cost of air pollution interventions expressed in terms of DALYs can vary significantly as shown in table 2, with some of the possible actions outside the transport sector showing very high cost-effectiveness (low cost per DALY or per life), particularly in the low-income, high-mortality countries. It would make sense for these countries to select the measures with extremely low cost per DALY first. As low-cost measures are implemented and income rises, higher-cost measures are adopted.

The short-term significance of diminishing returns

Policymakers will normally seek to give priority to measures that offer the greatest environmental benefit per dollar invested. For that reason, the earliest measures adopted are likely to have the largest absolute impacts. For example, the U.K. government reports that compliance with Euro IV for gasoline vehicles in 2005, which yields an extra 4 percent reduction in NO_x and VOC, incurs an incremental cost of 200 Euros (€200) per vehicle. This is nearly as much as the cost of removing the first 75 percent of NO_x and VOC

TABLE 2

Estimated Cost of Air Quality Mitigation Measures

Mitigation measure	Cost in US$	Source
Improved stoves for reducing indoor air pollution, India	50–100 per DALY[1]	Smith 1998
Switching from coal to gas in boilers in Katowice, Poland	2,900 per DALY	World Bank calculations
Switching from wood stoves to distillate fuel oil in Chile	3,100 per DALY	World Bank 1994
Diesel truck control (U.S. EPA 1991 standard) in Chile	5,997 per DALY	World Bank 1994
U.S. Tier 1 emission standards in Mexico	44,642 per DALY	Lvovsky 2001
U.S. Tier 2 emission standards in the USA	850,000 per life saved[2]	U.S. EPA 1999a

[1]Disability-adjusted life-year or DALY concerns the life years lost due to premature death and fractions of years of healthy life lost as a result of illness or disability. One DALY can be thought of as one lost year of "healthy life."

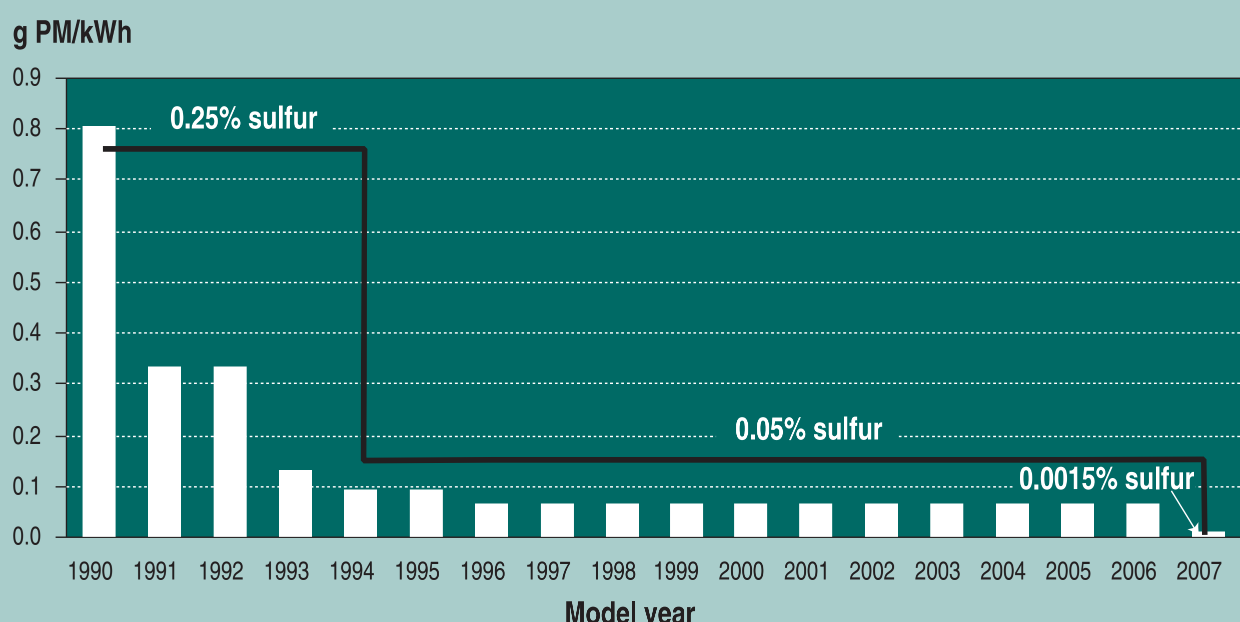
[2]The annual costs and number of lives saved are calculated for the year 2030. The costs (in 1997 US$) are $5.3 billion, and the number of lives saved 4,300. There are $1.84 billion in morbidity and other benefits that should be subtracted from the $5.3 billion. This implies a cost per life saved = $805,000. The median age of a person saved is 75, so that the cost per life-year saved is of the order of $100,000. One could argue that the *benefits* should not be subtracted at a value of $1.84 billion because they reflect U.S. morbidity values, which are high relative to those applicable in developing countries.

by adopting Euro I in 1992. The cost of the latter corresponds to the introduction of a three-way catalytic converter. Meeting Euro II standards in 1996 cost an additional €50 per vehicle corresponding to a further 12 percent reduction of NO_x and VOC. Meeting Euro III standards in 2000 incurred an additional €400 and reduced NO_x and VOC by another 6 percent. Thus the cost of removing that extra 6 percent from the exhaust was substantially more than the cost of removing the previous 87 percent (UK Commission for Integrated Transport undated). A similar phenomenon of diminishing returns is observable in respect to the impact of progressive reductions in sulfur content of fuels on particulate emissions.

Another interesting comparison is to look at both absolute and percentage reductions in exhaust emission levels. Urban buses in the United States were required to emit no more than 0.80 grams of particulate matter per kilowatt-hour (g/kWh) through the 1990 vehicle model year. This limit was lowered to 0.34 g/kWh for the 1991 model year, 0.13 g/kWh for 1993, 0.094 for 1994, and 0.067 for the 1996 model year (see figure 3). To achieve these reductions, the sulfur level in diesel was lowered from 0.25 percent to 0.05 percent in 1993, with no further changes required since. In 2007, thanks to the introduction of ultralow sulfur diesel and further advances in engine and exhaust aftertreatment technology, the limit will be reduced to 0.013 g/kWh. In absolute terms, the most significant change was from 0.80 to 0.34, a reduction of nearly 0.5 g/kWh, from 1990 to 1991, relying only on engine technology improvement. The changes in the PM emission limit between 1990 and 1993 and between 1993 and 2007 are broadly comparable in percentage terms, 83 percent in 1990–1993 and 90 percent in 1993–2007. However, the 1990–1993 change gave an absolute reduction in PM emissions of 0.67 g/kWh, more than five times the 1993–2007 reduction of 0.12 g/kWh. The difference between the 1990 and 1996 limits is even greater, 0.74 g/kWh. Moreover, this large reduction in PM emissions of 0.74 g/kWh between 1990 and 1996 was achieved without lowering sulfur in diesel to ultralow levels: the maximum allowable sulfur limit remained at 0.05 percent between 1993 and 1996. In contrast, ultralow sulfur diesel is an essential requirement for the 2007 limit, which gives a

FIGURE 3

U.S. Particulate Emission Standards for Urban Buses



Sources: U.S. EPA 1997a and 2000b.

reduction of 0.05 g/kWh over the 1996 standard. Limiting particulate emissions to a maximum of 0.013 g/kWh is a remarkable technological breakthrough and will allow additional emission reductions in those countries and cities where ultralow sulfur diesel is introduced. However, for those many developing country cities where the current emission levels are still at 0.8 g/kWh or even higher, going down to 0.07 or even 0.1 g/kWh—which can be achieved by lowering sulfur in diesel to 0.05 percent together with engine improvement and possibly an oxidation catalyst—can reduce transport-related air pollution considerably and should not be discounted in the discussion of cleaner fuels and emission reduction.

Given that many governments in low-income developing countries are hard-pressed to commit significant investment resources to address urban air pollution issues, the immediate implication of diminishing returns is that poorer developing countries should concentrate on finding ways of improving air quality that are most affordable and cost-efficient, given their current situation. That may mean focusing first on the measures already adopted in industrial countries with large pollution reduction potential, as illustrated in the U.K. government report above.

Economic development and technological change

The fact that there are short-term diminishing returns in air pollution reduction is not the end of the story, however. As countries grow richer and their resource constraints become less pressing, the opportunity costs of measures to improve air quality fall. New technologies may be developed that reduce the absolute costs of securing specific reductions in emissions, so that as assets such as refineries or vehicles come to require replacement, it becomes sensible to implement higher standards. For all of these reasons lower-income developing countries should not accept retaining old and less clean technologies, but should establish the institutional framework for the progressive tightening of emission and fuel quality standards in order to adopt emerging technologies as they become commercially available and affordable. The question is thus not whether, but *when* and *how* new technologies can be introduced.

Appraising Instruments: A Structure for Policy Appraisal

There are a number of aspects within which air pollution reduction from mobile sources can be sought. For purposes of illustration, reducing urban air pollution can be disaggregated into three factors[5] (figure 4):

- Less pollution per unit of fuel used
- Less fuel used per passenger- or freight-ton-kilometer traveled
- Fewer (motorized) transport services required.

Policy instruments for dealing with these three factors—reducing emissions per unit of fuel consumed, reducing the amount of fuel consumed per kilometer traveled, and reducing the number of kilometers traveled using motorized transport—are diverse. They can have effects on demand for or efficiency of supply of services, and can be implemented in a number of ways, including legislation, infrastructure investment, standard setting, and enforcement or fiscal incentives and disincentives. They involve government agencies in a wide range of sectors. Many policy instruments address more than one component at a time. For example, optimal urban planning and land use design may reduce the amount of motorized transport and, at the same time, decrease emissions and increase fuel economy by helping minimize the amount of stop-and-start operations. Many of the measures discussed are also most effective when they are taken together; for example, fuels and vehicles should be treated as a joint system for proper operation and emissions abatement.

The following three chapters discuss in turn each of these factors for air pollution reduction, and the range of instruments that can be used to achieve

[5]The equation can, of course be expanded to emphasize particular issues. For example, vehicle km traveled could be presented as equal to the product of the number of vehicles and the average km per vehicle in order to highlight the importance of limiting the fleet size. Or the emissions could be expressed per passenger-km to give a better insight into the trade-offs between private motorized vehicles and well-patronized large public transport vehicles in containing emissions. The product of the first two in many instances is better seen together, a good example of which is assessing vehicle emission characteristics by comparing emissions per vehicle-km traveled. The three factors were selected for ease of discussing different dimensions of transport emissions and are not intended to imply that fuels and vehicles should be treated separately or viewed in isolation from each other.

FIGURE 4
Factors Contributing to Transport Emissions

Transport emissions = Emissions per unit of fuel × Total transport services demanded × Fuel consumption per unit of transport service

them. Where an instrument has effects on more than one factor, it is usually discussed in the chapter where its impact is seen as greatest, and cross-references made. Mitigation measures affecting more than one component simultaneously occur particularly with the first two factors, so it is very difficult and often not possible to judge which factor the measure would affect more. The two are shown as separate factors for conceptual simplicity, but should not be regarded as significantly distinct in the type of policy responses required or mutually exclusive. Some measures do not fall neatly into any of the three factors. One example is redirecting traffic away from environmentally sensitive areas. The objective in this case is to reduce exposure, even if at the cost of increasing total distance traveled. Such measures with no obvious "home" are discussed under topics most closely linked to them. Therefore, there can be considerable subjectivity in assigning individual mitigation options to one of the three factors. Fiscal and institutional interventions are so all-pervading that they are treated in chapters 6 and 7.

CHAPTER 3

Reducing Emissions per Unit of Fuel Consumed

Substantial improvements in air quality can be obtained through the introduction of cleaner fuels and vehicle technology, treated as a system. Regulations on vehicle emissions need to be set in harmony with regulations on fuel standards in light of the prevailing automotive technologies, being set to allow satisfactory operation of vehicles while also limiting emissions (see annexes 1–4). ***Vehicles and fuels need to be treated as a joint system for emission abatement.***

Cleaner Fuels

The emission levels of two pollutants—lead and SO_2—are directly related to fuel composition. Eliminating lead from gasoline, which is not naturally found in gasoline but is added to enhance octane, will eliminate lead emissions associated with fuel combustion from all gasoline-powered vehicles. For most other pollutants, the emission levels tend to depend as much on the mechanical state of the vehicle and operating conditions as on the fuel property.

Reformulating gasoline

Eliminating lead as an octane booster in gasoline is a relatively low-cost step with high returns in terms of public health. Regulations to remove lead are typically accompanied by controls on alternative ways of boosting octane and by enforcing the use of catalytic converters (to take advantage of the possibility of reducing CO, NO_x, and hydrocarbon emissions dramatically) for new vehicles. A great deal has been learned about how best to move to unleaded gasoline since lead phase-out programs began in the 1970s. In particular, it is important that lead elimination be carried out in an integrated manner, considering the environmental effects of alternatives to lead, the impact on refinery upgrade schemes, and the effects on the existing vehicle fleet. In the latter context, it is noteworthy that valve-seat recession, the only vehicle performance problem of concern potentially affecting old vehicles switching from leaded to unleaded gasoline, has rarely been observed in practice, and certainly not on the scale anticipated based on engine laboratory tests. ***Elimination of lead from gasoline should be a high priority for all countries that have not already done so.***

Most governments set standards for the composition of transport fuels. In addition to the proscription of lead, controlled parameters for gasoline often include benzene, sulfur, volatility, total aromatics, olefins, and oxygen. These measures reduce air pollution in various ways (see annex 1 for more detail):

- Benzene is a carcinogen, and a fraction of benzene in gasoline is emitted unburned. Limiting benzene in gasoline is a very effective way of controlling benzene emissions, especially from vehicles not equipped with catalytic converters.
- Sulfur reduces the efficiency of catalytic converters, by far the most effective means of reducing harmful pollutants emitted by gasoline powered vehicles. Some of the state-of- the-art exhaust-control devices are extremely sulfur-intolerant, requiring the use of ultralow or "zero" sulfur fuels. As box 1 shows, the actual level of sulfur in gasoline in developing countries can be very low compared to regulated limits.
- Vapor pressure affects evaporative emissions. Reducing vapor pressure is one of the most cost-effective means of reducing the emissions of light hydrocarbons (see the discussion on olefins below).

- Aromatics are a concern for two reasons. Some aromatics are photochemically reactive and strong ozone precursors. Aromatics as a group also break down to form benzene in the engine, increasing benzene emissions.
- Olefins are strong ozone precursors. Consequently, in cities with high levels of ozone, controlling olefins in gasoline is likely to be important. Limiting gasoline vapor pressure is a relatively inexpensive way of controlling the evaporative emissions of light olefins.
- In vehicles with no oxygen sensors, the presence of oxygen—in the form of alcohols or ethers—can facilitate combustion, reducing hydrocarbon and CO emissions if the vehicle is running "rich" (a low air-to-fuel ratio). This is an advantage primarily in old vehicles that do not have catalytic converters and oxygen sensors. However, some aldehydes formed from alcohol combustion are atmospherically active, potentially contributing to ozone formation. Oxygenates have high octane, making manufacture of unleaded gasoline easier. Oxygenates also "dilute" other undesirable components, such as benzene, sulfur, aromatics, and olefins.

Reformulating diesel

The characteristics of diesel that are of particular interest for air quality are density, sulfur, polyaromatic hydrocarbons (PAHs), and cetane (see annex 1 for more detail). Fuel properties are often intercorrelated and tend to move together. An example is density, aromatics, and cetane. It is therefore important to decouple fuel properties that change together before attributing the impact of each fuel parameter on emissions (Lee and others 1998). The impact of increasing cetane number on particulate emissions is engine-specific. In the majority of cases cetane has little influence, but in some cases particulate emissions increase, and in others decrease, with increasing cetane. Total aromatics generally have no impact on particulate emissions. Decreasing density as well as polyaromatics reduces particulate emissions in older technology, high-emitting vehicles, but has little or no impact on modern, lower-emitting engines. Back-end distillation control (reducing the amount of fuel components that boil at high temperatures) has little impact on particulate emissions (Lee and others 1998). However, if the final distillation fraction consists of high-density PAHs, reducing back-end volatility can be helpful, as found with light-duty vehicles in the European Programme on Emissions, Fuels, and Engine Technologies (EPEFE) (ACEA and Europia 1995).

Sulfur occurs naturally in crude oil, and the amount of sulfur in "straight-run" diesel (diesel obtained from primary distillation of crude oil without further processing) is correlated with the crude sulfur content. The sulfur content of straight-run diesel tends to be much higher than that of unleaded gasoline. During combustion, sulfur produces SO_2, which contributes to secondary particulate emissions through transformation in the air to sulfates. Sulfur reduction also has another advantage. The organic (as opposed to elemental) carbon component of particulate emissions from diesel vehicles can be reduced by means of oxidation catalysts. Effective operation of such catalysts requires sulfur in diesel to be no more than 500 wt ppm and preferably lower, since catalyst effectiveness increases with decreasing sulfur. An-

BOX 1

Actual Levels versus Limits

The actual level of a given fuel parameter may be quite different from the legal limit, which cannot be exceeded at the pump. In some cases, actual levels are substantially lower. For example, the gasoline sulfur limit in Pakistan is 1,000 parts per million by weight (wt ppm) but the actual level is more than an order of magnitude smaller because of the reliance on reformate (which contains essentially no sulfur) as the main blending component. As such, gasoline in Pakistan may be classified as ultralow sulfur gasoline in practice. In the United States, the current limit on diesel sulfur is 500 wt ppm, but most fuels contain 200–300 wt ppm sulfur.

For fuels that have to meet a limit of 10 or 15 wt ppm at the pump, the sulfur level at the refinery gate needs to be much lower—possibly half of the legal limit at the pump—because of potential sulfur contamination during storage and transportation. If fuels with very different sulfur levels are sold on the market, there is a serious risk of cross-contamination.

other reason for limiting sulfur is that an oxidation catalyst oxidizes sulfur and contributes to sulfate-based particulate emissions to varying degrees, depending on the catalyst activity (MECA 1999). ***The level of sulfur in diesel is an important fuel parameter affecting diesel emissions, and the target level should be set in light of national circumstances and resource availability.***

Some reports have argued that lowering sulfur leads to lower engine corrosion and acidification rates, and hence longer vehicle maintenance intervals and lower maintenance costs, offering significant cost savings (GTZ 2002, Asian Development Bank 2003, Blumberg and others undated, ICCT undated). It is worth clarifying that these observations generally refer to lowering sulfur from thousands of ppm to 500 ppm, rather than lowering sulfur from 500 wt ppm to an ultralow level (see annex 1, Diesel Quality Improvement, for more detail). Acid formation is already low at 500 wt ppm, and prolonged engine life on account of less corrosion is not expected when comparing 500 wt ppm and 10–30 wt ppm sulfur. ***The largest benefits of lower sulfur levels in terms of lower engine corrosion and reduced maintenance costs occur by reducing sulfur levels from thousands of ppm to 500 ppm.***

Several developing countries have already moved to a maximum of 500 wt ppm sulfur in diesel. Mexico and Thailand have had a legal limit on automotive diesel sulfur of 500 wt ppm for a number of years. In January 2004, the Philippines lowered the limit to 500 wt ppm, while Thailand moved to 350 wt ppm. Others, such as Brazil, Chile, and India, have not yet limited diesel sulfur to 500 wt ppm throughout the country, but the limit on sulfur in large cities is 500 wt ppm or lower while the rest of the country is supplied with higher-sulfur diesel, typically 1,500–2,500 wt ppm. The limit on sulfur in diesel in Santiago, Chile, is in fact being lowered further from 300 wt ppm to 50 wt ppm in 2004. Hong Kong, China, has switched entirely to 50 wt ppm sulfur diesel thanks to a significant tax differential between high- and low-sulfur diesel, initially costing the government around US$0.10 per liter (Ha 2002).

In contrast, many developing countries are still using diesel fuel with a high sulfur content, in some cases as high as 7,000–10,000 wt ppm (or 0.7–1.0 percent). In these cases, the impact on particulate emissions of lowering sulfur to 500 wt ppm can be considerable, especially if particulate pollution is characterized by a high proportion of sulfates (see International Experience 2, next page). For those countries with very high levels of sulfur in diesel where an immediate reduction to 500 wt ppm is difficult, a minimalist approach to secure consistency with Euro I or U.S. EPA 1991 emission standards would require lowering sulfur in diesel to 2,000 and 2,500 wt ppm, respectively. In some cases, this may be achievable at not much additional cost (see annex 1 for when sulfur can be reduced to these levels without much capital investment). ***Even where levels of sulfur in diesel fuels are very high, a strategy should be identified and implemented to reduce sulfur to 500 ppm or lower as a first step toward lower levels. In situations where reduction to 500 ppm is very difficult in the near term but lowering sulfur to 2,000–3,000 wt ppm is relatively inexpensive, immediate steps should be taken to lower sulfur to this level.***

The cost of lowering sulfur in fuels is complex and refinery-specific. In some cases, reducing sulfur to 2,000–3,000 wt ppm is relatively inexpensive, but lowering below that level is costly. In other cases, lowering to 10 wt ppm does not cost much more than lowering to 500 wt ppm so that it would make sense to move immediately to 10 wt ppm provided there is a market for ultralow sulfur fuels. Examples of the impact of different refining situations in developing countries on the cost of fuel sulfur reduction are given in box 2 and annex 1. It should be borne in mind that historically, there has been a tendency among those who will be bearing the investment costs to use conservative assumptions to estimate the cost of fuel quality improvement, resulting in relatively high figures. These estimates tend to represent upper bounds and the actual costs may even be much lower. Agencies setting standards may make assumptions about technology advances and associated cost reductions in the future, giving lower figures than industry esti-

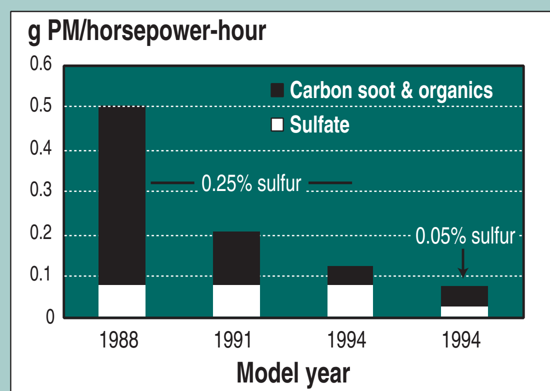
INTERNATIONAL EXPERIENCE 2

Diesel Sulfur Contribution to Emissions

The current debate on the merits and costs of mandating ultralow sulfur diesel in industrial countries has tended to focus policymakers' attention in developing countries on diesel sulfur to the exclusion of other considerations. It is important to understand how sulfur in diesel affects emissions. Sulfur is emitted as sulfure dioxide and sulfur trioxide, and transformed to sulfates in the atmosphere. Sulfates in turn can be combined with ammonia and other compounds to form so-called secondary particulate matter. The extent of conversion to sulfates depends on a number of factors, and the precise contribution of SO_x from mobile sources to secondary particulate formation can be difficult to quantify, especially if there are other major sulfur emissions, for instance from coal combustion or industrial processing.

In terms of tailpipe emissions, the early push to reduce sulfur in diesel arose from the need to lower the sulfate contribution to particulate emissions. An illustrative example is given in the figure below, showing mass particulate emissions from new heavy-duty diesel vehicles in the United States as a function of vehicle technology and diesel sulfur. In 1988, the majority of particulate emissions were carbon based, so that reducing sulfur would not have enabled large overall reductions in particulate emissions. By steadily improving vehicle technology, however, vehicle manufacturers achieved significant reductions in carbon-based particulate emissions. By the 1994 model year, sulfates constituted more than half of particulate mass, at which point it was not possible to meet the new diesel emission standards without reducing diesel sulfur further. Therefore, in 1993, the U.S. EPA mandated sulfur in diesel to be lowered by a factor of five from 0.25 percent by weight (2,500 wt ppm) to 0.05 percent (500 wt ppm). The European Union followed in 1996.

Particulate Emissions from New U.S. Heavy-Duty Diesels



Source: McCarthy 1994.

In countries where diesel sulfur is in the thousands of ppm and the particulate composition looks similar to the 1988 profile shown in the above figure, the first priority would be the reduction of carbon-based particles. For example, overfueling, a common practice in many developing country cities, increases the so-called black carbon emissions markedly, so that exploring measures to stop this practice can reduce particulate emissions (Kweon and others 2002). As steps are taken to reduce the carbonaceous components, diesel sulfur reduction can be pursued in parallel, targeting 500 wt ppm, if not lower. Some maintenance savings can be achieved by lowering sulfur from high levels, as the presence of sulfur in diesel leads to acid formation, corrosion of vehicle parts, and acidification of lubricants, requiring more frequent oil changes and shortening the engine life. Going down from thousands of ppm to 500 ppm will also help reduce ambient secondary sulfate particulate concentrations significantly.

Below 500 wt ppm, the direct benefit of further sulfur reduction on particulate emissions is small (Lee and others 1998, Asian Development Bank 2003). Because acid formation is already low at 500 wt ppm, vehicle maintenance benefits are also expected to be small (Weaver 2003, Lowell 2003). Lowering sulfur markedly below 350–500 wt ppm therefore makes sense primarily if the use of extremely sulfur-intolerant advanced exhaust control devices is planned.*

*The first program in developing country cities to retrofit diesel vehicles with particulate filters was in Hong Kong, China. The retrofitting of mechanical particulate filters in Hong Kong did not require diesel sulfur reduction (although the government provided a subsidy of US$0.10 per liter to switch to 50 ppm sulfur diesel) because there was no catalytic component in the trap. In the absence of automatic regeneration, these filters require washing as frequently as every two to three days (Ha 2002, Tsang and Ha 2002).

BOX 2

Cost of Fuel Reformulation: Examples from Latin America and the Caribbean and from Asia

The Latin American Energy Organization (OLADE) and the Regional Association of Oil and Natural Gas Companies in Latin America and the Caribbean (ARPEL) undertook an extensive study over two years to examine the refining sector in the region, anticipated demand and fuel quality changes, capital requirements, and related financial needs (ESMAP 2002b). For the purpose of the study, the Latin America and the Caribbean region was divided into four subregions. Two refined petroleum product demand growth scenarios were considered (high and low), and the product quality specifications included 2.5 percent benzene and 400 wt ppm sulfur in gasoline and 500 wt ppm sulfur in diesel in the reference target case. In addition, the option of reducing sulfur to 50 wt ppm was studied separately for region 3 comprising southern Brazil, Argentina, Uruguay, Paraguay, Chile, and eastern Bolivia.

In the high-demand scenario, going to the reference target case from the current situation entailed an investment of US$6.5 billion to meet the fuel quality specifications, and an additional $27.7 billion to meet product demand growth. The corresponding estimates for the low-growth scenario were $3.6 billion and $8.4 billion, respectively. In the step-out case for region 3, environmentally driven fuel quality changes including lowering sulfur to 500 wt ppm incurred an additional capital cost of $2 billion, but going down to 50 wt ppm increased the cost by an additional $4 billion to $6 billion (both costs reflect making fuel quality changes in one step and are for the high-growth scenario).

As with other similar refinery studies, simplifying assumptions made in the study have a large impact on the final cost estimates. As the study reports explain, construction costs were set equal to those in the U.S. Gulf Coast. In practice, experience in the region indicates that costs can be 40 percent higher. The use of an aggregate refinery model (one notional refinery was set up for each region) results in efficiencies that may not be achievable by individual refineries, which could underestimate capital costs by 10–20 percent. The need to process increasingly heavier crude oils in the future could also add to investment costs. Future advances in refinery process technologies, however, are likely to lower investment and operating costs significantly. Another factor that could lower the overall investment costs is optimization of intra-regional trade.

The potential costs of sulfur reduction have been studied elsewhere. As might be expected, the studies vary in purpose, focus, and level of detail. Some apparently low costs (0.4 U.S. cents per liter for gasoline and 1 cent per liter for diesel) have been quoted as being representative of cost figures in developing countries, based on a study of the refining sector in China (Yamaguchi and others 2002, ICCT undated). Based on these numbers, the cost of going in one step to 10 ppm gasoline and diesel has been claimed to be affordable even in developing countries (Blumberg and others undated). But the study on China was undertaken to indicate refinery process options available to China to produce low-sulfur fuels. The cost figures are based on refinery equipment costs only, and do not include operating and off-site costs, which could add 25–50 percent more to the costs according to the study report. Moreover, the capital cost figures are for standard-sized units at large refineries, suggested by the commissioning agency. Many of the capital cost assumptions were a fraction of capital costs experienced in the rest of the world. Verifying the capital cost figures was outside the scope of the study. In reality, there are many relatively small refineries in China for which investing in advanced sulfur removal technology would not be feasible. The low costs cited tell only part of the story, and therefore the study's authors made no claim that the costs were a fully built-up per-liter cost of producing sulfur-free fuels even in China, much less for other developing countries. Each market will have unique characteristics in terms of demand levels and patterns, crude resources, technology in place, prices, and capital and operating costs (Yamaguchi 2003).

mates. In addition, it is not uncommon for different agencies in the government—for example, environment and energy—to come to significantly different numbers for cost estimates.

The EU and North America are planning to move toward 10 (also called "sulfur-free") and 15 wt ppm sulfur limits in diesel, respectively, during the latter half of this decade, in order to take advantage of the advanced diesel exhaust emission reduction technologies that have extremely low tolerance for sulfur. These include particulate filters (traps), NO_x adsorbers, and selective catalytic reduction (see annexes 2 and 3).[1] These devices can make diesel vehicles essentially as clean as CNG vehicles. The combined use of ultralow sulfur diesel with particulate filters (currently suitable primarily for heavy-duty diesel vehicles, with advances being made to make filters robust for light-duty) and other advanced ex-

[1]Three-way catalysts capable of converting NO_x do not operate at high air-to-fuel ratio (also called "lean") typical of diesel engine operation. A lean de-NO_x catalyst is capable of converting NO_x even when the air and fuel mixture is lean.

haust control devices is collectively called "clean diesel," in contrast to conventional diesel. A corollary of requiring diesel sulfur to be lowered to ultralow levels should be to simultaneously require new diesel vehicles to meet extremely stringent particulate emission standards that require the use of particulate filters for PM control. If not, the benefits reaped from the large investment required to lower sulfur in diesel could be disproportionately small.

Reducing sulfur to 10–15 wt ppm in turn requires expensive hydrodesulfurization processes, although investment costs are expected to fall with increasing scale of application and experience. The incremental cost of producing ultralow sulfur fuels is generally the lowest in large-scale refineries. ***Where large refineries are being built or upgraded, countries should seriously consider investing in the necessary facilities to produce ultralow sulfur fuels. Importing countries can take advantage of ultralow sulfur fuels as they become increasingly available. For other non-importing developing countries, the cost-effectiveness of mandating ultralow sulfur fuels should be compared with other strategies for improving air quality.***

Harmonizing standards

Given the existence of substantial scale economies in manufacturing, harmonization of standards may reduce production costs of vehicles and fuels and stimulate regional trade. Vehicle manufacturers are therefore leading initiatives to harmonize fuel quality standards worldwide in accordance with vehicle needs. More specifically, European, North American, and Japanese automobile and engine manufacturers associations with their associate members around the world have issued the World-Wide Fuel Charter (ACEA and others 2002), which calls for consolidation of fuel specifications into four categories (see annex 4). Category 1 is the least stringent while Category 4 is designed for the most advanced vehicle technologies. Trade considerations (between Canada and the United States, within Central America, and within the EU) are a strong driving force for harmonizing fuel- and vehicle-emission standards. Fuel specifications in the EU and North America are already integrated, and similar measures have been proposed in Latin America and the Caribbean. In the former Soviet Union republics, fuel standards are already largely harmonized by virtue of the countries' history.

Countries that import the bulk of their transport fuels will find it easier to harmonize with those neighboring countries from which they import than will countries that have domestic refineries. However, if two neighboring countries (for example, India and Sri Lanka) have very different air pollution problems, it may not make sense to harmonize fuel- and vehicle-emission standards, unless the country with less serious air pollution problems is already importing the majority of fuels and vehicles from the other. Developing countries may benefit from regional harmonization agreements. At the same time, it is necessary to take into account the key transport pollution problems in individual countries, and the infrastructure capabilities of refining and distribution in the region.

One of the objectives of standard harmonization is to minimize the number of fuel types and vehicle emission requirements. From the point of view of manufacturers, the fewer the number of standards, the greater the potential for trade and for taking advantage of scale economies. That said, especially when harmonizing standards across a large region, it is inevitable that some countries have the resources and air-quality-based needs to impose tighter standards earlier than others. Early introduction of cleaner fuels by some member states is therefore common in harmonizing standards.

Regionally differentiated standards

Another approach is to introduce regionally differentiated or city-specific standards whereby more stringent standards are imposed on large metropolitan areas. This approach has been used in Brazil, Chile, India, and Mexico, and earlier in the former Soviet Union where leaded gasoline was banned in cities with a population of more than 1 million beginning in the 1980s. If tightening standards throughout the country is too costly in the near term, provided that the distribution system can handle segregation of fuels, it could be more cost-effective to supply cleaner transport fuels to large cities only, and confine the use of fuels with less stringent specifications to areas out-

FAQ 1

How do you decide when to lower transport fuel sulfur limits, and to what level?

The issue that dominates the debate on fuel quality in North America and Europe is limits on sulfur in gasoline and diesel. As a result, diesel fuel quality improvement has come to be synonymous with sulfur reduction in the minds of many policymakers.

In considering the levels to which sulfur in fuels should be limited, it is important to ask how sulfur reduction affects emissions, concentrating on diesel, because sulfur in diesel is a more serious problem in developing countries than is gasoline. In developing country cities, the most important pollutant to target is generally particulate matter. For a given diesel vehicle technology that does not rely on an oxidation catalyst, the main impact of reducing sulfur in diesel is to reduce the sulfate contribution of particulate emissions, including secondary particulate formation. For developing countries with high sulfur diesel, it would make sense, even in countries with refineries, to lower sulfur in diesel to at least 2,000–3,000 wt ppm (see annex 1 for more detail) as an immediate step and preferably to 500 wt ppm or lower. A sulfur limit of 500 wt ppm is needed to enable U.S. 1994 and Euro II emission standards. At sulfur levels in the upper tens of thousands of ppm, the sulfate share of total particulate emissions is likely to be significant, and there are indications that sulfur-containing particles are especially harmful. But where the carbonaceous contribution to particulate emissions dominates, as is often the case in the majority of heavily polluting diesel vehicles in developing countries, reducing sulfur alone may have a limited impact. Lowering density may be just as important in those circumstances.

The impact of sulfur reduction on particulate emissions from diesel vehicles is significant down to 500 wt ppm, below which the *direct benefit* (that is, without particulate filters) in terms of particulate emissions reduction becomes minimal (Lee and others 1998). For countries with refining capacity, reducing sulfur to 500 wt ppm almost always requires refinery upgrade, and the capital cost depends on such factors as the size of the refinery, availability of hydrogen from other processes, and the type of crude processed. Units for hydrotreating to reduce sulfur can cost tens of millions of dollars and require an adequate source of hydrogen. For countries that import some or all of their diesel fuel, the decision is simpler: the primary question is whether the incremental cost of purchasing lower sulfur diesel can be justified in terms of benefits and passed on to consumers.

The next important threshold is 50 wt ppm, below which particulate filters can be considered. This is the decision facing those developing countries and cities that have already moved to 500 wt ppm sulfur. The primary objective of ultralow (below 50 wt ppm, and preferably 10 or 15 wt ppm) sulfur limits is to meet extremely stringent particulate and NO_x standards *simultaneously* (for trade-offs between particulate and NO_x reductions, see the section in this chapter, Vehicle Technology). Mandating ultralow sulfur diesel makes sense only if (catalytic) particulate filters are also mandated for new vehicles. For those developing country cities that are willing and able to pay for particulate filters and dramatic sulfur reduction, this step is well worth considering.

There are teething problems in commercializing new technology. For example, while applications of diesel particulate filters have been mostly successful in the United States, a few problems have been encountered. In one case, engines equipped with exhaust gas recirculation (EGR) and particulate filters sold by a leading U.S. diesel engine manufacturer experienced problems with filter clogging, even though the technology supplier was actively involved in providing technical advice. This is not unlike the problems encountered with early-generation CNG buses. Waiting until many of these problems have been worked out may be a sensible option for those developing country cities with limited experience with maintaining modern technology vehicles. The technology to achieve reductions to 10–15 wt ppm, as well as the exhaust-control technology enabled by ultralow sulfur diesel, is undergoing continuous improvement. As a result, significant cost reductions are almost certain in the coming decade.

side urban centers with less serious air pollution problems. As increasingly stringent fuel quality and vehicle emission standards are contemplated, this ***targeting of large metropolitan areas for tighter standards, so that refineries have a longer period in which to upgrade their process units and have an outlet for lower-quality fuels during the interim, may present a cost-effective alternative to tightening standards throughout the country all at once.***

The logistics of delivering fuels of different qualities to different depots, as well as leakage and other enforcement problems, have made it difficult to implement regional differentiation cost-effectively in the past. For long-distance transport vehicles, refueling with different quality fuels in different parts of the country may preclude the use of fuel-sensitive exhaust control devices. These concerns notwithstanding, requiring that vehicles in large polluted cities providing intra-city passenger and goods transport meet much tighter emission standards and the entire city is supplied only with cleaner fuels to enable them to do so merits serious consideration.

Downstream petroleum sector reform

One of the important factors for making sustainable improvements in fuel quality is an efficient downstream petroleum sector. Where there are serious distortions in the sector, unsustainable subsidies, inefficiencies, a shortage of investment, or a lack of maintenance of existing assets, coupled with the protection of the sector, it is very difficult to realize significant fuel quality improvements. ***Fuel quality is often directly related to the efficiency of the downstream petroleum sector.***

This is especially problematic in countries with oil refineries. In a number of developing countries, the government is the sole owner of domestic refineries, which it protects by means of import restrictions, quotas, or high tariffs. In many cases, mounting government subsidies and the inability to attract capital for needed investment in the sector are two primary drivers for sector reform. Environmental considerations have typically played a minor role. While environmental degradation may not drive sector reform, fuel quality improvement cannot often be divorced from it, and ***in a number of circumstances sector reform is in fact a prerequisite for fuel quality improvement.***

In countries with inefficiently operated domestic refineries, a further consequence of protection of these refineries is that consumers are denied access to cleaner fuels that are available internationally and are often cheaper than dirtier, domestically produced fuels. As fuel quality specifications improve worldwide, it will become increasingly difficult for inefficient or small refineries to produce fuels that meet the standards without requiring even greater protection against competitively priced and cleaner fuels from outside the market. For example, the number of refineries in North America and Europe has declined in the last two decades as the downstream petroleum sector has become liberalized, and small or inefficient refineries have closed down in the absence of government protection. ***Fuel quality specifications in countries with protected, state-owned refineries tend to lag behind those of countries where the petroleum sector is more open.***

Even where the government does not have shares in the ownership of refining capacity, it can still be heavily involved in the sector, setting prices at various points in the supply chain, deciding who can import what and how much, and determining how fuels should be transported throughout the country. That denies the country the benefit of market signals that can help allocate resources efficiently. Even if there are no refineries within the country, if prices are controlled by the government or, worse, significant price subsidies are given to make fuels cheaply available to consumers, improving fuel quality, which entails cost increases, becomes problematic for the country. Short of raising fuel prices, government subsidies will increase. Raising fuel prices becomes highly politicized under these circumstances, making it difficult to pass the incremental cost to consumers. The alternative—carrying an even larger subsidy bill—is typically equally unacceptable to the government. Large subsidies also invite illegal diversion, thereby greatly reducing the access of the intended beneficiaries to the subsidized fuels. At a minimum, effective benefits and possible adverse environmental effects of fuel or refining subsidies need to be carefully considered. ***A competitive market reduces opportunities for corruption and provides a sound basis for attracting new investment without creating contingent liabilities for government or requiring the pledging of public assets.***

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 introducing cleaner fuels. An effective and well-regulated competitive market imposes relentless pressure on participants to improve efficiency and to share the gains with customers. Given vigorous competition on the world market, ***importing superior quality petroleum products can be the most cost-effective option for many developing countries.***

While refining, importing, and distributing are oligopolistic in nature because of the large invest-

FAQ 2

If it costs only a cent or two a liter to improve fuel quality, why can't we improve fuel quality immediately?

When translated to U.S. cents per liter, fuel quality improvement costs seem quite modest. This is especially true in the case of gasoline in countries where gasoline is already heavily taxed. Motorists, especially private car owners who tend to be from upper income groups in developing countries, may not even notice whether gasoline costs 70 or 71.5 cents per liter. Certainly, if a country relies on imports to meet part or all of its fuel demand, it makes sense to import higher-quality fuels for use in large cities, if not in the entire country. Several developing country governments have successfully managed regional differentiation of fuel quality, such as the early introduction of Euro II-compliant fuels in Chennai, Delhi, Kolkata, and Mumbai in 2000–2001 in India, some 4–5 years ahead of the rest of the country, and tighter fuel quality standards in Mexico City compared to the rest of Mexico.

For developing countries with domestic refineries, the first, and perhaps the most serious, barrier to fuel quality improvement is the need to raise financing for refinery revamp projects. One estimate of the cost of installing a diesel hydrotreater to reduce sulfur to below 500 wt ppm at a 50,000 barrels per day refinery in South Asia is $73 million (1998 US$) (ESMAP 2001b). Improving fuel quality without changing the product output does little to increase refinery profits. The return on investment to upgrade fuel quality is often very low. Under these circumstances, it is difficult to raise financing (foreign or domestic) for even a well-run refinery. The situation is much more difficult for an inefficiently run or small-scale refinery in a country with government price controls. This inability to raise financing has led to continuing use of leaded gasoline in some countries and high-sulfur diesel in a number of others.

As far as diesel is concerned, many developing countries levy a low tax rate to keep the end-user diesel price low. This makes the incremental cost of improving fuel quality larger as a percentage of the retail price compared with that of gasoline. Because the majority of road diesel is used in goods and public transport, an increase in the price of diesel has economy-wide repercussions. This in turn makes policymakers hesitant to raise the tax on diesel or adopt measures that will raise the price of diesel. These impacts can be lessened considerably without much reduction in environmental health benefits if cleaner fuels are targeted only in large metropolitan areas.

ments involved, international experience has shown that it is possible to achieve effective competition when individual players have 20 to 30 percent of the total market. For countries where the downstream petroleum sector is not yet open, restructuring the sector to introduce effective competition is a first step. To this end, governments should adopt licensing and regulatory regimes that provide a level playing field. ***Competitive efficiency will usually be enhanced by opening product imports, storage, distribution, and retailing businesses to new entrants.***

Within a liberalized fuel sector it becomes increasingly important for government to have a clear strategy for taxes and fiscal incentives. Many countries have used tax discrimination to assist the elimination of lead from gasoline, and some, such as some EU countries, are now using such incentives to accelerate the reduction of sulfur in diesel. Among developing countries, Hong Kong, China, introduced in July 2000 a net subsidy of US$0.10 per liter in favor of diesel containing 50 wt ppm sulfur (Ha 2002). Because this subsidy made the retail price of 50 wt ppm sulfur diesel lower than that of regular diesel (at the time up to 500 wt ppm sulfur was allowed in regular diesel), the entire diesel retail sector switched to 50 wt ppm. However, a subsidy of US$0.10 per liter is very high by any standard. The high cost of this subsidy was in turn largely due to the extremely limited availability of 50 wt ppm sulfur diesel in the region at the time. ***When significant implicit or explicit fuel subsidies are being considered, governments should compare the likely benefits with alternative uses of the funds, including the option of waiting until international prices come down.***

For all countries, the prices and quality of refined products sold in neighboring countries are important considerations in trying to enforce high domestic standards. If cheaper and inferior quality fuels are readily available along the borders, it becomes more difficult to tighten fuel specifications and enforce them. Similarly, widely different taxes on different fuels that are to some extent substitutable (for example, gasoline and naphtha for petrochemical production) make it difficult to enforce standards.

Maintaining Fuel Standards

Fuel quality standards are ultimately driven by the maximum vehicle emission levels to be permitted. Setting standards makes sense only if the government intends to enforce them, and enforcement can be difficult and costly. Take the case of emission standards for new gasoline vehicles. After lead elimination, many governments have rightly required that new gasoline vehicles be fitted with catalytic converters. But if adulteration of gasoline with (much lower-priced) kerosene occurs as a matter of routine, premature catalyst deactivation can occur. ***The cost of compliance and the probability of compliance are key questions in setting standards.***

Adulteration of fuels

Adulteration of standard fuels (World Bank 2002d) consists of the addition of other components to the base fuel. Adulteration typically occurs when either the seller or the purchaser of fuel sees some advantage to be taken, either in terms of lower costs of vehicle operation or greater profit from adulteration. This advantage arises from two main sources:

- Adulterants that have little market value (for example, waste industrial solvents or off-specification petrochemicals)
- Additives that reduce the cost of the fuel because of tax differences (for example, untaxed fuels for exports or subsidized kerosene).

Even if fuels meet specifications at the port of entry or the refinery gate, it is all too common for them to be adulterated somewhere in the supply chain (Kojima and Bacon 2001a). Examples include illegal addition of cheap lead additives from the Russian Federation to gasoline in Central Asia, addition of much lower-priced kerosene to gasoline in many countries, and addition of off-specification chemicals to gasoline and of heavier fuels to diesel. In a large number, if not the majority, of developing countries, gasoline carries a much higher tax than diesel. Kerosene is often untaxed, or even subsidized, as a basic cooking and lighting fuel for the poor, and hence can be used to reduce the cost of auto fuel. Industrial solvents and recycled lubricants are other materials with little or no tax, inviting adulteration. ***Financial gains arising from differential taxes or price controls are the primary cause of fuel adulteration.***

For *gasoline*, any adulterant that changes its volatility can affect drivability. High volatility (resulting from the addition of light hydrocarbons) in hot weather can cause vapor lock and stalling. Low volatility in cold weather can cause starting problems and poor warm-up. The most common form of adulteration that is damaging for emissions is adding kerosene to gasoline. Kerosene is more difficult to burn than gasoline, so that its addition results in higher levels of hydrocarbon, CO, and particulate emissions even from catalyst-equipped cars. The higher sulfur level of kerosene can also reduce the efficiency of the catalyst, thereby lowering catalytic conversion of engine-out pollutants. If too much kerosene is added, volatility is lowered and, more seriously, octane quality can fall below the octane requirement of the engines and engine knocking can occur. Besides possibly damaging the engine mechanically, knock can increase particulate, hydrocarbon (HC), and NO_x emissions. ***The addition of kerosene to gasoline increases emissions under all circumstances and should be discouraged by close monitoring and other means.***

For *diesel*, the most common form of adulteration is also kerosene addition. This is not always harmful. The blending of kerosene into automotive diesel fuel is in fact widely and legitimately practiced by the oil industry worldwide as a means of adjusting the low-temperature operability of the fuel. This practice is not detrimental to tailpipe emissions, provided the resulting fuel continues to meet engine manufacturers' specifications (especially for viscosity, cetane number, and sulfur); in some respects it may even reduce emissions. However, high-level adulteration of low sulfur (for example, 500 wt ppm) diesel fuel with higher-level sulfur kerosene may cause the fuel to exceed the sulfur maximum. Further, the kerosene blended into diesel may have poorer lubricity and promote fuel system wear, higher flammability, and potentially a lower cetane number, and produce higher NO_x emissions. The addition of heavier fuel oils to diesel is usually easy to detect because the fuel will be darker than normal. Depending on the nature of these heavier fuel oils and the possible presence of additional PAHs, there could be an increase in both exhaust particulate and PAH emissions.

Where extremely sulfur-intolerant exhaust control devices are in use, the adulteration of gasoline or diesel with higher-sulfur fuels could be very damaging. If kerosene containing 1,000 wt ppm sulfur is added to diesel containing 10 wt ppm sulfur, the blend could permanently deactivate sulfur-sensitive devices. Even with less sulfur-sensitive devices, the addition of, for example, railroad diesel containing 5,000 wt ppm sulfur to automotive diesel containing 350 wt ppm sulfur could result in considerable harm.

It is possible to adulterate fuels and still comply with fuel standards. When gasoline is judiciously adulterated with gasoline boiling range solvents such as toluene, xylenes and other aromatics, or light materials such as pentanes and hexanes (rubber solvents)—available at low or zero tax for their normal industrial use—the gasoline may continue to meet all specifications and not exhibit drivability problems. But larger amounts of toluene or mixed xylenes could cause an increase in hydrocarbon, CO, and NO_x emissions and significantly increase the level of air toxins, especially benzene, in the tailpipe exhaust. Extremely high levels of toluene (45 percent or higher) could cause premature failure of neoprene, styrene butadiene rubber, and butyl rubber components in the fuel systems. This has caused vehicle fires in some parts of the world, especially in older vehicles. The adulterated gasoline itself could also have increased potential human toxicity. Adulteration of gasoline by waste industrial solvents is especially problematic because the adulterants are so varied in composition. Adulterants may contain halogens, silicon, phosphorus, or other metallic elements (found in recycled lubricants); these are quite outside the normal gasoline composition range. They will cause increased emissions and may even cause vehicle breakdown by corroding fuel injection systems and carburetors and by causing deposits on valves, fuel injectors, spark plugs, oxygen sensors, and exhaust catalysts. Even low levels of adulterants can be very injurious and costly to the vehicle operator. ***Adulteration of gasoline with cheaper fuels and waste industrial solvents can be highly dangerous.***

In cases where adulteration does not increase emissions, it may still be socially undesirable because of its indirect effects. For example, large-scale diversion of rationed kerosene subsidized for household use to the diesel automotive sector does not necessarily increase emissions from diesel vehicles, but deprives the poor of kerosene for cooking. Lack of availability of subsidized kerosene forces the poor to continue to use biomass and may expose them to high levels of indoor air pollution. ***Protection of the supply of subsidized cooking and lighting fuel to poor households calls for more vigorous enforcement of the ban on the use of rationed kerosene as an automotive fuel adulterant.***

When engines are out of tune with the specifications set by the manufacturers or are poorly maintained, they will emit substantially more pollutants—even when operating on fuels that meet all specification requirements—than properly maintained vehicles. Whenever considering the impact of fuel adulteration on air quality, it is important to keep the impact of adulteration in perspective. ***The effects on emissions of basic engine design and maintenance usually far outweigh changes in fuel composition.***

Enforcing fuel standards

Identifying and checking fuel adulteration presents a difficult challenge in the face of enormous incentives to adulterate in some countries. As vehicle emission standards are progressively tightened and fuel quality and vehicle technology are increasingly integrated, having fuels that meet the specifications becomes all the more important for meeting the new emission standards. It is one thing to prohibit adulteration of fuel in developing countries and quite another matter to enforce it. Governments need to have well-organized procedures to detect and eliminate adulteration.

An important step in tackling fuel adulteration is to reduce the incentives to engage in it. These depend on the relative benefit (from adding low-priced materials) and cost (from the risk of being caught and fined, losing one's market share on account of declining reputation, or having one's business license revoked). The benefit arises from differential taxation, tax evasion, and lower production costs of adulterants. Though tax incentives can always be reduced, fiscal policy has multiple objectives: concerns about fuel adulteration, however serious, cannot be the sole driver of fiscal policy. The cost to those engaged in adulteration depends on the ability of the regulating authorities to detect adulteration and to impose sufficiently punishing sanctions to deter recurrence of fuel adulteration. ***Government policies on fuel quality enforcement are likely to be most effective if they combine the reduction of incentives to adulterate with measures to detect and punish criminal adulteration.***

A number of analytical techniques are available to detect adulteration: density measurements, determination of evaporation and distillation properties, hydrocarbon composition analysis by gas chromatography, and use of trace markers in fuels. Field techniques produce results quickly and conveniently, but are not as detailed or quantitatively accurate as laboratory tests. For the majority of the tests, accurate data on uncontaminated fuels are also a prerequisite. ***In all cases, it is important to have good sampling techniques and access to a good petroleum analytical laboratory.***

Fuel adulteration has significant financial benefits for those engaged in it. Therefore, anyone investigating it must have the direct protection of local law enforcement agencies in taking field samples. Even in the best of circumstances, taking and maintaining samples for checking fuel quality is not easy. In developing countries, finding proper sample containers and avoiding harassment at retail outlets while sampling are real operational problems. These problems are compounded by lack of experience in checking specifically for adulteration. Precision and repeatability could be improved by setting up programs for cross-checking inter-laboratory variability. This requires action by the responsible agencies within government. The first step is recognition of the existence and seriousness of the problem—both from the consumer and environmental perspectives—by sufficiently high levels of government. Given historical problems with fuel adulteration in many developing countries, ***strong political will needs to be generated before appropriate regulatory and enforcement steps can be taken.***

The manner in which retail fuels are distributed has an important bearing on fuel adulteration. For example, having large numbers of small, independent transport truck operators moving fuels from terminals to the point of sale creates an environment conducive to adulteration. Adulteration may also occur with the collusion of the retail outlet operator. If government officials are involved in adulteration, establishing a good monitoring and enforcement mechanism becomes all the more difficult. ***An effective market-based approach is practiced in many industrial countries where oil companies market at retail and assume responsibility throughout the supply chain to guarantee fuel quality in order to protect their public image and market share.*** (See International Experience 3 for an example.)

Smuggling is a problem in many countries. Having many ports of entry or fuels trucked in from other countries makes it very difficult to check fuel quality because of the large number of fuel samples involved. In contrast, it is relatively easy to check fuel quality at the refinery gate, because most countries have only a handful of refineries. Fuels that are smuggled into a country are not certified for fuel quality, and smuggled fuels are commonly not only cheaper but also of inferior quality. ***Control of fuel smuggling is an important element of a fuel quality policy.***

Alternative Fuels

Alternative fuels include gaseous fuels such as compressed natural gas (CNG) and liquefied petroleum gas (LPG), biofuels, and electricity. They are detailed below and in annex 6.

Gaseous fuels

Gaseous fuels lower particulate emissions significantly compared with conventional diesel. Gaseous fuels are especially attractive in countries with abun-

INTERNATIONAL EXPERIENCE 3

Market-Based Approach to Tackling Abuses in Fuel Markets: "Pure for Sure" in India

Bharat Petroleum in India has recognized that one of the basic needs of fuel-buying customers is standard-compliant quality and an accurate quantity of fuel sold. As one of the major initiatives in this direction, Bharat Petroleum has launched a nationwide voluntary effort to dispense standard-compliant quality and the correct quantity of fuel. This program is being launched in phases. The first phase consists of certifying retail outlets covering 108 sites in six of the country's largest cities. Another 600 to 700 sites are to follow, in two more phases in other cities. The retail outlets covered under this program display the "Pure for Sure" sign. At such retail outlets, Bharat Petroleum guarantees that the correct quality and quantity are dispensed. In order to enable them to do so, strict quality control and tracking measures have been put in place from the supply point (depot) to the customer's fuel tank.

Before certification, the retail outlets are subjected to stringent tests to ensure that all parameters of the program are strictly adhered to. The main pillars of this program are:

- **Tamper-proof locks.** Products are supplied to retail outlets in modified tank lorries fitted with tamper-proof locks.
- **Comprehensive sealing.** Dispensing units are sealed in a comprehensive manner, which makes meter tampering impossible.
- **Periodic and surprise checks by staff.** Stringent periodic and surprise checks are carried out to check for correct delivery and the sealing of the pumps.
- **Testing of product samples.** Regular comprehensive testing of samples is done without warning.
- **Certification of retail outlets.** Periodic audits and recertification of retail outlets are carried out by a reputed certification agency.
- **Dedicated staff.** Dedicated field staff has been placed to monitor and sustain the program. Anonymously conducted audits and extensive inspections are carried out at these retail outlets to ensure that they continue to comply with the requirements of the program.

These measures have been supported by the Mashelkar Committee's "Report of the Expert Committee on the Auto Fuel Policy," prepared for the government of India, which has recommended that similar steps be made obligatory for all petroleum companies.

Sources: Rogers 2002, Bharat Petroleum undated.

dant reserves of natural gas or associated gas (from oil production). A recent report by the European Commission on alternative fuels identified natural gas vehicles as one of the most viable solutions to environmental and energy security problems associated with the automotive industry (Alternative Fuels Contact Group 2003). For successful fuel switching, however, it is necessary to consider fuel availability and distribution networks; refueling infrastructure; and costs related to vehicle modification, maintenance, and operation.

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

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. Conversion of gasoline vehicles is much easier than that of diesel vehicles to gaseous fuels. 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 also increase, rather than decrease, emissions of some pollutants other than particulate matter. In cities where ambient ozone concentrations are high, increased emissions of NO_x, an ozone precursor, resulting from conversion from diesel to CNG can exacerbate the ozone problem. Experience with conversion of in-use heavy-duty diesel vehicles to CNG has been particularly problematic. It is essential that CNG conversions, whether stoichiometric (air-to-fuel ratio matching exactly the chemical requirements for combustion) or lean burn (high air-to-fuel ratio), have a tamper-proof air-to-fuel ratio control using oxygen sensors, or else emissions of either NO_x or CO may rise over time. Poor conversion can also lead to safety hazards, as demonstrated by bus and taxi fires in some cities. It is therefore 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.***

Because the cost of vehicles designed for gaseous fuels is higher than that of vehicles powered by conventional liquid fuels, partly due to the smaller size of the market, they will be attractive to consumers only if the higher incremental cost of vehicle acquisition can be offset through lower maintenance and operational expenses. This is not the case when switching from diesel to CNG or LPG in many countries, where low taxes on diesel make fuel switching from diesel to CNG or LPG financially unattractive for vehicle operators. ***In order to achieve reductions of particulate emissions by switching to gaseous fuels, it is important that relative tax levels are set to encourage the substitution for diesel and not merely for gasoline.***

Typical preconditions for successful implementation of CNG vehicle programs include the following, and are discussed further in Frequently Asked Question 3:

- A natural gas distribution pipeline for other uses of natural gas is in place.
- Adequate safety and performance standards that are monitored and enforced are established.
- A realistic plan to match supply and demand during the initial phase is in place. Adequate refueling infrastructure for the number of CNG vehicles is in operation, and a sufficient number of CNG vehicles, given the number of refueling stations, is in existence or is soon to 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 they refuel at only a handful of locations.
- Managers of CNG fleets have made a commitment to provide technical support to deal with CNG-related maintenance and operational problems not generally encountered with diesel vehicles.

Biofuels

Biofuels are supported in a number of countries as a means of diversifying energy sources, reducing lifecycle GHG as well as tailpipe exhaust emissions, and promoting or protecting domestic agriculture. They are promoted as a contribution to the efforts to increase the share of renewables in world energy supplies as developed in the 2002 World Summit for Sustainable Development Plan of Implementation. Feedstocks for biofuels, mostly plants, are much more evenly distributed around the world than oil and gas. Two of the most commonly used biofuels are ethanol,

FAQ 3

Since CNG produces markedly lower particulate emissions than diesel, why not promote switching from diesel to CNG in all cities with serious particulate air pollution?

There are several important considerations in deciding whether switching from diesel to CNG 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.
- **Are there sufficient supplies of natural gas that are available to the city?** If yes, CNG is a potentially viable option. Having large domestic reserves of gas alone is not sufficient for a successful CNG vehicle program. Constructing gas distribution pipelines is expensive, so that large industrial users of natural gas need to be in close proximity to justify a pipeline network. If there are abundant domestic gas supplies and an adequate gas distribution network in place, natural gas may be an attractive option for use in the transport sector even if diesel combustion does not contribute significantly to air pollution, in order to diversify energy sources. If the country is short on natural gas and is importing liquefied natural gas, then CNG is unlikely to be economic compared with diesel.
- **Is diesel taxed sufficiently?** In most developing countries, diesel is not taxed much and is typically taxed much less than gasoline. Under these circumstances, substantial subsidies would be needed to make switching from diesel to CNG close to financially neutral. If CNG for all vehicle users is made cheap compared with diesel, the first result would be mass conversion of gasoline to CNG, not diesel to CNG, resulting in a significant loss of fuel tax revenue to the government. In Argentina, the largest CNG vehicle market in the world, there has been virtually no fuel switching from diesel to CNG. In Delhi, India, where CNG conversion was mandated for certain commercial diesel vehicles (buses and taxis), large-scale conversion from gasoline to CNG among private cars created a shortage of CNG in the early days of the 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 because buses in large fleets all "come home" to one refueling station at night, making fueling with CNG easier. An extensive program carried out by the bus transit authority in New York City found that CNG buses are the most technically challenging of the three technologies tested in terms of operation and maintenance: CNG, diesel-electric hybrid, and "clean diesel" technology using particulate filters and ultralow sulfur diesel (MTA New York City Transit Department of Buses 2000). In a recent review of natural gas bus fleet experience in the United States conducted by the National Renewable Energy Laboratory (NREL), the majority of fleets participating in the survey reported higher overall costs for the natural gas buses. In the same survey, the most critical factor cited for a successful natural gas program was training, especially of maintenance personnel (Eudy 2002). As with any program, experience varies from location to location and bus operator to bus operator; one fleet operator in the NREL study reported no failures, only successes, and extreme satisfaction with natural gas buses. As natural gas vehicle technology matures, many of the maintenance difficulties and even higher first costs are expected to diminish. The key is to understand and anticipate potential technical difficulties and incremental costs, and have a total commitment at all levels of the organization for the long-term sustainability of CNG vehicle programs.
- **Is fundamental reform in the transport sector needed to make the operation of vehicles being targeted financially viable?** Reform issues, such as in a financially nonviable bus sector, may need to be dealt with first before saddling cash-strapped fleet operators with financially and technically challenging fuel switching from diesel to CNG.

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

for which the world's leading producers and consumers are Brazil (from sugarcane) and the United States (from corn), and biodiesel, for which the world's leader is the Federal Republic of Germany (from rapeseed oil). Biodiesel fuels are oxygenated organic compounds—methyl or ethyl esters—derived from a variety of renewable sources such as vegetable oil, animal fat, and cooking oil. The technologies for making ethanol from sugarcane and corn, and biodiesel from plant- and animal-based oils, are quite mature and well established.

The addition of ethanol, or any oxygenate for that matter, to gasoline reduces the emissions of CO and hydrocarbons in old engines running "rich" (low air-to-fuel ratio). Ethanol has a high octane number, and was used extensively in Brazil as a replacement for lead. If too much ethanol is added to gasoline in a vehicle that has a fixed air-to-fuel ratio, however, the vehicle may run lean, misfire, and potentially produce greater NO_x or HC emissions. The "dilution" effect of ethanol is also beneficial: denatured ethanol contains little or no sulfur, aromatics, and olefins, so that adding ethanol to gasoline lowers the concentrations of these components that have direct and indirect harmful effects on health.

Ethanol-blended gasoline has little, if any, advantage in modern gasoline engines equipped with an oxygen sensor. The addition of 5–10 percent ethanol to gasoline raises the fuel's volatility markedly. If fuel volatility is not controlled, there will be significantly higher evaporative hydrocarbon emissions. If volatility is not to be increased, hydrocarbons with four and five carbons may have to be taken out of the base gasoline. Because they can be cheap sources of octane, this in turn adversely affects the cost of gasoline production. In cities with serious ozone problems (such as Mexico City, Santiago, and São Paulo), the addition of ethanol to gasoline leads to higher emissions of formaldehyde, which is an ozone precursor. In requesting a waiver from the federal oxygenate requirement in reformulated gasoline, the California Air Resources Board in 2003 submitted to the U.S. EPA documents showing higher NO_x emissions after the state began using more ethanol-blended gasoline (Platts Oilgram Price Report 2004). Ethanol is thus most suited for cities with little ozone problem, high concentrations of CO, and a large stock of old-technology gasoline vehicles. In most developing country cities, outdoor CO is typically not a serious health hazard except along heavily congested traffic corridors and at intersections.

Biodiesel typically has high cetane and little or no sulfur. The addition of biodiesel to conventional diesel can lower particulate, CO, and HC emissions. Biodiesel fuels are biodegradable, making them especially suitable for marine or farm applications. Biodiesel has better lubricity than petroleum diesel, making it suitable for blending into low and ultralow sulfur diesel, which lacks lubricity. Diesel blends containing 5 percent or less biodiesel are widely accepted by vehicle manufacturers. Biodiesel seems to increase NO_x emissions slightly in vehicle exhaust and biodiesel fuels have shown poor oxidation stability. When they are used at low ambient temperatures, filters may plug, and the fuel in the tank may thicken to the point where it will not flow sufficiently for proper engine operation. There are also concerns over the compatibility of biodiesel with seals and fuel system materials. Biodiesel is an excellent medium for microbial growth. Because water accelerates microbial growth and is more prevalent in biodiesel than in petroleum diesel, care must be taken to keep fuel tanks free of water. An important aspect of promoting biodiesel is to establish clearly defined and enforced fuel quality standards, as Germany has done.

In practice, the drive for mandating the use of biofuels in North America and Europe in the coming years has more to do with support of domestic agriculture than environmental improvement. This is likely to preclude the replacement through trade of high-cost, locally produced biofuels by cheaper imported biofuels. Diversification of energy sources, closely linked to concerns about energy security, has also become an increasingly important political consideration in recent years, especially in the United States, where environmental reasons are now scarcely mentioned in the debate on ethanol. For developing countries there may also be agricultural and energy supply considerations favoring the promotion of biofuels.

The greatest barrier to widespread use of biofuels, especially biodiesel, is the higher cost of fuel production. Biofuels can be significantly more costly to manufacture than hydrocarbon-based fuels and biodiesel is currently much more expensive to manufacture than ethanol. Ethanol and biodiesel alike have required substantial explicit and implicit subsidies in all countries that have promoted them in order to

FAQ 4

Biofuels are renewable and hence should surely form an important component of sustainable transport, so shouldn't all governments actively promote biofuels?

Biofuels such as ethanol and biodiesel are actively promoted in North America and the EU. The EU has in fact set time-bound targets for increasing the use of biofuels in transportation. The European Commission acknowledges that biofuels will offer little emission advantage over gasoline and diesel in the future given the extremely stringent emission standards that will come into effect in the coming years, and that biodiesel costs two to three times as much to produce as petroleum-derived diesel (European Commission 2001). The largest European environmental citizens' organization, the European Environmental Bureau, has issued statements rejecting the promotion of biofuels derived from conventional agricultural crops on the grounds that there are much cheaper options for reducing greenhouse gas emissions, and that intensive cultivation of agricultural crops can worsen ecosystem health and reduce biodiversity (Jonk 2002).

For developing countries, biofuels offer greater emission reduction advantages than in industrial countries. That said, most developing countries embarking on biofuel projects will need to provide considerable financial assistance to make biofuels competitive with conventional fuels and even other alternative fuels. Under what circumstances would it make sense for developing countries to promote biofuels?

- **Is the cost of procuring petroleum products high?** Landlocked countries, or remote parts of large countries, with no sources of petroleum products nearby are probably already paying very high prices for gasoline and diesel fuel. High landed costs of gasoline and diesel can therefore help to offset the relatively high production costs of biofuels, making the latter more competitive. Conversely, countries with easy access to competitive international oil markets, and with relatively well-established internal distribution lines, will find it more difficult to promote biofuels from an economic perspective.
- **Are suitable biofuel feedstocks available in sufficient quantities that can be collected and transported to a processing plant at reasonable cost?** The conditions for biofuel promotion are obviously much more favorable if there are already surplus crops or products (such as molasses) that are suitable feedstocks for biofuel production, than if land must be cleared and planted with new energy crops. The issue is whether the surplus crops or products are concentrated within a small radius so that they can be collected in sufficient quantity and transported to a processing plant at reasonable cost.
- **Are taxes on petroleum fuels sufficiently high to allow partial or full tax exemption to make biofuels competitive?** The reason Germany is able to provide a considerable tax benefit to biodiesel is that petroleum diesel carries a very high tax rate. Assuming the cost of biofuel production is higher than the landed costs of petroleum fuels, tax exemption—an implicit subsidy—is typically the first line of approach for government assistance.
- **If considerable subsidies are needed, what is the objective of the biofuel program?** While biofuels have been marketed for decades, no country to date has been able to sustain a biofuel program without considerable implicit and explicit subsidies. An examination of production cost structures suggests that without significant changes in feedstock and technologies, there will not be dramatic cost reductions for biofuels in the foreseeable future. Therefore, if subsidies are needed today, they are likely to be required over the long term, and governments are likely to ask about the alternative uses of subsidies earmarked for biofuels. If the aim is primarily to reduce exhaust emissions, and the tax exemption granted is on the order of US$0.10–0.15 per liter as in Brazil and the United States for ethanol, the cost-effectiveness of this approach is likely to be low. Greenhouse gas emission reduction may also become an important driver of biomass in general and biofuels in particular. However, many argue that there are many cheaper options for greenhouse gas reduction even within the transport sector, let alone in other sectors. If job creation in rural communities is the goal, then the subsidies should be compared with other government-supported job creation schemes such as public works, or investments in infrastructure, education, and improvement of the business environment.

In the absence of large government subsidies (explicit and implicit), the key to a successful biofuel program is currently where there are surplus feedstocks, especially "waste streams" from industry or agricultural processing, and in countries where conventional liquid fuels are expensive. In the longer term, technological breakthroughs, such as in the conversion of cellulosic materials to ethanol, may greatly expand the opportunities around the world for producing cost-competitive ethanol.

make them competitive with petroleum gasoline and diesel. U.S. Treasury figures show that the revenue loss from the partial exemption from the excise tax for ethanol between fiscal year 1980 and fiscal year 2000 is estimated to amount to $11 billion, adjusted to 2000 US$ (U.S. GAO 2000). To date, the policy of the government of Brazil is to tax ethanol much less than gasoline, with the difference between gasoline and hydrous ethanol amounting to R$0.52 (about US$0.18) per liter as of late 2003 (USDA 2003). The government of Germany exempts biodiesel fully from the mineral oil tax levied on diesel of €0.47 (about US$0.57) per liter. The fiscal incentives provided to biofuels by industrial countries need to be seen in the light of the large subsidies provided to their agricultural sectors. The EU's outlays on agriculture grew to a peak of €41 billion in 1996, excluding government spending on agriculture by individual member countries. Grains, oilseeds, and protein crops account for almost half of the EU's agricultural expenditures (USDA 2002). In the United States, US$34.5 billion was paid in subsidies to corn growers between 1995 and 2002 (EWG 2003).

The main current exception to this high cost pattern is that of ethanol manufactured from sugarcane in Brazil, the world's lowest-cost biofuel producer. Some industry analysts believe that the Center-South region of Brazil can manufacture ethanol from sugarcane for as low as US$0.15 per liter (USDA 2003). It is possible that this cost might be replicable in other sugarcane-producing countries if markets grew. However, this low cost of production arises partly because capital costs form a small fraction of the total production cost due to the fact that many ethanol plants in Brazil are nearing the end of their lifecycle, and that a considerable amount of initial investment financing was subsidized by the government. The replicability of the quoted low costs for unsubsidized new producers is thus in question. The greatest promise for dramatic cost reduction lies in ethanol production from cellulosic materials on which there is much ongoing research. On balance, however, ***given current technologies and established production cost structures, biofuels are unlikely to be cost-effective in combating urban air pollution in the near to medium term.***

Electric propulsion

Electric vehicles are the least polluting at the point of operation. They also have the advantage that they allow the recovery of some energy during braking. For public transport vehicles, direct collection of current by trams or trolleybuses is well established, with the limitations being the inflexibility of routes and the typically higher overall expense compared with diesel propulsion. Electric trains or trolleybuses are therefore most likely to be cost-effective for fixed-route public transport operations on high-volume routes.

For private automobiles, whose flexibility requirements preclude the use of an external current, the future of electricity as a source of propulsion would appear to be most promising with hybrid technology rather than with battery-electric vehicles. Hybrid vehicles have much higher fuel economy and lower emissions than vehicles running on liquid fuels alone and have overcome one of the biggest drawbacks to battery-electric vehicles—vehicle range and "refueling." It may also be attractive to use hybrid technology in dedicated downtown shuttles and taxis operating in sensitive areas. ***The development of cost-effective hybrids appears to be the most promising way of mobilizing the emission reduction advantages of electric propulsion.***

Vehicle Technology

Historically, North America, Europe, and Japan have led the world in pursuing the best available technology for further reducing emissions from new vehicles. This has been achieved largely through regulations requiring vehicle manufacturers to meet extremely low emission standards—so low that exhaust measurements are actually becoming difficult—and the use of fuels to match state-of-the-art vehicle technology. A critical question for developing countries is how quickly, and at what price, cleaner vehicle technologies can be transferred to them.

Vehicle emission control technologies

Vehicle emission standards are the primary technical policy instrument for controlling emissions from vehicles in use. For gasoline vehicles, on which the use and maintenance of catalytic converters can dramatically reduce emissions of NO_x, CO, and hydrocarbons, ***the imposition and enforcement of standards have proven a very effective environmental policy in many countries.***

Many developing countries import vehicles that are already equipped with three-way catalytic converters. Once lead is removed from gasoline, the major impediment to their use disappears. In some countries, rampant adulteration of gasoline with materials such as kerosene and poor vehicle maintenance results in frequent engine misfiring and can seriously undermine the effectiveness of catalytic converters. ***After lead elimination, governments should develop a strategy of tightening emission standards for in-use gasoline vehicles so as to force more effective utilization and maintenance of catalytic converters.***

Aside from catalytic converters, proven control technologies for gasoline vehicles include positive crankcase ventilation (recycling back exhaust gases that escape past the piston rings into the crankcase), canisters for controlling evaporative emissions, electronic ignition, computerized ignition, and fuel injection. Hydrocarbon losses during refueling can be controlled by returning vapor from the vehicle to the service station tank, by using a large carbon canister on the vehicle that traps the fuel vapors, or by adopting both measures. On-board diagnostic (OBD) systems that monitor emission control components are also beginning to be well established. Proven control technologies for diesel vehicles include direct injection, various forms of turbocharging, high-pressure injection, electronic controls, cylinder design for high swirl, and exhaust gas recirculation (EGR). ***New technologies are capable of significantly reducing emissions per unit of fuel consumed.***

Sometimes there can be trade-offs between fuel economy and emissions reductions, depending on the technology options selected. One well-known example is the inability of conventional three-way catalytic converters, successful in gasoline-engine applications, to operate at high air-to-fuel ratios (referred to as "lean burn" and common in diesel engines). Lean burn technology increases fuel economy markedly. Three-way catalytic converters cannot work in lean burn conditions and require stoichiometric operation (the air-to-fuel ratio is set very close to the level that will give just enough oxygen for complete combustion of the fuel to CO_2, with residual products of incomplete combustion reducing NO_x to nitrogen). These converters are very effective at reducing CO, HC, and NO_x emissions, but at the expense of fuel economy.

A recent example of trade-offs between fuel economy and emissions for diesel engines is "cycle beating" in the United States. At the heart of this incident—whereby engine manufacturers were caught selling 1.3 million engines that were emitting NO_x at levels up to three times higher than allowed by the standards in place—was the trade-off between fuel economy and NO_x emissions. These engines had computer software that altered the engines' fuel injection timing, improving fuel economy at the expense of NO_x emissions.

In some cases, trade-offs are not inevitable. For example, if a move to Euro II emission standards is accompanied by a change to electronic fuel injection and turbocharging with air-to-air aftercooling, as in Europe and with the 1991 diesel standards in the United States, both exhaust emissions and fuel consumption can be lowered. If, however, the engine manufacturers achieve Euro II NO_x emission levels by retarding injection timing and keeping mechanical injection systems (as in some developing countries), there is a noticeable fuel economy penalty. ***Possible trade-offs between local pollutant emission rates and fuel economy should be borne in mind in considering alternative emission control technologies.***

There can also be trade-offs between different pollutant control measures. The most technically challenging trade-off facing engine and equipment manufacturers in industrial countries today is between NO_x and PM emissions control for diesel engines. NO_x is formed at high temperature in the presence of air, the same conditions that reduce PM emissions. As a result, it is difficult to reduce NO_x and PM emissions simultaneously using a single technical strategy. (For basic gasoline engine chemistry there is a trade-off between CO and NO_x, but this can easily be managed by use of a three-way catalyst.) Exhaust gas recirculation (EGR) lowers NO_x emissions by reducing the amount of oxygen supplied and lowering temperature during fuel combustion, but at the cost of increased particulate emissions. The combined use of particulate filters and EGR, selective catalytic reduction, or NO_x adsorbers will be used by a number of vehicle manufacturers to meet the tighter emission standards in the latter half of this decade in North America and Europe. However, many of these strategies to reduce both PM and NO_x result in decreased fuel economy.

Technologies that carry collateral environmental and financial benefits should be pursued as a first priority. For this reason, electronic fuel control is an obvious starting point for emissions improvements in all internal combustion engines (running on liquid as well as gaseous fuels), as it both improves fuel economy and reduces emissions, especially in higher speed operations. Although electronic fuel control requires more sophisticated maintenance, fuel cost savings may quickly pay back the investment in training maintenance technicians. ***Because of its emissions and fuel economy benefits, electronic fuel injection should be promoted for new vehicles.***

In order to ensure the sustainability of emission standards, industrial countries are increasingly requiring vehicle manufacturers to guarantee the durability of exhaust control systems. In the United States, for example, light-duty vehicles (LDVs), provided they are properly maintained, have to meet emission standards during the "useful life" of the vehicle (160,000 km or higher). Higher durability requirements exist for heavier vehicles. However, vehicle manufacturers will guarantee durability only if it can be reasonably demonstrated that the vehicle has been well maintained and not fueled with adulterated fuels. In part because maintenance and fuel adulteration problems are common, durability requirements for the performance of emissions control devices are rare in developing countries. ***Regulation of fuel quality and vehicle maintenance through enforcement of in-use emission standards can greatly facilitate the introduction of effective durability standards for vehicle emission systems.***

Standards for new vehicles

Because vehicle life in developing countries is often longer and the vehicle population growth rate higher than those in industrial countries, there is a strong argument for mandating clean standards for new vehicles. Several factors need to be taken into consideration when setting those standards. The most stringent of the standards to be implemented in the industrial countries (Euro IV and V for Europe and Tier 2 in the United States—see annexes 2 and 3 for more detail) require sophisticated vehicle technology and severely reformulated fuels. Because the magnitude of investments required can be substantial (for cost estimates of fuel reformulation, see box 2 on page 27 and annex 1), the ability to raise financing for the investment projects is often a limitation. Some countries continue to use lead in gasoline because their domestic refineries have been unable to raise financing for something as straightforward as lead elimination. In other countries, the inability of refineries to raise capital has led to long delays in refinery revamp projects and an increasing probability that the target dates for tighter fuel quality and emission standards will not be met. In addition to upfront refinery investments, vehicle purchasers have to cover the incremental cost of vehicles with new technology and there is also a need for adequate investment in vehicle maintenance to reap the corresponding benefits of improved vehicle technology and fuel quality.

Given the frequently high contribution of diesel vehicles to transport sector emissions, one option is to move directly to the most advanced diesel technologies being introduced in industrial countries. As discussed previously, this may merit serious consideration in some cities. The assessment of whether mandating diesel particulate filters is likely to be a sensible and effective policy option is discussed in Frequently Asked Question 5. This example highlights the use of passive catalyzed particulate filters, which are the most widely used type of filters and which do not require an external energy input (heat, oxygen, or fuel injection). Although this example is given in the context of setting standards for new vehicles, there are also successful experiences of retrofitting in-use modern heavy-duty diesel engine vehicles with particulate filters.

The considerations in Frequently Asked Question 5 suggest that large and professionally managed fleet operators in cities that have already moved to modern engines, such as electronic fuel injection, are most suited for filter technology. Industrial countries that are moving to adopt advanced exhaust control devices requiring ultralow sulfur fuels have undergone incremental tightening of standards. This has given fleet owners and mechanics in Europe, Japan, and North America a number of years to move from working with wrenches to computerized diagnosis of vehicles. When natural gas buses were first introduced in the United States, despite the sophisticated level of maintenance skills available, lack of familiarity of mechanics with natural gas bus technology was a major problem. In those developing countries where few established companies 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 limited capital, it will take time to acquire the necessary infrastructure. While there are quite a few cities that can adopt the filter technology effectively, and indeed some are already doing so, it is not self-evident that requiring state-of-the-art emissions technology in many other developing country cities for all new vehicles would be beneficial for the environment or cost-effective compared to other options. ***It is recommended that governments should, in consultation with vehicle users organizations, identify and enforce the most stringent standards for new vehicles that are affordable, sustainable, and consistent with maintenance capabilities, and ensure that fuel quality standards are harmonized with vehicle emission standards.***

Regulatory loopholes are a common problem. In one country with Euro II standards, vehicle manufacturers are allowed to put new vehicle bodies on old engines and chassis, some of which are imported, and these "new" vehicles do not have to meet the new vehicle emission standards. A problem for exhaust emissions as well as fuel economy in some developing countries is the import of large, previous-generation technology, private cars. ***Controls on vehicle imports should include those on old vehicles and close loopholes that can bypass stringent emission standards.***

Many of the advanced vehicle technologies, particularly for reducing NO_x emissions of heavy diesel vehicles, are still under development. For example, the debate on the use of NO_x traps (favored by the U.S. EPA) versus selective catalytic reduction (favored by the German federal environment authority, Umweltbundesamt) continues. There is a large fuel economy penalty associated with NO_x traps, but unlike selective catalytic reduction, their use does not require addition of urea, and the U.S. EPA is concerned about operators' failure to fill urea storage tanks. Selective catalytic reduction is more durable than NO_x traps, and enables higher fuel economy. Some argue that the concern about operators' failure to refill urea tanks can be overcome by electronic OBD systems for NO_x emissions (Global Refining & Fuels Report 2003).

It goes without saying that new emission control technologies need to be actually purchased and used if they are to help improve air quality. Estimating the impact of installing new emissions control devices on future vehicle purchase patterns is not always straightforward. If fleet operators perceive vehicles meeting new emission standards to be much more costly to purchase, operate, and maintain—for example, if they believe that new vehicles are less robust and reliable—then they may keep existing vehicles longer or pre-buy new vehicles ahead of the implementation of new emission standards or possibly do both. This illustrates the importance of giving adequate information to vehicle purchasers, providing fleet operators with prototype vehicles to test to build their confidence, and working closely with fleet operators in the early days of new vehicle use. There are often costs and technical problems associated with new technology. While costs may be confidently anticipated to fall substantially and technical problems overcome, ***developing countries for the most part are probably well advised to let the industrial countries bear the costs of that development, as well as the teething problems associated with early implementation.***

Many countries have no vehicle manufacture facilities and no emissions certification laboratories. For setting emission standards for new imported vehicles, it is important to take into account the countries of origin and the standards in these countries, including the driving cycles for certification. Making slight modifications that would require recertification

FAQ 5

When would it make sense to install passive catalyzed particulate filters?

Passive catalyzed particulate filters are capable of reducing particulate emissions to 0.01–0.02 g/kWh. Whether adopting them is a sensible step to take depends on a number of factors. For the program to be reasonably successful, the following conditions need to be met.

- **Is the supply of appropriate-quality diesel guaranteed?** Diesel fuel with consistently ultralow sulfur, below 50 wt ppm and preferably close to 10–15 wt ppm, is the primary requirement.
- **Is the duty cycle suitable for filter regeneration?** Particulate filter regeneration requires a certain minimum exhaust gas temperature at the inlet of the filter, typically around 300°C for 20–40 percent of the duty cycle. This is what makes filter operation in light-duty diesel engines more difficult because the exhaust gas temperature tends to be lower. Vehicles, even buses, operating in very congested traffic with frequent stops and starts may encounter problems reaching this minimum temperature and hence in filter regeneration. Some diesel engines also operate at lower exhaust temperature than others. The location of the filter on the vehicle can also affect performance. In general, the filter should be located as close to the engine's exhaust manifold or turbocharger outlet as possible in order to minimize heat and temperature loss between the engine and the filter. If filters must be located far away from the engine due to space constraints, highly efficient insulation may be required on the exhaust piping between the engine and filter, especially in areas that experience low ambient temperatures for part or all of the year.
- **Is there a mechanism in place to allow only reputable manufacturers with proven technology to supply filters and their replacements?** Particulate filter standards must be established together with enforcement and a particulate filter certification process. Filter retrofits should be carried out only by authorized, trained, and equipped workshops that are capable of diagnosing and repairing previous engine conditions.
- **How clean is the base engine technology?** The higher the level of engine-out emissions, the larger the filter must be in order to operate successfully. Some engines are too "dirty" for practical application of a particulate filter. In the United States, there has been little success in applying catalyzed particulate filters to pre-1993 engines with certified emissions levels in excess of 0.13–0.2 g/kWh when these vehicles operate in slow-speed urban duty cycles. If currently operating vehicles are considered for retrofits, particulate filters should not be considered in mechanically governed engines, or engines in a bad state of repair. For these vehicles, retrofitting with more modern engines, even without particulate filters, can be very effective in reducing emissions.
- **Is there a culture of proactive engine maintenance?** In diesel engines, many engine problems result in increased black smoke from the exhaust. While in many cases the engine will still operate, a proactive maintenance culture would use the black smoke as a signal that engine maintenance was required and the engine would be repaired. Particulate filters mask engine problems because the black smoke that might otherwise have indicated the problem is removed. This excess smoke can result in clogging of the filter. This means that more sophisticated diagnostic techniques need to be employed. In particular, when using particulate filters, the exhaust back pres-

(continued)

would add little value to environmental improvement while increasing the costs of vehicle supply and enforcement of standards.

It is also important to note that driving cycles have a significant impact on exhaust emissions. EU emission standards and U.S. emission standards are not directly comparable because different driving cycles are used to certify vehicles. Reference fuels used to certify vehicles can also differ from country to country. Unfortunately, there are few direct comparisons linking different engines, fuels, and test cycles.

Motorcycles are the most widely owned motor vehicles in many developing countries, especially in Asia. While four-stroke engine motorcycles can be approximately 15 percent more expensive than their two-stroke equivalents, they have much better fuel economy. Especially for high annual km vehicles such as commercial motorcycles and three-wheel taxis, vehicle owners may recover the extra costs over a relatively short period. Despite this, many individuals still prefer to own two-stroke motorcycles or three-wheel taxis because they are easier to keep on the road with self-maintenance. This is a classic case of a conflict between the private interests of vehicle owners and the public interest of controlling vehicular emissions. Because of the narrow and falling cost dif-

FAQ 5

When would it make sense to install passive catalyzed particulate filters? *(continued)*

sure should be continuously monitored and checked, and remedial action taken immediately if there are signs of the back pressure building up.

- **Are there suitably trained mechanics and appropriate equipment to deal with mechanical problems?** If maintenance and repair personnel are not well versed in dealing with computer diagnostics and electronic fuel injection, and equipped with appropriate diagnosis and repair tools, filter operation may present a major challenge. A good and adequately funded maintenance program is a precondition for successful filter operation. Such a requirement is not specific to particulate filters or even to advanced diesel engine and exhaust control technology in general, but applies equally to "very clean" gasoline engines or CNG engines.
- **Will fleet operators be able to recover the incremental cost?** If bus fares are controlled by the government and difficult to raise, moving to more expensive technology and fuel could pose financial problems for fleet operators.
- **Will vehicles for which filters are mandatory have to compete in the market with vehicles that are exempt from this requirement?** Other things being equal, operators that have to install filters will be carrying higher operating costs, making them less competitive if there are differential regulations for different fleets. Careful consideration may have to be given to pricing and taxation policies if the move to cleaner technology reduces the (often limited) profit margin for some and not for others, or else vehicle owners will resist particulate filters (or any other technology for reducing emissions).

Because of the above requirements, moving to particulate filter technology will have higher chances of success with large fleet operators than small operators owning only one or two vehicles. Whether particulate filters will bring marked relief from urban air pollution depends on several factors.

- **What are the current particulate emission standards?** If the standards are already at the equivalent of Euro II or the 1993 U.S. standards for new vehicles, then going down to 0.01–0.02 g/kWh for a large number of heavy-duty diesel vehicles may make a noticeable difference in air quality. If recent models and all in-use heavy-duty diesel vehicles are emitting close to 1 g/kWh or higher, then going down to 0.1 g/kWh—which is possible with sulfur diesel of 500 wt ppm and upgraded engine technology—may still achieve significant air quality improvement at much less cost.
- **Is the incremental cost likely to be of the magnitude that could slow down vehicle renewal markedly?** The incremental cost of going to vehicle technology that includes particulate filters may be substantial if fleet operators are spending very little on vehicle maintenance and repair at present because vehicle technology is relatively simple, problems are easy to diagnose (because most vehicle parts are mechanically controlled), and repairs can be performed in-house without having to buy expensive parts—that is, if the predominant culture is self-diagnosis and self-repair. Under these circumstances, operators may "pre-buy" new vehicles before filters become mandatory, and keep old vehicles longer than they would have otherwise.

ferentials between the two- and four-stroke technologies, the high probability that poor maintenance will further accentuate the emissions of two-strokes, and the undisputedly high pollution caused by in-use two-strokes, the most effective pathway for addressing motorcycle emissions may be to move to four-stroke engine technology. Emerging technologies may enable two-stroke engine vehicles to meet very tight emission standards so that two-stroke engines are not inherently polluting, but the important policy question is what emission standards will be set for new two- and three-wheel vehicles. Standards that are very lenient and easily allow the continuing use of traditional two-stroke engines, or worse, differentiated standards that are more lenient for two-stroke than four-stroke engines, should be re-examined and tightened. ***Developing countries would be well advised to require suitably tight emission standards achievable by four-stroke engines for all except the very smallest (50 cubic centimeters) new motorcycles, and for all three-wheel motorized vehicles.***

Enforcing policy for in-use vehicles

Establishing fuel- and vehicle-emission standards is an important first step, but such standards need to be effectively enforced on vehicles in use. For controlling emissions from in-use vehicles by means of proper vehicle maintenance, a number of governments have introduced inspection and maintenance (I/M) programs (see annex 6). ***The underlying principle of inspection and maintenance programs is to identify vehicles that are not in compliance with emission standards and to get them repaired or replaced.***

Where vehicles grossly exceed emission standards and where it may not be cost-effective to repair vehicles to bring the emissions down to the maximum levels allowed, incentives may be offered to secure the immediate withdrawal of such vehicles from operation. Three main types of incentive have been used to try to improve the average quality of vehicle fleets: (1) incentives to scrap without replacement *(cash for scrappage)*; (2) incentives to replace with new, or less polluting, vehicles *(cash for replacement)*; and (3) other fiscal and administrative devices that, although not offering direct financial incentives to scrap, operate through their impact on the scrapping decision *(indirect scrappage incentives).* The design of scrappage schemes is discussed in the next section. They are not easy to implement. However, ***if carefully designed to ensure cost-effectiveness, vehicle replacement schemes can be effective in reducing emissions from in-use vehicles.***

The success of emission standards for in-use vehicles in industrial countries has been based on the setting of realistic standards and wide acceptance of the need to comply. Vehicle fleets in many developing countries, in contrast, consist predominantly of older, earlier-generation vehicles with correspondingly high emissions. Lack of regular preventive maintenance and proper tuning increases emission levels further. 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 three-fold. A plugged air filter can increase particulate and CO emissions in both gasoline and diesel engines. Turbochargers and injectors in diesel trucks that are not replaced when they should be because these replacements are costly for the owner increase emissions. Old, poorly maintained vehicles may have leakage past rings and crankcase vents open to the atmosphere, increasing crankcase emissions. ***These considerations show the vital importance to air quality of improved maintenance practices and operation of in-service vehicles.***

High costs of compliance raise a collateral problem in the case of emission standards for in-use vehicles. Setting standards that are almost sure to result in high rates of noncompliance is bound to lead to evasion, corruption, "false passes" in inspections, and the public perception of environmental regulations as fundamentally flawed. A more effective policy might be to set relatively lenient, but rigorously enforced, standards (perhaps expecting a "real" failure rate of about 20 percent). Standards could then be tightened progressively over time. This has been the approach adopted in Mexico City. For this approach, it is necessary to sample vehicles and measure emissions to obtain a distribution profile of emissions before finalizing the emission standards. ***It is advisable to set emission standards for in-use vehicles that are achievable, with some effort, by a majority of vehicles, but that effectively eliminate the worst polluters.***

Emission standards for in-use vehicles can be enforced only if emission levels are accurately measured, gross polluters are correctly identified, and the vehicles found to be in violation are properly repaired to lower emissions. I/M programs in developing countries must meet these key requirements for successful implementation (for more detail, see annex 7):

A vehicle emissions inspection system using centralized, high-volume, test-only centers operated by private sector firms, as shown here in Mexico City, can be effective.

- 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 a common approach for tackling this problem. ***An accurate vehicle registration system can help ensure that target gross-polluting vehicles are made to show up at test centers.***
- The emissions inspection system must be credible. If gross polluters pass the test because their measured emission levels are low, and if clean vehicles fail because they are falsely identified as gross polluters, then the credibility of the system is called into question and public acceptance falls. Avoiding this situation requires choosing a test protocol that is difficult to cheat on or to bypass, and implementing rigorous audit and supervision schemes. It also requires well-trained technical staff and proper equipment. The lack of proper equipment maintenance, inadequate calibration, and unsuitable test procedures are three common problems leading to inaccurate measurements. Tampering with test results by I/M staff for financial gain is another common problem. Independent auditing of established test procedures is required. ***Emission levels need to be accurately measured, and vehicle testing procedures devised to discourage temporary, "pass-the-test" adjustment of engine settings.***
- There must be proper follow-up once gross polluters are correctly identified. This requires adequate infrastructure for vehicle servicing including good diagnostic equipment and qualified technicians. In the absence of effective enforcement of emission standards, the market for service and repair facilities is typically limited, focusing on the vehicle's drivability but not that it be repaired to be less polluting. Under these circumstances, 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. ***Identified gross polluters need to be repaired or scrapped.***

Probably the most extensive experience in developing an effective I/M program in a developing country is that of Mexico City (see annex 7). Many of the lessons learned in the evolution of I/M in Mexico City, particularly in respect to the use of centralized, high-volume, test-only centers operating in the hands of the private sector and market incentives to secure effective testing, are applicable to other developing country cities (Kojima and Bacon 2001b). It is noteworthy that in Mexico City in January 1996, despite the political implications, licenses were withdrawn from all the 600 decentralized test-and-repair garages against the backdrop of an estimated 50 percent of approval certificates being falsely obtained and increasing public opinion of the emissions control program as being fundamentally fraudulent.

For a privatized I/M system to be effective, the following conditions have to be met:

- 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. This includes remote-auditing and developing centralized software that controls not only data entry, storage, real-time transmission of the captured data to a central database, and analysis, but also equipment calibration, zero-referencing, test protocols, and digital signature and printing of the certificate.
- An up-to-date and reliable vehicle registration system needs to be in place, with retirement of old vehicles accurately reflected.
- The legal framework must include sanctions for failure to carry out the testing protocols correctly.
- Testing stations must be subject to monitoring by independent bodies. All testing centers must be subject to equally rigorous implementation of protocols and inspection of their procedures.

- Testing protocols should enable reproducible results to be obtained across different test centers with a large numbers of operators and instruments (possibly of different makes), produce accurate and meaningful results, and minimize the chances that individual testers will give false passes.
- 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 performance for regular driving.
- Display of the test certificate on vehicles must be efficiently monitored.
- The fine for not displaying or not having a legal emissions test certificate must be sufficiently high to act as an incentive to pass the test.
- The number of test centers has to be limited to ensure that operators of licensed centers can obtain a reasonable living without reducing the rigor of their tests to attract customers.

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. 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.***

Two-stroke engine lubricants

Lubricants for two-stroke engines have a significant impact on emissions because lubricants are introduced directly along with the intake air-fuel mixture. Of special concern are the quality and quantity of lubricant added to two- and three-wheel vehicles with two-stroke engines, which are numerous in Asia (see annex 5). While both can be regulated, and premixed fuel supplied, enforcement of quality at the pump has historically been difficult to achieve. ***Poor lubricant quality and addition of excess lubricant remain the two main causes of high particulate emissions from two-stroke engine gasoline vehicles.***

The first step is to promote use of the proper lubricant: that is, using only 2T oil (lubricants manufactured for use in two-stroke engine vehicles). The use of so-called straight mineral oil, intended for use only in stationary engines, leads to higher emissions. In one study testing three-wheelers commercially operated as taxis in Dhaka, Bangladesh, switching from straight mineral oil to regular 2T oil lowered mass particulate emissions (measured in grams per km) by more than 60 percent (annex 5, Kojima and others 2002).

The second step is to ensure that lubricant is used only in amounts recommended by vehicle manufacturers. The use of excess lubricant is often practiced in the mistaken belief that this will increase fuel economy and enhance engine life. Lowering the quantity of lubricant added from the commonly used 8 percent to 3 percent (the level recommended by the vehicle manufacturer) in the above Dhaka study lowered particulate emissions by another 60 percent. Although 2T oil is more expensive than straight mineral oil, reducing the quantity added to 3 percent actually saves money for the drivers. ***Campaigns to reduce emissions from two-stroke engines by improved lubrication can be inexpensive and cost-effective.***

Vehicle Replacement Strategies

Elimination of gross polluters can be an important instrument for reducing transport-generated air pollution because of their disproportionately high contributions to pollution. There is also likely to be the added advantage of improving road safety when old, polluting vehicles are removed, since they tend to be less mechanically safe. In practice, environmentally motivated scrappage schemes have not always been successful (World Bank 2002d).

Targeting gross polluters

Some vehicles visibly pollute more than others, but some pollute without showing visible signs. Even among the visible polluters, those that pollute the most cannot be determined by visual inspection alone. Moreover, the method for identifying gross polluters would need to be inexpensive and simple to carry out. As discussed in annex 7, identification of gross particulate emitters is extremely difficult except when tests are carried out in a sophisticated emissions laboratory.[2] ***Vehicle replacement strategies need to be carefully targeted at proven high polluters if they are to be cost-effective.***

In the absence of adequate infrastructure for measuring emissions, or simply to save costs, vehicle age is often used as a proxy for high emissions. However, mandatory scrappage based on vehicle age unnecessarily penalizes those vehicle owners who have taken good care of their vehicles. Age-based scrappage schemes are especially problematic if a given vehicle category has a large number of owners with different maintenance behaviors and driving patterns. Imposing a relatively low age limit—beyond which vehicles must be taken outside the city at a minimum or even scrapped altogether—may actually discourage the practice of regular vehicle maintenance. If, on the other hand, the level of vehicle maintenance, as well as accumulated kilometers, is fairly uniform across a given vehicle category—for example, if all large buses belong to one public sector bus company—then vehicle age is probably a good indicator of vehicle emission levels. Even then, if the vehicles have been run down and poorly maintained because the fleet operator is cash strapped as a result of mismanagement, fare controls, or undue restrictions placed on its operation by government regulations, these problems need to be addressed in parallel. One reasonable approach in countries that have been progressively tightening emission standards is to select age limits on the basis of when the emission standards for new vehicles were made more stringent. In this way, age limit decisions are based on the dominant forms of vehicle technology employed. ***The decision to impose an age limit, as well as the age to be selected, should take into account available data on emissions, vehicle ownership patterns, past history of emission standards for new vehicles, and the financial state of fleet operators where fleets are involved.***

[2]The sum of the cost of identification and the market value of the vehicle being scrapped or the repair cost should not exceed the environmental benefit of removing or repairing the vehicle. While the environmental benefits are difficult to calculate precisely, a scrappage program in which the cost of identifying participating vehicles exceeds their market values, for example, is unlikely to be acceptable to policymakers or the general public.

Choosing a strategy: repair or scrap?

After gross polluters have been identified, the next question is whether they should be repaired or scrapped. A simple rule can be applied here: ***If the cost of repairing a vehicle to reduce emissions to a reasonably low level exceeds the market value of the vehicle, then the vehicle should be scrapped.***

If the decision is to repair, retrofitting with more recent technology engines and parts, rather than simply repairing to the original vehicle specifications, could be an effective strategy. Retrofitting buses undergoing engine overhaul in a municipal bus fleet with much cleaner modern engines could provide a good opportunity for retrofit. An example is the Urban Bus Retrofit/Rebuilt Program in the United States, which targets buses in major cities for retrofitting with a combination of modern engines and exhaust-treatment systems (certified to reduce particulate emissions) at the time of engine rebuild (U.S. EPA 1999b), although these urban bus retrofits are quite expensive. However, less expensive versions could be considered: for example, an engine that is naturally aspirated may be replaced with a similar turbocharged block which has far lower particulate emissions at the same power output. Incentives for retrofitting vehicles with catalytic converters have been offered in Germany and Hungary for many years. It is also necessary to ensure the efficacy and sustainability of the proposed retrofit. For example, retrofitting catalytic converters on very old gasoline two-stroke engine two- and three-wheelers may not be effective if "engine out" emission levels are high, significantly shortening the life of the converter. ***The standard to which vehicles should be repaired should be based on the cost-effectiveness of achieving different levels of emissions.***

Financial incentives may be used to encourage premature scrapping of vehicles for environmental reasons. These may be paid simply for the scrapping of a target vehicle or only if the target vehicle is replaced by a less polluting one. Either way, it is important to ensure that the vehicles are actually scrapped, and not sold elsewhere. The cost-effectiveness of vehicle scrappage or replacement incentive policies depends on a range of variables.[3] Other things being equal, benefit per dollar spent increases as the following variables increase:

- Emission levels of vehicles scrapped
- Cleanness of the replacement vehicles
- Number of replacement vehicles attracted per dollar
- Residual life of the vehicles scrapped
- Annual kilometers traveled of the vehicles replaced.

In practice these criteria are not independent of each other, and hence it is necessary to understand the complexity of the vehicle and service supply markets in order to ensure the cost-effectiveness of a scrappage scheme. ***It will usually be sensible to concentrate incentive schemes on high-usage, high-emission urban vehicles that still have a significant economic life in the absence of the incentive.***

Incentive schemes: the importance of the vehicle market structure

The effect of any incentive scheme, whether it be to scrap or to replace, depends crucially on the vehicle market structure. Vehicles are owned and operated by individuals (in the case of motorcycles and cars) and commercial operators, and both are largely motivated by financial costs and benefits. Their response to financial incentives affects the entire vehicle market, and not just those who participate directly in scrappage or replacement schemes. Even where a scrappage grant is not in cash (for example, in Canada, one option offered was a free family public transport pass), experience throughout the world has shown that most owners choose to replace their scrapped vehicles. ***An important question is whether the scrapped vehicle is replaced with another vehicle, and, if so, what effect this process has on vehicle usage and the vehicle stock.***

For car and motorcycle replacement, the market appears to be segregated into two categories. People in the first category, higher income or users of cars for business, tend to replace existing vehicles with new vehicles every few years. Individuals in the second category, purchasers of second vehicles or lower-income households, normally buy used vehicles and replace them with younger, but still used vehicles. Even the bus and truck markets are often effectively segregated into large fleet operators at the top end of the market, using newer vehicles, and smaller operators supplying that part of the market demanding lower quality of service with older, secondhand vehicles. For example, the bus industry in Bangkok is segmented by vehicle quality: private sector subcontractors to the publicly owned Bangkok Mass Transit Authority (BMTA) supply basic, low-fare, service with old, often very polluting vehicles sold to them by BMTA. Only a relatively small proportion of vehicle operators replace old vehicles directly with new ones. ***Efficient design of scrappage incentive schemes depends on understanding how vehicle replacement decisions are taken by vehicle owners.***

Cash for scrappage

In cash-for-scrappage schemes, the size of the incentive is an important variable. The larger the bonus, the more vehicles that are likely to be scrapped. However, if the oldest and most-polluting vehicles are the first to respond, there will be diminishing returns from an environmental perspective as the scrappage bonus increases. A U.S. study (Hahn 1995), based on a pilot

[3] The total cost of a scheme is the unit cost per vehicle (C) multiplied by the number of vehicles scrapped (N). The environmental benefit is the difference between the product of the emission rates per km traveled (ER) and the number of vehicle km traveled (VKT) within a given time period for the old vehicles and for their replacements, multiplied by the number of vehicles replaced and the length of period over which benefits continue (L). A cost-efficiency indicator can thus be simply written as:

$$\frac{C \cdot N}{(ER_{old} \cdot VKT_{old} - ER_{rep} \cdot VKT_{rep}) \cdot L \cdot N}$$

A more sophisticated indicator would discount benefits and costs appearing at different points in time to a common base date. But the fundamental logic is unchanged, and this indicator can be used not only for comparing alternative scrappage schemes but also for comparing public expenditures on scrappage schemes with expenditures on other ways of obtaining equivalent environmental benefits. In principle the distance driven may not be the same for the old and replacement vehicles: replacements may be more comfortable and consume less fuel than the originals and hence attract greater use. But the empirical evidence is that this effect is likely to be very small.

scrappage study in Delaware, concluded that a scheme with a very low incentive by U.S. standards (US$250) would likely be cost-effective, while those with higher bonuses to encourage higher take-up rates would not. The cost-effectiveness of vehicle scrappage schemes may also fall sharply as the average environmental quality of vehicles improves. ***Scrappage-without-replacement schemes can be effective for private cars, but typically only if carried out on a relatively small scale and if the vehicles to be scrapped are carefully selected.***

The number of vehicles scrapped is not necessarily a good criterion for success. A scheme implemented in Norway in 1996 gave a bonus of the equivalent of US$880 (1997) for the scrapping of any vehicle over 10 years of age and the program secured a net increase of 150,000 vehicles (above the number that would have been scrapped without the scheme). The scheme, however, did not impose any limits on the replacement vehicle, many of which were also relatively old and polluting (ECMT 1999).[4] ***Scrappage schemes must be carefully designed and coordinated with other public policies affecting the vehicle market.***

Cash for replacement

Cash replacement schemes for scrapped vehicles often insist that a new vehicle be bought, since new vehicles embody cleaner technology and the cleaner technology is likely to be longer-lasting. However, attempts to force replacement by a new vehicle tend to be attractive to those who are replacing relatively young vehicles, such as high-income households and users of cars for business. Experience in Denmark, France, and Italy shows that only 10 percent of annual replacements involve replacing a car more than 10 years old by a new one. A scheme in Hungary that targeted old, highly polluting, two-stroke engine models and required replacement by a new model failed to attract many participants. ***It will normally require a very large inducement indeed to bring about the direct replacement of a significant number of very old vehicles with new ones.***

[4]Aside from reduced environmental benefits, an ex-post analysis of the program showed a poor benefit-to-cost ratio of 0.5.

Cash-for-replacement schemes may attract a higher take-up rate if replacement by secondhand vehicles also qualifies. But this has environmental benefits only if the emissions of the replacement vehicles are tested and shown to be significantly lower than those of the vehicle being scrapped. In Greece the bonus was paid only if the replacement vehicle had a catalytic converter. Ideally, eligibility for a grant should be based on actual emissions of vehicles scrapped (and those replacing them if new vehicle purchase is not required). This approach, however, also creates a moral hazard in that owners might intentionally allow their vehicles to fall into disrepair in order to qualify. ***Cash-for-replacement schemes can miss the worst polluters or, if the worst polluters are replaced by only slightly less-polluting vehicles, can yield marginal emission reduction benefits.***

Despite these caveats, cash-for-replacement schemes can be successful if they target operators who normally keep their vehicles for the vehicles' whole lives, drive them regularly, and respond to economic signals and replace old vehicles (with deteriorating fuel economy and increasing maintenance costs) with newer, cleaner and more efficient vehicles. Large fleet operators of buses and trucks may be especially responsive for this reason. ***Scrappage-with-replacement schemes are most appropriate for large commercial fleets of heavy public transport and freight vehicles.***

Indirect incentives and supporting policies

A number of other measures can supplement or support scrappage programs.

The introduction and strict enforcement of environmental standards through an I/M program is essential. This approach encourages owners to keep their vehicles in good condition and to replace vehicles when it becomes increasingly expensive to meet the standards.

Tax incentives can help. For example, the German and Hungarian governments give tax advantages for the purchase of lower-pollution vehicles. A variation is a reduction in import duties for cleaner vehicles and engines. Nepal reduced import duties on component parts for electric minibuses to replace diesel equivalents that were banned in the Kathmandu Valley.

Public transport franchising policies can be very important, particularly where buses are a significant part of the problem. Both in Santiago and in Bogotá, environmental objectives have been incorporated in municipal public transport policies. Both schemes recognized the need to maintain affordable public transport service. Environmentally oriented vehicle replacement requirements were incorporated in a broader scheme that ensured the continued financial viability of the operating agencies. The Bogotá case (see International Experience 4) illustrates that forced scrappage of public transport vehicles can be effective in the context of well-regulated franchise systems, even if the emission standard of new vehicles is somewhat less than state-of-the-art.

In summary, the environmental benefits and costs of vehicle scrappage incentive schemes should be compared with other fiscal and administrative instruments. Hence, ***scrappage incentive schemes should be designed as part of a general strategy and supported, as necessary, by other administrative and fiscal interventions.***

INTERNATIONAL EXPERIENCE 4

Vehicle Replacement in Bogotá, Colombia, and Delhi, India

In preparing to implement TransMilenio, Bogotá's bus rapid transit system, the government of Bogotá took a series of measures that included the replacement of old buses by new. More specifically, the government:

- Required that operators bringing in new buses licensed to operate in TransMilenio demonstrate that the equivalent number of old buses were scrapped and their licenses canceled. For each new articulated bus operating in TransMilenio, 3.6 executive buses, 2.7 regular buses, 5.3 medium-size buses, or 10.7 microbuses had to be scrapped. The operators were required to produce a document certified by an international auditor proving that old buses had been scrapped.
- Suspended, in the early 1990s, registration of additional public transport vehicles for two and a half years (later extended to 31 December 2000, when TransMilenio became operational). However, the bus population continued to increase rapidly due to illegal entry.

In Delhi, India, some 60,000 commercial three-wheel auto-rickshaws have been replaced. This was achieved in two phases. The first phase involved the implementation of a Delhi Government program (which the Supreme Court intervened to expedite) to replace vehicles older than 15 years by new ones complying with the latest emission standards. Between July 1998 and March 2000, nearly 21,000 auto-rickshaws older than 15 years (constituting one-fourth of the auto-rickshaw population) were replaced with those meeting the Indian 1996 emission standards (the prevalent standards for new vehicles at that time). The second phase followed two Supreme Court mandates that called for: (1) the replacement of all pre-1990 auto-rickshaws and taxis with new vehicles on clean fuels, and (2) financial incentives for the replacement of all post-1990 auto-rickshaws and taxis with new vehicles on clean fuels. Although the court required financial incentives only for the second of its orders, the Delhi Government extended the package of incentives for the replacement of pre-1990 auto-rickshaws. Implementation of these orders started in May 2000, and more than 38,000 auto-rickshaws of pre-1991 vintage have been replaced with new ones powered by four-stroke CNG engines to date. In both cases, incentives combined with strong enforcement were employed.

Both phases of the Delhi program were successful because the vehicle owners saw a net benefit. In the first phase, the owners could get rid of very old vehicles and purchase new, superior products at an effectively discounted price. In the second phase, the higher initial cost of the replacement vehicle was offset by the lower fuel cost. Interestingly, in both phases, most owners preferred to scrap old auto-rickshaws even though they were given the option of selling them to buyers outside of Delhi.

Sources: World Bank 2002e, Iyer 2003.

CHAPTER 4

Reducing Fuel Consumption per Unit of Movement

Reduced fuel consumption per unit of movement can have direct benefits for reducing the emissions of harmful local pollutants such as fine particulates, and can also bring reductions in greenhouse gas (GHG) emissions.[1] The main exceptions to this occur when measures to improve fuel economy are made at the expense of increased emissions of local pollutants (see discussion of "lean burn" in chapter 3, Vehicle Technology) or by shifting from gasoline to diesel.

There are several ways in which fuel consumption can be reduced. One way is to increase the inherent fuel economy of individual vehicles. Another is to encourage vehicle operation that minimizes fuel consumption. A well-known approach is to smooth out traffic speed so that for the same distance traveled, much less fuel is used. Shifting the mode of transport, such as from motorized to nonmotorized transport or from private cars to public transport, can also reduce fuel consumption. Promoting or protecting nonmotorized transport should generally result in significantly reduced fuel consumption and should be supported for equity reasons in any case.

Improving Fuel Efficiency through Vehicle Technology

Vehicle technology options for improving fuel economy include increasing engine efficiency, decreasing vehicle weight, improving aerodynamics, and lowering rolling friction for tires. Fuel efficiency increases with increasing engine compression ratios. It also increases at a higher air-to-fuel ratio (lean burn), with precise injection timing, and anything else that increases the completeness of fuel combustion. ***Switching from mechanical to electronic fuel injection is one of the most important steps developing countries can take to improve fuel economy.***

Everything else remaining the same, lowering the vehicle weight (and hence decreasing the vehicle size) and power increases fuel economy. The principal reason fuel economy in the mainstream vehicle fleet in some industrial countries has not improved over the past two decades is that technological advances in energy efficiency have been overwhelmed by the trend towards increased power and speed of vehicles and the simultaneous shift to larger and heavier vehicles. In many developing countries, vehicle size and power are much smaller than in industrial countries, so that there is not much scope to reduce them further. Overall reductions in fuel consumption and emissions are possible in industrial countries and in developing countries in the future if motorists can be persuaded, and encouraged through fiscal policies, to accept reduced engine power and smaller vehicle size. Small vehicles must also be crashworthy, to ensure that there is not a serious trade-off between safety and fuel economy. ***Standards for new vehicles must be continuously reviewed and revised to take advantage of the technological potential to improve fuel economy and reduce air pollution.***

A shift from gasoline to diesel for fuel economy reasons can have potentially negative environmental effects. Diesel is an inherently more efficient fuel than gasoline, and worldwide, future demand growth for motor fuels is anticipated to favor diesel, while demand growth for gasoline is expected to stagnate. Unfortunately, conventional diesel engines produce much more particulate emissions in mass than do

[1] When looking at GHG emission reductions, the entire cycle from "well to wheel" should be examined since the consumption of fuel is only one component of the energy costs of a vehicle.

gasoline engines. This can be overcome by the use of advanced control technologies and ultralow sulfur fuel. At the present time, PM control technologies are still emerging for light-duty diesel vehicles, and with heavy-duty vehicles, a number of preconditions must be met for the control devices to be effective (see Frequently Asked Question 5 on pages 44 and 45). ***Careful consideration should be given to the likely impact on particulate emissions when deciding whether to encourage a shift from gasoline to conventional diesel for fuel economy reasons.***

Some governments have imposed fuel economy standards or negotiated them with the auto industry. The best-known case is the development of the corporate average fuel economy (CAFE) standards in the United States. Unfortunately, the CAFE standards have changed little since their inception in the 1970s, with improvements in technology permitting increased vehicle power rather than progressively reducing total fuel consumption and emission levels. Low fuel taxes have contributed to this trend. The lack of progress in U.S. fuel economy has been exacerbated by legislation that sets lower fuel economy and emission standards for light trucks—such as pick-up trucks, passenger vans, and sport utility vehicles (SUVs)—and by a large tax exemption on these vehicles for small businesses. As a result, the average fuel economy of all new vehicles in the United States peaked in the mid-1980s, and has declined since. The increasing fraction of light trucks in the total new vehicle sales, now exceeding 50 percent, has been the main cause. For light trucks with low fuel economy, there is no comparable "gas guzzler tax," a graduated tax on new passenger cars based on fuel economy. Some of the largest SUVs are in fact classified as heavy-duty trucks. There have been cases where vehicle manufacturers increased weight ratings of some popular pick-up models to avoid fuel economy standards, or redesigned them to avoid being classified as light trucks (Wells 2003). ***It is important to minimize opportunities for vehicle manufacturers to exploit loopholes or act in an opportunistic manner in an attempt to circumvent fuel economy and emission standards.***

In the EU, where fuel taxation is generally much higher, vehicle manufacturers entered voluntary agreements with the European Commission to reduce average CO_2 emissions from new passenger cars to 140 g/km by 2008 and to 120 g/km by 2012. The Commission confirmed at the end of 2002 that European manufacturers were on course to meet their target. However, by the end of 2003, available data indicated that European automotive manufacturers are unlikely to meet 2012 goals for CO_2 emission reductions. Monitoring figures showed that emissions increased from 164 g/km in 2001 to 165 g/km in 2002. As in the United States, this is primarily because of the trend towards larger and heavier vehicles with an emphasis on performance in terms of acceleration and top speed rather than fuel economy. The "performance race" of recent years lies at the heart of the problem. Manufacturers cited growing consumer demand for SUVs and higher vehicle weights associated with tighter safety standards as two primary reasons for this trend (Automotive Environment Analyst 2003a).

Among developing countries, the People's Republic of China is planning to phase in minimum fuel economy standards on new cars beginning in July 2005. The proposed standards are reportedly much more stringent than those in the United States (Automotive Environment Analyst 2003b).

Lastly, it is important to bear in mind that travel demand has a tendency to increase as a result of a technical improvement in energy efficiency, and this is known as the rebound effect. ***As with traffic management discussed below, it is important to offset this tendency for increased travel resulting from improved fuel economy by the simultaneous introduction of demand management instruments.***

Increasing Fuel Efficiency through Vehicle Operation

Poor vehicle maintenance and certain operational practices—such as overly retarded injection timing, not correctly inflating tires, or driving behavior characterized by sudden acceleration and deceleration—

lower fuel economy. Retarded injection timing increases fuel consumption under all circumstances. Low tire pressure increases vehicle rolling resistance causing higher engine power levels and increased fuel consumption by 5–10 percent, raising in parallel the emissions of NO_x and possibly particulate matter. Some studies have reported fuel consumption differences of as much as 15 percent. Driver behavior also affects fuel economy: minimizing unnecessary braking, observing the speed limit, and avoiding excessively rapid acceleration can improve fuel economy by a few percent over normal driving behavior. It is possible to increase fuel economy by another few percent via optimal vehicle maintenance. Poorly maintained roads make it difficult for drivers to maintain a steady speed and lower fuel economy markedly. Further, if roads are in very bad condition, there may be an incentive for larger four-wheel drive vehicles or SUVs, even in situations where a small car might otherwise do. Overloading, a common practice in many developing countries, accelerates damage to roads. ***Proper vehicle and road maintenance as well as proper vehicle operation can improve fuel economy significantly.***

In countries where transportation fuels are cheap, as in Turkmenistan or Venezuela, a recent report by the U.S. Congressional Budget Office on instruments for improved fuel economy may be informative. Examining three different approaches to decreasing fuel consumption by 10 percent, the report indicated that the cheapest and most effective path would be a substantial increase in the fuel tax. Simply raising the CAFE standard would be the most costly to consumers, adding an average US$153 to the cost of a new vehicle. Raising gasoline taxes would not only cost less than the other two approaches considered (both of which involved raising CAFE standards), but it would start reducing consumption immediately, and the market effect would gradually drive the transition to more fuel-efficient vehicles (Automotive Environment Analyst 2004). ***Raising fuel prices to reflect the real cost to the economy is an important consideration in stimulating fuel economy as well as in reducing non-essential trips, especially in developing countries.***

Encouraging Nonmotorized Transport

Traffic mix is an important determinant of emission levels for two reasons. First, because most emissions from motorized vehicles are highest at cold start of the engine, short trips are disproportionately polluting. These are the trips that are most suitable for nonmotorized transport (NMT). Unfortunately, in many developing country cities, walking or using other nonmotorized forms of transport is so inconvenient and dangerous that even very short motorized trips are common. Eliminating impediments to NMT by providing adequate sidewalks and bicycle lanes and ensuring the safety of pedestrians and cyclists can deter the use of the most polluting motorized vehicles for short trips. An equally important, or an even more important, consideration is that segregated lanes for bicyclists and pedestrians can enhance public safety and help to reduce the number of deaths and injuries markedly—every year more than 1 million die in road accidents worldwide, over four-fifths in developing countries, and as many as 50 million are injured (The Economist 2004). ***Provision for safe and comfortable walking and other forms of nonmotorized transport should be an integral part of an urban air quality strategy.***

Second, traffic mix has a substantial impact on variability of traffic speed. This is a serious problem where motorized and nonmotorized traffic share road space. Measures to segregate these types of traffic on main thoroughfares are thus as important for environmental as for safety and efficiency reasons. For example, in Dhaka, the presence of a large number of cycle rickshaws has historically made the operation of bus transport very difficult. In contrast, in residential areas it may be better to use traffic-calming measures to harmonize speeds of different traffic categories at a safe level. Traffic calming also has the indirect effect of deterring traffic from using residential roads as a short cut. ***Careful differentiation of traffic segregation policies by type of road can reduce environmental impacts and accidents while increasing average speed for all traffic.***[2]

[2]See the various reports of the U.K. Standing Advisory Committee for Trunk Road Assessment.

Segregating bicyclists from the rest of traffic, as this road in Beijing does, promotes nonmotorized transport, protects bicyclists' safety, and helps to keep traffic speed higher than when motorized and nonmotorized traffic are mixed.

Bicycles can account for as much as 50 percent of total movements in some low-income countries in Africa and in many Asian cities. Despite this, the bicycle tends either to be neglected or is actively discriminated against. This is partly because the bicycle is considered by government to be associated with poverty, and hence to be a mode that will disappear as incomes increase. In China, bicycles are viewed by government as a barrier to modern road transport and are consequently being banned from roadways in many cities. Often this is being done without a consequent provision of alternative space for bicycles, or without adequate consideration to mobility decisions of displaced bicyclists. In Vietnam, it is striking how quickly bicycles are being replaced by (predominantly four-stroke) motorcycles as incomes rise in the major cities, and consequently how high is the level of individual mobility in those cities. ***There is a danger that the motorcycle is the first step in the direction of reliance on the private automobile, which would not be sustainable given the density of the central cities.***

The appropriate policy response, now being adopted in a number of industrial countries, is to view the bicycle as an environmentally friendly mode for shorter trips and to plan positively to make it attractive. Some of the earlier initiatives to re-establish the bicycle through provision of sections of bicycle track, as in Lima, Peru, have had limited success. There are many components to making a bicycle promotion program work, including segregated infrastructure, provision for modal integration with public transport, promotion (particularly through safety and security campaigns), and other incentives. The message, exemplified by long experience in the Netherlands and by the increased bicycle use that has more recently been achieved in Bogotá, is that ***a comprehensive package of measures, including extensive connectivity in the bicycle network, is necessary in order to make the bicycle attractive and sustainable as incomes rise.***

Traffic management

This report distinguishes between traffic management, which consists of supply-side measures to improve performance of roads with existing traffic volumes, and demand management, which consists of measures to improve performance by reducing traffic volumes (World Bank 2002b). The former is discussed in this chapter and the latter in the next chapter. Both may require some physical measures, usually referred to as "traffic engineering." The engineering involved in traffic management tends to have a short gestation period and low cost. Traffic management has the potential to achieve reductions in air pollution and to be affordable, even by poor countries.

The objectives of traffic management

The adverse impact of local air pollution is highly location-specific and, to a lesser extent, time-specific. It is greatest where most people are exposed and where emissions lead to high ambient concentrations (on account of high emission intensity and low dispersion of pollutants). A high level of exposure is thus the product of a series of decisions or circumstances that determine the number of trips made, their distribution over space and time, the choice of routes, the driving characteristics of drivers, and where people spend time. Traffic management in industrial countries has been estimated to reduce emissions by 2–5 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 developing country cities.***

Both fuel consumption and exhaust emissions vary significantly with variability of vehicle speed. Traffic management can, in principle, reduce fuel consumption and exhaust emissions by making traffic flow more smoothly. Other things remaining the same, it would therefore be desirable to manage traffic to secure uninterrupted movement at free-flow speed. A steady speed is also the key to reducing the emissions of harmful pollutants per unit distance traveled. A number of devices, such as one-way street systems, linked traffic signal systems, and traffic control systems can contribute to smoothing traffic flow. ***From an environmental point of view, the most important features to address by traffic management are the variability of traffic speed and the location of major traffic flows, particularly congested flows.***

There is one major drawback. As average traffic speed increases so will trip lengths. Traffic management may induce more or longer trips to be made so that congestion is little relieved and total emissions may even increase. Detailed evidence of the traffic-generating effects of urban ring roads has been assembled in analysis of the M25 motorway around London. 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 ***the adverse effects of new traffic generated by improved traffic management be offset by the simultaneous introduction of demand management instruments to limit traffic growth and protect areas where exposure is greatest.***

Traffic signal systems

Traffic signal control systems are the most common traffic management instruments aiming to secure traffic flow objectives. However, their impact on air quality has been controversial. Some have argued that because they achieve their travel flow objectives by systematically bringing some traffic flows to a stop, they are likely to increase air pollution and should be replaced by roundabouts or fly-overs (OECD 1991). Others have challenged this claim, arguing that the impact of traffic signals on pollution is highly situation-specific.

Some conclusions on traffic signals are widely accepted, however. 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. The most efficient systems are area traffic control (ATC) systems, which link signals across whole networks. These systems can be made traffic-responsive on a real-time basis but are more expensive in terms of capital equipment (partly because of the need for more traffic-sensing equipment). However, in developing countries ATC has a history of contract failure, dispute, and procurement difficulties, as well as operational weaknesses. The Phase I ATC system in Bangkok, installed in 1996, still functioned imperfectly by 2000 because of a lack of sustained cooperation from the traffic police (Cracknell 2000). ***Effective use of traffic signal systems to improve air quality requires careful design and committed institutional coordination.***

Road system design

Ring roads and by-passes are not traffic-management strategies per se, but they are often advocated as the basis on which it is possible to introduce environmental traffic management. The argument is that if such roads provide adequate capacity to navigate across a town it will be possible to keep through-traffic out of environmentally sensitive areas. In some small or medium cities that have restricted vehicle access to central areas, this has worked well (Freiburg, Germany, is one example). But in many areas, it has not. There are two main reasons for this:

- Improved radial or ring road performance increases the number and length of trips made to such an extent that total traffic and total emissions actually increase. This is sometimes called the "rebound effect." Both average speeds and journey times may be increasing simultaneously.
- The supporting traffic management necessary to take advantage of the "breathing space" is not implemented. This has been a particular problem in Chinese cities such as Guangzhou and Shanghai.

This experience indicates that ***increasing infrastructure capacity will result in improved air quality only if embedded in a comprehensive urban transport strategy involving parallel restraint of vehicles and local environmental protection.***

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. CO and PM concentrations fall rapidly with increasing distance from these roads. Schools, hospitals, homes for the elderly, and shopping streets should therefore be located several hundred meters away from busy traffic corridors. For existing hot spots, traffic management can be used to minimize the impact of traffic on local air quality. ***New infrastructure should be designed to minimize chances of creating hot spots.***

The influence of hills on emissions can be significant. Emissions do not rise substantially on diesel trucks until the terrain is sufficiently steep to require use of brakes on downhills and power re-supplied on uphills. The situation is made worse if congestion causes stop-start driving on a hill. ***Major arteries through cities should avoid severe grades where possible.***

Local environmental management

Pedestrianization of city centers began to gain popularity in Europe about 40 years ago and is now a feature of most city-center plans. The sort of measures used include the shading of pathways, attractive paving materials, use of materials to dissipate heat, integration with public transport stations, landscaping, and better pedestrian corridor links with major destinations. In contrast, pedestrians are generally poorly served in developing countries, where they tend to be controlled rather than provided for. Footways are often not provided; when they do exist, they are often in a poor state of repair or taken over by traders and parked vehicles. The consequence is that pedestrians are forced to walk in the highway pavement. This is not only unsafe but also contributes to traffic congestion and consequently increased emissions. In many cities the roads are so unsafe for pedestrians that they use motorized transport even for short trips. ***Provision of adequate pedestrian facilities improves air quality by keeping traffic away from sensitive, high-exposure locations and by encouraging walking as the preferred mode for short trips.***

Other restraints on vehicle movements are usually targeted at particularly sensitive areas. The most common spatial restrictions relate to access to central business districts (CBDs). The "cell system," introduced in Gothenburg and replicated in British towns such as Oxford and Leeds, uses physical restrictions on cross-center movements to keep through-traffic of private vehicles, but not buses, out of the CBD. Some schemes also discriminate by vehicle type. For example, the bus franchising system in Santiago limits the number of buses licensed to operate into the CBD, although it is not well enforced and currently under revision. Many cities such as Delhi specify particular routes for heavy goods vehicles or even ban their access to central areas during the daytime. ***Discriminating traffic controls can be used to protect environmentally sensitive areas.***

The difficulty for many developing countries, however, is that important generators of heavy freight vehicle movements, such as ports (as in Manila) and major markets (as in Dhaka), are located in or close to downtown areas. Relocation of these facilities, as currently being implemented in Ho Chi Minh City in Vietnam, is very costly and can only be achieved over a long time period. The evidence is that ***integrated planning of urban land use, urban public transport, and traffic management is the best basis for improving air quality in the most sensitive locations.***

Incident detection and intelligent transport systems

Much congestion in large cities can be attributed to the dislocation effects of relatively trivial accidents. Traffic incident detection, coupled with prompt appropriate response, can improve traffic flow and reduce congestion significantly. This requires appropriate real-time transfer of information and close collaboration among traffic management, police, health, and rescue agencies. ***The ability to identify incidents, remove obstructions, and redirect traffic can help reduce traffic congestion and improve air quality.***

Regulation and Control of Public Road Passenger Transport

Public transport affects urban air pollution both directly, through emissions of public transport vehicles, and indirectly, by providing an alternative to a much larger number of private cars (World Bank 2001). Operation of public transport vehicles may result in losses of car speed, resulting in slightly higher emissions from cars. If public transport is not efficient, it is unlikely to contribute effectively to the reduction of urban air pollution. However, provided that public transport is sufficiently attractive to draw passengers away from private vehicles to high-occupancy public transport vehicles and is well maintained, on balance public transport promotion can bring significant environmental benefits (though these benefits should be calculated and not simply assumed). ***Policy for public transport can minimize its direct air pollution impacts by making it clean and maximize its indirect benefits by making it sustainable and attractive.***

Traffic management for public transport

Buses typically move at only about two-thirds the speed of cars because they must frequently stop and re-enter the traffic flow. Given the limited density of bus networks, taking buses also involves longer terminal walking times than using private cars, with the overall result that a bus journey usually takes at least twice as long as an equivalent car journey. This discrepancy accentuates the advantage of the private car and encourages its use. Although auto-rickshaws offer point-to-point service, they also add to congestion. Mixing public transport vehicles, whether buses or auto-rickshaws, with other vehicle categories reduces the average speed of traffic compared with what could be achieved if traffic were segregated. ***Public transport priorities—dedicated lanes or totally segregated busways—are essential to counteract the problems of mixed traffic.***

The simplest measures are priority bus lanes. But they have major limitations. They make roadside access to premises more difficult. When they are operated in the same direction as the main traffic flow, they are particularly susceptible to invasion by other traffic. Operation against the direction of flow is more self-enforcing but can increase pedestrian accidents. ***Simple non-segregated bus lanes have proven difficult to enforce, thus providing limited improvements in bus efficiency and air quality.***

Totally segregated busways using central lanes, along with protected pedestrian crossings at stations, overcome the problems of accidents and problems of access to roadside premises associated with bus lanes. Furthermore, by developing busways as trunk links in a physically and commercially integrated network, the travel time and cost of public transport can be made more competitive with that of the private car. Although schemes that dedicate existing road space to public transport may be opposed by car users, ex-

Bus lanes cannot prevent mixing public transport vehicles with other vehicle categories, as the above photograph of a trolley bus and private cars in Moscow shows.

INTERNATIONAL EXPERIENCE 5

Bus Rapid Transit in Bogotá

As part of a comprehensive urban mobility strategy including promotion of nonmotorized transportation and restriction of automobile use, the municipality of Bogotá has developed a bus rapid transit system called TransMilenio. The infrastructure of the system includes exclusive busways on central lanes of major arterial roads, roads for feeder buses, stations, and complementary facilities. Trunk line stations are closed facilities with one to three berths varying from 40 meters (m) to 180 m in length, located in the median every 500 m on average. Trunk lines are served by articulated diesel buses with 160-passenger capacity, while integrated feeder lines are served by diesel buses with capacity of 80 passengers each. To maximize capacity, trunk lines accommodate express services, which stop only at selected stations, as well as local services, which stop at all stations. This combination allows the system to carry up to 45,000 passengers per hour per direction. Services are operated by private consortia of traditional local transport companies, associated with national and international investors and procured under competitively tendered concession contracts on a gross-cost basis. By the end of 2002, 750,000 passengers per day were carried on 41 km of exclusive lanes and 309 line km for feeders on local roads, with 61 stations, 470 articulated buses, and 241 feeder buses. During peak hours, 35,000 passengers per hour per direction were being transported in the heaviest section. TransMilenio is intended to expand over a 15-year period to include 22 corridors with 388 km of exclusive lanes. By 2020, 85 percent of the city is envisaged to be within 500 m of the trunk system, and the rest of the city covered by short distance feeder systems.

Overall system management is performed by a new public company (TRANSMILENIO S.A.) funded by 3 percent of the ticket sales. TRANSMILENIO S.A. operates a control center, supervising service and passenger access. The system was developed between January 1988 and December 2000, when service commenced. By May 2001 it carried 360,000 trips per weekday, at a ticket cost of US$0.36 and without operating subsidies on 20 km of exclusive lanes, 32 stations, 162 articulated buses, and 60 feeder buses. Productivity was high, with 1,945 passengers per day per bus and 325 km per day per bus. Fatalities from traffic accidents had been virtually eliminated along the trunk corridors, and users' travel time reduced by one-third. Measurements indicated that particulate emissions in the corridors were reduced by up to 30 percent, simply by replacing many old, polluting vehicles with larger, but still conventional, diesel vehicles. As the system has proved profitable for the operators, it is intended to tighten the vehicle quality requirements in later rounds of service tenders to reduce air pollution even more.

Sources: Hidalgo 2001 and 2003.

perience in Curitiba, Brazil, and Bogotá (see International Experience 5) has demonstrated that, ***with good traffic management to minimize car delays, segregated bus systems can produce both efficiency gains and environmental benefits.***

Improving internal efficiency of operations

The internal efficiency of formal bus operating companies in developing countries can usually 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. But this has to be balanced against the losses of efficiency inherent in monopoly operation. While there are some scale economies in staff training, supply procurement, and management information systems, international experience indicates that these are not of a magnitude to justify monopoly operation of large urban systems. 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 important requirement is usually the need for internal incentives to efficiency, the most effective of which is some competitive threat.***

Public transport franchising

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 until the early 1990s), the use of old, polluting vehicles (as in Lima today), or dangerous operating practices (as in Delhi). ***Unregulated competition can clearly be dangerous, inefficient, and environmentally damaging.***

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 simply 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 (see International Experience 6). ***Institutional and regulatory reform to create orderly competition for franchises has improved performance and maintained public transport share in many countries.***

For competitive tendering to be effective, a franchising authority must be technically and administratively able to design and award franchises with sen-

INTERNATIONAL EXPERIENCE 6

Addressing the Environmental Impacts of Bus Competition in Santiago, Chile

At the end of 1977, public road passenger transport in Santiago was provided by a public sector operator with 710 large (90-seat) buses, a number of strictly regulated private associations operating 3,167 regular (78-seat) buses, and 1,558 (40-seat) "midi"-buses. The public operator lost money and service was mediocre. Between November 1979 and June 1983, both entry to the market and fares were deregulated. The public sector operator was driven out of the market, and total capacity more than doubled. But by 1985, regular bus fares had tripled, and the average age of buses had increased from 7 to 11.6 years. Competition concentrated on routes to the center of the city, which became congested and polluted by buses with too-few passengers.

Initial attempts to rectify the situation included banning 20 percent of the bus fleet from operation on each day of the week and banning buses more than 22 years old. These measures gave little relief. So, in the early 1990s, the government introduced a system of competitive tendering for franchises to operate buses on routes entering the city center. The capacity was thus constrained by the authorities. The fare to be offered was one main criterion in selecting franchisees; another was the environmental characteristics of the vehicles offered. Congestion, air pollution, and fares all fell dramatically. By the mid-1990s, improved service, an important benefit of competition, had been retained, while the drawbacks associated with competition had largely been eradicated. In a 10-year period between 1992 and 2002, the number of buses fell from 14,000 to 7,500, and the average age of buses from 15 years to 5 years.

Sources: World Bank 2002f, López 2002.

sible 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 Bogotá and Santiago). 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 developed effective competition.***

FAQ 6

Does privatization of public transport lead to worsening urban air pollution?

In industrial countries, publicly owned public transport operators are subject to stringent quality standards (including for emissions) that are satisfied adequately in many countries. But the operators usually achieve this on the basis of substantial, and open-ended, public subsidies. Where those subsidies are not available, as is now the case in many of the independent republics that emerged from the former Soviet Union, publicly owned buses are old, poorly maintained, and heavily polluting. It is thus the subsidy, rather than the public ownership, that allows stringent quality standards to be met.

In many countries, both industrial and developing, the size of the subsidies has become so great that governments have begun to seek methods of reducing the subsidies by introducing competition among private sector operators. Where, as now in Lima or as in the late 1980s in Santiago, this liberalization took the form of free entry with little attempt at regulation of quality, many old and polluting buses took to the streets. But where, as in many of the industrial countries, the competition took the form of competition "for the market"—that is, for the right of private companies to operate regulated franchised services—air pollution was well contained. It is thus the lack of quality regulation in privately operated bus sectors, not private ownership per se, that is the cause of pollution.

The lesson is clear. Both unsubsidized public sector operations and unregulated private operations can be very polluting. For poor countries that cannot afford heavy subsidies to public sector operations, regulated competition for the market is an intermediate path that can better reconcile affordability with service quality than either free entry or public monopoly can.

Emission standards for public transport vehicles

A number of countries have embodied high aspirations for the environmental quality of public transport by enacting strict standards for public service vehicles. In some cities, such as Kuala Lumpur, this has had the perverse effect of reducing the commercial viability of public transport. In others, such as Bangkok, environmentally clean vehicles have been put in service only at premium fares that reduce the availability of service to the poor. Conversely, cities such as Bogotá—which have concentrated on giving priority to public transport vehicles but have not enforced very high environmental standards per se—have been able to reduce air pollution by attracting passengers into large buses and eliminating many of the oldest, most polluting, vehicles. ***Imposing stringent vehicular emission standards without attention to the financial sustainability of public transport operations can undermine the viability of public transport and have counterproductive effects.***

Bus priorities and bus rapid transit

Bus priority systems change the relative travel times by bus and car and, particularly if supported by parking restraints, encourage people to use the more space-efficient public transport modes. Congestion levels may thus be reduced. More important, they increase the average speed and reduce the variability of speed of bus movements. For turbocharged diesel engines, the importance of maintaining steady engine load (steady speed or gentle speed changes) to reduce particulate emissions cannot be overemphasized. A range of priority measures was shown to reduce bus exhaust emissions in London by 7–60 percent (table 3).

As table 3 shows, the segregated busway, or bus rapid transit (BRT) system, is the most environmentally effective although there is minimal use of the segregated busway in London. BRT has been developed extensively as the core of mass transit systems in Bogotá and Curitiba. Such systems make it possible to replace four or five small vehicles with one larger ve-

TABLE 3

Bus Priority Measures in London

Measure	Proportion of buses affected	Exhaust emission reduction per bus affected
Peak period bus lane	5%	20%
Contra-flow lane, all day	2%	35%
Signal pre-emption	20%	12%
Segregated busway	2%	60%
Priority turns	5%	7%

Source: Bayliss 1989.

hicle, which 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. The secret of their success 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.***

One interesting characteristic of BRT systems is that they have achieved their substantial environmental impacts without initial emphasis on advanced clean technology. The passengers are attracted by the affordability, travel time, security, safety, comfort, cleanliness, and ease of use of the system. For example, conventional diesel bus technology has been used in both Bogotá and Curitiba systems. In Bogotá more stringent environmental requirements on vehicles are proposed to be introduced in the next phase of development. The lesson (IEA 2002) appears to be that ***development of a BRT system has environmental benefits by itself but can also provide an economically viable platform for the introduction of improved technologies.***

Total segregation of bus lanes from the rest of the traffic, such as what was done for TransMilenio in Bogotá, markedly reduces both emissions and travel time.

The Role of Mass Transit

Electrically propelled transit modes are without doubt the least locally polluting form of mass transit. That would include electric or fuel-cell powered road vehicles as well as the more traditional electric railway. Very often, however, mass transit is thought of only in terms of rail-based systems. These have the advantage of giving a perception of permanence and quality on the basis of which people in many large industrial countries, particularly in Europe, have been willing to choose residential locations from which they can make their regular journeys to work by rail rather than by car. Unfortunately these are very costly. Recent new underground railways have cost between US$40 and $100 million per kilometer, which is beyond the resources of most developing country cities (JJ&B Consultants 2001). ***Electric rail transport is very clean at the point of use, but expensive.***

The cost of rail transport is important to individuals making these joint decisions on residential location and choice of transport mode. In the absence of direct charges for road use (see International Experience 7 in chapter 5) many European cities have subsidized urban rail transport heavily to compensate for its high cost. This has three main drawbacks. First, it is difficult to get a sufficiently large road/rail fare charging differential by increasing subsidies whereas in principle any size of differential can be obtained by raising road charges. Second, whereas road pricing generates revenue for the public authority, a public transport subsidy is a drain on city budgets, which is particularly important for typically cash-strapped cities in developing countries. Third, a compensating subsidy to public transport has the effect of encouraging longer trip lengths, more sprawling development patterns, and hence a higher long-term tendency to rely on private transport. ***Rail mass transit subsidies are likely to have only a weak influence on urban air quality and should be relied on only in the context of a comprehensive urban transport strategy.***

Fortunately there are some more affordable mass transit alternatives. Where rail tracks exist, surface rail or light rail transit systems can be constructed more cheaply, but usually have lower capacity (Halcrow Fox and Traffic and Transport Consultants 2000). Segregated busway systems can yield almost equivalent mobility benefits at about 10 percent of the capital cost for traffic volumes of up to 20,000 peak passengers per lane per hour in the peak direction, albeit at a lower speed than rail mass transit (though in the right circumstances BRT may produce speeds that are comparable with those of light rail transit). By combining busways with cleaner vehicle technology (such as electric trolleys or buses fueled by CNG), large environmental benefits can be achieved without conflict with system financial sustainability. For example, operators of the Bogotá TransMilenio system were required to buy new, high-quality vehicles to compete for franchises, but claim that the increased efficiency of movement has allowed them to vastly improve service and to increase their profitability without an increase in fares (Hidalgo 2001). ***More affordable mass transit alternatives can often yield substantial environmental benefits at much reduced cost.***

CHAPTER 5

Reducing Total Transport Demand

Shortening trip lengths, discouraging non-essential trips, and restraining private car use are some of the measures that can be taken to reduce the overall demand for motorized transport. Use of private vehicles can be limited both by pricing and by administrative regulation.

Land Use Policy

The environmental importance of land use policy

Demand for movement is derived from the demand to undertake activities at different locations. This demand can in principle be reduced by planning land use in ways that minimize travel requirements, and particularly minimizes private car movements, for a given level of activity (Kenworthy and others 1999). The shape and geography of a city and the pattern of distribution of land use thus affect air quality (World Bank 2002c). ***The establishment of a land use and transport structure plan is the best basis for the application of environmentally friendly transport developments.***

Several different dimensions in land use planning can be managed to influence urban air pollution:

- Density
- Structure
- Diversity
- Local design.

Density

Population density affects motorized trips in two ways. First, for a given population, the higher the density, the shorter the distances between the locations of different activities and the higher the number of people who can comfortably walk to work, shops, or school. With high densities, multiple purposes may also be served by a single trip. Second, the higher the density, the easier it is to provide frequent and easily accessible public transport services and thereby reduce demand for private motorized transport. The "sprawling" of cities, particularly through artificial discontinuities in development resulting from competition for activities between neighboring jurisdictions, tends to increase trip lengths and the need for private motorized transport. ***To control aggregate transport emissions, it would be helpful to develop a policy that increases, or at least maintains, the population density.***

In practice, the impact of increasing density on air quality has not always been positive because of inadequate handling of traffic management. In South Asia, where urban densities have increased, the number of two- and three-wheelers has increased appreciably in part because of their maneuverability in congested traffic. On account of the large number of operators involved, these vehicles are difficult to control for emissions as well as for traffic management. ***Poor traffic management can negate to a considerable extent the potential benefits of good land use planning.***

At first view, a densification strategy may appear to make larger demands on public funds than a lower-density strategy. But this can be misleading. In many cases the additional investments required in trunk and distributional infrastructure to accommodate an equivalent growth at low density in the periphery may be even greater in aggregate, although they may be hidden by the fact that they are distributed among a number of agencies or budget heads. ***Developing country cities would be well advised to attempt to estimate the infrastructure development costs of alternative land use patterns.***

Structure

Structure is also important. It is easier to operate an efficient public transport system when the destination of the majority of trips is concentrated within the central business district (CBD). As a consequence, in cities that are predominantly "monocentric" (most jobs and retail concentrated in the CBD), the share of trips using public transport tends to be higher than in "polycentric" (no dominant center) cities where the CBD contains only a small fraction of the total number of jobs and retail shops. However, in concentrating business and retail activities, it is important to avoid the creation of "hot spots" where pollutant concentrations are extremely high. ***Policies that favor the concentration of employment and retail activity in a CBD can reduce transport-generated air pollution.***

In reality, large cities are rarely purely monocentric, but have both a core CBD and a number of subcenters with different activity compositions. In such cities a large share of the trips to and from the CBD are likely to be by public transport, while those from suburb to suburb are more likely to be by private transport. This has generated the idea of concentrating development around transit nodes, sometimes referred to as transit-oriented development. As a broad guide, maintaining contiguous urbanization and a high-density CBD is not feasible for cities with more than 5 million people. Therefore, ***a degree of polycentricism should be allowed in megacities while maintaining the primacy of the CBD to reduce trip length and to maintain a high share of public transport.***

Moreover, as mentioned earlier, even if a city moves toward the "right" structure, if traffic is poorly managed in the CBD, air quality may not improve and may even worsen. High densities and monocentric city planning require a higher level of primary infrastructure investment and more rigorous management and traffic law enforcement than are required in lower-density, more dispersed cities. Despite this, ***dispersing business outside of the CBD primarily to save expenditures on traffic management is not usually a cost-effective strategy.***

Diversity

People must live, work, shop, and be educated, usually in different locations. Much traditional land use planning was directed towards strict separation of land uses, for environmental reasons, given the high level of air pollution caused by traditional heavy industry. That separation was taken to its extreme in the planning of development in many socialist cities of Eastern Europe where high-density residential development was put in peripheral areas of the city, and linked to the main employment locations by high-volume mass transit links. As industrial structure has changed, industrial processes have become less polluting, and private transport has developed, the balance between industrial- and transport-generated pollution has changed substantially. The more closely activities are co-located, the less will be the demand for transport to satisfy them so that mixing land uses is therefore likely to minimize transport generated air pollution. ***In many cities the traditional separation of land uses has become a net source of air pollution rather than a protection against it.***

Even now, the balance is not everywhere the same. Coal-fired power stations and other heavy industrial plants are the major sources of air pollution in many Chinese cities. In contrast, some cities, such as Curitiba, while locating their heavy industry away from residential areas, have controlled total travel demand by mixing commerce, light industry, and residential land uses and have influenced the choice of mode by concentrating development in transit corridors. ***Judicious mixing of low pollution land uses can be combined with the relative isolation of very high polluters in a strategy to reduce urban air pollution.***

Local design

The most polluting private motorized trips are the short ones, due to high emission rates from cold starts. Hence, disproportionate benefit can be obtained by designing cities to discourage such short motorized trips. Good safe provision for pedestrians and cyclists is particularly important as many short trips in middle-income developing country cities are taken by car and taxi because of the danger and discomfort of walking or cycling. This should include the provision and protection of pedestrian sidewalks, safe well-located crossing places on heavily trafficked roads, and adequate cycleways and cycle parking. ***Cities can reduce pollution from short motorized***

trips substantially by good design of local facilities for nonmotorized transport.

Problems of implementation

Despite the importance of market forces in shaping cities in developing countries, planners can influence urban structure both through regulation of private land use as well as through public infrastructure investments. Regulations can allow high densities, but they cannot increase density if there is no demand. For that reason planners have sometimes attempted to increase density by restricting land supply in order to curb urban sprawl. The most common legal tools used to curb sprawl are "green belts" and urban growth boundaries. But these often result in acute housing shortages, particularly for the poor, and in high land prices, as in Seoul, Republic of Korea. The lack of developable land may curtail the creation of new businesses and may have a negative effect on the city's economy. ***Land markets are often better than land use regulation in determining the efficient level of residential densities.***

In a quite contrary direction, Indian cities such as Bangalore have adopted regulations that attempt to keep density low in the interest of avoiding congestion. These measures can also be counterproductive as they typically lead to an imbalance between supply and demand of land and push up average land prices. ***Regulations limiting density in the commercial areas in the CBD should be critically reassessed.***

The primacy of the CBD can often be maintained by giving priority to the reinforcement of radial services (particularly public transport) over the construction of multiple ring roads. A well-developed network of public transport can also support the CBD and maintain speed in the downtown area. While a good orbital facility may be required to prevent truck traffic from crossing the CBD, excessive investment in arterial road capacity is likely merely to increase private transport trip lengths. ***Managing high densities requires adequately structured supporting infrastructure investments, including those in expensive mass transit in some circumstances.***

Using land use planning instruments to reduce air pollution is challenging due to the divergent, and sometimes incompatible, objectives of city governments. For example, urban planners may have to weigh the benefits of creating employment opportunities in cities by allowing new industrial plants to be set up with the potential adverse effects of those industries and associated traffic on air quality. ***It is crucial to coordinate land use policies across key sectors, such as public utilities, social services, urban development, and transport, to realize air quality improvement.***

Road Pricing

In practice, the demand for movement is a function not only of the location of activities but also of the costs of movement. Any form of subsidy of transport, whether public or private, will tend to increase trip lengths by broadening the range of locations at which it is affordable to satisfy particular demands. Correcting that by the introduction of road congestion pricing or some proxy, such as high fuel taxation or parking charges, may be essential to the creation of appropriate long-term incentives on activity location and trip distribution decisions. ***Underpricing the use of transport infrastructure is likely to have adverse effects on urban air quality.***

Where externalities of road traffic—both in the form of congestion and environmental impact—are substantial, the cost of road space to the road user is likely to be considerably below its marginal social cost. While physical restraint measures have hitherto proven more acceptable than direct charges for road use both in industrial and developing countries, even in industrial countries their effectiveness appears to have been exhausted. Although only Singapore has a thoroughly developed direct road charging system (see International Experience 7), the situation appears to be changing as other cities such as London, Oslo, Stockholm, and Seoul have recently proposed to introduce or have introduced congestion charging systems. For example, congestion charging, introduced in February 2003 in London, appears to have been

INTERNATIONAL EXPERIENCE 7

Congestion Pricing in Developing Countries

In September 1998, the government of Singapore replaced the manually enforced area licensing scheme (ALS) that had operated since the mid-1970s with electronic road pricing (ERP). The new system generally covers the same area as the ALS, but has been extended to approach and bypass roads. All vehicles are required to have an electronic in-vehicle unit (IU) that accepts credit in the form of a smart card. Tolls are automatically paid when the vehicle passes under a gate and a liquid crystal display indicates the current credit balance. Tolls do not fluctuate in relation to actual traffic volumes but are adjusted quarterly to ensure optimum traffic speeds. The system cost S$200 million (US$115 million at the exchange rate of September 1998) to implement, half of which was for the free fitting of IUs. Once new traffic patterns stabilized, weekday traffic volume entering the restricted zone declined 20–24 percent, from 271,000 vehicles per day to between 206,000 and 216,000. With those lower traffic volumes, average traffic speeds in the zone increased from 30–35 km/h to 40–45 km/h. Improvements are less clear on the three expressways in the ERP scheme, and the Land Transport Authority is reviewing ERP charges to further optimize traffic flow.

Traffic congestion in Seoul, Republic of Korea, increased dramatically during the 1980s and early 1990s, despite extensive construction of new urban freeway and subway lines. In 1996, the Seoul Metropolitan Government commenced charging 2,000 won (US$2.20) for the Namsan #1 and #3 Tunnels, two corridors with high private vehicle use linking downtown Seoul to the southern part of the city. Private cars with three or more passengers and taxis, as well as all buses, vans, and trucks, were exempted from charges, as was all traffic on Sundays and national holidays. In the two years following commencement of the congestion pricing scheme for the Namsan #1 and #3 Tunnels, there was a 34 percent reduction in peak period passenger vehicle volumes. The average travel speed increased by 50 percent from 20 to 30 km/h, and the number of toll-free category vehicles increased substantially in both corridors. On the alternative routes, traffic volumes increased by up to 15 percent, but average speeds also increased as a result of improved flows at signaled intersections linked to the Namsan corridors and increased enforcement of on-street parking rules on the alternative routes. The whole of the annual revenue from the two tunnels (equivalent to about $15 million) goes into a special account used exclusively for transport projects, including transport systems management and transport demand management measures throughout the city.

Other cities, such as Bangkok, Hong Kong, and Kuala Lumpur, have previously begun introducing road pricing but have abandoned it in the face of political difficulties. As congestion increases, and other instruments to control it fail, it is likely that they, among many others, will have to reconsider the pricing instrument that, as a by-product of reducing congestion, reduces urban air pollution to an even greater extent.

Source: World Bank 2002f.

successful in shifting motorists to public transport and reducing journey times. ***Direct pricing of road use has a high potential in developing countries both as a means of generating local revenue and of reducing congestion and air pollution.***

Direct pricing (excluding fuel taxation) can include charges for entering or traveling within a designated part of the city experiencing congestion (typically the CBD), for use of selected road links, or for parking. Even Singapore—which has for many years taxed vehicle ownership very heavily and has been a pioneer in charging motorists for traveling into the city center—is now placing a greater emphasis on vehicle use than on restrictions on ownership. In the few cases in OECD countries where direct cordon or area congestion prices are charged, part or all of the revenues have been earmarked for public transport improvements. ***For cities in developing countries that lack resources to finance urban transport, the introduction of direct charges might be expected to have a double attractiveness: that is, as a source of finance as well as an instrument of restraint.***

Physical Restraint Policies

Physical restraints on vehicle use have been used both in industrial and developing countries. The most popular restraint measures are schemes that limit use of vehicles on specific days according to their registration plate number. Such schemes have been introduced in many cities, including Athens, Bogotá, Lagos, Manila, Mexico City, Santiago, São Paulo, and Seoul, both to reduce congestion and to improve the environment. They have achieved public acceptance as a demonstration of commitment by government to reduce congestion and air pollution, and have proved less difficult to enforce than might have been expected. In the short term they have achieved their objectives (Bogotá reports 20 percent increase in average travel speeds). If well designed to discourage peak use and coupled with public transport improvements, as in Bogotá, ***administrative restraint mechanisms can at the very least give a "breathing space" to develop more effective traffic restraint policies.***

There are, however, obvious risks with this kind of policy. It may encourage an increase in the number of vehicles owned and induce more trips by permitted vehicles than would otherwise have been made. In particular, it may encourage the retention in operation of old, high-polluting vehicles that would otherwise have been scrapped. Moreover, the experience of Bogotá suggests that careful design of the system—for example, limiting the restriction to the peak time and having the proportion of non-use days sufficiently large to make it difficult to evade by the possession of a single extra vehicle—may minimize the possibility of counterproductive behavior. ***Physical restraint policies need to be accompanied by appropriate economic measures to strengthen and maintain their effectiveness.***

One aspect of restraint is particularly important. It is politically difficult to restrict the movement of private vehicles unless there is obviously a viable alternative. Both theory and practical experience indicate that, at least in respect of trips to central areas, ***a coherent policy is likely to include a combination of car restraint and public transport improvement.***

Parking Policies

Parking policies have been widely and successfully used in European countries, particularly to discourage commuting trips by car. Such policies often combine limitations on the amount or location of parking space with high charges for long-term (commuter) parking. In developing countries this has often been more difficult to achieve because of the institutional inability to control on-street parking. At the very least, in developing countries, ***avoiding the provision of publicly funded free car parking can have beneficial fiscal and environmental effects.***

Parking policies have an impact on the effective supply of road space as well as on the demand for it. In many developing countries, highways and walkways are often encumbered with parked vehicles that congest traffic and as a consequence increase air pollution. ***Strong regulation to limit on-street parking to locations where it has no effect on traffic flow is likely to be the appropriate supply-side response in most circumstances.***

In order to reduce on-street parking, many cities and countries impose minimum parking provision requirements in all new developments to create enough off-street parking space to cater to all vehicles wishing to access the development. The logic underlying this is that as long as the costs of parking space are recovered through property rents, parking users can be said to be paying directly or indirectly for the space allocated to parking. Unfortunately, road space and parking space are jointly demanded and the provision of off-street parking space may actually attract new traffic, thereby offsetting the gains from removing parked cars off the streets. If road space is provided below cost, then parking—a jointly demanded good—should be charged more than its full costs in order to avoid excessive vehicle use of roads. For that reason, many industrial country cities use parking pricing and availability as a demand-restraint measure. The amount of parking in any area is then limited to the maximum level considered necessary to support an "optimal" amount of road use. Pricing and parking supply regulation is used to implement this strategy, which also implies specification of maximum (rather than minimum) parking provisions for new developments. ***Parking strategies for developing country cities should be part of a comprehensive transport plan and, particularly in central areas of cities, should not necessarily aim at accommodating all possible vehicle parking demands.***

The Special Problem of Motorcycles

Motorcycles present some special problems, particularly in Asia. In many cities that have previously been bicycle dominated, particularly in Vietnam and Taiwan, China, motorcycle ownership and use have grown at a phenomenal pace as incomes increase. In congested cities, motorcycles are cheaper and quicker than conventional public transport. As a consequence, the level of private motorized mobility in some relatively poor countries such as Vietnam is actually comparable with that of many industrial countries.

At first sight increased motorcycle use might seem like a very desirable outcome because motorcycles are small, thereby occupying less road space, and much more fuel-efficient than other vehicle categories. But accident levels for motorcycles are very high and, in countries where two-stroke motorcycles are prevalent, they have a considerable negative impact on air quality. In the short run, air quality impact can be reduced by programs to enforce the use of appropriate amounts of suitable lubricant and by relatively simple traffic-management devices such as directional separation. In the longer term, the air quality impact of motorcycles can be reduced most substantially by a shift to four-stroke motorcycles, as in India, Vietnam, and Taiwan, China, or to direct injection two-stroke engines. ***Stringent technical regulation is necessary to control the environmental and safety impacts of traffic in motorcycle-dominated cities.***

The real problem arises in the longer term. With further increases in income, and in the absence of adequate public transport alternatives, motorcycles are likely to be progressively replaced by private cars. In many of the Asian cities with relatively low proportions of space devoted to roads, this will generate heavy congestion and have an even greater negative impact on air quality. Despite the great political difficulty in restraining freedom of movement of motorcycles, ***it will be essential to introduce restraints on private motor vehicle movement at an early stage if city environments are to be protected against the almost inevitable shift from motorcycles to cars.***

CHAPTER 6

Designing a Supportive Fiscal Framework

The fragmentation of decisionmaking in transport among so many private and financially motivated agents (including private individuals) puts great emphasis on getting the prices right. Where there are uncharged-for external effects, as in the case of air pollution, it is likely to be necessary to make appropriate adjustment of relative prices through fiscal measures. This may take the form of taxes, subsidies, or direct capital expenditures. An appropriate set of supporting fiscal policies can increase the effectiveness of administrative and regulatory measures. ***Developing country cities may improve the effectiveness of their attempts to reduce air pollution by using existing powers or by seeking new powers to use fiscal instruments.***

Direct Taxation on Emissions

The economic ideal would be a system of direct taxation on emissions. If such a system could be devised, it would not be necessary to have complex administrative controls, because there would be strong incentives for all agents to limit their emissions levels. Choice of vehicle and fuel technology would both be driven straightforwardly by these economic incentives. Insofar as the level of emissions is determined by the vehicle design (including the fuel for which it is designed), taxation on the capital cost of vehicles is an approach along these lines. For vehicle-manufacturing countries it would also be possible in principle to use a system of tradable emissions certificates to harness market incentives to encourage economic, clean technology. For non-manufacturing countries it could be embodied in import duties that vary according to the vehicle's emission characteristics. However, even this does not affect the way in which vehicles are maintained and operated, and it would still be necessary to have some other complementary taxation on the vehicles in use.

Fuel Taxation

Unfortunately, for vehicles in use, the continuous measurement of emission levels and application of variable taxation levels are technically a long way off. It will therefore be necessary to devise the best proxy tax or taxes. Because many pollutants are emitted in rough proportion to the amount of fuel burned, fuel taxation is an obvious candidate (Gwilliam and others 2001).

The incentive properties of fuel taxation

One way of assessing the potential of transport fuel taxation as an environmental instrument is to look at its efficacy with respect to reducing vehicle km traveled, fuel consumption per km, and emissions per unit of fuel consumed:

- **Reducing overall vehicle km traveled.** High taxation on transport fuels will encourage a reduction in trip numbers and trip lengths as well as favor public over private transport modes. Although the mode shift effects themselves may be small because of the range of different dimensions of adjustment, the overall price elasticity of demand for gasoline may be between –0.5 and –0.8, although that for diesel is likely to be considerably lower.
- **Reducing fuel consumption per km.** A high tax on fuel will encourage the use of more fuel-efficient vehicles. But the level of congestion is the most important factor in determining fuel consumption, and the fuel tax is not very efficient as a charge for congestion.
- **Reducing emissions per unit of fuel consumed.** The high degree of differentiation of environmental damages from the same fuels across various users, technologies, and locations limits the effectiveness of fuel taxes for controlling air pollution (Lvovsky and Hughes 1999).

Fuel tax has good incentive properties for reducing the amount of vehicle kilometers traveled and encouraging the use of fuel-efficient vehicles, but it fails to reflect the location of emissions.

The multiple objectives of fuel taxation

In many developing countries, fuel taxation is usually the responsibility of central government and taxes on hydrocarbons can account for as much as one-fifth of all central government tax revenue (Bacon 2001). These taxes are usually considered a reliable revenue source because fuel has a low overall elasticity of demand with respect to price and the taxes can be collected cheaply. But they usually are expected to fulfill at least four functions:

- **Revenue function.** They are primarily aimed at raising revenue for general (non-transport) expenditure purposes.
- **Road user charge function.** Taxes on transport fuels are often the primary means through which vehicles can be charged for the use of roads, and some part of fuel tax revenue is often earmarked for financing road provision and maintenance.
- **Redistributive function.** As part of central government policy, their redistributive characteristics might also be of great importance.
- **Environmental function.** In the absence of direct charges for air pollution they may be expected to be a surrogate environmental charge.

It is clearly not possible to achieve so many objectives simultaneously and efficiently through a single tax. The challenge of satisfying multiple objectives is especially difficult in low-income countries, where fewer policy instruments are available. ***In the use of fuel taxes, compromises have to be made between the effects on government revenue generation, income distribution, the efficient use of roads, and air pollution.***

The principles of fuel taxation

Some useful guidance for evaluating these compromises can be obtained from the general principles of optimal commodity tax theory, which focus on minimizing the loss of welfare to consumers in raising a given sum of money for the government through commodity taxation (Newbery and Stern 1987). ***A fundamental principle is that in order to avoid economic distortions taxes should, as a rule, be levied on final consumption goods rather than on intermediate goods.*** This principle suggests that fuel taxation should be concentrated on gasoline, which is used predominantly by private cars as a consumption good, rather than on diesel, which is used in large quantities by freight and public transport vehicles as a producer good.

Such a prescription, however, has three major difficulties. First, not all consumption goods (for which diesel is an input) are taxed and it may be necessary to tax the inputs instead. Second, freight transport of producer goods generates air pollution, but operators have less incentive to use less fuel (lower fuel consumption would normally lower overall emissions) when fuel is cheap. However, by far the greatest problem with differential fuel taxation concerns the effects of inter-fuel substitution. In the long run, diesel, gasoline, CNG, and automotive LPG are all technologically possible substitutes. The common combination of a high gasoline tax and a low diesel tax may encourage vehicle owners to switch from gasoline to diesel when they buy or replace light-duty vehicles (as has already happened in some countries such as France, and is being advocated for fuel economy reasons in the United States).[1,2] While "clean diesel" in the EU and North America may mitigate the impact of such fuel switching, the same phenomenon in developing countries would most certainly mean much higher particulate emissions.

[1]A recent study by M. Cubed, commissioned to provide economic and technical input into California Assembly Bill 2076, argues that because diesel passenger vehicles are typically 35 to 50 percent more fuel efficient than similar-sized gasoline vehicles, a shift to diesel vehicles could substantially reduce the state's dependence on petroleum. The full report is available online at www.dieselforum.org.

[2]To avoid this anomaly, a low tax on diesel fuel might be supplemented by a high tax on light-duty diesel vehicles, particularly those used primarily in intra-city transport.

A complementary principle is the well-known "Ramsey pricing" rule, which proposes that tax rates on consumer goods be so set as to be inversely proportional to the goods' own price elasticities of demand in order to minimize the overall loss of welfare. Normally, application of this principle in its pure form is likely to be distributionally perverse, since the demand for most basic necessities (such as staple foods) is inelastic, while that for nonessential goods is likely to be more elastic. However, this is less of a problem in urban transport. Demand for fuel for private cars is believed to be (mildly) inelastic. Given the concentration of car ownership and use in the upper-income groups in developing countries and weak systems for direct taxation, a high incidence of taxation on gasoline makes for a very progressive tax. Hence, if the basic distribution of income is viewed as inequitable, indirect taxes may be structured to have a greater impact on the goods that make up a relatively larger share of the budgets of higher-income households than on the goods that are more important for low-income households. For these reasons, ***relatively high taxes on gasoline can be both economically efficient and distributionally attractive.***

Not all efficiency arguments militate in the direction of high differentiation between gasoline and diesel tax rates. In principle, users ought to pay the long-run marginal costs of road use, including the costs of capital. Many developing countries have poor-quality road systems because of underfunding of maintenance. A fuel tax, or surcharges on the fuel tax that are designated specifically as road user charges, may be the most obvious and acceptable proxy for direct charging, especially when the revenues are transferred directly to a user-managed road fund (Gwilliam and Shalizi 1999). As wear and tear is caused primarily by heavy vehicles, which are fueled primarily by diesel, this suggests that diesel tax might be an appropriate proxy for direct road maintenance charges. Diesel tax, however, has serious shortcomings in this respect. It does not accurately reflect the road deterioration caused by different vehicle categories and provides inefficient signals on vehicle size and weight. ***Even within the automotive diesel fleet, a tax on diesel needs to be supplemented by some charge on vehicle axle loadings, preferably levied on the basis of distance traveled.***

From the point of view of air quality, diesel vehicles are typically much more damaging than gasoline vehicles, especially when compared to gasoline vehicles equipped with three-way catalytic converters, an increasingly common phenomenon as developing countries move to 100 percent unleaded gasoline. Heavy-duty vehicles worldwide run on diesel, but light-duty vehicles can run on either gasoline or diesel. For vehicles of comparable size, diesel vehicles are more expensive to purchase, but if diesel tax is markedly lower, fuel cost savings can compensate for the higher purchase price of diesel vehicles. Diesel vehicles are especially suitable for high annual km vehicles. Diesel fuel should be properly taxed in order to reflect the marginal social damage caused by increasing air pollution. This is likely to mean that ***in nearly all developing countries, the tax on diesel would need to be raised to capture marginal social damage per liter of fuel.***

Aside from political opposition from truckers and other heavy users of diesel, one concern about increasing diesel tax is the impact on the economy, and on the poor in particular. The share of expenditure on all fuels as a percentage of total household expenditure consists of direct consumption of fuels and indirect consumption through purchases of goods and services that have fuels as inputs. Direct consumption tends to be concentrated at the top of the income distribution for both gasoline and diesel, but the indirect effect is more important for lower income groups for diesel because it is an important input to many goods and services. Studies that have examined the impact of raising diesel tax on household expenditures in developing countries have shown a modest impact which is mildly regressive—that is, the total expenditures of poor households rise more in percentage terms than those of the rich when the price of diesel is increased, although these effects are small. ***Because of the significant impact of higher taxation on non-automotive uses of diesel—in rail transport, agriculture, and industry, for example—it may be sensible to give rebates on the higher diesel tax to industrial and agricultural users of diesel.***

Taxation on Vehicles

Given the complexity just outlined, it is not possible to structure taxation on fuels to simultaneously satisfy all of the policy objectives. For instance, fuel taxation discriminates relatively poorly between vehicles of different axle weights, which is critical in determining the amount of road damage done by vehicles and hence the appropriate charge for their use of roads. For that reason differentiation of annual license duties among vehicle categories is common. Where that is the case, ***it is sensible to consider the possibility of using differentiation of vehicle license duties to encourage cleaner technologies.***

Another common source of revenue for governments is import duties on vehicles. Usually the level of such duties is motivated either by revenue maximization or by protection of local manufacturers. In either event, the result is typically that duties are based on the market values of vehicles so that those on new vehicles are greater than those on old, and duties on sophisticated vehicles greater than on those of simpler technology. Even if duties are differentiated to reflect differing exhaust emission levels, different age limits can provide a loophole. In Sri Lanka, for example, diesel vehicles carry higher import duties than gasoline vehicles, but the age limit is three for cars and five for dual-purpose vans, so that there has been a steady shift from gasoline cars to diesel vans (Cambridge Economic Policy Associates 2002). The overall effect is to discourage best-practice technology from an air quality viewpoint. ***The impacts on air quality should be borne in mind when determining the structure of duties on vehicle imports.***

Similar considerations apply to physical measures on imported vehicles where it is common to be more restrictive on the import of new vehicles than old. In some countries importing secondhand engines and chassis and putting new bodies on them is one way of bypassing emission standards for new vehicles. ***While maintaining type approval control of import of new vehicles, it is important to concentrate effort on controlling imports of old vehicles or rehabilitated components.***

Constructing a Road Transport Tax Package

In the absence of other direct charges for road use, pump prices of transport fuel should cover the resource cost of the fuel, the costs of road use (both road damage and occupation of road space), and the environmental costs associated with the fuel use if not otherwise charged for (some costs might be recouped through differential vehicle taxation). Although fuel taxes can strongly affect fuel consumption patterns, they have other significant welfare impacts, including spillover effects. Some basic guidelines for fuel taxing follow from this:

- In addition to fuel taxes, more precisely targeted alternatives (such as differentiated vehicle taxes and road user charges) should be considered wherever possible, in view of the limitations of fuel taxes in achieving multiple objectives.
- Environmental externalities should be corrected for by taxing polluting vehicles and fuels, not by subsidizing less-polluting alternatives. If the objective is to achieve a certain amount of pollution reduction by reducing demand for polluting goods, subsidizing less-polluting alternatives costs society more than increasing taxes on polluting goods.

Sale of imported secondhand diesel engines is common in developing country cities.

- There is a strong case for setting the gasoline tax above the general tax rate on commodities. Rich households spend a higher proportion of their budgets on gasoline than do poor households, gasoline vehicles give rise to a number of externalities, and emissions from gasoline engines may affect poor households more than rich households.
- There is also a strong case for a diesel tax. Although some diesel is used as an intermediate good, the taxation of even this segment of the market is justified if it is the principal way of charging heavy vehicles for wear and tear on the road and if the final goods (for which diesel is an input) are not necessarily taxed.
- Given diesel's high long-run substitutability for gasoline in light-duty vehicles and its strongly negative externalities in urban areas, tax policies for petroleum fuels should take careful account of, and minimize, the possibilities for socially undesirable interfuel substitution, such as the so-called dieselization of light-duty vehicles.

Property Taxation and Fees

The land use objective to minimize transport emissions is to promote contiguous and dense development. A standard *ad valorem* property tax is probably the best fiscal tool to achieve this. Confiscatory capital gains taxes on real estate, while appearing equitable because they concern "unearned income," in fact have a disastrous effect on land use efficiency. Increasing capital gains tax increases the threshold for the profitability of land conversion; as a result, obsolete, inefficient, and low-intensity land uses are maintained for a much longer time than they would be in the absence of such tax. Impact fees on new construction, whether for business or residential purposes, should cover the public costs of improving infrastructure (roads, drainage, sewerage, public utilities). Insofar as these are higher for dispersed and greenfield site development than for densification or infill, such fees would discourage urban sprawl. ***Tax incentives may be important in influencing the land use structures that, in their turn, influence transport demand and emissions.***

Public Expenditure Policies

Environmentally oriented investment policies

Fiscal policies include policies on public expenditure as well as on taxation. Taxes, road tolls, parking charges, tax rebates on public transport fuels, and capital investment in transit infrastructure may all be directed at achieving environmental ends. The most important consideration is that any such allocation needs to be justified in terms of the benefits that it actually achieves. ***Air pollution reduction is one of the benefits that should be systematically taken into account in assessing urban public expenditure priorities.***

Public transport subsidies

The imposition of stringent emission and other vehicle standards, without simultaneously introducing bus priority measures to improve efficiency, tends to increase capital costs without offering compensating reduction in operating costs. This raises the problem of the financial sustainability of service. Many industrial country cities subsidize public transport fares. While this may seem to be a reasonable approach, it is not generally cost-effective as an environmental policy. First, there is strong evidence that up to half of any subsidy "leaks" to benefit transport industry interests including owners and employees. Second, because most car owners' use of their vehicles is not sensitive to public transport fare levels—cross-elasticity being of the order of 0.1—there is little shift of travelers from private to public transport. Third, because the modal shift is small but the subsidy is paid to all, ***subsidizing public transport fares, however desirable on other grounds, is not likely to be a cost-effective way to reduce environmental impact.***

Given the poor public image of public transport, subsidies to improve public transport quality might be somewhat more effective in affecting mode choice, particularly in countries where car ownership is restricted to the relatively rich. But even for higher-income groups, regulatory reform to encourage express or air-conditioned buses to attract car owners is likely to be more effective than giving subsidies, as experience has shown in cities of varying average income levels such as Bangkok, Buenos Aires, Dhaka, and

Seoul. ***Some liberalization of market entry is likely to be the most effective way of developing public transport services to attract patronage from private cars.***

Subsidies on clean fuels

The most direct approach would be to subsidize cleaner vehicles and fuels. However, the need to ensure financial sustainability applies. The cleaner vehicles must be capable of being operated reliably and economically. This may require not only an initial capital subsidy but also substantial investment in training and maintenance facilities for the new technology, as well as fiscal effort to keep the price of the fuel attractive. If that is the case, then ***it is necessary to ask which alternative policies (for example, investment in busways) might have been introduced at the same cost to the government as the fuel-duty loss involved in subsidizing clean fuels.***

Several countries follow the policy of keeping fuel taxes relatively low and giving positive incentives for the use of relatively cleaner fuels. This has been the approach of promoting fuel from agricultural crops in the United States and promoting CNG in a number of countries. But such measures can be expensive to the public budget and, to the extent that fuel prices that consumers face are lower, encourages excessive use of fuel. As far as externalities are concerned, the generally accepted philosophy (Sandmo 1975) is therefore that ***tax rates on goods that have external costs should be adjusted upward to reduce their consumption to a social optimum, and any additional revenue collected used to adjust general tax rates downward.***

CHAPTER 7

The Supporting Institutional Framework

The Range of Institutions Involved in Urban Air Quality

Steps taken to tackle mobile sources of urban air pollution affect, and are affected by, a wide range of sectors and institutions. Transport, petroleum, environment, finance, urban planning, and even agriculture (for biofuels) are among the sectors involved. A number of groups are engaged to varying degrees in policy formulation and implementation, including the auto and oil industry; goods delivery and passenger service firms; vehicle repair and service industries; manufacturers of emissions measurement equipment; environmental nongovernmental organizations (NGOs); firms with their own fleets; private vehicle owners; municipal, state, and national governments; and regional trade organizations. Air quality policy, more than most other policy areas, needs a high level of integration with, and within, the policy of agencies for which air quality is not the central issue of concern.

The Role of Central Government

Central government has a number of functions critical to the establishment and implementation of an air quality improvement strategy at the city level.

First, central government is usually the only agency that is commissioned to set policy and standards for fuel and vehicles. Municipal governments may be able to impose tighter standards in some cases, but they cannot "relax" the standards set by central government even if that would mean much more effective enforcement in practice. Vehicle inspection is a good example. A number of countries have regulations that require that every vehicle in the country be inspected regularly. In reality, only a small fraction of vehicles are inspected, using tests that can be easily cheated on. In order to make inspection more effective, an obvious approach is to employ more effective test procedures and quality-control measures and target vehicle categories likely to contain a disproportionately large fraction of high-circulation gross polluters in large cities. But such a selective approach with test protocols different from those set by central government would normally not be permitted. ***When delegating the enforcement of environmental standards to municipal agencies, national governments should carefully consider likely probability of effective enforcement in light of financial and human resources available***.

While government should consult industry and civil society about vehicle emission and fuel standards, it should not outsource responsibility for policy development and standard setting. If refinery revamps are involved, a lead time of several years is typically 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 fuel quality and vehicle technology improvement***.

Other regulatory frameworks may be equally important. For example, the ability to increase public transport operating efficiency through competitive tendering of franchises, including the imposition of strict environmental standards on contracting suppliers, depends on the existence of an appropriate legal framework for franchising. Further, franchising arrangements can be designed to positively encourage relatively non-polluting operators. ***Framework legis-***

lation on urban public transport should pay explicit regard to its air pollution impacts.

Central government also usually has the ultimate power in fiscal matters. The level and structure of fuel taxation, which is usually a central government prerogative, is most important as an inducement to environmentally sensitive decisionmaking on the choice of technology as well as on the amount of transport demanded. An example is that maintaining a high tax differential between gasoline and diesel to raise revenue from the relatively well-off (namely, gasoline car owners) may simply stimulate the purchase of more polluting diesel vehicles in developing countries. ***It is important that taxation powers be exercised with environmental, as well as revenue generation, considerations in mind***.

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 environmental research, central laboratory facilities, and environmental education and information programs. ***Central government should accept the responsibility for encouraging clean air by having a policy on clean air related public expenditures***.

Concerted action within and among actors in different sectors is important for optimal policy formulation. Transport, finance, environment, 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 transport-related air pollution. In some cases the problem is simply a matter of lack of coordination; in others there may be clear conflicts of interest between 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, transport, finance, and energy on air pollution strategy***.

The Hierarchy of Government and Inter-Jurisdictional Collaboration

The division of function between levels of government on a general subsidiarity principle (that powers should be devolved to the level in the hierarchy of government at which they can be most effectively implemented) is generally sensible. Sensitivity to that fact may require the granting of some powers to local authorities to levy surcharges as part of local environmental policy or to be able to retain as local trading income the revenues of local road pricing schemes. ***Where responsibility for urban transport is decentralized, appropriate fiscal arrangements must be made to facilitate local ability to meet those responsibilities***.

But fragmentation of responsibility between hierarchies of government may also cause problems. If different cities with comparable air pollution and population exposure allocate varying amounts of funds for air quality monitoring and mitigation measures, then some large cities that have chosen not to allocate much funding for air quality monitoring could end up not collecting even basic data on ambient air quality. In the absence of such fundamental and critical data, it would be difficult for central government to formulate a sensible air quality management strategy. Another example can be found where different municipal governments pursue their own version of vehicle I/M. As annex 7 argues, there are considerable merits to centralized software development and standardizing test protocols and equipment specifications. Not having the same air quality monitoring equipment specifications and procedures is yet another example of collected data not being conducive to analysis and inter-city comparison. ***Standardizing equipment specifications and data collection procedures across major cities in the country, and ensuring that essential data be collected in very large cities, would be useful for policy formulation at both the national and municipal level.***

In public transport, the division of responsibility between the state and municipalities for the provision of bus services has inhibited coordination of services in many Brazilian conurbations. Similarly, competition between independent municipal jurisdictions in continuous conurbations has often resulted in "beggar-my-neighbor" policies that are seen to be in the short-term advantage of the individual jurisdiction but that, when pursued by all, make all worse off.[1] Unwillingness to pursue restrictive parking policies or, even worse, the provision of subsidized parking to attract trade, is a prime example.

There are several different institutional ways of confronting this. In a number of countries in the industrial and developing worlds, there are single-purpose, conurbation-wide agencies for urban transport planning and management that have priority in strategic decisions over the separate jurisdictions in urban transport matters (World Bank 2002f). In others, there are formal consultation and collaboration arrangements.[2] ***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***.

The Organization of Municipal Government

Air pollution problems are location-specific. Once standards are set, particularly if there is geographic differentiation, it is state 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.

Problems arising from different objectives in different ministries and departments need to be addressed. At the national level such conflicts may be well aired and find their resolution in high-level cabinet decisions. At the municipal level, the police, city planning, transport, and other agencies are frequently less well coordinated. For example, 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 type of conflict is accentuated where 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 suboptimal resolution of such conflicts.

The institutional requirements for effective traffic management

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 developing countries. 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 systems implemented in Manila and Mumbai in the 1980s are now largely out of commission because of institutional failures. ***Institutional factors are critical to the success of traffic management.***

Conflicts of interest frequently arise over traffic management. At the technical level, traffic signal settings for delay minimization differ from those for emission minimization. At the political level, conflicts

[1]This is a clear case of the "prisoner's dilemma" phenomenon as expounded by Luce and Raiffa.

[2]Such as the coordination committees set up in the major Brazilian conurbations to bring together state and municipal interests.

of interest may occur among jurisdictions competing for business because restraining parking freedom can discourage trade in their area. In fact, available evidence in western Europe suggests that city center pedestrianization actually increases trade in the controlled area, and can be facilitated by regional collaboration to prevent misplaced "beggar-my-neighbor" policies to attract trade (that is, hoping that other districts, but not one's own, will restrain parking). ***Conflicts of interest can be minimized by better information and institutional coordination.***

At the municipal or city region level the solution may be found in the establishment of a department or agency with comprehensive responsibility for establishment of a transport and land use plan, with air quality as one of its objectives, to which contributory technical functions (traffic management, public transport policy, road investment) must conform. Examples of such agencies are to be found in most of the United States and European cities that have well-integrated urban transport policies. ***It is important to establish a specific responsibility for urban air quality within the municipal government structure.***

Involving the Private Sector

Many of the agents that implement activities affecting urban air quality are in the private sector. They include fuel and vehicle manufacturers and marketers, public transport companies, industrial and commercial firms operating their own transport fleets, and, of course, individuals using private transport 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***.

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.***

The private sector can play a positive role, provided that certain conditions are met. If rules and regulations appear to be established without adequate consultation or at short notice, it might become difficult even for efficient private sector firms to comply and stay in business. If firms are not treated equally—for example, if subsidies are given only to state-owned enterprises but not to private sector firms—it would be difficult for private firms to compete efficiently. If standards and regulations are weakly enforced, there could be partial or total degradation of the market whereby those who "cheat" end up driving out those who do not. ***For the private sector to play a meaningful role in air quality improvement, the government needs to create an enabling policy environment whereby there is a clear and transparent regulatory framework, a level playing field, and enforcement of standards and regulations on all actors.***

Vehicle manufacturers

Vehicle manufacturers can be involved in discussions about technically feasible emission or fuel economy standards, such as the CAFE standards in the United States or the more recent European voluntary fuel-economy agreements. The auto fuel policy report in India, completed in August 2002, involved extensive consultation with government agencies, vehicle manufacturers, refiners, and research institutions to set future fuel quality and vehicle emission standards, thereby greatly enhancing the probability of compliance at the manufacturing level.

The possibilities of perverse adaptation to the regulations need to be carefully protected against. Both manufacturers and consumers may be expected to find ways around standards that they find restrictive. For example, the exclusion of SUVs and vans from the light-duty vehicle emission and CAFE standards has permitted their rapid growth in the United States, significantly reducing the effect of the standards on both local and global emissions. This has been exacerbated by the considerable tax exemption enjoyed by this vehicle category. ***It is very important to look out for loopholes in the specification of standards.***

In some developing countries, there are significant environmental risks attached to the protection of a domestic manufacturer embodying seriously outdated technology, as in the case of the Ambassador car in India until the opening of the market to new suppliers. Other ways of involving the manufacturers, such as requiring them to guarantee the durability of performance of their vehicles to the agreed standards, would be extremely useful. Durability requirements are rare in developing countries and require significant strengthening of capacity to enforce in-use vehicle emission standards by means of regular vehicle maintenance and fuel quality standards at the point of sale, but ***government and the private sector should work together to adopt durability requirements that are universally implemented in industrial countries today, and considered essential for controlling exhaust emissions.***

The implementation and enforcement of stringent standards may be an effective way of "forcing" technological development in countries that manufacture vehicles or refine fuels. In both India and Taiwan, China, the governments have progressively tightened emission controls on motorcycles, with the effect that four-stroke engines have replaced two-stroke in new vehicle manufacture in Taiwan, China. At the same time, increasingly tighter standards have also led to improvements in the two-stroke engine technology itself as well as the development of suitable catalytic converters. ***Setting stringent standards when there are cost-effective, commercially proven technology alternatives to meet the standards can be instrumental in forcing out old polluting technologies***.

The refining industry

Particularly in the case of sulfur reduction, tightened standards impose high capital costs on the manufacturers. If the industry considers the time-frame set by the government or the level of emissions reductions targeted to be unrealistic, policy implementation is likely to encounter delays, or worse, result in loss of credibility for environmental regulations. In one country, a number of tighter fuel quality specifications have been issued with specific implementation dates, only to have the dates missed time and again and revised dates issued because the government-owned domestic refineries were in no position to produce tighter specification fuels. ***Close consultation with the refining industry is an important component of effective fuel policy in countries with domestic refineries.***

There are usually different ways of meeting the same emission standards. The diesel certification process in California allows refiners to come up with much cheaper alternative diesel formulations to the "reference" diesel (defined by the state government), as long as they meet the same emission levels. This approach ultimately saves consumers money (see box 3 in annex 2). While the particular certification process is complex, the basic principle nevertheless offers a useful lesson: ***whenever possible, suppliers should be engaged in the standards discussions and be given the flexibility to seek the lowest-cost options for meeting specified emission targets.***

One sector distortion that has an adverse environmental impact is protection of government-owned monopoly oil companies, which tend to acquire considerable political power, especially in oil-producing countries. This has resulted in major oil producers continuing to supply leaded gasoline on the domestic market when countries that are much poorer have long since banned it. Addressing this sector distortion requires a strong political will, and often occurs only after there is a major change in government, as in Nigeria in recent years. ***Given the damaging economy-wide impact of protection of state-owned monopoly oil companies in many countries, concerted efforts should be made to alleviate this sector distortion.***

Public transport operators

Public transport companies are often operating the largest fleets of heavy and high-annual-km vehicles. In many countries these vehicles are manifestly ill-maintained and likely to be highly polluting. They are easy to identify, and can be subject to environmental control, even where there are not adequate facilities to regularly test all vehicles. But it must be remembered that the main objective of public transport policy is sustainable provision of mobility, usually to lower-income segments of the population. The improvement of environmental quality is an important, but not primary, consideration. Hence it is important that measures to improve the environmental quality of buses be part of a comprehensive public transport regulatory regime. Evidence in cities such as Lima, where there is relatively free entry into the business, suggests that this form of competition is likely to be environmentally damaging. But it should also be noted that, in Lima at least, free entry vastly improved service availability in comparison with that provided by the former parastatal monopolist. Hence an intermediate form of controlled competition for franchises, requiring a substantial public sector planning and procurement effort, is likely to yield the best environmental outcome, as well as be economically efficient. Cities such as Bogotá have achieved significant improvements in service quality and reductions in air pollution by buses along the TransMilenio corridors without setting extremely stringent technical standards. The lesson appears to be that ***attempts to reduce pollution by the bus sector need to be embodied in a comprehensive sector policy—one that usually requires substantial regulatory reform.***

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, all two-stroke engine three-wheelers were banned as of 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.

Nongovernmental Organizations and Civil Society

Nearly all of civil society is affected by air quality management. Tighter standards usually mean more expensive fuels or vehicles or both. Emissions inspection means that vehicle owners have to report to test centers, pay a fee to be tested, and pay to repair their vehicles should they fail the test. Private car restraint will inconvenience car owners.

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 offend them. A classic example is a monopoly state oil company resisting gasoline lead elimination. 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. ***Broader sector policy reforms, often essential for the introduction of cleaner vehicles and fuels, bring great benefits to society at large.***

Good information is important. 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 information campaigns. 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) 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. Campaigns to raise awareness about smoke emissions, proper vehicle maintenance or operation, and air quality have been successfully conducted in a number of developing country cities. ***NGOs and the media can urge and help the government implement new policy measures by playing an advocacy role.***

To this end, removing institutional and market barriers to the involvement of NGOs and the private sector in areas such as fuel quality monitoring and vehicle inspection and maintenance programs would be a useful first step. There is already extensive evidence on how to avoid corruption and increase efficiency in vehicle I/M in Mexico. 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 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. In this regard, having test stations in the hands of the private sector would make it much easier for the government to supervise and monitor the stations. It is more difficult for one government agency to apply sanctions to another government agency (for example, by taking away the license to operate test centers or firing staff found to be engaging in corruption) than it would be to take this step against a private sector contractor. ***The potential for NGOs and the private sector to take over from the government some monitoring and enforcement responsibilities should be explored.***

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 in which 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 to 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 frauds in fuel or auto part markets increases, so that those who guarantee quality can expand their market share (see International Experience 3). This underscores the importance of public education. "Naming and shaming," whereby those in fragrant violation of environmental regulations are published by name, can be another effective strategy, as is public listing of "green" companies and products. ***Creating market conditions that would encourage private sector actors to police themselves for compliance with regulations and standards is a "no regret" situation.***

Campaigns to educate the public about proper vehicle maintenance and use of lubricant for two-stroke engines, such as one organized by motorcycle manufacturers in Bangkok shown here, promote cost-effective mitigation measures.

CHAPTER 8

Synopsis: Constructing an Effective Package of Measures

Adopting a Positive Policy Stance

The transport sector has contributed to the deterioration of air quality in many large cities worldwide. But in a number of industrial country cities, declining air quality has been halted or reversed. Initially that improvement was associated with the elimination of major pollution from stationary sources, phasing out the use of coal in a number of coal-consuming cities, and more recently by addressing air pollution from the transport sector where the introduction of cleaner vehicle and fuel technology has resulted in dramatically lower emissions. Traffic demand management measures, bus priority measures, and the promotion of cycling have also played a role in reducing air pollution in a growing number of cities in both developed and developing countries. In some richer developing country cities the situation is not far removed from the situation of the industrial countries, where the value to society of improving air quality has increased faster than the marginal cost of advanced technologies. In those cities—for example, Santiago—investment in state-of-the-art fuel and vehicle technologies can be a logical and cost-effective step in air quality improvement.

Cost-effectiveness is a key consideration for developing countries as they devise their air quality policies. It should be remembered that only *after* adopting lower-cost options have industrial countries considered more costly mitigation measures requiring the use of emerging technology. In fact, the significant improvements in reduction in pollution from mobile sources that have allowed most industrial countries to meet the air quality guidelines recommended by the World Health Organization have come through well-established technological and operational strategies that are discussed in this report. The most advanced state-of-the-art technologies are still waiting to be introduced on a large scale even in the high-income industrial countries. Developing countries moving directly to more costly measures for controlling air pollution may simply divert resources from investments that offer greater reduction in environmental pollution or incur significantly more expenses to achieve smaller additional reductions in absolute terms.

The most aggressive and bold actions to control transport-related emissions should be undertaken in those cities with the most serious air quality problems and where the transport sector is a major contributor. However, even where transport's contribution is not currently high—such as in major coal-consuming countries or in low-income cities with a high percentage of solid fuel use—there is no excuse for taking a resigned attitude to air pollution from mobile sources. It is wise to anticipate the increase in transport emissions that has accompanied economic growth in every municipality worldwide.

Because of the great variety of national situations there is no universally applicable strategy for optimal reduction of transport sector emissions. Rather, it is necessary for decisionmakers to consider policies within their own technical, economic, political, and institutional circumstances.

The policy tools at their disposal can be broadly classified into two types:

- Direct policy tools that specifically target air quality improvement
- Indirect policy tools with objectives other than air quality improvement, but where there are collateral benefits in environmental improve-

ment, economic growth, and long-term poverty reduction.

Direct Policy Tools

Direct policy tools have air quality improvement as their primary objective. Some have very low cost-to-benefit ratios (“low-hanging fruit”), and hence substantial robustness to differences in national situations.

Targeting the greatest dangers to health

The initial targets for action in developing countries should be those pollutants that are known to cause the greatest damage to health:

- **Lead** is strictly a matter of gasoline specification, and the move to ban lead in gasoline is effective. Stopping the addition of lead to gasoline, which can be done at a relatively low cost, instantly stops lead emissions from all gasoline-fueled vehicles, regardless of their age or state of repair.
- **Fine particulate matter** originating especially from diesel-powered vehicles and two-stroke engine two- and three-wheelers, is a serious problem in developing countries.
- **Ozone** precursor control is a high priority in a limited but growing number of cities, often with specific climatic conditions.

Gross polluters

Worldwide, much of the emphasis has been on the emission characteristics of new vehicles. Even in the United States, however, a study 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). The problem of old and poorly maintained vehicles is even more transparently obvious in most developing countries. Dealing with these requires:

- Efficient identification of target groups (usually old, high mileage trucks and buses)
- Development of instruments for their testing and repair
- In some circumstances, assistance with premature scrapping.

Fuels and fuel standards

The appropriate standards for fuel will depend on country circumstances, including the level of air pollution and the costs of upgrading. But some general guidelines can be stated. The first three steps are expected to have high benefit-to-cost ratios:

- The first priority should be to move to unleaded gasoline while ensuring that benzene and total aromatics do not rise to unacceptable levels.
- Sulfur in gasoline should be lowered to a maximum of 500 wt ppm and preferably lower as soon as possible to enable efficient operation of catalytic converters (following lead removal).
- Where sulfur content in diesel is very high, a strategy to lower it to 500 wt ppm or lower should be identified and implemented. When combined with modern engine technology and good maintenance practice, sulfur reduction to 500 wt ppm would enable significant reductions in particulate emissions. Where moving to 500 wt ppm is very difficult in the near term but lowering sulfur to 2,000–3,000 wt ppm is relatively inexpensive, efforts should be made to move to this level immediately.
- Where the resource and infrastructure conditions for natural gas are favorable and those for clean diesel technology are much less so, consideration may be given to shifting high mileage public transport fleets from diesel to CNG.
- In countries with current or potentially high levels of air pollution from mobile sources, especially those that have already taken steps toward 500 wt ppm, or where new oil refining capacity is being added or major renovations being undertaken, the cost-effectiveness of moving to ultralow sulfur standards should be examined, taking into account maintenance capability and the concomitant investments in the necessary emission control technologies to exploit lower sulfur fuels.

Vehicles and vehicle standards

The setting of appropriate standards for vehicles is an essential complement to the determination of fuel standards. General guidelines for setting these standards are listed below. The third and fourth recommendations for motorcycles and catalytic converters are likely to have high benefit-to-cost ratios.

- Emission standards for in-use vehicles should be set at levels that are achievable by a majority of vehicles with good maintenance, and should be tightened over time.
- Vehicle emission standards for new vehicles should be progressively tightened to levels consistent with improving fuel quality.
- All new two-stroke engine motorcycles should be required to meet the same emission standards as four-stroke motorcycles.
- The installation and continued maintenance of catalytic converters should be required for all new gasoline-powered vehicles in countries where lead in gasoline has been eliminated.
- The introduction of particulate filters and other devices to reduce end-of-pipe emissions from diesel vehicles should be considered where ultralow sulfur diesel is available. As filter and other device technology develops and prices fall, and as low-sulfur fuels become more widely available, this strategy will become more robust.

Inspection and maintenance

A targeted and effective vehicle inspection program is necessary to make vehicle standards effective. International experience suggests the following advice on establishment of an I/M system:

- Centralized, test-only private sector centers with modern instrumentation, maximum automation, and "blind test" procedures, and subject to independent monitoring are most effective.
- In some circumstances, targeted incentive schemes for scrappage or replacement of high mileage gross polluters may be considered for complementing I/M.
- Education campaigns and clinics should be undertaken to improve two-stroke engine maintenance and lubrication.

Urban design

Much suspended particulate matter in developing country cities comes from re-suspension of road dust. This can often be addressed by simple urban designs and landscaping that 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.

Institutional development

Ensuring that transport and environmental policies are consistent and well integrated requires an appropriate institutional basis. A basis specifically targeting air quality improvement requires:

- An effective air quality monitoring regime be established in large cities, with institutional responsibility clearly assigned and with adequate resources allocated.
- Institutions for administering and enforcing vehicle emission standards be established with a primary task of identifying and removing from the road gross-polluting vehicles.

Legal sanctions

Where regulatory measures and fines are insufficient to curb the worst offenders of local air quality, legal sanctions should be developed and implemented to:

- Prevent fuel adulteration and the smuggling of low-quality fuels from neighboring countries. Consideration may be given to hold fuel marketers legally responsible for quality of fuels sold.
- Prevent the import of grossly polluting vehicles.
- Ensure that testing stations are following correct procedures.

Indirect Policy Tools

Some policy measures are indirect policy tools with primary objectives other than air quality improvement, but which can give sizeable collateral air quality benefits. They tend to have long "gestation" periods, but can derail air quality management in the long run if poorly handled.

Sector reform

Many of the measures needed to reduce transport-related air pollution will be suboptimal or ineffective over the longer term without the reform of the transport or fuel sector. The oversupply of bus or taxi fleets, the misallocation of clean fuels such as natural gas, or simply poor quality gasoline and diesel fuel can all be symptoms of market distortions or regulated inefficiencies. Therefore, prior to or in parallel with instituting regulatory and administrative measures for reducing transport-related emissions, cities and countries should ensure that transport and fuel sectors are efficiently (and equitably) organized. A few examples of where sector reform can produce improvements in air quality are described below:

- Rationalize public and private transport fleets, reduce predatory behavior by paratransit, and ensure that private road users are not disproportionately favored over public transportation. To the extent that traffic congestion is a result of the organization of the transport sector, a city can make major improvements in air quality by improving the efficiency of the sector.
- Reduce direct and indirect subsidies and protection of domestic petroleum refineries and require that they meet increasingly stringent fuel quality standards. Rather than investing large sums of capital in inefficient and unprofitable refineries, the sector should be opened to new entry with the long-term objective of creating an open and competitive market. Allowing imported fuels to compete with domestic refineries is a particularly effective way of forcing efficiency improvement in the sector.
- Establish and enforce transparent and clearly defined regulations. Lack of enforcement is another way of protecting inefficient operators. Rigorous enforcement will also reduce the incentives for smuggling of fuels and fuel adulteration which are a major obstacle to maintaining fuel quality and reducing vehicle emissions in developing countries.

Where prices are controlled by the government, unsustainable subsidies that discourage uptake of cleaner fuels should be phased out. While sector reforms cannot be the sole solution for reducing emissions from mobile sources, the efficiency of the transport and energy sectors must be a concern for environmental policymaking. Some of these reforms, such as import liberalization for clean fuels, will be national in scope, whereas others, such as urban transport sector reform, will be local. In both cases, they are likely to have significant economic and social benefits aside from their environmental benefits, and in this sense should be seen as "no regret" measures.

Appropriate fiscal policies

Fuel taxes should be used to reduce private vehicle use, encourage fuel-efficient vehicles and the use of cleaner fuels, and compensate for road wear and tear and environmental damages. The main implications of this are as follows:

- In many countries this will mean raising taxes on diesel fuel for transport use.
- In addition to fuel taxes, separate vehicle charges should be considered based on vehicle weight, axel-loadings, and annual mileage.
- Direct charges for the use of urban road space should be introduced, including congestion charges.
- Taxes, import duties, and vehicle licensing disincentives should be introduced for polluting vehicles and engines.
- Serious consideration should be given to eliminating subsidies to public off-street parking as well as not permitting free on-street parking, especially where they increase congestion by generating private transport trips to congested locations, or where on-street parking increases congestion by reducing available road space.

Integration in transport planning and management policies

All of the technological improvements need to be set within a favorable transport planning and management policy framework. That framework requires the following:

- Transit-oriented development strategies should be developed to reduce trip lengths and concentrate movements on efficient public transport axial routes.
- Air quality audits of all new major transport infrastructure projects should be undertaken as part of environmental impact assessment procedures to determine if projects will lead to or worsen exceedances of ambient air quality standards.
- Priority should be given to buses in the use of road infrastructure, and particularly the creation of segregated busway systems, in order to improve and sustain environmental standards for buses.
- The efficiency of bus operation should be improved through the design of more efficient route networks, better cost control, and by the creation of incentives for improvement through commercialization and competition.
- Adequate pedestrian and bicycle facilities should be established in order to promote nonmotorized options for short distance trips.
- Protocols for traffic signal system settings should be established and implemented which result in reduced air quality emissions without compromising pedestrian and bicyclist safety.
- Fiscal and/or administrative devices should be implemented for restraining private-car traffic in congested areas, particularly at peak times.
- Competitive bidding for transport franchises should be promoted based on performance-based criteria, including emission characteristics of vehicles.
- Urban traffic management centers should be established, involving police in traffic management system design and training.
- A municipal department or agency with comprehensive responsibility for integrated land use and transport planning, including environmental protection issues, should be created.

Political and Technical Consistency

Experience suggests that strategies for reduction of urban air pollution are most likely to be successful where they are internally consistent in a technical sense, and as far as possible consistent with other sector strategies.

Technical consistency

Regardless of what vehicle emission and fuel quality standards are set, they should be technically consistent. The following are a few real world examples where technical consistency has *not* been followed:

- Mandating catalytic converters for gasoline vehicles in the absence of a reliable supply of unleaded gasoline.
- Mandating oxidation catalysts in buses when diesel available on the market contains relatively high levels of sulfur (significantly exceeding 500 wt ppm), which not only leads to rapid catalyst deactivation but also increases particulate emissions markedly by facilitating the oxidation of sulfur to sulfate while the catalyst is still effective.
- Mandating particulate filters in all diesel vehicles when the sulfur content of diesel sold on the market is in the thousands of wt ppm, incapable of enabling effective operation of the filter.
- Setting the same emission standards for vehicles irrespective of their weight, so that heavy trucks are required to meet the same particulate emission standards in g/km as small passenger cars.
- Failing to establish sufficient refueling capacity before or at the same time as mandating a large-scale conversion to CNG.

An audit on the technical consistency of a strategy, including consideration of upstream (fuel and other infrastructure) and downstream (transport sec-

tor service conditions) interactions is an essential requirement of an urban air quality strategy.

Avoiding conflict with transport economy

Ultimately, policies for air quality have to be politically feasible. This means that they have to be seen as not inimical to the interests of those capable of building a political consensus against them. A very common conflict is that with economy of transport. For example, a major source of particulate pollution is likely to be heavy diesel engine trucks and buses. In those circumstances simply forcing higher-cost vehicles on to the formal public transport sector (whether gas or modern diesel) may have the perverse effect of causing that sector to be replaced, legally or illegally, by a fragmented, smaller-vehicle informal sector that may be no less polluting but much more difficult to control. To avoid this, a multi-strand policy is likely to be required. Modernization of fleets through assisted scrappage programs, served by effective inspection programs to identify the appropriate vehicles for replacement, may be effective. International experience has demonstrated that ***attempts to improve the quality of the public transport fleet are most likely to be effective if undertaken in the context of a thorough reform of regulation of the sector.***

Social acceptability

An even more difficult conflict arises where existing high levels of personal mobility are constrained in order to reduce air pollution. For example, if pollution arises from privately owned two-stroke engine motorcycles (typical of many Asian cities), the most effective short-term instruments are likely to be programs to improve lubrication behavior. For the medium term, the most effective response would be to tighten emission standards, leading to significant replacement of two-stroke engines by four-stroke engines (as well as introduction of new direct injection two-stroke engine technology). In the very long term, however, this is not likely to be a sustainable solution, because the motorcycles are replaced by motor cars as income rises, and congestion increases. Hence, even in cities such as Hanoi or Ho Chi Minh City in Vietnam, which have high levels of four-stroke engine motorcycle ownership and very high levels of personal mobility, further long-term action will be needed to manage and restrain car use. Such long-term action may call for a broad policy, including traffic management and restraint through parking and other policies, together with public transport development. That would include bus priorities and segregation, or possibly even rail system development in the largest cities. Those types of investment, while environmentally beneficial, will probably also be justified by transport-efficiency considerations.

"Horses for Courses"

The policy stance adopted in this report is that strategies need to be adapted to local problems and possibilities. Mostly that impinges on the pace at which state-of-the-art technology can be adopted as incomes increase. But some other characteristics of cities also influence the selection of strategies.

Cities in fuel-producing countries

Curiously, cities in fuel-producing countries may face particular difficulties with fuel quality. This is because they may perceive a need to protect the local manufacturers and be tempted to do this by a liberal approach to fuel quality. This is a particular problem in countries with government-owned refineries, where finance ministries may be resistant to the very large investments necessary to improve fuel quality (particularly to bring down sulfur content). They may also resist competition from cleaner imported fuels for balance-of-payments reasons. It is not uncommon to find a politically powerful and connected monopoly state oil company resolutely opposing tightening of fuel standards, even something as straightforward as gasoline lead elimination.

The solution is to set what are considered to be economically and environmentally supportable fuel standards and to open the market to imported as well as domestically refined fuels. But there is no easy path to this solution. What is worth doing, however, is to undertake a study of achieving different levels of standards and to compare costs of imports with those of domestically refined fuels. If the cost of the former is markedly lower, it is important to understand why and inform the public openly so that benefits and costs of protecting the domestic oil industry can be fully appreciated.

If the country is fortunate enough to have an indigenous supply of natural gas and an existing distribution network, a program of assisted fuel switching to CNG in heavy vehicles may be a consideration. Usually, however, CNG is not markedly cheaper than diesel as a transport fuel, so that the cost-effectiveness of the use of CNG is a major problem. The structure and levels of fuel taxation may also need to be adjusted to give the appropriate incentives to operate gas vehicles without seriously depleting tax revenues or simply generating a replacement of gasoline, rather than diesel, vehicles by natural gas. Even for a country with gas resources and city distribution, such as Colombia, the distribution costs from gas field to market may leave the full distributed cost of gas uncompetitive with that of liquid fuel, so that supporting tax discrimination will still be necessary for large-scale switching from diesel to CNG. ***The apparent balance-of-payments benefit of using a domestic resource needs to be carefully weighed against the sector efficiency and macroeconomic costs of subsidy to domestic fuel producers.***

Cities in vehicle-manufacturing countries

Vehicle-manufacturing capacity is unlikely to cause a country any problem if it is privately owned, subject to competition from imports, and at least in part dependent on exports for its livelihood. In those circumstances vehicle quality is unlikely to be a big problem as companies will need to meet standards that would be acceptable in industrial-country markets. That has been the case in emerging manufacturing countries such as the Republic of Korea. However, it is not unusual in these cases for the auto industry to be pitted against an oil industry that does not want to bear the costs of manufacturing fuels to the higher standard. Government needs to mediate and arrive at a compromise position.

The presence of vehicle-manufacturing capacity may also make vehicle I/M easier to the extent that there is likely to be greater local technical capacity to handle I/M. In non-manufacturing countries all vehicles are imported. The appropriate stance then would seem to be to adopt standards related to those of the source country that can be achieved by properly maintained vehicles. That would to some extent be hampered because local technical expertise in vehicle I/M would likely be lower, making enforcement of standards more difficult.

The greatest danger in developing countries that manufacture vehicles is likely to arise from protective trading policies. There will be a temptation to proscribe, or severely tax, the import of new vehicles competing with those manufactured domestically. At the same time, because of a perceived need for cheaper, secondhand vehicles, in some countries restrictions on the import of used vehicles are likely to be nonexistent or much less stringent. This is likely to have the perverse effect of encouraging the import of older, lower-standard vehicles.

The role of economic philosophy: the command economies

Some of the most severe problems of transport-generated air pollution arise in the command economies and the transition economies. In such economies, formal sector public transport provision, fuel pricing, and vehicle imports tend to be tightly controlled by the government. But the disappearance of the former sources of support for public transport in the transition economies and the increasing difficulty of maintaining it in some of the remaining controlled economies (for example, the central Asian republics of the former Soviet Union) have led to a collapse of the traditional large vehicle public transport services on which the population was primarily dependent to meet its movement needs. Public transport vehicles are not being adequately maintained or replaced, with the effect that those still on the road are highly inefficient and polluting by industrial country standards. The disappearing traditional service tends to be supplemented or replaced by informal sector services operating under inefficient, quasilegal regulatory arrangements, often with inappropriate vehicles. For example, public transport in the secondary cities of Uzbekistan is increasingly dependent on the seven-seater Daewoo Damas minivan.

Sector reform is crucial in those countries. Indeed, significant progress in urban air quality management is unlikely unless sector reforms are carried out in parallel with imposition and enforcement of emission standards. The agenda for such countries thus appears to be that of leveraging private capital, promoting market-based solutions, and undertaking public education to create market conditions favorable to emissions reductions.

Some special cases?

Some cities will inevitably not be adequately comprehended in this limited taxonomy. For example, many historic cities do not have enough space to carry the traffic volumes generated or to provide segregated public transport systems. For those cities, the experience of some of the European cities such as Zurich may offer the most appropriate model. In that and many other cases, some locations have been closed completely to motorized traffic; in others entry is limited to public transport. The success of some of the European cities in maintaining public transport access in constricted space can be replicated in developing countries if the political will exists to give adequate priority to public transport in the allocation of space.

At the other extreme are cities that have been developed at artificially low densities, such as the cities of apartheid South Africa. On the one hand, these cities present enormous social problems; on the other, they offer the possibility for innovative planning solutions in the process of restructuring land use. Land use planning and the allocation of adequate space for segregated public transport is particularly important to air quality in those cities.

Conclusion

While the specific actions for reducing transport emissions will vary from city to city, there are several underlying principles that this report seeks to emphasize for building an effective policy package:

- Raise awareness among policymakers and the general public about urban air pollution levels and damages and specify and promote the role that transport plays.
- 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 in business as well with consumers about business “best practice” that is also likely to bring about environmental benefits to society.
- Work with, not against, the economic incentives of various transport actors.

ANNEX 1

Conventional Fuel Technology

The majority of vehicles worldwide will continue to use gasoline and diesel for the foreseeable future. This annex focuses on fuel and vehicle technology involving these two liquid fuels. It discusses fuel quality improvement and what is driving the evolution of fuel specifications. The specific fuel and vehicle standards are treated in annexes 2, 3, and 4. (Two- and three-wheelers are treated in annex 5.)

Gasoline and diesel fuels are made up primarily of hydrocarbons. Virtually all components are naturally found in these fuels with the exceptions of olefins (which are formed in refining processes) and lead, oxygenates, and detergents (which are externally added). The primary product of combustion is CO_2, a greenhouse gas with no adverse health effects. Other combustion products include CO and hydrocarbons, both products of incomplete combustion; NO_x, which is formed when nitrogen in air is subjected to high temperature in the presence of oxygen in the combustion chamber; and various decomposition (for example, benzene from nonbenzene aromatics) or polymerization, dehydrocyclization (for example, PAHs), and dehydrogenation (for example, soot) products. Some fuel parameters affect emissions of all vehicles essentially equally. For example, the amount of lead emitted is approximately proportional to the amount of lead contained in gasoline multiplied by the amount of gasoline consumed. For the most part, however, pollutant emission levels are determined not only by the fuel composition and the engine type but also by specific engine and driving characteristics that interact in complex ways. A given vehicle using the same fuel will show different emission levels depending on the driving cycle.

There have been enormous changes in fuel specifications worldwide in the last three decades. These changes can be categorized into two groups:

- Those leading directly to reductions in exhaust or evaporative emissions. Beginning with lead phase-out, these steps have historically been taken in stages over a number of years.
- More recently, those for enabling the market introduction of very advanced emission control technology. The dramatic reductions in fuel sulfur envisaged in Europe and North America during the latter half of this decade are prime examples of this.

Gasoline Quality Improvement

Gasoline is a volatile fuel, and hence evaporative emissions of hydrocarbons need to be taken into account in addition to exhaust emissions. Properly tuned gasoline vehicles typically emit far less particulate matter in mass than conventional diesel technology vehicles. That said, gasoline vehicles may have high number counts of particles, and number counts may be of interest in the future. The gasoline fuel parameters that affect air quality are listed in table A1.1.

The extent to which undesirable fuel components can be reduced is primarily a question of the costs of removing them—for example, dramatic reductions in benzene and total aromatics or production of sulfur-free gasoline would be expensive.

Benzene and total aromatics tend to increase initially as lead is phased out to make up for the octane shortfall. Benzene is a carcinogen and is found in gasoline as well as formed as a by-product of combustion of other aromatics. Various studies have indicated the cost-effectiveness of controlling benzene itself rather than total aromatics. Controlling total aromatics, which are benzene and ozone precursors, is an important consideration but not as much as controlling benzene itself.

TABLE A1.1

Gasoline Fuel Parameters that Affect Air Quality

Parameter	Characteristic feature
Lead	Lead is an inexpensive octane enhancer and has historically been added to gasoline as alkyl lead. It deactivates catalytic converters permanently. Because lead is extremely toxic, its use in gasoline has been banned in a growing number of countries.
Benzene	Benzene, the smallest aromatic compound with no alkyl groups, is a carcinogen. It is emitted from gasoline as a result of evaporation and as unconverted benzene from the exhaust pipe. Benzene has an extremely high octane rating, and is hence a good gasoline blending component from the point of view of combustion.
Sulfur	Sulfur in gasoline acts as a poison for conventional catalytic converters. (The effect of the poison is temporary and reversible to a large extent.) Vehicle manufacturers recommend for conventional catalytic converters that the level of sulfur in gasoline be kept below 500 wt ppm, and preferably below 100 wt ppm. The impact of reducing sulfur on the performance of catalytic converters follows a nonlinear relationship, with emissions decreasing more rapidly below 100 to 150 wt ppm (MECA 1998). Sulfur not trapped in catalytic converters is emitted as SO_x, some of which undergoes chemical transformation to become secondary particulate matter or acid rain.
RVP	The Reid vapor pressure is a measure of gasoline volatility. Lowering RVP is a cost-effective way of controlling VOC emissions, including the emissions of light olefins. This requires lowering the level of butanes, and, possibly, C_5 hydrocarbons (hydrocarbons with five carbon atoms). Butanes are the cheapest source of octane, and their removal typically adversely affects refinery economics. Lowering RVP, however, can make starting carbureted vehicles difficult, particularly in cold weather, and may cause misfires and higher tailpipe HC emissions. RVP should be within a certain range depending on vehicle technology and ambient conditions.
Aromatics	Aromatics with two or more alkyl groups are photochemically reactive and contribute to ozone formation. Alkyl-aromatics (that is, nonbenzene aromatics) also dealkylate (lose alkyl groups) during combustion, and a fraction is emitted as benzene. However, it takes 10–20 times as much alkyl-aromatics to form benzene in the exhaust gas as benzene found in gasoline itself. The photochemical reactivity of aromatics and their decomposition to benzene are the two primary environmental concerns with aromatics. Aromatics have extremely high octane ratings, and hence are good gasoline blending components from the point of view of combustion.
Olefins	Olefins in gasoline are formed primarily during cracking processes. Olefins are photochemically reactive and are ozone precursors. This is the primary concern. In addition, at elevated levels, olefins increase the emissions of NO_x. NO_x is a precursor for ozone, particulate matter, and acid rain. Olefins have fairly high octane ratings, and hence saturating them to reduce their quantity adversely affects the combustion characteristics of gasoline.
Alkylates	Alkylates are high-octane paraffinic hydrocarbons with essentially no adverse effects on air quality. They are excellent substitutes for less desirable blending components such as aromatics. However, alkylation is an expensive process and requires the presence of a catalytic cracking unit at the refinery.
VOCs	Volatile organic compounds contain photochemically reactive hydrocarbons. Reductions in VOC emissions will therefore reduce the amount of ozone precursors in the atmosphere. VOCs could also adsorb onto particles and increase particle mass. Evaporative emissions consist entirely of VOCs; VOCs are also found in exhaust gas.
Oxygen	Oxygenates such as ethers and alcohols have high-blending octane and hence help compensate for octane shortfall after lead removal. The presence of oxygen in oxygenates also facilitates clean combustion in vehicles that are not equipped with oxygen sensors and that are running rich (low air-to-fuel ratio). If a vehicle is reasonably adjusted, however, oxygenates could raise NO_x, and also cause lean misfire, raising HC emissions. Oxygenates can increase the emissions of undesirable compounds such as aldehydes. Oxygenates also dilute gasoline, thereby decreasing the amount of such undesirable gasoline components as benzene, sulfur, total aromatics, and olefins. Oxygenates are more miscible with water than gasoline, and contamination with ground and drinking water with MTBE, an ether, has been a concern in the United States.
Additives	Gasoline in industrial countries contains additives to prevent the accumulation of deposits in engines and fuel supply systems. Deposits can increase tailpipe emissions.

Volatility control reduces hydrocarbon evaporative emissions and can be especially effective for addressing ozone if the low boiling fraction of gasoline contains a sizable amount of light olefins, which are strong ozone precursors. In cold weather, lower volatility can cause problems with starting and accelerating old carbureted vehicles and may cause a rise in tailpipe discharge of unburned fuel. Fortunately, ozone is primarily a summertime problem in many cities, making volatility control important during the summer. Lowering gasoline volatility, with careful seasonal management of volatility control, merits serious consideration in cities where ozone is a concern.

In addition, in order to take advantage of the growing number of catalyst-equipped cars, sulfur reduction should be seriously considered in countries with gasoline containing high levels of sulfur. Sulfur reduces the efficiency of the catalyst, and decreasing sulfur has a large impact on reducing exhaust emissions. Phosphorus is another catalyst poison, so additives containing phosphorus should be restricted.

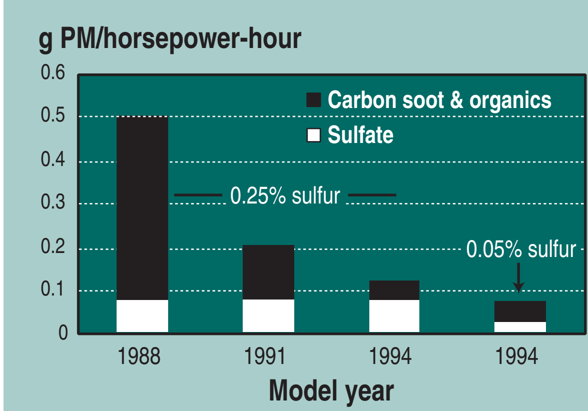
In contrast, lead has traditionally been *added* to gasoline as an octane booster to ensure smooth combustion. In the 1970s, little was known about the toxicity of lead, but it was known that lead in gasoline deactivated catalytic converters. The initial reason for lead removal was thus as an *enabling specification* to facilitate the installation of catalytic converters in cars. Only in the 1980s did there begin to emerge mounting evidence on the adverse health impact of lead exposure, even at levels previously considered safe, and particularly to young children.[1] The first step in gasoline reformulation is therefore typically to stop the addition of lead. A crucial issue in lead elimination is selecting alternative octane sources in a way that minimizes their adverse effects on air quality. Developing countries that are now phasing lead out of gasoline have the advantage of learning from the experience of countries that have already done so.

Diesel Quality Improvement

Diesel combustion gives rise to high levels of small particles and NO_x. Smoke in diesel exhaust is caused by incomplete combustion. White smoke is caused by tiny droplets of unburned diesel resulting from engine misfiring at low temperature. This smoke should disappear as the engine warms up. Black smoke could be caused by a faulty injector, insufficient air, underpowering or overfueling the engine, or both. Blue-gray smoke is the result of burning lubricating oil and is an indication that the engine is in poor mechanical condition.

Vehicle exhaust particulate emissions consist of carbonaceous and sulfate-based components. Because vehicle technology improvement addresses carbonaceous components only, in the United States sulfate contributions to particulate emissions, which are a function only of diesel sulfur content, became significant by 1993 in percentage terms, and hence the need to reduce sulfur in diesel to 500 wt ppm. Evolving contributions of carbonaceous and sulfate components to particulate emissions are illustrated in figure A1.1. It is clear from the figure that by the 1994 model year, the vehicle technology improvement for minimizing particulate emissions reached the point where

FIGURE A1.1 Particulate Emissions from New U.S. Heavy-Duty Diesels



Source: McCarthy 1994.

[1]Countries that have already banned lead in gasoline include Brazil (1991), the Slovak Republic (1996), Thailand (1996), Mexico (1997), Hungary (1999), Bangladesh (1999), the Philippines (2000), Georgia (2000), India (2000), Vietnam (2001), Sri Lanka (2002), and a host of Central and South American countries beginning in the early 1990s. But some large countries, including Indonesia, Venezuela, and a number of countries in Sub-Saharan Africa, still have leaded fuel.

it would not have been cost-effective, or even possible, to reduce particulate emissions by means of further vehicle technology advances only.

Many developing countries have relatively high T_{90} or T_{95} so as to maximize the yield of diesel. This tends to exacerbate the problem of particulate air pollution because heavy diesel "ends" are more difficult to combust. Lowering density (which, broadly speaking, would mean lowering the back-end of the distillation curve) makes the fuel-air mixture become leaner, since diesel engines inject a constant volume of fuel into a fixed amount of air. Leaner mixtures lower particulate emissions.

In order to reduce particulate emissions from diesel engines, standard engine overhaul and maintenance, coupled with diesel quality improvement, can have a significant impact. The environmental impact of various diesel parameters is listed in table A1.2.

The significance of sulfur in diesel

Many policymakers in developing countries equate dramatic reductions in diesel sulfur with a marked improvement in air quality. This arises in part from observing the heated debate that occurred between the auto and oil industries in Europe and North America about whether or not it would be cost-effective to mandate "sulfur-free" (10–15 wt ppm sulfur or lower) diesel to control particulate and NO_x emissions. For the purpose of controlling particulate emissions, the composition of particles matters. If the majority of particles are carbon and not sulfate based, lowering sulfur in diesel may do little to reduce par-

TABLE A1.2

Diesel Parameters that Affect Air Quality

Parameter	Characteristic feature
Density	Diesel fuel is metered volumetrically, so that the higher the density, the more mass is injected. The use of a fuel with greater density than that used in the pump calibration could even result in overfueling at maximum load, resulting in substantially higher smoke emissions.
Sulfur	Sulfur in diesel contributes to secondary particulate formation, elevated ambient concentrations of SO_2, and acid rain. It also decreases the efficiency of oxidation catalysts, increases sulfate-based particulate emissions while the catalyst is active, and degrades advanced exhaust treatment devices (such as particulate filters) rapidly.
Aromatics	Polyaromatic hydrocarbons (aromatics with more than one benzene ring) have been linked to higher particulate emissions. The impact of reducing aromatics on vehicular emissions is less clear. Although reducing aromatics is often linked to lower emissions, a cooperative program between Esso and Statoil found, for example, that reducing total aromatics from 32 percent to 10 percent had no marked effect on particulate emissions (Betts and others 1992).
T_{90}, T_{95}	T_{90} and T_{95} are the temperatures at which 90 and 95 percent, respectively, of diesel evaporates. Decreasing T_{90} or T_{95} could have a favorable impact on emissions, especially if heavy PAHs are removed as a result. Findings on the impact of varying T_{95} are discussed further under the European Auto-Oil Programme in annex 3.
Cetane	Cetane is a measure of the ignition quality of a diesel fuel. A high cetane number indicates a shorter lag between fuel injection and ignition. The cetane number is measured in an engine test (based on an outmoded engine that does not match modern engines). A cetane index is an approximation of the cetane number calculated from the density and distillation temperatures. Cetane improvement additives will increase the cetane number but not the cetane index, and hence many countries set cetane specifications as minimal cetane index *or* cetane number.
Cleanliness	With respect to satisfactory operation of diesel vehicles, cleanliness refers to the absence of water and particulate contamination. Dirt and water can plug fuel filters and cause serious damage to the fuel injection system because of the close tolerance of fuel pumps and injectors. Diesel engines are equipped with fuel filters to protect the fuel delivery system.
Stability	Stability is the ability of a fuel to resist the formation of gums and insoluble oxidation products. Fuels with poor oxidation stability contain insoluble particles that can plug fuel filters, potentially leading to decreased engine performance or engine stalling from fuel starvation.

ticulate emissions. In industrial countries, vehicle technology has been steadily improving so that particulate and NO_x emissions from new diesel vehicles are already very low. The only way to lower their emissions further would be to employ advanced exhaust-control technologies, some still under development, such as continuously regenerating traps (the performance of which may not be as good in passenger vehicle applications as that in commercial vehicles because passenger vehicles use full power less) and NO_x adsorbers (not yet fully proven on the road, and no tests demonstrating durability as yet) or reduction catalysts that can work at high air-to-fuel ratios. Most of them in turn are extremely sulfur-intolerant.

There are a number of developing countries where the limit on sulfur in diesel is as high as 10,000 wt ppm (equivalent to 1 percent). In such countries, lowering the diesel sulfur limit merits immediate attention. In parallel, steps should be taken to lower carbonaceous contributions (unrelated to fuel sulfur) to particulate emissions. An important milestone in the early stage of sulfur reduction is to lower diesel sulfur to 500 wt ppm, as the United States did in 1993 and the European Union in 1996. Sulfur reduction down to 500 wt ppm or lower is likely to have a measurable impact on particulate emissions from existing vehicles. This would also enable the use of oxidation catalysts in diesel vehicles. Although oxidation catalysts do not deal with graphitic carbon, they do lower soluble hydrocarbons attached to particles, lowering mass particulate emissions. However, oxidation catalysts oxidize sulfur, contributing to sulfate-based particulate emissions, so that it is important to ensure that suitable catalysts be selected from the point of view of minimizing sulfate formation over the catalyst, or else particulate emissions can even increase rather than decrease. Another point that should be addressed is that lowering sulfur levels in diesel fuels from, for example, 3,000 ppm to 350 ppm reduces the lubricity of the fuel and can adversely affect the wear on high pressure injection pumps. When diesel fuels with up to 500 wt ppm sulfur were first introduced in some markets, there was a rash of fuel injector O-ring failures causing fuel system leaks. The failures were limited to older vehicles, and the problems have not recurred. The damage to seals caused by the use of low sulfur fuels is an important issue that should be anticipated with an appropriate response prior to implementing a large sulfur reduction.

Lowering sulfur in diesel can also have beneficial effects on engine life and oil change intervals. Sulfur in the fuel burns in the combustion chamber and reacts with water to form sulfurous and sulfuric acids. These acids cause corrosive wear on the engine. They also degrade the oil and facilitate the formation of gums and varnishes. Alkaline additives are introduced into the oil to neutralize acidic compounds, and the speed at which these alkaline additives are neutralized in turn depends on the fuel sulfur content. A further contaminant is fuel soot from the incomplete combustion of fuel in the cooler parts of the combustion chamber. Soot increases viscosity and also causes wear. Soot and water in the lubricant can produce a sludge in the oil, resulting in lubrication problems if the oil is not changed frequently.

The impact of lowering sulfur below 500 ppm on oil change intervals depends on what is governing the interval: acid formation or soot in the oil. As an illustrative example, the Department of Buses of the MTA New York City Transit has been operating 4,200 buses on 30 wt ppm sulfur diesel since September 2000. As of April 2004, 2,800 of these buses were equipped with particulate filters. Oil change intervals have been shortened by the use of exhaust gas recirculation (EGR)—for NO_x control—due to oil degradation from greater soot formation. One bus company in Finland reported doubling of the oil change interval from 10,000 km to 20,000 km when it switched from 500 wt ppm sulfur diesel to reformulated diesel containing less than 50 wt ppm sulfur (Mikkonen and others 1997). This would indicate that acid formation, and not soot, was governing the oil change interval. Whether acidity or soot determines the oil change interval depends on the engine technology; modern, less polluting engines tend to force more soot through the oil than others. If the soot level is very much below the maximum level and the oil has to be changed because of acid formation, then diesel sulfur reduction is likely to lead to longer oil change intervals. On the other hand, if soot levels are near the maximum limits, then a dramatic reduction in sulfur is unlikely to lengthen the oil change interval. EGR increases soot formation significantly, so that the effect of soot from EGR, rather than the acidification tendency of fuel sulfur, is likely to dominate. In industrial countries with diesel sulfur in the vicinity of 300–350 ppm, the amount of soot is the primary parameter governing oil change intervals, and sulfur in diesel fuel at this level or lower has been found to have little effect.

Diesel operation and maintenance practice that increases smoke emissions

Trucks worldwide have traditionally been loaded to the maximum possible—often well beyond the designed load of the vehicle—in order to increase revenue and profit. For example, the principal long distance goods carrier in India is a two-axle, 9-ton truck. But these are often overloaded to 14–20 tons on outward-bound trips, although they operate closer to specifications on the return segment. When trucks are routinely overloaded, the following effects are typically seen:

- The engine has to work harder to produce the power needed, resulting in more smoke, especially among older engines.
- Working the vehicle harder tends to increase wear (affecting the engine, tires, brakes, and other vehicle components), but the vehicle is often not serviced any more frequently. As a result, the engine usually operates in a worse state of repair than a vehicle that is not routinely overloaded.
- Because the vehicle requires more power when overloaded, there is a tendency to overfuel the engine. Overfueling in turn is a significant cause of higher black smoke emissions.

In industrial countries, professional truck fleets have learned that they are financially better off in the long run when they use newer trucks and operate within the vehicle specifications. This can reduce their maintenance costs and virtually eliminate vehicles breaking down on the road (a particularly high-cost problem for trucks carrying perishable cargo). In many developing countries, however, the underlying conditions needed to promote improved maintenance, including effective enforcement of emission standards, do not yet exist.

The impact of overloading on overall emissions is complex because the basis for proper comparison is emissions per ton of goods moved. It is not obvious that one overloaded truck would emit more to move the same amount of goods as the equivalent number of properly loaded trucks. Even when vehicles are not overloaded, however, overfueling on naturally aspirated engines is common because it gives more power (and vehicles are often underpowered). Overfueling leads to higher particulate emissions.

Underpowering and overloading would not be identified in periodic I/M because heavy vehicles are typically required to report unloaded. Overfueling would also be difficult to catch: truck drivers can retune their engines temporarily so as not to be overfueled and pass emissions tests. For smoke tests, they can also keep injection timing advanced at the expense of NO_x emissions to minimize smoke.

Many automotive repair garages in developing countries are underequipped, and their workers lack adequate training. The prevalent culture of repairing vehicles when they break down, rather than programming preventive maintenance, is both the cause and effect of the lack of qualified technicians using good diagnostic and repair equipment. Rigorously enforcing emission standards is the first step toward creating demand for upgrading and expanding service and repair facilities.

Malfunctioning and incorrect adjustment (through tampering or lack of regular vehicle service) of the engine’s air and fuel systems are important causes of high smoke emissions. Dirt, clogging, wear, and incorrect pressure settings in diesel fuel injectors, together with inadequate repair and calibration of fuel injection pumps and turbochargers, are common causes of high visible exhaust smoke levels. Inadequate and dirty air filters and restrictive exhaust systems will increase smoke at high loads when the engine is operating at near full throttle or accelerating quickly. An engine in poor mechanical condition can also consume lubricating oil, thereby emitting higher levels of smoke and hydrocarbons. In terms of tampering, increasing the fuel delivery of the diesel fuel injection pump and resetting the engine's speed governor to a higher number of revolutions per minute are two common practices, both likely to increase smoke emissions.

Another cause of high emissions is the use of inferior-quality spare parts. In developing countries, there are different grades of spare parts, starting with genuine original equipment parts with guaranteed quality, followed by varying classes of less expensive parts with lower levels of quality. Most vehicle owners try, within their financial means, to use "closer-to-genuine" parts for critical assemblies such as engines and transmissions, and lower-cost components for noncritical areas such as brakes and electronics.

The engine components that most affect emissions are probably fuel injection pumps, fuel injectors, and turbochargers. Because of the high cost of these components, a significant fraction of these parts are repaired rather than replaced, using components from alternative sources, some of dubious quality. The use of secondhand injectors from a different engine version is especially problematic: the injectors may have a different flow rate or release pressure. If the injection pressure is too high or the injector hole size is too small, the fuel will penetrate more into the chamber; if the fuel hits the chamber wall (in the piston crown), there will be erosion, and the fuel that is cooled by touching the wall will not be fully combusted. Conversely, if the injection pressure is too low or the injector hole size is too large, the fuel will not penetrate enough into the chamber. It will have less air to mix with, adversely affecting both power and emissions.

Impact on the Refining Industry

The most significant impact of fuel quality specifications on the refining industry in the coming years is likely to concern fuel sulfur reduction. Much of the refinery investment in North America and Europe this decade will be channeled toward reducing sulfur in gasoline and diesel to ultralow levels. In developing countries, there are other fuel parameters that can be controlled to reduce overall vehicle emissions.

The sulfur content of fuels can be lowered by using low-sulfur crude oil or by treating fuels with hydrogen or both. Some Asian and African crude oils have relatively little sulfur, producing diesel with close to 500 ppm sulfur without further treatment with hydrogen. But because low sulfur crude oils are more expensive, there is a trade-off between making refinery investments to process high-sulfur crude and paying more to purchase low-sulfur crude and investing less in refinery upgrade schemes. Worldwide, the sulfur content of crude oil is increasing, requiring additional refining processing to achieve sulfur reduction. From a refining perspective, reducing sulfur in gasoline tends to be easier and cheaper than reducing sulfur in diesel. Unleaded gasoline typically has a much lower sulfur content than straight-run diesel. Refineries that rely primarily on reformate for octane, such as those in Pakistan, have very low gasoline sulfur, although at the cost of having elevated aromatics and benzene. However, if gasoline contains a lot of cracked naphtha (which has a high sulfur content), as in Colombia, Mexico, and Peru, it becomes quite expensive to reduce sulfur to ultralow levels even in gasoline.

The level to which a refinery can reduce the sulfur content of diesel fuel with relative ease is very much situation-specific. For example, because equipment (a low-pressure kerosene hydrotreater and a small diesel hydrotreater) were already in existence, the refinery in Sri Lanka was able to meet the country's 5,000 ppm sulfur target in 2003 and plans to reduce the sulfur level to 3,000 ppm in 2005. Going below 3,000 ppm for this refinery will require sizable investment and is unlikely to make economic sense unless the refinery size is substantially increased. In contrast, all of the four refineries in Pakistan would require significant investments to lower diesel sulfur below the current level of about 6,000–7,000 ppm because there are no spare hydrotreating or hydrogen-generation capacities.

The ease of sulfur reduction also depends on factors such as whether or not sulfur "sinks"—products that do not have to meet lower sulfur specifications—are allowed. In the study of the Chinese refining sector cited in box 2 (Yamaguchi and others 2002), a significant amount of diesel is used by industry, and industrial diesel oil served as a sulfur sink for which the specifications were not tightened. More importantly, there is a danger that industrial countries will export difficult-to-upgrade products such as cracked naphtha (high in both sulfur and olefins) to developing countries as they face increasingly stringent fuel specifications in the latter half of this decade. It is important for developing countries to take steps to ensure that cheap but dirty blending components from imports are not increasingly used.

If major reinvestment in large refineries or new investment (again for large refineries) is being undertaken, the incremental costs of going for ultra-low sulfur fuels as opposed to low sulfur fuels will be relatively small, so that it would make sense to go down to 10 or 15 ppm sulfur in one step. For example, when the Sitra refinery in Bahrain was recently considering revamping to achieve 500 ppm sulfur in diesel, it realized that it could go to 10 ppm for not much more additional cost. Given that it expected to export most of its product, going for the higher standard in one step made financial as well as environmental sense. In examining this case, it is important to bear in mind the scale of the refinery and the project: the refinery at 250,000 barrels per day (b/d) is large by international standards, and the diesel output alone is about 85,000 b/d, larger than many refineries in developing countries. The total cost of the refinery upgrade project is US$0.9 billion, of which about half is for diesel sulfur reduction.

Scale economics are one of the most significant factors when considering diesel sulfur reduction to 10 ppm. For many existing refineries in developing countries, severe sulfur reduction of this magnitude cannot be carried out economically, and the two options are (1) refinery closure (a difficult political decision in most circumstances) or (2) significant refinery expansion. Refinery expansion for a small country may not be economic if size expansion means that the refinery has to begin exporting a large fraction of its product slate. However, over the longer term, the growing demand for fuels in developing countries will mean that significant refinery expansion in some countries is likely, providing an opportunity for fuel quality improvement. For the immediate future, especially where refineries are small and sub-economic for producing ultralow sulfur fuels, considerable refinery sector restructuring would need to occur in order to produce these fuels.

There are other alternatives for improving fuel quality that can be pursued without major capital investments. Developing countries with refineries may wish to reexamine their diesel distillation control. The portion of diesel that boils at high temperature (as measured by T_{90} or T_{95}) can affect particulate emissions. High boiling point components can be more difficult to burn completely, and they also tend to contain a greater proportion of PAHs, which have been shown to increase particulate emissions. High T_{90} and T_{95} can also lead to faster and higher deposit buildups in the engine, particularly in the fuel injectors, causing malfunctioning and higher smoke and particulate emissions. To avoid greater deposit buildups, more frequent maintenance of the fuel injection system is needed. Because of the high diesel-to-gasoline demand ratio in developing countries, refiners try to optimize diesel production by raising T_{90} or T_{95}. Lowering these parameters can affect refinery economics but could bring environmental benefits. For diesel with low cetane numbers, increasing cetane to 45 could also lower emissions. Increasing cetane above 45 may do little for newer, high-swirl, direct injection turbo-diesel engines. Increasing the cetane level above 45 may help older, naturally aspirated engines. There may be low-cost options for improving fuel quality in the refining process that can be considered prior to moving to ultralow levels of sulfur.

Different fuel formulations can be used to meet the same emission targets. For example, sulfur, which adversely affects the performance of catalytic converters, can be balanced against other fuel parameters such as benzene and total aromatics: if the sulfur content is extremely low, catalytic converter efficiency will increase, converting more benzene and other aromatics in the engine-out exhaust, thereby reducing emissions. In order to reduce the cost of emission reduction, refiners in the United States have been given the flexibility to select an optimal combination of fuel parameters to meet the same emission standards. While monitoring fuel quality may be more complicated in such a system, this flexibility has enabled U.S. refiners to reduce emissions at lower costs than if gasoline formulation were precisely specified. Moreover, it is apparent that different components are associated with different pollutants and pollution problems. What is important in one country may be less important in another. Domestic problems and vulnerabilities should be reflected in national gasoline standards. Whenever feasible, refiners should be allowed to meet specific emission standards rather than have precise fuel composition specified, which can increase the cost of regulation.

ANNEX 2

Trends in Vehicular Emission Standards and Fuel Specifications in the United States

This annex discusses vehicular emission standards in the United States. The U.S. standards have a significant impact on Latin America and the Caribbean and, together with EU standards, give a good indication of the direction in which future standards are likely to develop in the rest of the world. A major auto and oil industry study undertaken in the United States is treated at some length, as the findings provide valuable data on the complex relationships between vehicular emissions, gasoline quality, alternative fuel use, and vehicle technology. In interpreting the numbers presented in this annex, it is important to bear in mind that the driving cycle used to generate emission data has a significant impact on the emission levels. Reference fuels used are also different, although their impact would normally not be as large as that from differences in the driving cycle. For these reasons, the emission standards elsewhere, such as the EU or Japan, should not be compared directly with those presented here on an absolute numerical basis.

The U.S. Congress passed the first major Clean Air Act (CAA) in 1970, requiring a 90 percent reduction in emissions from new automobiles by 1975 and establishing the U.S. EPA and assigning it broad responsibility for regulating motor vehicle pollution. The required standards were, however, not met until 1981. Congress amended the Clean Air Act in 1990 and required further reductions in hydrocarbon, CO, NO_x, and particulate emissions. The amendments also introduced more stringent emission testing procedures, expanded I/M programs, new vehicle technologies and clean-fuels programs, and transportation management programs (U.S. EPA undated a).

The emission standards for heavy-duty vehicles were introduced in 1970 (U.S. EPA undated b). The first particulate emission standards were introduced for 1988 model year (MY) (autumn 1987) and tightened progressively for 1991 and 1994 MY.

The U.S. reformulated gasoline (RFG) program came into force in 1995. As of the early 2000s, RFG constituted about 35 percent of the U.S. gasoline supply, the rest being "conventional" gasoline with much less stringent specifications. The RFG program gives more flexibility than perhaps any other program worldwide, allowing refiners to seek the least-cost approach to meeting vehicular emission standards. The U.S. auto and oil industry study generated a large amount of data correlating vehicular emissions, gasoline quality, vehicle technology, and air quality. The vehicular emission and fuel quality standards will be considerably tightened in the United States with the introduction of the so-called Tier 2 emission standards, which come into effect beginning in 2004 for gasoline vehicles and in 2006 for diesel vehicles.

Clean Air Act Amendments of 1990

The CAA Amendments of 1990 required significant changes in the U.S. refining industry. The amendments defined two categories of regulated gasoline—oxygenated gasoline (OxyFuel) and RFG. OxyFuel, which is gasoline with an oxygen content of 2.7 percent by weight (wt%)—corresponding to 15 percent by volume (vol%) methyl tertiary-butyl ether or 7.3 vol% ethanol—is specified for CO nonattainment areas[1] during the winter months, when CO emissions

[1]Nonattainment areas are those areas that are not in compliance with national air quality standards. Separate regulations apply to CO and ozone nonattainment areas. Noncompliance with CO standards is primarily a winter problem. Noncompliance with ozone standards is primarily a summer problem in the United States.

are high. "RFG" refers to a more extensive change in gasoline properties that reduces VOC emissions and toxic emissions. RFG is required in the areas in the United States that have the most serious problems with ozone pollution. RFG requires 2 wt% oxygen throughout the year, corresponding to 11 vol% MTBE or 5.4 vol% ethanol.

The CAA Amendments require vehicle emission reductions in two phases. For Phase I, beginning in 1995, the law specified a minimum of 15 percent reduction in VOC emissions during the high-ozone season and a minimum of 15 percent reduction in toxin emissions during the entire year. The U.S. EPA estimates that the impact of Phase I of the RFG program was to reduce annual emissions by 17, 2, and 17 percent for VOCs, NO_x, and air toxics, respectively, since 1995. Under Phase II, which began in 2000, the program will cut VOC, NO_x, and air toxics emissions by 27, 7, and 22 percent, respectively, compared with 1995 (U.S. EPA 1999c). The baseline gasoline in 1990 and fuel specifications to meet these reductions are given in table A2.1–table A2.3, and federal diesel standards in table A2.4.

As table A2.2 and table A2.3 show, Phase I was further divided into two periods, using the Simple Model and the Complex Model, respectively. The Simple Model established three different sets of equations to calculate toxics reduction from the baseline gasoline. The Complex Model was more detailed, consisting of different systems of equations to calculate VOC, NO_x, and toxics emissions. A different set of Complex Model equations have been established for Phase II. There are minimal numerical requirements on fuel composition in both cases.

The above illustrates one prominent feature of the U.S. fuel specifications, in sharp contrast to the rest of the world: they are performance based. The specifications rely on empirically derived models to identify a range of fuel compositions that will achieve emission targets. They require an extensive database of emission levels as a function of fuel composition and vehicle characteristics. The empirical relationships may have to be updated from time to time as the vehicle fleet characteristics evolve over time. Monitoring is

TABLE A2.1 U.S. Industry Average Baseline Gasoline, 1990

Gasoline parameter	Unit	Summer	Winter
RVP	psi	8.7	11.5
Benzene	vol%	1.53	1.64
Total aromatics	vol%	32.0	26.4
Olefins	vol%	9.2	11.9
Sulfur	wt ppm	339	338
Oxygen	wt%	0.0	0.0

psi Pounds per square inch.

Source: UOP 1994.

TABLE A2.2 Simple Model, 1 January 1995–31 December 1997

Gasoline parameter	Unit	RFG Per gallon	RFG Averaging	Conventional gasoline
Summer RVP, maximum	psi	7.2[a] / 8.1[b]	7.1[a] / 8.0[b]	—
Benzene, maximum	vol%	1.0	0.95	—
Oxygen, minimum	wt%	2.0	2.1	—
Air toxics emission reduction	%	15.0	16.5	—
Exhaust benzene emissions		—		Same as refinery's 1990 gasoline
Sulfur, olefins and T_{90}	Capped at refinery's 1990 levels			Capped at 1.25 × refinery's 1990 levels

psi Pounds per square inch; — not applicable.

[a]VOC control region 1, southern half of the United States.
[b]VOC control region 2, northern half of the United States.

Source: UOP 1994.

TABLE A2.3

Complex Model, 1 January 1998–31 December 1999

Gasoline parameter	Unit	RFG Per gallon	RFG Averaging	Conventional gasoline
Benzene, maximum	vol%	1.0	0.95	—
Oxygen, minimum	wt%	2.0	2.1	—
VOC reduction	%	35.1[a]/15.6[b]	36.6[a]/17.1[b]	—
NO_x reduction	%	0.0	1.5	—
Air toxics emission reduction	%	15.0	16.5	—
Exhaust toxics emissions		—		Same as refinery's 1990 gasoline

psi Pounds per square inch; — not applicable.

[a]VOC control region 1, southern half of the United States.
[b]VOC control region 2, northern half of the United States.

Source: UOP 1994.

more complicated, because the compositional analysis of the fuel must be checked against empirical equations. These standards may hence be more expensive to implement and enforce than composition-based standards, which are currently in force in developing countries.

Once the mathematical models are set up, however, these specifications offer far greater flexibility to refiners, enabling them to select the most economic way to meet emission targets, which, in turn, depend on the air quality of a given region. This approach has the potential of providing a significant cost advantage to the refining sector in the United States, making it less expensive to meet clean air targets than if there had been uniform, nationwide, composition-based fuel specifications.

TABLE A2.4

Federal Diesel Standards

Gasoline parameter	Unit	Low sulfur No. 1-D	Low sulfur No. 2-D
Cetane number, minimum		40	40
T_{90}, minimum	°C	288	338
Kinematic viscosity at 40°C	cSt	1.3–2.4	1.9–4.1
Sulfur, maximum	wt ppm	500	500
Cetane index, minimum[a]		40	40
Aromaticity, maximum[a]	vol%	35	35
Flash point, minimum	°C	38	52
Ash, maximum	wt%	0.01	0.01
Ramsbottom carbon on 10% residue, maximum	wt%	0.15	0.35

cSt Centistokes.

[a]One of the two properties must be met.

Source: ASTM 1997.

Another example of the flexibility offered by performance-based standards is the California diesel regulations. California has been a leader in emission control legislation and has generally adopted limits more severe than the federal CAA limits that apply to the rest of the United States. With respect to diesel, the California Air Resources Board (CARB) adopted a diesel fuel specification of 500 wt ppm sulfur and 10 vol% aromatics from October 1993. It is important to recognize that there are different ways of certifying diesel in California. Reducing aromatics to 10 percent would be very costly, and an alternative approach used in California is explained in box 3. According to CARB, most refiners are not complying with the default 10 percent aromatics limit in the CARB diesel rule, but instead use certified alternative formulas that usually include achieving a high cetane number by means of cetane improvers while reducing sulfur (CARB 2000a). In designing performance-based fuel specifications, it is important that the performance measures be representative of real vehicle and fuel use.

BOX 3

Diesel Certification in California

The importance of understanding how different fuel compositions can meet the same vehicle emission standards can be seen in the California program regarding NO_x emissions and diesel fuel composition. California issued specifications for diesel fuel that set a maximally permissible level of 500 wt ppm for sulfur and 10 percent for aromatics. In addition to the fuel specification, California also offers an alternative method for certifying a diesel fuel—namely, that a fuel produce the same NO_x reduction when compared with a California reference fuel run in a Detroit Diesel Series 60 engine. The California reference fuel controlled many more parameters than the specification. These parameters are shown below. Also shown are four alternative diesel fuel formulations certified by CARB that are equivalent to the California reference in NO_x reduction. The four alternative diesel formulations are much less costly to produce (because they require less severe hydrotreating) than the California reference.

Diesel Formulations Certified by CARB

Diesel property	California reference	Chevron		ARCO	
		G2	D4781	D-25	D-26
Maximum vol% aromatics	10.0	15.1	19.0	21.7	24.7
Maximum wt% PAHs	1.4	3.6	2.2	4.6	4.0
Maximum wt ppm sulfur	500	202	54	33	42
Maximum wt ppm nitrogen	10	341	484	20	40
Minimum cetane number[a]	48.0	54.8	58.0	55.2	56.2

[a]With cetane-improvement additives.

Source: CARB undated.

Because cetane improvement additives are effective in increasing the cetane number but not cetane index, diesel specifications should give the option of using either the cetane number or index, but not mandate the minimum for the cetane index only.

Up until now, MTBE has been widely used in gasoline in the United States, in part to meet the minimum oxygen content requirement. In March 1999, the governor of California announced that California would begin immediate phase-out of MTBE from gasoline, with complete elimination to be achieved no later than 31 December 2002 (later postponed to 2003). The principal reasons cited were MTBE contamination of lakes, particularly in recreational areas,[2] as well as fears that MTBE may be making its way in significant amounts into the state's groundwater supplies.[3] As of June 2002, 15 other states had announced their intention to ban MTBE eventually. As shown in annex 3, the EU has taken a different position on MTBE.

Air Quality Improvement Research Program

The U.S. Air Quality Improvement Research Program (AQIRP)—conducted by three U.S. auto companies and 14 oil companies at a cost of US$40 million between 1989 and 1995—was set up to provide data to help legislators and regulators achieve the nation's clean air goals through a research program consisting of (1) extensive vehicle emission measurements, testing vehicles as old as MY 1983 as well as "advanced" prototype vehicles; (2) air quality modeling studies to predict the effects of the measured emissions on

[2]The dispute over MTBE has become particularly acute in recreational areas where large numbers of personal watercraft such as Jet Skis and small boats are common, many of them powered by two-stroke engines. According to some estimates, up to 30 percent of the fuel in the Jet Skis' two-stroke engines is released unburned into the water.

[3]One study by researchers at the Lawrence Livermore National Laboratory concluded that more than 10,000 sites have been contaminated by MTBE since 1992.

ozone formation; and (3) economic analysis of some of the fuel/vehicle systems. The program focused on gasoline and alternative fuels but did not cover diesel. It was the largest and most comprehensive research program of this nature ever conducted in the United States. Some of the findings are summarized in the paragraphs that follow.

Ozone

Reducing aromatics (note: those with two or more alkyl branches are ozone precursors) in gasoline from 45 percent to 20 percent had no statistically significant impact on predicted ozone. For vehicles not equipped with catalytic converters, increasing aromatics in gasoline increased NO_x emissions. NO_x is an ozone precursor.

Fuel composition changes that reduced the predicted ozone contributions of light-duty vehicles were T_{90} and T_{50} (the temperature at which 50 percent of gasoline evaporates) reduction, olefin reduction, sulfur reduction (for catalyst-equipped cars), and volatility (RVP) reduction.

Reducing gasoline olefins from 20 percent to 5 percent increased exhaust hydrocarbon emissions and reduced NO_x emissions, reduced the photochemical reactivity of exhaust and evaporative emissions, and led to a marked decrease in predicted ozone.

Decreasing RVP from 9 pounds per square inch (psi) (62 kilopascals, kPa) to 8 psi (55 kPa) reduced evaporative emissions as well as exhaust HC and CO, and led to a marked decrease in predicted ozone.

Gross emitters

High-emitting, poorly maintained vehicles on the road contributed about 80 percent of total vehicular emissions but represented only about 20 percent of the vehicle population. Identification and repair of these vehicles can result in substantial emission reductions. Among gross emitters, there are tailpipe gross emitters, evaporative gross emitters, and "drippers" leaking fuel.

Air toxics

Of the four CAA-designated toxic air pollutants measured—benzene, 1,3-butadiene, formaldehyde, and acetaldehyde—benzene (a carcinogen) had the largest concentrations in the emissions. Decreasing fuel benzene or the total aromatic content reduced benzene emissions.

Oxygenates

Adding oxygenates to gasoline reduced exhaust HC and CO in the 1989 and earlier vehicle models, and raised NO_x with low aromatic fuels. The 1993 and later model year vehicles did not show any emission change. This is to be expected because later model year cars are equipped with oxygen sensors (which let the vehicle adapt to the fuel type to maintain a target oxygen-to-fuel ratio).

Sulfur

Decreasing sulfur generally reduced exhaust toxics, hydrocarbon, CO, and NO_x for cars equipped with three-way catalysts.

In the above findings, of particular interest is the surprising result that reducing the amount of aromatics more than two-fold in gasoline had no impact on predicted ozone. Since aromatics are an important source of octane in gasoline as well as hydrogen (which is needed to reduce sulfur in fuels) at refineries, dramatic aromatics reductions would have a considerable adverse impact on refinery economics while not having much benefit in the way of air quality improvement once the vehicle fleet is equipped with catalytic converters. This implies that once the majority of gasoline-fueled vehicles are equipped with catalytic converters, the only significant adverse health impact of aromatics will be benzene emissions. However, for benzene control, it is typically more cost-effective to control benzene in gasoline than total aromatics.

Tier 1 and Tier 2 Emission Standards

The so-called Tier 1 vehicle emission standards for light-duty vehicles in the United States were introduced progressively from 1994. Starting in 1996, vehicles have had to be certified up to 100,000 miles (160,000 km) or to the higher of "useful-life" limits. The durability of the emission-control device must be demonstrated over this distance, with allowed deterioration factors. The heavy-duty truck regulations for 1987 and later require compliance over longer periods, representative of the useful life of the vehicle. The exhaust emission standards for light-duty vehicles are shown in table A2.5.

The standards for compression ignition engine vehicles are shown in table A2.6. The manufacturer warranty period is five years or 160,000 km, whichever comes first. The useful life of the engine, over which compliance with emission standards has to be demonstrated, is as follows for the 1987–2003 model years:

- Light heavy-duty diesel engines: 8 years or 176,000 km (whichever occurs first)
- Medium heavy-duty diesel engines: 8 years or 296,000 km
- Heavy heavy-duty diesel engines: 8 years or 464,000 km.

TABLE A2.5

Tier 1 U.S. Federal Exhaust Emission Standards for Light-Duty Vehicles, Federal Test Procedure, Cold CO (g/km)

Vehicle type	NMHC	CO	NO_x	PM	NMHC	CO	NO_x	PM
	5 years or 80,000 km				**10 years or 160,000 km**			
LDV	0.16	2.13	0.25	0.05	0.19	2.63	0.38	0.06
LDT1	0.16	2.13	0.25	0.05	0.19	2.63	0.38	0.06
LDT2	0.20	2.75	0.44	0.05	0.25	3.44	0.61	0.06
	5 years or 80,000 km				**11 years or 192,000 km**			
LDT3	0.20	2.75	0.44	—	0.29	4.00	0.61	0.06
LDT4	0.24	3.13	0.69	—	0.35	4.56	0.96	0.08

NMHC Nonmethane hydrocarbons; LDV light-duty vehicle, a passenger car or car derivative capable of seating 12 passengers or less; LDT1 light-duty truck 1, any light light-duty truck up through 3,750 pounds (1,705 kg) loaded vehicle weight; LDT2 light-duty truck 2, any light light-duty truck greater than 3,750 pounds loaded vehicle weight; LDT3 light-duty truck 3, any heavy light-duty truck up through 5,750 pounds (2,611 kg) adjusted loaded vehicle weight; LDT4 light-duty truck 4, any heavy light-duty truck greater than 5,750 pounds adjusted loaded vehicle weight; — not applicable.

Source: U.S. EPA 2000b.

TABLE A2.6

U.S. Federal Heavy-Duty Exhaust Emission Standards Compression Ignition and Urban Buses (g/kWh)

Year	CO	HC	NMHC+NO_x	NO_x	PM	Smoke[a]
1990	20.8	1.7	—	8.0	0.80	20/15/50
1991–1993	20.8	1.7	—	6.7	0.34 / 0.13[b]	20/15/50
1994–1997	20.8	1.7	—	6.7	0.13 / 0.09[c] / 0.07[d]	20/15/50
1998+	20.8	1.7	—	5.4	0.013 / 0.07[d]	20/15/50
2004+	20.8	—	3.2 or 3.4 with a limit of 0.7 on NMHC	—	0.13 / 0.07[d]	20/15/50
2007	20.8	0.19 for NMHC[e]	—	0.27[e]	0.013	20/15/50

NMCH Nonmethane hydrocarbons; — not applicable.

[a]Data are in percentages; these apply to smoke opacity at acceleration/lug/peak modes.
[b]Standards for urban buses for 1993.
[c]Standard for urban buses for 1994-95.
[d]Standard for urban buses from 1996 and later.
[e]Phased in together between 2007 and 2010.

Sources: U.S. EPA 1997a and 2000d.

The useful life requirements were later increased to 10 years, with no change to the above mileage numbers, for the urban bus PM standard (1994+) and for the NOx standard (1998+). Beginning with the 2004 model year, EPA revised useful engine life as follows:

- Light heavy-duty diesel engines: 10 years or 176,000 km
- Medium heavy-duty diesel engines: 10 years or 296,000 km
- Heavy heavy-duty diesel engines: 10 years or 696,000 km or 22,000 hours.

The emission levels of new vehicles are measured in a certified driving cycle using reference fuels of specific compositions covering limited ranges for various fuel parameters. A test driving cycle called FTP75 (Federal Test Procedure 75) has been used in the United States since 1975. As required by the CAA Amendments, the U.S. EPA re-evaluated typical driving patterns and found that the FTP test cycle does not cover about 15 percent of driving conditions. As a result EPA issued a Final Rule in August 1996 setting out modifications. The main element of this rule is a Supplemental Federal Test Procedure (SFTP), covering the driving patterns not included in FTP75. This was to address a potential concern that became known as "cycle beating." Cycle beating refers to scenarios whereby vehicle manufacturers design vehicles to meet the emission standards in FTP75, but where emission levels increase significantly in other driving cycles. SFTP includes two new driving cycles, one representing aggressive and microtransient driving, and another representing driving immediately following vehicle startup.

In order to meet the Tier 1 emission standards for particulate emissions from diesel-fueled vehicles in the United States, a sulfur limit of 500 wt ppm was imposed from October 1993. Up until that point, particulate emissions were controlled by continuous improvement in vehicle technology without lowering diesel sulfur below 2,500 wt ppm (0.25 wt%). This is illustrated in annex 1, figure A1.1.

Beginning with the 1994 MY (autumn 1993), light-duty vehicles and light-duty trucks have been required to be equipped with on-board diagnostic (OBD) systems. OBD systems monitor emission control components for any malfunction or deterioration that cause emission limits to be exceeded, and alert the driver of the need for repair via a dashboard light when the diagnostic system has detected a problem. EPA made changes to the federal OBD requirements starting in the 1999 MY (autumn 1998). The modifications include harmonization of the emission levels above which a component is considered malfunctioning with California's OBD Generation Two (OBD II) requirements. OBD systems are generally seen as a complement to traditional I/M programs rather than a substitute. By January 2001, all areas with basic and enhanced I/M programs were required to implement OBD checks as a routine part of I/M programs. Failure of the OBD test would require mandatory repair. In fact, in Maryland, for example, the OBD II check light is a substitute for a chassis dynamometer emissions test.

In the future, Tier 2 vehicle emission standards will aggressively pursue significant emission reductions. Tier 2 is a comprehensive national control program that regulates the vehicle and its fuel as a single system. The new tailpipe emission standards for passenger vehicles will reduce NO_x emissions by 77 percent from cars and up to 95 percent from SUVs and trucks. The standards for SUVs and trucks will be brought in line with those of other cars for the first time, and the same standards will be applied to gasoline, diesel, methanol, ethanol, natural gas, and LPG fuels. The exhaust emission standards for these light-duty vehicles are given in table A2.7 (only permanent, and not temporary, certification bins are shown) and will be phased in between 2004 and 2009, as shown in table A2.8. The exhaust emission standards are structured into eight certification levels called "certification bins." Vehicle manufacturers can choose any of the eight bins, but must meet the average NO_x standard for the entire fleet of 0.04 g/km (0.07 grams per mile). The vehicle "full useful life" has been extended to 192,000 km.

The corresponding schedule for gasoline sulfur standards is given in table A2.9. Sulfur in gasoline is required to be reduced to a mandatory average of 30 wt ppm. "Small refiners" (with an average crude capacity of less than 155,000 b/d and employing fewer than 1,500 people) are eligible for hardship provisions that permit an annual average sulfur limit of up to 300 wt ppm until 31 December 2007. The cost to consumers is estimated by EPA to be less than US$100 for cars, $200 for light-duty trucks, and less than $0.02 per gallon (0.5 U.S. cents per liter) for gasoline sulfur reduction, with the overall cost to industry on the order of $5.3 billion against health and environmental benefits of about $25 billion (U.S. EPA 1999d).

For gasoline sulfur reduction, U.S. EPA has based its incremental cost calculations on two new hydrodesulfurization technologies, Mobil's Octgain and CD Tech's CDHydro/CDHDS, neither of which had been commercially proven at the time the incremental costs were computed. For the U.S. refining industry overall, the difference in capital investment between conventional technologies and emerging technologies may be dramatic: estimates have varied by a factor of two or more. Separate refinery modeling exercises by the EPA, the auto industry, and the oil industry confirm that newer desulfurization technologies are nearly 50 percent less costly than older technology. EPA concluded the cost of achieving 30 ppm sulfur would initially be 1.95 (1997) U.S. cents per gallon (0.5 U.S. cents per liter), while the newer technology would achieve the same reduction at a cost of

TABLE A2.8

Phase-in Percentages for Tier 2 Emission Standards for Light-Duty Vehicles, Light-Duty Trucks, and Medium-Duty Passenger Vehicles

Model year	Percentage of vehicles that must meet Tier 2 requirements
Light-duty and light light-duty trucks	
2004	25
2005	50
2006	75
2007 and subsequent	100
Heavy light-duty trucks and medium -duty passenger vehicles	
2008	50
2009	100

Source: U.S. EPA 2000c.

TABLE A2.9

Gasoline Sulfur Limits in the United States

	Averaging period beginning		
	Jan. 2004	Jan. 2005	Jan. 2006 and subsequent
Refinery or importer average	—	30 wt ppm	30 wt ppm
Corporate pool average	120 wt ppm	90 wt ppm	—
Per-gallon limit	300 wt ppm	300 wt ppm	80 wt ppm

— Not applicable.

Source: U.S. EPA 2000c.

TABLE A2.7

Tier 2 FTP Exhaust Emission Standards for Light-Duty Vehicles, Light-Duty Trucks, and Medium-Duty Passenger Vehicles, Permanent (g/km)

	80,000 km					192,000 km				
Bin	NMHC	CO	NO_x	PM	HCHO	NMHC	CO	NO_x	PM	HCHO
8	0.063	2.1	0.088	—	0.0094	0.078	2.6	0.125	0.0125	0.0113
7	0.047	2.1	0.069	—	0.0094	0.056	2.6	0.094	0.0125	0.0113
6	0.047	2.1	0.050	—	0.0094	0.056	2.6	0.063	0.0063	0.0113
5	0.047	2.1	0.031	—	0.0094	0.056	2.6	0.044	0.0063	0.0113
4	—	—	—	—	—	0.044	1.3	0.025	0.0063	0.0069
3	—	—	—	—	—	0.034	1.3	0.019	0.0063	0.0069
2	—	—	—	—	—	0.006	1.3	0.013	0.0063	0.0025
1	—	—	—	—	—	0.000	0.0	0.000	0.0000	0.0000

NMHC Nonmethane hydrocarbons; HCHO formaldehyde; — not applicable.

Source: U.S. EPA 2000c.

1.26 U.S. cents per gallon (0.3 U.S. cents per liter) (U.S. EPA 1999e).

In July 2000, U.S. EPA issued a final rule for the first phase of the program on heavy-duty trucks and buses, taking effect beginning in 2004 (U.S. EPA 2000a). The emission standards for heavy-duty diesel vehicles—a combined standard for NO_x and HC of 3.2 g/kWh—represent a reduction of more than 40 percent in emissions of NO_x as well as HC. The rule requires OBD systems for engines between 8,500 and 14,000 pounds (3,864 and 6,364 kg) to be phased in, beginning in 2005. Heavy-duty gasoline vehicles less than 6,364 kg are subject to emission standards and testing similar to the current program for light-duty vehicles and light-duty trucks. As a result of a legal settlement reached between six engine manufacturers and the government, the date for meeting the 2004 emission standards was advanced 15 months to October 2002 (see chapter 3, Vehicle Technology, Vehicle emissions-control technologies). The emission standards are shown in table A2.10. EPA estimated that an average projected long-term incremental cost of this program would be less than US$400 per vehicle for heavy-duty diesel engines and less than $300 per vehicle for heavy-duty gasoline engines.

In December 2000, U.S. EPA also signed emission standards for MY 2007 and later heavy-duty highway engines (U.S. EPA 2000d). The regulation introduces new, very stringent exhaust emission standards: 0.013 g PM per kWh, 0.27 g NO_x per kWh, and 0.19 g non-methane hydrocarbons (NMHC) per kWh. This is the second phase of the control program for heavy-duty vehicles and will achieve emission reductions of upwards of 90 percent over levels achieved by the Phase 1 reductions described in the preceding paragraph. The PM emission standard will take full effect for diesels in the 2007 MY. The NO_x and NMHC standards will be phased in for diesel engines between 2007 and 2010. The phase-in would be on a percent-of-sales basis: 50 percent from 2007 to 2009 and 100 percent in 2010. Gasoline engines will be subject to these standards based on a phase-in requiring 50 percent compliance in 2008 and 100 percent compliance in 2009. Emission certification requirements also include the SET (supplementary emission test),[4] with limits equal to the FTP standards, and NTE (not to exceed)[5] limits of 1.5 × FTP standards.

Diesel sulfur is limited to 15 wt ppm, down from the previous limit of 500 wt ppm. Refiners will be required to start producing the 15 wt ppm sulfur fuel beginning 1 June 2006. At the terminal level, highway diesel fuel sold as low-sulfur fuel must meet the 15 wt ppm sulfur standard as of 15 July 2006. For retail stations and wholesale purchasers, highway diesel fuel sold as low sulfur fuel must meet the 15 ppm sulfur standard by 1 September 2006. This limit is based on EPA's assessment of how sulfur-intolerant advanced aftertreatment technologies will be. EPA estimates the cost of the program to be about US$1,200 to US$1,900 per new vehicle, and the incremental production and distribution cost of lowering sulfur from the current limit of 500 wt ppm to 15 wt ppm to be approximately US$0.045–0.05 per gallon (1.2–1.3 U.S. cents per liter).

In response to these new rulings and proposals, the automotive industry is confident of being able to

TABLE A2.10 Heavy-Duty Gasoline Exhaust Emission Standards for 2004 and Later Model Year

GVWR		Old		New		
From	to	HC	NO_x	HC	NO_x	HC+NO_x
kg	kg	g/kWh	g/kWh	g/km	g/km	g/kWh
3,864	4,545	1.5	5.4	0.18	0.56	—
4,545	6,364	1.5	5.4	0.21	0.63	—
6,364	—	2.5	5.4	—	—	1.3

GVWR Gross vehicle weight rating; — not applicable.

Source: U.S. EPA 2000a.

[4] The SET is a 13-mode steady-state test that was introduced to help ensure that heavy-duty engine emissions are controlled during steady-state type driving, such as a line-haul truck operating on a freeway. The test is based on the EU 13-mode European stationary cycle (ESC) schedule (commonly referred to as the "Euro III" cycle in the United States).

[5] The NTE approach establishes an area under the torque curve of an engine where emissions must not exceed a specified value of any of the regulated pollutants. The NTE requirement would apply under any engine operation conditions that could *reasonably* be expected to be seen by that engine in normal vehicle operation and use, as well as a *wide* range of *real* ambient conditions.

meet Tier 2 standards for cars, but is less certain about sport utility vehicles (SUVs). As for diesel vehicles, particulate control technology is considered feasible although particulate filters have not yet been demonstrated on low-power operation vehicles in cold climates. NO_x emission control is not yet proven and there is no general consensus that the 2007 NO_x emission limits can be met *and* be durable for the engine life. What the automotive industry is especially concerned about are the supplementary requirements, and especially the NTE requirements, which are proposed to take effect starting in the 2007 model year. This illustrates the interdependence between test driving cycles and emission levels and the importance of not concentrating on establishing emission levels only.

As for sulfur levels, a significant consideration in the United States is cross-contamination of low sulfur fuels, particularly diesel, in the distribution system by higher sulfur fuels. If chances of cross-contamination are not negligible, having to ensure a maximum of 15 wt ppm sulfur in diesel at the pump would mean much lower sulfur levels at the refinery gate. For example, pipeline operators expect that refiners will have to provide diesel fuel with sulfur levels as low as 7 wt ppm in order to compensate for possible contamination from higher sulfur products in the system. Even at 7 wt ppm, industry representatives believe the likelihood of contamination during the delivery of the fuel through the distribution system is extremely high. Once contamination occurs, the product cannot be sold as automotive diesel fuel, thereby diminishing the fuel supply (U.S. GAO 2004).

Another concern is the contribution of sulfur, phosphorus, and ash found in lubricants which would cause legislation compliance problems if the levels found in today's lubricants are maintained. Viscosity modifiers normally contain sulfur, and anti-oxidant additives can contain phosphorus. Straightforward reductions in sulfur and phosphorus can harm piston cleanliness and shorten the life of the lubricant (Bunting 2003).

ANNEX 3

Trends in Vehicular Emission Standards and Fuel Specifications in the European Union

This annex discusses vehicle emission standards in the European Union (EU). These standards have a significant impact on Eastern Europe, the former Soviet Union Republics, and Asia. The first set of directives for controlling emissions from motor vehicles was issued in Council Directive 70/220/EEC of 20 March 1970. This directive has been amended numerous times since, increasingly tightening standards.

A major auto and oil industry study undertaken in two phases, examining both gasoline and diesel (although the U.S. auto and oil study did not examine diesel vehicles), is treated at some length in this annex. The findings provide information on the complex relationships between vehicular emissions, fuel quality, and vehicle technology. There are useful lessons for developing countries from these studies, discussed below.

European Auto-Oil Programme

At the end of 1992, the European Commission invited the European auto and oil industries to participate in a technical program to carry out an objective assessment of cost-effectiveness of different measures for reducing emissions from the road transport sector. This effort became known as the "Auto-Oil Programme." Its scope included studying the future development of emissions from the European vehicle fleet, modeling air quality under different policy scenarios, examining vehicle–fuel quality interactions (the European Programme on Emissions, Fuels and Engine Technologies), and estimating cost-effectiveness of different mitigation options.

The first Auto-Oil Programme was concluded in 1996 and was instrumental in shaping subsequent emission and fuel quality standards. Auto-Oil I confirmed that the relationships found among fuel properties, engine technologies, and exhaust emissions are complex. Changes in a given fuel property may lower the emissions of one pollutant but increase those of another. (For example, decreasing aromatics in gasoline lowered CO and HC emissions but increased NO_x emissions for catalyst-equipped cars.) In some cases, engines in different vehicle categories, such as heavy-duty and light-duty vehicles, had opposite responses to changes in fuel properties. (For example, reducing PAHs in diesel reduced HC emissions in heavy-duty engines but increased HC, CO, and benzene emissions in light-duty vehicles.)

With respect to both gasoline and diesel vehicles, individual vehicles and engines showed a wide range of response to the fuel properties investigated. In the case of gasoline vehicles, some vehicles that showed low fuel sensitivity for CO and HC emissions showed high sensitivity for NO_x and vice versa. In the case of diesel vehicles, the impact of the vehicle/engine set on emissions was larger than that of the matrix of fuel properties except for NO_x emission on heavy-duty engines. These findings underscore the importance of targeting the vehicle hardware.

European Programme on Emissions, Fuels and Engine Technologies

The European Programme on Emissions, Fuels and Engine Technologies (EPEFE) was designed to enhance the understanding of the relationships between fuel properties and engine technologies and to quantify the reduction in vehicular emissions that can be achieved by combining advanced fuels with the vehicle/engine technologies (ACEA and Europia 1995). The EPEFE marks an unprecedented cooperation between the European motor industry (represented by the Association des Constructeurs Européens d'Automobiles [ACEA]) and the European oil industry (represented by EUROPIA, the European government affairs organization of the oil refining and marketing industry in the EU and the European Economic Area). Unlike the U.S. Air Quality Improvement Research Program (AQIRP), EPEFE examined diesel in addition to gasoline.

The results concerning diesel fuel and vehicle interactions from EPEFE should be interpreted with caution because the ranges of fuel parameters examined often fell outside of the ranges found in many developing countries and typically represent much "cleaner" diesel. Decreasing density from 857 kilograms per cubic meter (kg/m³) to 829 kg/m³ decreased PM emissions in light-duty vehicles and NO_x emissions in heavy-duty engines, but increased NO_x emissions in light-duty vehicles and HC and CO emissions in heavy-duty engines. Decreasing density had no significant effect on PM emissions from heavy-duty engines. EPEFE examined the impact of varying PAHs on vehicular emissions and found that decreasing PAHs from 8 percent to 1 percent decreased both particulate and NO_x emissions from light-duty and heavy-duty diesel vehicles. Lowering T_{95} from 370°C to 325°C had mixed effects, increasing HC and CO emissions from heavy-duty engines and NO_x from light-duty vehicles, but decreasing particulate emissions from light-duty vehicles and NO_x from heavy-duty engines. Increasing cetane number from 50 to 58 decreased NO_x emissions from heavy-duty engines only, increased particulate emissions in light-duty vehicles with no significant effect on heavy-duty vehicles, and decreased HC and CO emissions from both light-duty vehicles and heavy-duty engines.

Examination of vehicle and fuel technology interactions under Auto-Oil II

The Auto-Oil II Programme ran from 1997 to 2000 as a follow-up to Auto-Oil I (European Commission 2000a). The two principal aims were to (1) assess future air quality and establish a consistent framework within which different policy options to reduce emissions can be assessed using the principles of cost-effectiveness, sound science, and transparency; and (2) provide a foundation for the transition toward longer-term air quality studies covering all emission sources.

The air quality modeling in Auto-Oil II suggested that meeting the particulate air quality standard posed the greatest challenge during the period 2000–2010. Special attention was paid to measures that could reduce PM emissions from diesel vehicles. The program investigated the impact of varying density (835 to 823 kg/m³), PAHs (5.7 percent to 1 percent), cetane number (53 and 55), and T_{95} (355°C to 317°C) for diesel on emissions. Emissions from heavy-duty diesel engines were found to be rather insensitive to changes in diesel quality. Euro II-compliant passenger cars and light-duty diesel engines, by contrast, responded more to decreasing density, PAHs, and T_{95}. Reducing these three parameters from 835 kg/m³, 5.7 vol%, and 355°C, respectively, to 823 kg/m³, 1 vol%, and 320°C lowered PM emissions by 20 percent for light-duty vehicles but only 3.1 percent for heavy-duty vehicles. (These fuel parameter changes gave the largest reductions in the study.) It is difficult to vary density, polyaromatics, and T_{95} in diesel independently, and hence the reasons for these reductions are not easy to identify readily.

Another consideration is that lowering density and T_{95} would decrease the yield of middle distillates, an important observation when many developing countries find it difficult to meet middle distillate demand while having a surplus of gasoline. Even in the EU, the combination of diesel parameters mentioned in the preceding paragraph made it difficult for the refining sector to meet the demand for middle distillates.

Current and Future Standards

In order to support increasingly tighter emission standards, fuel specifications have been made stringent over the years. Table A3.1 shows the evolution of gasoline specifications in recent years. Lead was banned effective 1 January 2000 in the EU, but Greece, Italy, and Spain were granted until 2002 to phase lead out. The EU has not taken the same position regarding MTBE as the United States. There is no mandate for the use of oxygenates in gasoline. In November

TABLE A3.1

Automotive Gasoline Specifications in the EU

Parameter	Unit	1993[a]	2000	2005	2009
Lead, maximum	g/l	0.013	0.005	0.005	0.005
Summer RVP	kPa	Various	60/70[b]	60/70[b]	60/70[b]
Benzene, maximum	vol%	5.0	1.0	1.0	1.0
Aromatics, maximum	vol%	—	42	35	35
Olefins, maximum	vol%	—	18	18	18
Oxygen, maximum	wt%	2.7	2.7	2.7	2.7
Methanol, maximum	vol%	—	3.0	3.0	3.0
Ethanol, maximum	vol%	—	5.0	5.0	5.0
Isopropyl alcohol, maximum	vol%	—	10.0	10.0	10.0
Tert-butyl alcohol, maximum	vol%	—	7.0	7.0	7.0
Iso-butyl alcohol, maximum	vol%	—	10.0	10.0	10.0
Ethers, C5+, maximum	vol%	—	15.0	15.0	15.0
Other oxygenates, maximum	vol%	—	10.0	10.0	10.0
Sulfur, maximum	wt ppm	500	150	50	10

— Limits not specified.

[a]Specifications for unleaded gasoline.

[b]60 except for member states with arctic or severe winter conditions for which a limit of 70 kPa applies.

Sources: Concawe 1997, EU 2003.

2000, the EU Working Group on the Classification and Labeling of Dangerous Substances examined the status of MTBE in a meeting of experts. The discussion resulted in the EU deciding that MTBE would not be classified as a carcinogen, mutagen, or reproductive toxin. The EU risk assessment, presented in January 2001, concluded that MTBE is not a toxic threat to health, but that it can give drinking water a bad taste. In its draft directive for new fuel quality laws, published in May 2001, the EU set no limitations on the use of MTBE in fuel after 2005. The EU has, however, recommended that MTBE be prevented from seeping into groundwater through storage tanks at service stations. As an example, the EU in September 2001 approved a Danish tax initiative—tax breaks of €0.02 per liter of gasoline sold at service stations fitted with leak-resistant underground tanks—to improve the quality of storage tanks.

Recent changes in EU diesel specifications are shown in table A3.2. Concerned about the effects of sulfur in diesel on particulate control aftertreatment devices, Germany has taken steps to make diesel fuel specifications even more stringent and set the maximum limit to 10 ppm from January 2003. As a preliminary step, sulfur in diesel sold in Germany from November 2001 had to be limited to 50 ppm. Germany has also urged other EU countries to adopt the 10 ppm diesel sulfur standards in time for the scheduled 1 October 2005 implementation date for Euro IV

TABLE A3.2

On-Road Diesel Specifications in the EU

Parameter	Unit	1993	1996 (Oct.)	2000	2005	2009
Sulfur, maximum	wt ppm	2000	500	350	50	10
Cetane number, minimum		49	49	51	51	51
Cetane index, minimum		46	46	—	—	—
T_{95}, maximum	°C	370	370	360	360	360
PAHs, maximum	%	—	—	11	11	11
Density, maximum	kg/liter	0.860	0.860	0.845	0.845	0.845

— Not applicable.

Source: Concawe 1997, EU 2003.

truck and bus emission legislation. In early 2002, the EU Council of Ministers (Environment) agreed in principle that sulfur-free gasoline and diesel be introduced in every member state beginning in January 2005, and that it be made mandatory by January 2009, two years earlier than the previously proposed date.

The exhaust emission limits for passenger cars and light commercial vehicles differentiated by the type and weight of vehicle are given in table A3.3 and table A3.4. EU emission standards for new light-duty vehicles were originally specified in 1970. In June 1991, the Council of Ministers of the European Community adopted the Consolidated Emissions Directive. Exhaust emission standards had to be certified on the basis of a combined United Nations Economic Commission in Europe (ECE) 15 (urban) cycle and EUDC (extra-urban test cycle). In March 1994, the Council of Ministers adopted another directive with tightened limits from 1996 onwards in which separate standards were given for gasoline- and diesel-fueled vehicles. The most recent limits for the so-called Euro III and Euro IV were issued in 1998 in Directive 98/69/EC.

Taking effect from 1 January 2000, for new types and from 1 January 2001, for all types, gasoline vehicles used for carrying passengers with no more than eight seats in addition to the driver's seat (the so-called M1 category)—except vehicles with a maxi-

TABLE A3.3

EU Exhaust Emission Standards for Passenger Cars (g/km)

Tier	Year	CO	HC	$HC+NO_x$	NO_x	PM
			Diesel			
Euro I	1992	2.72	—	0.97	—	0.14
Euro II–IDI	1996	1.0	—	0.70	—	0.08
Euro II–DI	1996–99	1.0	—	0.90	—	0.10
Euro III	2000	0.64	—	0.56	0.50	0.05
Euro IV	2005	0.50	—	0.30	0.25	0.025
			Gasoline			
Euro II	1996	2.2	—	0.50	—	—
Euro III	2000	2.3	0.2	—	0.15	—
Euro IV	2005	1.0	0.1	—	0.08	—

— Not applicable; IDI indirect injection; DI direct injection.

Source: Concawe 1997.

TABLE A3.4

EU Emission Standards for Light Commercial Vehicles (g/km)

Class	Tier (Euro)	Year	CO	HC	$HC+NO_x$	NO_x	PM
				Diesel			
1	I	1994	2.72	—	0.97	—	0.14
	II–IDI	1998	1.0	—	0.70	—	0.08
	II–DI[a]	1998	1.0	—	0.90	—	0.1
	III	2000	0.64	—	0.56	0.5	0.05
	IV	2005	0.50	—	0.30	0.25	0.025
2	I	1994	5.17	—	1.4	—	0.19
	II–IDI	1998	1.25	—	1.0	—	0.12
	II–DI[a]	1998	1.25	—	1.3	—	0.14
	III	2002	0.80	—	0.72	0.65	0.07
	IV	2006	0.63	—	0.39	0.33	0.04
3	I	1994	6.9	—	1.7	—	0.25
	II–IDI	1998	1.5	—	1.2	—	0.17
	II–DI[a]	1998	1.5	—	1.6	—	0.2
	III	2002	0.95	—	0.86	0.78	0.1
	IV	2006	0.74	—	0.46	0.39	0.06
				Gasoline			
1	I	1994	2.72	—	0.97	—	—
	II	1998	2.2	—	0.5	—	—
	III	2000	2.3	0.2	—	0.15	—
	IV	2005	1.0	0.1	—	0.08	—
2	I	1994	5.17	—	1.4	—	—
	II	1998	4.0	—	0.65	—	—
	III	2002	4.17	0.25	—	0.18	—
	IV	2006	1.81	0.13	—	0.10	—
3	I	1994	6.9	—	1.7	—	—
	II	1998	5.0	—	0.8	—	—
	III	2002	5.22	0.29	—	0.21	—
	IV	2006	2.27	0.16	—	0.11	—

IDI Indirect injection; DI direct injection

[a]After September 30, 1999, DI engines are required to meet IDI engine limits.

Notes: For Euro I and II, the weight classes were Class 1 (<1250 kg), Class 2 (1250–1700 kg), and Class 3 (>1700 kg). For Euro III and IV, Class 1 <1305 kg, Class 2 1305–1760 kg, and Class 3 >1760 kg.

Source: Dieselnet undated.

mum mass exceeding 2,500 kg—and vehicles of class 1 above are required to be fitted with an on-board diagnostic (OBD) system. Taking effect from 1 January 2001, for new types and from 1 January 2002, for all types, vehicles of classes 2 and 3 above and vehicles of category M1 exceeding 2,500 kg must be fitted with an OBD system (European Parliament 2000).

For diesel vehicles, taking effect from 1 January 2003, for new types and from 1 January 2004, for all types, category M1 vehicles—except vehicles with a maximum mass exceeding 2,500 kg or vehicles designed to carry more than six occupants including the driver—must be fitted with an OBD system. All other types of M1 category vehicles and new types of class 1 vehicles above must be fitted with an OBD system taking effect from 1 January 2005. New types of class 2 and class 3 categories above are required to be fitted with an OBD system taking effect from 1 January 2006 (European Communities 1998).

Emission standards for heavy-duty and other engines are given in table A3.5 and table A3.6. In examining vehicle emission standards in the EU, it is important to bear in mind that EU test driving cycles' reference fuels are different from those in the United States, so that the numerical emission limits are not strictly comparable. This holds especially in the case of heavy-duty vehicles. The EU did not adopt a transient driving cycle, which is more stringent than a steady-state mode for particulate emissions, until 2000, whereas the U.S. EPA mandated a transient test in 1985, replacing a steady-state 13-mode test (Concawe 1997).

TABLE A3.6

Emission Standards for Diesel and Gas Engines, European Transient Cycle Test (g/kWh)

Tier	Date and category	CO	NMHC	CH_4[a]	NO_x	PM[b]
Euro III	Oct. 1999, EEVs only	3.0	0.4	0.65	2.0	0.02
	Jan. 2000	5.45	0.78	1.6	5.0	0.16 0.21[c]
Euro IV	Jan. 2005	4.0	0.55	1.1	3.5	0.03
Euro V	Jan. 2008	4.0	0.55	1.1	2.0	0.03

NMCH Nonmethane hydrocarbons; CH_4 methane; EEV environmentally enhanced vehicle.

[a]For natural gas engines only.
[b]Not applicable for gas fueled engines at the year 2000 and 2005 stages.
[c]For engines of less than 0.75 cubic decimeter swept volume per cylinder and a rated power speed of more than 3,000 per minute.

Source: Dieselnet undated.

TABLE A3.5

EU Emission Standards for Heavy-Duty Diesel Engines (g/kWh)

Tier	Date and category	Test cycle	CO	HC	NO_x	PM	Smoke[a]
Euro I	1992, <85 kW	ECE R-49	4.5	1.1	8.0	0.612	—
	1992, >85 kW	ECE R-49	4.5	1.1	8.0	0.36	—
Euro II	Jan. 1996	ECE R-49	4.0	1.1	7.0	0.25	—
	Jan. 1998	ECE R-49	4.0	1.1	7.0	0.15	—
Euro III	Oct. 1999, EEVs only	ESC and ELR	1.5	0.25	2.0	0.02	0.15
	Jan. 2000	ESC and ELR	2.1	0.66	5.0	0.10 0.13[b]	0.8
Euro IV	Jan. 2005	ESC and ELR	1.5	0.46	3.5	0.02	0.5
Euro V	Jan. 2008	ESC and ELR	1.5	0.46	2.0	0.02	0.5

kW Kilowatts; — not applicable; EEV environmentally enhanced vehicle; ESC European stationary cycle; ELR European load response.

[a]Smoke in m^{-1}.
[b]For engines of less than 0.75 cubic decimeter swept volume per cylinder and a rated power speed of more than 3000 min^{-1}.

Source: Dieselnet undated.

ANNEX 4

World-Wide Fuel Charter

The World-Wide Fuel Charter was developed by four groups—the Association des Constructeurs Européens d'Automobiles (ACEA), Alliance of Automobile Manufacturers, Engine Manufacturers Association (EMA), and Japanese Automobile Manufacturers Association—and some of their affiliates. The objective of the global fuel harmonization effort, according to the auto makers, is to develop common, worldwide recommendations for "quality fuels," taking into consideration customer requirements and vehicular emissions technologies that will, in turn, benefit customers and all other affected parties. The auto makers hope that implementation of the recommendations will (1) reduce vehicular emissions, (2) consistently satisfy customer performance expectations, and (3) minimize vehicle equipment complexities with optimized fuels for each emissions control category.

The charter establishes four categories of unleaded gasoline and diesel. Category 1 is intended for markets that require minimal emissions controls. Category 2 is for markets with stringent requirements for emissions controls. Category 3 fuels are designed for markets with advanced requirements for emissions control as these technologies are designed today. Category 4, which was not included in the original charter but was added in the April 2000 edition, is for markets with further advanced requirements for emission control (such as Euro IV and U.S. Tier 2) to enable sophisticated NO_x and particulate matter aftertreatment technologies. The only difference between category 3 and category 4 is the level of sulfur.

Some of the key features of gasoline fuel properties are given in table A4.1. The charter states that where oxygenates are used, ethers are preferred. The limit on oxygen corresponds to a maximum of 7.7 vol% ethanol. Where up to 10 vol% ethanol is permitted by preexisting regulation, the blended fuel must meet all fuel requirements and fueling pump labeling is recommended. Methanol is not permitted, and higher alcohols with more than 2 carbon atoms are limited to a maximum of 0.1 vol%.

Key diesel fuel properties are given in table A4.2. A maximum of 5 vol% fatty acid methyl esters (biodiesel) are permitted in categories 1–3 but not category 4. Ethanol and methanol must both be below the detection limit for all four categories: that is, so-called e-diesel, a blend of ethanol and diesel, is not permitted.

The above specifications show the extent to which they are driven by the standards in industrial countries. While most developing countries are in a position to meet category 1, there is a significant leap from category 1 to category 2. For example, diesel sulfur is lowered from 5,000 wt ppm to 300 wt ppm. In the evolution of diesel sulfur specifications, industrial countries did not take such a large step. While some countries may find it cost-effective to move immediately to low or ultralow sulfur levels, others (such as the case of Sri Lanka discussed in annex 1) could move from 5,000 wt ppm to 3,000 or 2,500 wt ppm at little cost, but find it prohibitively expensive to move from 5,000 to 350 wt ppm. Inserting several categories between category 1 and category 2 to address the needs and reality of developing countries might be useful, but would also go against the objective of minimizing the number of categories. This illustrates the dilemma in harmonizing standards across the world against the background of varying environmental goals, air quality problems, climatic and geographical conditions, resource endowments, and refinery configurations.

To the extent that harmonization can be beneficial, fuel specifications should be harmonized with emission limits, vehicle technology, and test cycles. Not doing so and going after category 2 or category 3 fuel specifications, or worse, selecting just one fuel parameter in the fuel specifications (such as diesel sulfur), could result in the selection of suboptimal mitigation strategies.

TABLE A4.1

World-Wide Fuel Charter Gasoline Specifications

Gasoline parameter	Unit	Category 1	Category 2	Category 3	Category 4
91 RON, minimum	RON	91.0	91.0	91.0	91.0
	MON	82.5	82.5	82.5	82.5
95 RON, minimum	RON	95.0	95.0	95.0	95.0
	MON	85.0	85.0	85.0	85.0
98 RON, minimum	RON	98.0	98.0	98.0	98.0
	MON	88.0	88.0	88.0	88.0
Lead, maximum	g/liter	0.40[a]	Below detection[b]		
Sulfur, maximum	wt ppm	1,000	200	30	Sulfur-free[c]
Oxygen, maximum	wt%	2.7	2.7	2.7	2.7
Olefins, maximum	vol%	No limit	20	10	10
Aromatics, maximum	vol%	50	40	35	35
Benzene, maximum	vol%	5.0	2.5	1.0	1.0
Density	kg/m³	715–780	715–770	715–770	715–770

RON Research octane number; MON motor octane number.

[a]Where lead is legally permitted.
[b]At or below detection limit of test method used, no intentional addition.
[c]5–10 wt ppm based on available data on advanced technology vehicles. As more data become available, a more specific maximum will be defined.

Category 2 for markets with stringent requirements for emission controls or other market demands.
Category 3 for markets with advanced requirements for emission controls or other market demands
Category 4 for markets with further advanced requirements for emission control, to enable sophisticated NO_x technologies.

Source: ACEA and others 2002.

TABLE A4.2

World-Wide Fuel Charter Diesel Specifications

Diesel parameter	Unit	Category 1	Category 2	Category 3	Category 4
Cetane number, minimum[a]		48	53	55	55
Cetane index, minimum[a]		45	50	52	52
Density at 15°C	kg/m³	820–860	820–850	820–840	820–840
Kinematic viscosity at 40°C	cSt	2.0–4.5	2.0–4.0	2.0–4.0	2.0–4.0
Sulfur, maximum	wt ppm	5,000	300	30	Sulfur-free[b]
Aromatics, maximum	wt%	Not specified	25	15	15
PAHs, maximum	wt%	Not specified	5	2	2
T_{90}, maximum	°C	Not specified	340	320	320
T_{95}, maximum	°C	370	355	340	340

cSt Centistokes.

[a]Compliance with either cetane index or cetane number is allowed.
[b]5-10 wt ppm based on available data on advanced technology vehicles. As more data become available, a more specific maximum will be defined.

Source: ACEA and others 2002.

ANNEX 5

Two- and Three-Wheelers

Emissions from the large and rapidly growing number of two- and three-wheel vehicles are a major source of air pollution in a number of countries, especially in Asia. Because they are less expensive than other vehicles, two- and three-wheelers play an important role in the transport market. In South Asia, they accounted for at least half of all vehicles as of 2000. Two-wheel vehicles, which include mopeds, scooters, and motorcycles, are used mostly for personal transportation, although in some cities (for example, Bangkok) they are used as taxis. Three-wheel vehicles, which include small taxis such as autorickshaws and larger vehicles that hold as many as a dozen passengers, are used commercially. In the early 1990s, the majority of three-wheelers and two-wheelers in Asia had two-stroke engines.

Conventional two-stroke engines have several advantages over four-stroke engines. These include lower cost, excellent power, mechanical simplicity (fewer moving parts and resulting ease of maintenance), lighter and smaller engines, greater operating smoothness, lower crankcase emissions throughout the life of the vehicle, and lower NO_x emissions (because two-stroke engines run so rich that NO_x formation is suppressed). They also have disadvantages compared with four-stroke gasoline engine vehicles, including higher particulate and hydrocarbon emissions, lower fuel economy, and louder noise.

Until recently new two-stroke engines without catalysts emitted as much as an order of magnitude more particulate matter than four-stroke engines of similar size. When vehicle age, maintenance, lubricant, and fuel quality are taken into account, two-stroke engines in developing countries probably emit particulate matter at an even higher factor. As much as 15 to 35 percent of the fuel-air mixture from two-stroke engine vehicles escapes through the exhaust port. These "scavenging losses" contain a high level of unburned gasoline and lubricant. Some of the incompletely burned lubricant and heavier portions of gasoline are emitted as small oil droplets that increase visible smoke and particulate emissions.

Recently vehicle manufacturers in industrial countries have been turning to direct-injection small two-stroke engines to meet extremely tight exhaust emission standards. There are concerns that these engines may increase the number (as opposed to mass) of particles emitted. Since environmental legislation is increasingly turning to the importance of controlling particle size and number, this question needs to be investigated further.

While particulate emissions from traditional two-stroke engines are high, it is worth bearing in mind that particles emitted by two-stroke gasoline engines are fundamentally different from those emitted by diesel vehicles. The health impact of oil droplet-based particles from two-stroke engine vehicles is not well understood. Most health impact studies have been carried out in countries that do not have large two-stroke engine vehicle populations and where the principal sources of fine particulate emissions are diesel vehicles and stationary sources. In all studies, sickness and death are regressed on the overall ambient particulate concentrations, not against vehicular particulate emissions. Most of the particulate matter from two-stroke engines is soluble organic matter, whereas particulate matter from diesel vehicles and stationary sources contains a significant amount of graphitic carbon. Their behavior in the atmosphere in terms of nucleation, agglomeration, dispersion, and condensation could be quite different. This area of research merits further investigation.

The age and poor maintenance of many two- and three-wheelers in developing countries increase emissions well above any applicable standards. In addition, many drivers use lubricants of poor quality, leading to two distinct but related problems (Kojima and others 2000):

- Drivers in some countries use widely available straight mineral oil—intended for use only in slow-moving stationary engines but not in vehicles—or new or recycled four-stroke engine oil rather than the specially formulated 2T oil recommended by vehicle manufacturers. These oils build up deposits in the engine, increasing emissions.
- Drivers may also use excessive quantities of lubricant. Some drivers simply lack knowledge about the correct amount of lubricant to add and the adverse effects of using too much. Others believe that adding extra lubricant improves vehicle performance, increases fuel economy, or provides greater protection against piston seizure. Because straight mineral oil may not mix with gasoline as well as 2T oil, a greater quantity of lubricant is needed for lubrication. In reality this practice provides little or no benefit to drivers, but significantly increases the level of emissions and reduces the quality of air for society at large.

Drivers are also encouraged to buy much more lubricant than needed by filling station operators, who earn higher margins on oil than on gasoline. Furthermore, adulteration of gasoline with kerosene is widespread in a number of developing countries because of the large difference in the retail price of the two fuels. This practice increases emissions because kerosene has a higher boiling point than gasoline and is therefore more difficult to burn. As a result more deposits build up in the engine and damage the engine over time, and more unburned hydrocarbons and particles are emitted in the exhaust gas.

Relationships between Mass Emissions and Vehicle and Fuel/Lubricant Technology

Of special concern to policymakers are emission characteristics of in-use vehicles. Type approval and conformity of production tests are carried out on new vehicles using certified reference fuels and lubricants. With increasing vehicle usage, lack of maintenance, and perhaps use of improper lubricants or adulterated gasoline, vehicle emission levels can be severalfold higher.

One recent study (Kojima and others 2002, ESMAP 2002a) measured mass emissions from three two-stroke engine gasoline three-wheelers commercially operated in Dhaka, Bangladesh. Although it is not possible to obtain statistically meaningful results without conducting tests on a large fleet, the study provides some stylized observations. The three vehicles were manufactured by Bajaj Auto, India, in 1993 (vehicle 3), 1995 (vehicle 1), and 1996 (vehicle 2). Vehicle 2 was manufactured to meet the 1996 Indian emission standards. The parameters investigated for their impact on pollutant emissions were the vehicle age (4, 5, and 7 years); state of vehicle maintenance; quality of gasoline (1998 "reference" gasoline purchased in India with 87 research octane number [RON], and a blend of gasoline from five filling stations in Dhaka with 80 RON; gasoline sold in Dhaka is often adulterated with kerosene); quality of lubricant (straight mineral oil used in Dhaka by three-wheeler drivers, 2T oil meeting JASO FB[1] specifications purchased in India, and JASO FC grade "low smoke" oil purchased in India); quantity of lubricant (3 percent as recommended by the vehicle manufacturer, and 8 percent representing the common practice in Dhaka of using excessive quantities of lubricating oils); and the installation of an oxidation catalyst (manufactured by Allied Signal).

Vehicles 1 and 3 were tested before and after servicing, which consisted of cleaning or adjusting the spark plug, carburetor, air filter, and clutch/gear/accelerator play, and correcting for leakage in the exhaust system. The test sequence was randomized to reduce the impact of systematic errors. In order to fur-

[1]In 1990, the Japanese Standards Organization (JASO) created a two-stroke lubricant standard with three levels of quality (FA, FB, and FC). Lubricity and detergency quality increase from FA to FC, and exhaust blocking and smoke emission improve. Maximum permissible levels of smoke density are 50 percent for FA oil, 44 percent for FB oil, and 24 percent for FC oil. Japanese manufacturers of two-stroke vehicles identify FC (low-smoke lubricants) as their minimum requirement.

ther provide a check on systematic errors, vehicle 2 was designed to be tested without undergoing a service. Unfortunately, vehicle 2 had a major breakdown after six tests and had to be repaired. The repair carried out on vehicle 2 was intended to represent minimal "reconditioning" of the vehicle and not the service performed on vehicles 1 and 3. Only the seized piston and rings were replaced with utmost care while ensuring that the engine deposits and so on were not disturbed. However, the results obtained showed that even this reconditioning lowered emissions. The results were analyzed using multiple linear regression analysis. The explanatory variables are shown in table A5.1. The "base case" was selected to be vehicle 2 after reconditioning without the catalyst using the Indian reference gasoline and 3 percent 2T oil. This combination gives one of the lowest particulate emission levels.

The results for particulate emissions are given in table A5.2. The mass particulate emissions from three in-use three-wheelers operating in Dhaka were high, ranging from 0.16 to 2.7 g/km, and averaging 0.7 g/km. Mass particulate emissions followed the expected trend with the exception of vehicle service—using straight mineral oil, increasing the concentration of lubricant added, and using gasoline purchased in Dhaka (which, as noted above, is often adulterated with kerosene) increased emissions. The base case gave particulate emissions of 0.19 g/km. The emissions from vehicle 3 before repair were nearly five times higher than those for vehicle 2 after reconditioning. Repairing vehicle 3 reduced particulate emissions by less than 30 percent, and the mass emissions remained substantially higher than those of unserviced vehicles 1 and 2. Although vehicle 2 went through only reconditioning rather than a full service, this seems to have had a considerable impact on particulate emissions, resulting in a decrease of 40 percent. In the case of vehicle 1, repairing actually increased emissions by one-third. Increasing the concentration of lubricant from 3 to 8 percent increased emissions by 61 percent. Using straight mineral oil instead of 2T oil increased emissions by about the same amount. Using gasoline from Dhaka rather than the gasoline purchased in India increased emissions by 14 percent.

An interesting finding is that while lubricants meeting JASO FC specifications are known to produce much less visible smoke than regular 2T oil based only on mineral oil, the so-called low-smoke oil showed no improvement in terms of mass particulate emissions. It is clear from the above findings that the mechanical condition of the vehicle has the most significant impact on particulate emissions.

The results of HC and CO emissions are given in table A5.3 and table A5.4, respectively. There was essentially no impact of the quality of lubricant. Increasing the concentration of lubricant lowered HC and CO emissions, as did the use of gasoline from Dhaka.

The oxidation catalyst halved HC emissions, lowered particulate emissions by about one-third, and reduced CO emissions by about 15 percent. There was some correlation between smoke measurements and mass particulate emissions, but the relationship was weak. The correlation between smoke and mass particulate emissions was poor below 1 g/km. For idle smoke, there was a reasonable relationship above particulate emissions of 1 g/km. Under free acceleration, the smoke meter reached saturation above 1 g/km.

TABLE A5.1 Independent Variables in Regression Analysis

Parameter	Description
V1	1 if the vehicle is 1 before service, 0 otherwise
V2	1 if the vehicle is 2 before reconditioning, 0 otherwise
V3	1 if the vehicle is 3 before service, 0 otherwise
V1S	1 if the vehicle is 1 after service, 0 otherwise
V3S	1 if the vehicle is 3 after service, 0 otherwise
L1	1 if the lubricant is straight mineral oil, 0 otherwise
L3	1 if the lubricant meets JASO FC specifications, 0 otherwise
Q2	1 if the lubricant quantity is 8%, 0 if 3%
G1	1 if gasoline is from Dhaka, 0 if it is 87 RON "reference" gasoline from India
Cat	1 if vehicle 2 is equipped with an oxidation catalyst, 0 otherwise
SN	Numbers ranging from 1 to 43 corresponding to the test number in the experimental program

TABLE A5.2

Log Particulate Emission Model Specification

Variable	Coefficient	Standard error	t-Statistic	$10^{(coefficient)}$
Constant	-0.72	0.028	-25.9	0.19
V2 (vehicle 2)	0.14	0.037	3.9	1.39
V3 (vehicle 3)	0.69	0.034	20.4	4.92
V1S (V1 after service)	0.13	0.038	3.3	1.34
V3S (V3 after service)	0.55	0.035	15.7	3.53
G1 (Dhaka gasoline)	0.06	0.024	2.4	1.14
L1 (straight mineral oil)	0.21	0.026	8.3	1.63
Q2 (8% lubricant)	0.21	0.024	8.8	1.61

Mean dependent variable	-0.26	Durbin-Watson statistic	2.33
Dependent variable standard deviation	0.33	Jarque-Bera statistic	1.79
R-squared	0.96	F-statistic	109

TABLE A5.3

Log HC Emission Model Specification

Variable	Coefficient	Standard error	t-Statistic	$10^{(coefficient)}$
Constant	0.96	0.008	114.3	9.03
V3 (vehicle 3)	0.48	0.012	41.1	3.02
V3S (V3 after service)	0.31	0.012	26.2	2.02
L3 (low smoke oil)	0.02	0.009	2.1	1.04
Q2 (8% lubricant)	-0.02	0.008	-2.9	0.95
G1 (Dhaka gasoline)	-0.08	0.008	-8.9	0.84

Mean dependent variable	1.1	Durbin-Watson statistic	2.15
Dependent variable standard deviation	0.2	Jarque-Bera statistic	6.69
R-squared	0.99	F-statistic	451

TABLE A5.4

CO Emission Model Specification

Variable	Coefficient	Standard error	t-Statistic
Constant	15.5	0.53	29.0
V1 (vehicle 1)	-6.50	0.81	-8.1
V2 (vehicle 2)	-6.35	0.71	-8.9
V3 (vehicle 3)	10.13	0.67	15.1
V1S (V1 after service)	-10.70	0.75	-14.2
V3S (V3 after service)	1.78	0.68	2.6
Q2 (8% lubricant)	-1.54	0.44	-3.5
G1 (Dhaka gasoline)	-1.03	0.45	-2.3

Mean dependent variable	13.4	Durbin-Watson statistic	2.21
Dependent variable standard deviation	6.7	Jarque-Bera statistic	1.31
R-squared	0.97	F-statistic	128

Since these trends may be a function of the instrument used to measure smoke (Celesco Model 300 Portable Opacity Meter, produced by Telonic Berkeley Inc., California, United States, was used in this study), more work should be carried out to check this correlation. If the correlation is indeed poor, this brings into question the merit of setting low smoke emission limits for in-use two-stroke engine vehicles other than to check lubricant use.

Emission Standards for Two- and Three-Wheel Vehicles

Despite concerns about high particulate emissions from two-stroke engines, no country has mass particulate emission standards for two- and three-wheelers. The United States, Europe, and Japan did not have tight emission standards for two- and three-wheel vehicles in the 1990s. In fact, Japan did not have any emission standards for two-wheelers for most of the 1990s and adopted exhaust emission limits for the first time in 1998/1999. Areas in Asia with large two- and three-wheel populations, such as India and Taiwan, China, have historically adopted much more stringent emission standards.

The U.S. EPA adopted emission limits for motorcycles in 1978 but excluded motorcycles with engines smaller than 50 cubic centimeters (cc) (table A5.5). California has steadily tightened emission standards for motorcycles. The EPA in July 2002 proposed revised emission standards, and included standards for previously unregulated two-wheelers with engines smaller than 50 cc such as scooters and mopeds (table A5.6). The EPA expects the class III standards to be met by an increased use of technologies already demonstrated as being effective in four-stroke motorcycle engines, such as secondary air injection, electronic

TABLE A5.6

Future U.S. Motorcycle Exhaust Emission Standards

Class	Engine size (cc)	Implementation date	HC (g/km)	$HC+NO_x$ (g/km)	CO (g/km)
I	<180	2006	1.0	—	12.0
II	180–279	2006	1.0	—	12.0
III	≥280	2006	—	1.4	12.0
III	≥280	2010	—	0.8	12.0

— Not applicable.

Source: U.S. EPA 2003.

TABLE A5.5

U.S. Emission Limits for Motorcycles over 50 cc Capacity

Regulation	Model year	Engine capacity D (cc)	CO (g/km)	HC (g/km)
Federal and California	1978 and subsequent	50 to less than 170	17.0	5.0
		170 to less than 750	17.0	5.0 + 0.0155×(D-170)
		750 or greater	17.0	14.0
California only	1980–81	50 or greater	17.0	5.0
	1982 and subsequent	50–279	12.0	1.0
	1982–1985	280 or greater	12.0	2.5
	1985–1987	280 or greater	12.0	1.0[a]
	1988–2003	280–699	12.0	1.0[a]
	1988–2003	700 or greater	12.0	1.4[a]
	2004–2007	280 or greater	12.0	1.4[a, b]
	2008 and subsequent	280 or greater	12.0	0.8[a, b]

[a] Corporate average.
[b] $HC + NO_x$.

Sources: Concawe 1997, CARB 2000b.

fuel injection systems, and catalytic converters. The standards are not expected to result in the universal use of catalytic converters. The EPA projects average costs of US$26 per motorcycle to meet the 2006 standards and US$35 to meet the 2010 standards.

In Europe, ECE Regulation 40 was adopted in 1979 and applies to two- and three-wheelers with an unladen weight of less than 400 kg and having a maximum design speed exceeding 50 km/h or an engine capacity greater than 50 cc. ECE Regulation 40 was amended in 1988 to become ECE 40.01. Table A5.7 shows the emission limits that ECE 40 and 40.01 required to be met in a driving cycle. There was also a CO idle emission limit of 4.5 vol%. These limits were made more stringent in Directive 97/24/EC, which became mandatory for new EU type approvals beginning in June 1999 (table A5.8).

The above limits will be tightened further in 2003 (table A5.9). Unlike the existing standards, the new proposal does not distinguish between two- and four-stroke engines. Previous emission limits for tricycles and quadricycles were set at roughly 1.5 times those of two-wheeled motorcycles, but the new proposed standards for those vehicles have been set at about 1.25 times the proposed motorcycle standards. The EU allowed the use of fiscal incentives to encourage the early introduction of the 2003 standards. It also introduced permissive values for member states wishing to encourage emission standards beyond those previewed for 2003 through the use of fiscal incentives. For three-wheelers, the limits are 7.0, 1.5, and 0.4 g/km for CO, HC, and NO_x, respectively, also beginning in 2003.

India and Taiwan, China, are among the world leaders in setting stringent emission standards for motorcycles. Their respective standards are shown in table A5.10 and table A5.11. Although the CO limits are numerically higher in 2003 in Taiwan, China, than

TABLE A5.8

EU Motorcycle Emission Limits, 1999–2003

Type	CO (g/km)	HC (g/km)	NO_x (g/km)	Cycle
Two-stroke	8.0	4.0	0.1	ECE-40
Four-stroke	13.0	3.0	0.3	ECE-40

Source: European Commission 2000b.

TABLE A5.9

Common Position on Motorcycle Emission Standards Adopted in July 2001 by the European Council (g/km)

	Legal limit from 2003			Voluntary limits for tax incentives		
Engine size	CO	HC	NO_x	CO	HC	NO_x
≤150 cc	5.5	1.2	0.3	2	0.8	0.2
>150 cc	5.5	1.2	0.3	2	0.3	0.1

Source: European Commission 2000b.

TABLE A5.7

ECE Regulation 40/40.01 for Type Approval Exhaust Emission Limits for Four-Stroke Engine Motorcycles

Reference weight	CO (g/km)		HC (g/km)	
R[a] (kg)	ECE 40	ECE 40.01	ECE 40	ECE 40.01
Four-stroke				
<100	25	17.5	7	4.2
100–300	25+25/200×(R-100)	17.5+17.5/200×(R-100)	7+3×(R-100)/200	4.2+1.8×(R-100)/200
>300	50	35	10	6
Two-stroke				
<100	16	12.8	10	8
100–300	16+24×(R-100)/200	12.8+19.2×(R-100)/200	10+5×(R-100)/200	8+4×(R-100)/200
>300	40	32	15	12

[a]Reference weight R = motorcycle weight + 75 kg.

Source: UNECE 2002.

TABLE A5.10

Type Approval Emission Standards for Gasoline- and Diesel-Powered Two- and Three-Wheelers in India (g/km)

	Two-wheelers		Three-wheelers		Two- and three-wheelers
Year	CO	$HC+NO_x$	CO	$HC+NO_x$	PM
1991	12–15[a]	8–9[a, b]	30	12[b]	—
1996	4.5	3.6	6.75	5.4	—
1998	4.5	3.6	6.75	5.4	—
2000 gasoline	2.0	2.0	4.0	2.0	—
2000 diesel	2.72	0.97	2.72	0.97	0.14
2005 gasoline	1.5[c]	1.5[c]	2.25[c]	2.0[c]	—
2005 diesel	1.0[d]	0.85[e]	1.0[d]	0.85[e]	0.10[c]

— Not applicable.

[a]Emission standard depends on the reference mass of the vehicle.
[b]Limit applied to HC only and not to $HC+NO_x$.
[c]A deterioration factor of 1.2 applies to the first 30,000 km.
[d]A deterioration factor of 1.1 applies to the first 30,000 km.
[e]A deterioration factor of 1.0 applies to the first 30,000 km.

Notes: Tests of 1991 and 1996 vehicles were based on the warm Indian driving cycle. Tests of 1998, 2000, and 2005 are based on the cold Indian driving cycle. Test procedures for durability requirements for the year 2005 standards have not yet been notified as of April 2004. Until their notification, the actual emission levels of new vehicles are required to be lower than the stipulated limits by the corresponding deterioration factor.

Source: Iyer 2004.

in 1998, the requirement to test the vehicle using the cold-start ECE 15 driving cycle means that the standards are more stringent. Setting tighter standards in 2003 for two-stroke than for four-stroke motorcycle engines effectively rules out the use of conventional two-stroke engines. The authorities introduced durability requirements in 1991, set at 6,000 km, which were increased in 1998 to 15,000 km. The year 2000 Indian limit on CO of 2 g/km for two-wheelers is tighter than the EU limit of 5.5 g/km, which came into force in 2003. Similarly the year 2000 Indian limit on CO of 4.0 g/km for three-wheelers is tighter than the EU limit of 7.0 g/km. For the 2005 emission standards, the government of India, for the first time, set deterioration factors applicable for the first 30,000 km for two- and three-wheelers. This is twice the distance stipulated in the durability requirements in Taiwan, China. Furthermore, for the first time, the limits for type approval and conformity of production were made identical, making the limits much more stringent in practice than they appear in table A5.10.

Controlling Emissions from Two- and Three-Wheelers

Emissions from the *existing fleet* of two-stroke gasoline engines can be reduced by (a) ensuring that drivers use the correct type and quantity of lubricant, (b) improving vehicle maintenance, and (c) stopping the adulteration of gasoline with higher boiling point materials such as kerosene. For *new vehicles*, switching to four-stroke engine vehicles at the time of vehicle replacement would be very cost-effective. Other options include adopting direct injection two-stroke engine technology or using alternative fuels such as LPG, which is used extensively in three-wheelers in Bangkok, and CNG, which is used in three-wheelers in India and Pakistan.

TABLE A5.11

Emission Standards for New Production Motorcycle Models in Taiwan, China

Stage	Category	Effective date	Cycle	$HC+NO_x$ (g/km)	CO (g/km)	Durability (km)
1	All	1 Jan. 1988	ECE 40	5.5	8.8	None
2	All	1 July 1991	ECE 40	3.0	4.5	6,000
3	All	1 Jan. 1998	ECE 40	2.0	3.5	15,000
4	Two-stroke	1 Jan. 2004	ECE 15 cold start	1.0	7.0	15,000
4	Four-stroke	1 Jan. 2004	ECE 15 cold start	2.0	7.0	15,000

Note: The limits shown for 2004 correspond to motorcycles with an engine capacity smaller than 700 cc.

Source: Shu 2001.

Promoting the correct use of lubricant in existing two-stroke engine vehicles requires mass education of drivers, filling station attendants, vehicle owners, regulators, and even the public, which has a role in bringing political pressure to bear on the problem. In cities where drivers are using excess lubricant, cutting back to the correct amount recommended by manufacturers (3 percent or lower, depending on the vehicle type) could save drivers money even if they switch to superior quality (and hence more expensive) lubricant. Even though the oil itself is more expensive, analysis often shows that 2T oil used in the proper amount costs less than drivers currently pay for larger amounts of lower-grade oils. In addition there are difficult-to-quantify benefits of longer engine life and lower emissions.

ANNEX 6

Alternative Fuels

Vehicles fueled by gasoline and diesel can be very clean if equipped with advanced exhaust- treatment devices that are maintained well to ensure durability and if fuels of required quality are used. However, it is expensive to deploy advanced-gasoline (for example, the equivalent of U.S. Tier 2) and advanced-diesel vehicles, and the requisite quality fuels, especially with regard to sulfur, are not available in many developing countries. Another way of reducing emissions is to switch to inherently cleaner fuels. Gaseous fuels in particular burn cleaner than liquid fuels do, and the combustion of hydrogen, as well as the use of electricity, does not emit any harmful pollutants at the tailpipe.

This annex presents an overview of some of the more commonly used alternative fuel vehicles, or those that are considered to offer the greatest future potential. The fuels selected are natural gas, liquefied petroleum gas (LPG), electricity, biofuels, and hydrogen (used in fuel cell technology). There is already quite a bit of worldwide experience with natural gas, LPG, and ethanol. The experiences with alternative fuels seem to suggest a longer transition away from conventional fuels than initially anticipated.

Natural Gas

Natural gas (NG) offers a significant potential for reducing harmful emissions from vehicles, especially those of fine particles, compared to conventional (as opposed to advanced or "clean" diesel with ultralow sulfur and employing advanced control technology) diesel. As of late 2003, there were more than 3.3 million natural gas vehicles (NGVs) and 6,600 refueling stations worldwide. More than half of the total natural gas vehicle population was in Argentina and Brazil (IANGV undated). By far the majority of natural gas vehicles are gasoline vehicles converted to compressed natural gas (CNG). The alternative of storing natural gas in the liquid state, liquefied natural gas (LNG), is much less common, although the liquefaction process removes impurities and gives higher purity natural gas (higher methane content) than CNG.

Methane, which constitutes the bulk of CNG, has an antiknock index (average of research and motor octane numbers) of over 120. Dedicated CNG vehicles can take advantage of this high octane number of the fuel and operate at a high compression ratio. In practice, the composition of pipeline natural gas varies depending on the source and processing of the gas, as well as the time of year. As a result, not only does the fuel octane number vary, but also the heating value can vary by as much as 25 percent, affecting vehicle performance. Moreover, when used as a fuel in vehicles, the heavier hydrocarbons in natural gas can condense, and the condensation and revaporization lead to fuel-enrichment variations that affect both emissions and engine performance. The presence of higher hydrocarbons and compressor oils can cause knock. Natural gas should be stripped of heavier hydrocarbons before distribution to avoid this problem.

There are two primary reasons for switching to natural gas:

1. **Diversification of energy sources** has been the historical reason for selecting natural gas as a motor fuel. At the end of 2002, the ratio of proven reserves to production of natural gas was estimated to be 61 years, 50 percent higher than that of oil at 41 years (bp 2003).
2. **Much lower emissions**, especially compared with conventional diesel vehicles. This is the primary reason for switching from diesel to natural gas today.

In terms of fuel supply, there are three types of NGVs:

- **Bi-fuel vehicles**, which can run on either natural gas or gasoline.
- **Dual-fuel vehicles**, which run on diesel only or diesel and natural gas with the combustion of diesel used to ignite the natural gas. The stop-and-start nature of urban bus cycles limits the substitution of diesel by natural gas, and makes dual-fuel unsuitable if the objective is to reduce emissions (see box 4).
- **Dedicated vehicles**, which run entirely on natural gas. There is a significant difference in technology between dedicated NGVs that are stoichiometric—typically gasoline-derived engines with a three-way catalyst—and "lean burn" built up from diesel blocks and designed to keep NO_x formation low.

All three types can be manufactured from the start to use natural gas by original equipment manufacturers (OEM) or converted from vehicles that were originally manufactured to run on gasoline or diesel only.

Either way, there is an incremental cost in vehicle purchase or conversion relative to vehicles using conventional liquid fuels, and this additional cost should ideally be recovered from savings in operating costs, typically lower fuel costs. For minimizing emissions, OEM vehicles are considered superior to converted ones, but they are more expensive. Conversion of vehicles in poor condition, as well as poor conversions, are two of the most serious potential problems in developing country cities, and could even compromise the purpose of switching to NG.

The advantages of NGVs include

- Very low particulate emissions
- Very low emissions of airborne toxins
- Negligible sulfur-containing emissions
- Quieter operation, having less vibrations and less odor than the equivalent diesel engines.

Their disadvantages are as follows:

- Much more expensive fuel distribution and storage. Natural gas has to be transported through a pipeline network and compressed to 200 times the atmospheric pressure or even more (for CNG) or liquefied to -162°C (for LNG). LNG's complex on-board storage system makes it suitable only for heavy-duty vehicles.
- Higher vehicle cost, primarily due to the higher cost of fuel cylinders.
- Shorter driving range. CNG and LNG contain less energy per unit volume than gasoline or diesel.
- Heavier fuel tank. This reduces fuel economy and leads to greater braking distance.
- Potential performance and operational problems compared to liquid fuels (Watt 2001, Eudy 2002). There are consistent reports that the performance of the generation of natural gas buses from the early 1990s was less than satisfactory. More recent models have shown much improvement, but NG buses are not without problems. The New York City Metropolitan Transportation Authority has been operating a fleet of CNG buses, numbering 90 in 2000. Their experience with CNG buses between 1995 and 2000 showed, however, that CNG buses were only 50 to 75 percent as reliable as diesel buses, 40 percent less energy-efficient in urban service, and significantly more expensive to operate (MTA New York City Transit Department of Buses 2000).

With respect to emissions, it is worth noting that advanced technology gasoline vehicles with three-way catalysts are so clean that the fuel itself (that is,

BOX 4

From Dual-Fuel Buses to Dedicated CNG: Lesson from Seattle, United States

Seattle put 129 CNG dual-fuel vehicles into service in 1992. Drivers, however, were found not to like using CNG. In 1998, the city's usage of natural gas in the dual-fuel buses was discovered to be a mere 8 percent. An education campaign was mounted, and the natural gas usage increased to 41 percent in response. The city is now choosing dedicated CNG buses instead of dual-fuel vehicles, and these single-fuel CNG buses are being deployed closer to refueling stations.

Source: Automotive Environment Analyst 2000.

whether liquid or gas) plays a minor role, especially for the regulated emissions. Under these circumstances, converting an advanced gasoline vehicle to gaseous fuel could have little or no emissions benefits, with the exception of lower evaporative emissions of non-methane hydrocarbons.

NGVs have a marked advantage over conventional diesels. Example data taken from the United States comparing CNG with diesel shown in table A6.1 amply illustrate this point.

TABLE A6.1

Emissions Benefits of Replacing Conventional Diesel with CNG

Fuel	CO	NO_x	PM
Diesel	2.4 g/km	21 g/km	0.38 g/km
CNG	0.4 g/km	8.9 g/km	0.012 g/km
% reduction	84	58	97

Note: Medium-duty diesel buses, central business district test cycle.

Source: Frailey and others 2000.

A well-configured CNG bus produces lower NO_x emissions than a pre-2003 U.S. diesel bus, but post-2003 diesel buses are approaching the same low NO_x level through the use of exhaust gas recirculation (EGR). The emergence of so-called clean diesel, pilot-tested in North America and Europe and slated for mandatory deployment by the latter half of this decade, poses a serious challenge to NGVs. As mentioned in the first three annexes, most clean diesel technologies rely on dramatic reductions in the level of sulfur in diesel to enable the use of such exhaust treatment devices as continuously regenerating particulate filters and lean deNO_x catalysts. Available data indicate that particulate emission levels between clean diesel and CNG may be essentially the same (table A6.2), although particulate emissions from state-of-the-art CNG vehicles (with a stoichiometric air-to-fuel ratio and a three-way catalyst) may still be lower than those from state-of-the-art clean diesel vehicles. Note that table A6.2 shows total hydrocarbons, which include methane, and most of the hydrocarbon emissions from CNG buses comprise methane, which is a powerful greenhouse gas but nonreactive and has virtually no impact on urban air pollution.

TABLE A6.2

Comparison of CNG and "Clean-Diesel" Buses in New York (g/km)

	Central business district cycle		New York bus cycle	
Pollutant	CNG	Diesel	CNG	Diesel
Particulate matter	0.011	0.015	0.044	0.023
NO_x	15	16	32	45
Total hydrocarbons	10	0.01	42	0.038

Note: Heavy-duty diesel buses (1999 model year) using diesel containing 30 ppm sulfur and Johnson Matthey's continuously regenerating particulate trap system (but not lean deNO_x catalysts); CNG buses (1996, 1998, and 1999 model year) equipped with oxidation catalysts.

Source: MTA New York City Transit Department of Buses 2001.

While many technical breakthroughs have been announced for the deployment of clean diesel, including refining processes to produce ultralow sulfur diesel at a fraction of the cost employing conventional technologies, clean diesel is likely to be some years away for widespread application in a number of developing countries, where natural gas remains the only commercially tested clean fuel alternative for heavy-duty engine applications. Strong technical support and awareness-raising are crucial for promoting the switch from diesel to natural gas vehicles (see box 5).

Two contrasting country cases: Argentina and New Zealand

Argentina and New Zealand were once two world leaders in the NGV market. Today, Argentina's market remains the largest in the world, while the New Zealand's NGV market has declined precipitously since the late 1980s. The difference in experience of these two countries is instructive.

Argentina launched its CNG vehicle program in 1984. By then, there was an extensive network of natural gas pipelines reaching most cities. The government offered no direct subsidies; the incentive for fuel switching stemmed entirely from the high tax on gasoline. The fuel prices in December 1999 were

BOX 5

Natural Gas Buses: Experience of Bus Fleet Operators

Phoenix Transit, USA. The bottom line is *training, training, and more training.* Phoenix Transit initially met resistance from the operators, mechanics, fuelers, and subsequently the union. The company trained everyone, from top management to bus washers. The main challenge is to have operators and maintenance staff who can observe and report changes in the buses while in operation and during preventive maintenance. The next challenge is to have bus manufacturers and component manufacturers working in partnership with the service and maintenance contractors.

Sydney buses, Australia. Perception problems about poor drivability were put to rest with comparison trials with diesel buses. The conclusion was that the lack of noise from the natural gas buses gave the drivers the impression of lack of acceleration!

Source: Watt 2001.

US$1.04 per liter of premium gasoline, $0.50 per liter of diesel, and $0.33 per cubic meter ($m^3$) of CNG. At these prices, the payback period for those vehicle owners converting from gasoline to CNG could be a matter of months depending on the total number of kilometers traveled a year (figure A6.1).

While one of the original objectives of this program was to substitute diesel with CNG, that substitution has not occurred because the price difference between diesel and CNG is not sufficient to recover the incremental cost of NGVs within a reasonable period. As a result, no CNG buses are in regular operation today, while diesel is actively competing with CNG to capture the taxi market from CNG.

In stark contrast to Argentina, the government of New Zealand was heavily involved in the NGV program from the outset. It provided generous financial incentives both for conversion and establishment of refueling stations. The number of CNG vehicles doubled every year, seriously stretching the ability of the industry to cope. The industry was so preoccupied with meeting the demand for conversion that quality at times became a secondary priority, resulting in the perception of CNG as a second-rate fuel that was used only because it was much cheaper than gasoline.

When the new Labor government began to deregulate the economy, withdrawing financial incentives for the CNG industry, the market essentially died. NGVs in early 2004 numbered some 1,500 compared to the peak of 110,000 (Harris 2004).

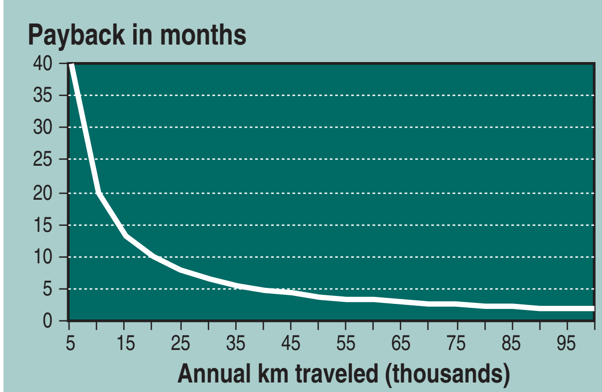
Observations from around the world

The following preconditions are typically needed for successful NGV programs:

- Natural gas should be available at low cost, which is the case if the country has large reserves of natural gas.
- A NG distribution pipeline for other users of NG should be in place.
- The government should establish a proper regulatory framework to provide a fair and level playing field for all stakeholders.
- The government should establish adequate safety and performance standards that are monitored and enforced.
- The retail price of NG needs to be considerably less than that of the liquid fuel. This makes NG substitution of diesel difficult, because the tax on diesel is low in most developing countries so that making NG cheaper might even entail a direct subsidy. Making NG much cheaper than diesel would be especially difficult in countries that import LNG.

FIGURE A6.1

Payback for Conversion from Premium Gasoline to CNG in Argentina, 1999 Fuel Prices



Source: Francchia 2000.

- In the early days of a NGV program, a champion coordinating activities among different stakeholders and publicizing the benefits of NGVs may be needed.

Worldwide experience with NGV has shown that:

- Poor conversions can lead to higher emissions and operational problems, giving NGVs a bad name. When gasoline vehicles were converted to NG, one of the unpleasant surprises in industrial countries was that the converted NGVs were found to be more polluting when tested for emissions in cases where recent model year vehicles had been converted.
- NGVs are especially suitable for high-usage vehicle fleet operators who can exploit economies of scale.
- There are consistent reports that NG 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 NG engine technologies are still being refined to achieve performance comparable to that of their diesel equivalents.
- Successful NG bus programs are based on dedicated OEM, and not converted, buses. Conversion of existing diesel vehicles has typically not been acceptable to owners or users.
- Transit buses in many, if not most, developing countries 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 NG 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 NG bus programs to failure.
- The number of refueling stations and NGVs must be balanced so that there are no unacceptably long queues for refueling on the one hand and underutilization of filling stations on the other. During the early days of NGV programs, the government may consider giving incentives to provide a critical mass of both, such as by granting permits where filling stations were not allowed earlier (Argentina) or by providing subsidies of limited duration.

Liquefied Petroleum Gas

Liquefied petroleum gas is a mixture of light hydrocarbons, mainly propane/propene and butanes/butenes. LPG is a product of refining petroleum as well as a component of natural gas, and a key demand for the product in the developing world has been as a household cooking fuel. LPG is easier to distribute and store than CNG; it requires pressures ranging from 4 to 13 atmospheres, compared with 200 atmospheres for CNG. Among LPG's good environmental features are its limited amount of highly reactive hydrocarbons and its relatively low sulfur content. It does, however, contain olefins, which are photochemically reactive.

Although the octane number of LPG is not as high as that of natural gas, LPG has excellent antiknock characteristics. Propane has an antiknock index of 104, allowing dedicated propane vehicles to take advantage of engines with slightly higher compression ratios than can be used with gasoline. LPG, being a gas, gives similar exhaust emission reduction benefits to those of natural gas.

As of the early 2000s, there were in excess of 4 million LPG-powered vehicles in use around the world. Italy led the world with more than 1.1 million LPG-powered vehicles, followed by Australia with over 500,000, North America with over 400,000, and the Netherlands in excess of 360,000 vehicles using LPG (LPG Autofuel Systems 2002). Since then, the number of LPG-powered vehicles has fallen in some countries, while it has risen sharply in others. By early 2004, there were 1.6 million LPG-powered vehicles in the Republic of Korea. Three-wheel taxis in Bangkok run on LPG, as do many taxis in Japan. Most substitute for gasoline, although there are some heavy-duty vehicles running on LPG instead of diesel. It should be noted that two-stroke engine LPG vehicles, such as the three-wheel taxis in Bangkok, provide essentially no benefits with respect to particulate emissions compared to two-stroke engine gasoline vehicles, and emit considerably more particulate matter than four-stroke engine gasoline vehicles (Hare and Carroll 1993).

The main potential problems in introducing LPG to the transport sector have to do with sources of supply and the distribution system. Demand for LPG worldwide is estimated by one industry analyst to grow at 3.5 percent per year between 2000 and 2010; annual petroleum demand growth was only 1.8 percent during the same period (Chandra and others 2001). High growth of LPG demand in the Far East coupled with other factors made the East of Suez region a net importer of LPG for the first time in 2001. This change, along with greater price volatility seen in recent years, has raised questions about supply stability. On the distribution side, LPG is stored under pressure both inside the vehicle and in the refueling tanks. Special refueling equipment is needed to transfer the pressurized liquid from storage tanks to the vehicle and to ensure that no LPG escapes during refueling. The required investments in LPG distribution and refueling stations have not been made in most developing countries, constraining widespread use of LPG.

As with NG, LPG displacing conventional diesel will have especially beneficial effects on particulate emissions. LPG buses are also quieter. Conversion of diesel engine vehicles to LPG, however, is as complex as is conversion to CNG, as the compression ratio has to be decreased and a spark ignition system added. The city of Vienna has a fleet of more than 400 LPG-fueled buses, the largest in the world. The operators report higher fuel consumption and increased servicing requirements, in addition to higher bus purchase cost.

Electric/Hybrid

For public transport vehicles direct collection of current by trams or trolleybuses is well established, with the limitations being the inflexibility of routes and the typically higher expense compared with diesel propulsion. For private automobiles, flexibility requirements preclude direct collection of current.

Historically, there has been a great deal of interest in battery-electric vehicles as zero tailpipe emission vehicles. On account of lack of sufficient progress in battery technology, however, battery-electric vehicles are no longer considered a viable mainstream technology by most industry analysts. Recently, increasing efforts have been directed to hybrid electric-internal combustion engines rather than battery-electric-engine vehicles. A hybrid combines an electric power source and a fuel to drive the vehicle.

Battery-electric

The battery of an electric vehicle is central to its fuel system and its success. Lead-acid batteries are currently used as a low-cost option in electric vehicles. Nickel-metal hydride and nickel-cadmium offer a greater driving range but are more expensive than lead-acid batteries. Other technical options are very costly or still under development. There is no consensus as to what type of battery may be best for the future. Depending on the battery type and the voltage used, battery recharging can take 4–14 hours. Because the driving range is short, batteries also need to be recharged frequently. Lead-acid batteries emit hydrogen as they recharge, so indoor recharging facilities must be well ventilated.

The main disadvantages of electric vehicles are the length of time needed for recharging them, their much shorter driving ranges, and their higher purchase costs. Battery life is also limited to a number of recharges, and lead-acid battery life is reduced if batteries are fully discharged. Battery charge and discharge efficiency are quite poor for lead-acid batteries. The danger of electric shocks is a concern. Crashworthiness of battery-powered vehicles is still being studied. The economics of electric vehicles depend, among other things, on the price of electricity. The long-term viability of electric vehicles should be evaluated from the standpoint of market-based energy pricing. Given the current state of the technology, electric vehicles would not be expected to have widespread application, but could play a useful role in reducing emissions along fixed routes and can be especially attractive in countries with abundant sources of low-cost electricity.

Hybrid

Hybrid vehicles are most appropriate for circumstances in which there is a lot of stop-start driving or where large loads have to be carried, requiring large internal combustion engines (such as buses and delivery trucks), because of the characteristics of hybrid drives. Some industry observers view gasoline/diesel hybrid-electric as a bridge to fuel cells. Diesel-hybrid vehicles in particular offer a great potential for reducing greenhouse gas (GHG) emissions.

Heavy-duty hybrid vehicles are still undergoing development and are not yet commercially competitive. The New York City Metropolitan Transportation Authority tested five diesel-hybrid transit buses between 1998 and 2000. The experience was positive "for a new technology," with emission benefits matching those of CNG buses (the hybrid buses were equipped with particulate filters) and fuel economy surpassing diesel or natural gas. However, hybrid buses were less reliable than diesel buses, starting off half as reliable, and bus availability during morning peak service did not reach the target during the test period September 1998 to March 2000 (MTA New York City Transit Department of Buses 2000).

Given the evolving nature of this technology and technical issues to be addressed before hybrid vehicles become commercially viable, hybrids are unlikely to play a significant role in mitigating vehicular emissions in developing country cities in the near term. However, just as in the case of battery-electric vehicles, but perhaps more so, they can play a carefully targeted role in special circumstances, including as fleet vehicles, and along heavily polluted traffic corridors.

Biofuels

The two most commonly used biofuels in vehicles are ethanol and biodiesel. Pure ethanol is used for transportation in Brazil, but its use has been declining in recent years. An alternative use of ethanol is to mix it with gasoline. Biodiesel is used in compression ignition engines, blended with petrodiesel or as neat (that is, 100 percent) biodiesel.

Ethanol

Ethanol has high octane and relatively clean combustion characteristics. Ethanol can be used neat or blended into gasoline. The presence of oxygen in ethanol facilitates combustion, reducing CO and HC emissions from old-technology vehicles (in contrast to newer models, which are equipped with oxygen sensors). Compared with diesel, ethanol produces substantially less particulate emissions. The emissions of formaldehyde, which is a toxin and an ozone precursor, are higher from ethanol than from conventional liquid fuels.

When the amount of ethanol in gasoline is relatively low—for example, 10 percent ethanol blended with 90 percent gasoline—ethanol increases the volatility of the resulting fuel mixture significantly. Production costs of specially formulated low-volatility gasoline to compensate for the high volatility of the ethanol-gasoline blend are normally higher. Ethanol has slightly more corrosive properties than gasoline. Because of its miscibility with water and its corrosive properties, ethanol should be handled separately from gasoline during distribution.

The largest "biofuel" vehicle program in the world has historically been Brazil's Proálcool. Ethanol has also been extensively used in the United States to satisfy the oxygen requirement under the 1990 Clean Air Act Amendments and more recently to replace methyl tertiary-butyl ether (MTBE). Fuel-grade ethanol in these countries is produced by fermentation of sugar from grains (more than 90 percent of ethanol production in the United States comes from corn) or sugarcane (in Brazil), followed by distillation. As such, the price of ethanol is determined by the prices of the starting materials (corn, sugar, wheat) on the international market, as well as the costs of extracting sugars and converting them into ethanol, which is energy-intensive.

The analysis of lifecycle GHG emissions for ethanol production is dependent on a number of factors. Assumptions about fertilizer, pesticide, and herbicide consumption, irrigation, farm equipment, and how to handle by-products can have a significant impact on the final net energy balance. The calculation of net GHG emissions is also complicated by the type of land that is used for biofuel crop production, and issues such as the carbon storage of different land use types. In the United States, the energy needed to grow the corn, harvest it, transport it, and distill it into ethanol has been widely discussed and debated. A recent study conducted for the Australian Greenhouse Office concluded that the addition of 10 percent ethanol from sugarcane to gasoline has a slightly negative impact on overall GHG emissions in Australia (Beer and others 2001).

Ethanol from sugarcane in the Center-South region of Brazil is undoubtedly the lowest-cost ethanol in the world. Nonetheless, it is difficult to quantify the precise production costs because of the significant subsidies that have been provided in Brazil for investment financing in the past, including for capital-intensive ethanol production plants. At the heart of the ethanol program in Brazil is the mandatory blending of ethanol with gasoline. Each year, a Presidential Decree sets a range for the percentage of ethanol that must be used in gasoline. The actual percentage is determined by an inter-ministerial committee comprising representatives of the Ministry of Agriculture, Ministry of Finance, Ministry of Mines and Energy, and Ministry of Industrial Development and Commerce. The blending rate has varied between 20 percent and 25 percent in recent years. The blending ratio tends to be increased when sugar prices are low, and decreased when sugar prices are high. The government also bans the use of diesel-powered personal vehicles; requires government agencies to buy 100 percent ethanol-fueled vehicles; offers ethanol storage credits to millers; and imposes an import duty on ethanol (except for the intra-zone trade of ethanol with Brazil's Mercosur partners) to protect the domestic ethanol producers, 21.5 percent as of late 2003. During the same period, gasoline was taxed at R$0.57 (US$0.20) per liter whereas hydrous ethanol was taxed at R$0.05 (US$0.017) and anhydrous ethanol at R0.06 (US$0.021) per liter (USDA 2003).

In other parts of the world, the production cost of ethanol is higher. In all cases, including Brazil, promotion of ethanol has required implicit and explicit subsidies. One of the largest fiscal incentives offered is the exemption made available to ethanol from the mineral oil tax levied on gasoline of €0.65 per liter in Germany.

Compliance with extremely stringent emission standards requires precise control of the air-to-fuel ratio. Therefore, there is a tendency to seek to minimize the *range* of oxygen content in gasoline. The World-Wide Fuel Charter, issued by vehicle manufacturers around the world, limits the amount of ethanol in gasoline to 7.7 percent by volume in all categories of gasoline, limits higher alcohols (those with three or more carbons) to 0.1 percent by volume, does not permit methanol, and states that ethers are preferred to alcohols where oxygenates are used. Where up to 10 percent ethanol is permitted by preexisting regulations, labeling at the pump is recommended (ACEA and others 2002). The European gasoline fuel specifications limit ethanol in gasoline to 5 percent (see table A3.1).

Biodiesel

Biodiesel is typically produced by reacting vegetable or animal fats with alcohol to produce a fuel similar to diesel. Biodiesel can be used neat or blended with petroleum diesel in a compression ignition engine. Engines running on biodiesel tend to have lower hydrocarbon, particulate, and CO emissions, but higher NO_x.

The technology for extracting oil from plant seeds has remained the same for the last decade or two, and is unlikely to change significantly in the future. Transesterification of oil with alcohol to make biodiesel is a relatively simple process and offers little scope for efficiency improvement. As a result, processing costs are unlikely to fall markedly in the coming years. Because plant oils and animal fats have alternative markets that tend to push up the feedstock prices, biomass that can grow on marginal land with little input and rainfall, such as Jatropha or honge nuts, may provide an attractive alternative as a feedstock for biodiesel for developing countries.

Similar to ethanol, interest in biodiesel as a transportation fuel has been driven by issues unrelated to urban air quality. The EU is a major producer of biodiesel where securing alternative sources of energy supply is cited as the principal reason for promoting biodiesel. Other reasons given are the need to lower GHG emissions and to promote economic development and maintain employment in the rural community. With respect to local air quality, the European Commission has stated that biofuels will offer little, if any, emission advantage over gasoline and diesel in the future (European Commission 2001). The European Commission further acknowledges that the cost of biodiesel production is two to three times that of gasoline and diesel. Therefore, fiscal incentives in the form of large subsidies would be necessary as the key driver for investment in liquid biofuels plants.

The World-Wide Fuel Charter limits the amount of biodiesel in diesel to 5 percent in its first three categories of diesel, and none in the fourth (most stringent) category. Where biodiesel is blended into diesel, labeling at the pump is recommended. The limit is motivated by present concerns about the effects of biodiesel on fuel viscosity and loss of fluidicity at low temperatures, corrosion, and the compatibility of biodiesel with seals and fuel system materials. The biodiesel should comply with internationally recognized fuel specifications, such as EN 14214 and ASTM D6751 (ACEA and others 2002).

Hydrogen and Fuel Cell Technology

In the long run, fuel cells have the potential to offer substantial benefits. Fuel cells can achieve 40 to 70 percent efficiency, significantly greater than the 30 percent efficiency of the most efficient internal combustion engines, although modern diesel engines today can achieve maximum brake thermal efficiencies in the range of 40 to 45 percent. Fuel cells produce electricity with high efficiency by combining hydrogen from a fuel with oxygen from air to produce energy and water. When the fuel is hydrogen itself, there are no exhaust emissions other than water. If hydrogen is produced from the electrolysis of water using electricity generated from renewable energy, then fuel cell vehicles can be said to be utilizing completely renewable energy sources. However, such a pathway is unlikely to be economic in the medium term, except in a few countries that have abundant hydroelectric or geothermal power such as Iceland. The alternative is to form hydrogen by "reforming" hydrocarbons from fossil fuels. These reformers can be on board a vehicle. During reforming, CO_2 and hydrocarbons are emitted as by-products.

Urban buses in particular seem suited to fuel cell technology because of fewer technical obstacles in larger vehicles, demand for more stringent emission standards because of higher population exposures to bus exhaust, and their tendency to be refueled at central refueling sites (thus avoiding the need for extensive refueling infrastructure). A number of fundamental technical issues still remain before full-scale commercialization of fuel cell vehicles:

- **Fuel choice.** Direct hydrogen is preferable from the point of view of the environment, but technology for workable on-board storage systems has not been developed, especially for cars. It will also take a long time to develop a refueling infrastructure for hydrogen. While distribution and storage of liquid fuels is more straightforward, viable processors for re-forming liquids into hydrogen have not been developed yet.
- **Vehicle cost.** Much more work is needed to bring down the costs of fuel cell vehicles. Even optimistic assumptions about future technological breakthroughs suggest that it will take at least a decade before fuel cell vehicles become affordable.
- **Other competitive alternatives.** Fuel cell vehicles are competing with the moving target of ever-improving conventional combustion engine and hybrid-electric technologies. The business case for fuel cell cars and light trucks is much weaker than that of urban buses for this reason.

Large-scale deployment of fuel cell vehicles is years, if not decades, away. Given the amount of research and development still needed before commercialization, it would be premature for developing countries to devote significant resources to pilot testing and developing fuel cell vehicles.

ANNEX 7

Maintaining Vehicles: Inspection and Maintenance Programs

Lack of cultural acceptance of regular, and especially preventative, vehicle maintenance is one of the most important contributors to air pollution from mobile sources. This is especially true in developing countries. An inspection system that measures vehicle emissions to identify gross polluters and requires those that do not meet the standards to be repaired is standard approach adopted worldwide to address this problem.

Developing countries face a number of challenges in implementing an effective inspection and maintenance (I/M) program. What is needed are reliable data on active vehicle population, suitable test protocols, and administrative control.

Data on Vehicle Population

Most developing countries do not have a reliable database on their active vehicle population. While new vehicles may be registered, vehicle retirement is often not recorded, making it difficult to identify which vehicles are still being driven. For example, there is no annual vehicle registration in India: vehicles are registered when new and are supposed to reregister only after 15 years' service. This makes it very difficult for the government to obtain accurate information on the vehicle population and to conduct an effective inspection program: the authorities cannot be sure which vehicles are still being operated and hence cannot estimate the percentage of vehicles that evade inspection. The problem is compounded by the fact that the data are least reliable on the very vehicles that are likely to be gross polluters, namely, old vehicles. In some developing countries, it is not rare for more than one vehicle to have the same registration number. One of the first steps in making I/M effective is to create a need on the part of vehicle owners to comply by reporting to test centers, but this is difficult without an up-to-date and accurate vehicle registration system.

Test Procedures

Much has been learned in industrial countries as to which test protocols are suitable for I/M. Test protocols that result in 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. It is difficult to sustain an emissions inspection program when substantial measurement differences exist among testing stations. The elimination of measurement differences must therefore be a high priority. This often requires changes in the equipment and test protocols used in the programs together with calibration audits and other activities.

Dilution of exhaust gas

In I/M, 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 O_2 and CO_2 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. Frequently, O_2 and CO_2 are not measured and their measurements are not required by the test protocol.

Preventing "late-and-lean" tuning in gasoline engines

It is easy to reduce the CO and HC emissions from an older vehicle by delaying the ignition timing and making the air–fuel mixture lean. This "late-and-lean" approach reduces CO and HC, but it also reduces engine power and can increase NO_x. Without testing vehicles under load or measuring 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. Most developing country cities do not have dynamometer-based testing, leaving the door open for the loophole of tuning "late and lean."

Remote sensing

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, CO_2, 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. It has also been used to post electronic signs informing passing drivers of the status of their vehicles' emissions status in an effort to raise public awareness.

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.

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 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.

At present, remote sensing can therefore be considered proven technology only 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.

Identifying high particulate emitters

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 do not readily identify mass particulate emissions.

Smoke tests

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.

Reproducibility is poor when this test procedure is utilized by a large number of testers using different equipment. In July 2002 in Mexico, a test was conducted 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.

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 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 revolutions per minute (rpm) readings from diesel engines, particularly the older ones, yet accurate rpm readings are essential to add to the controls as well. Finally, the ECE R24 procedure, but not SAE J1667, verifies that 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.

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 emissions tests. This and the resulting harassment of drivers were among the complaints voiced in the assessment of the emissions 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

Even when properly administered, smoke tests still have two distinct problems. The first concerns the snap acceleration test and can be addressed by using a more reproducible (and more expensive) form of testing, called a dynamometer test, which can also simulate real-world driving conditions better than snap acceleration. The second problem cannot be addressed, as it underscores the fundamental shortcoming of measuring smoke.

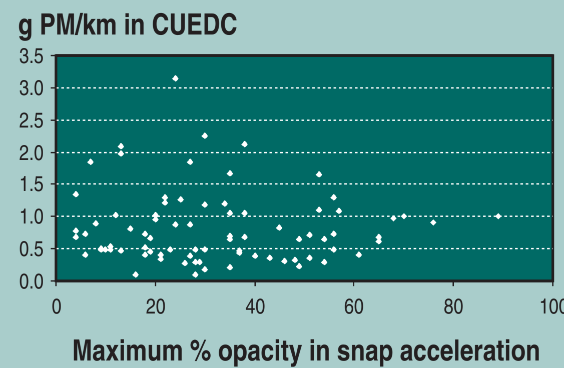
The snap acceleration test is not representative of normal operating conditions. More specifically, it is easier to prepare a vehicle to pass a snap acceleration test than a test under load using a dynamometer, especially if a transient (as opposed to steady-state) loaded test is used. In Hong Kong, for example, 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).

Furthermore, smoke measurements depend heavily on the driving cycle for a given vehicle-fuel combination. One study (NEPC 2001a) 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, and yet there may not be a "typical" driving cycle for all vehicles.

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 of most concern from a health perspective.

FIGURE A7.1

Correlation between Visible Smoke and Mass Particulate Emissions



Source: NEPC 2000.

Correlation between smoke opacity and mass particulate emissions

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 the public's health. The question immediately arises, therefore, as to how closely correlated "smoke" is with fine particulate matter.

To answer this and other questions, the National Environment Protection Council (NEPC) of Australia commissioned eight projects to collect data on the diesel vehicle fleet and emissions characteristics with the objective of developing cost-effective emissions management measures. (The Environment Protection and Heritage Council Web site, included in the References, provides information about the projects.)

Figure A7.1, taken from a project report (NEPC 2000), 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/freeway 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.

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 done 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.

Arising from this, an unfortunate scenario, from the point of view of managing a vehicle inspection and 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 (NEPC 2001b).

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.

Snap acceleration smoke tests are also ineffective for modern, electronically controlled engines or turbocharged engines with boost control. For these vehicle categories, an alternative test procedure is required. 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. 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.

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. Equally importantly, the fact of having to report for emissions testing will prompt some vehicle owners to pay closer attention to vehicle maintenance and exhaust emissions. Given the technical problems associated with measuring particulate emissions in a garage setting, smoke tests will therefore continue to play an important role in emissions testing programs for the foreseeable future.

Approaches to monitoring diesel vehicle emissions

Identifying gross diesel polluters is significantly more difficult than identifying gross gasoline polluters. One serious problem is the lack of a relatively inexpensive and quick method for measuring particulate emissions, the pollutant of most concern in the majority of developing country cities. There is no simple road map, and a multi-thrust strategy is needed:

- In order to encourage the development of adequately equipped and staffed service and repair facilities, more efforts should be directed at improving vehicle emissions inspection and enforcing standards.
- There is a need to raise public awareness and create market conditions that discourage overloading of commercial vehicles.
- There needs to be tighter control over the quality of spare parts.
- The most commonly used test for diesel vehicles—the snap acceleration smoke test—can play a limited but useful role, provided that the test procedure is carefully defined to ensure repeatability and the test protocol is strictly enforced.
- The smoke standards for snap acceleration tests should be lenient; if not there is a serious danger of having a high false failure rate. The test should be seen primarily as a means of identifying the worst gross polluters among old technology engine vehicles.
- For modern engine vehicles as well as high-annual-km commercial vehicles, serious consideration should be given to adopting dynamometer-based tests. This will also enable setting tighter smoke standards.
- Given the high costs of dynamometer testing facilities, especially for heavy-duty diesel vehicles, using on-road visual smoke checks as a screen-

ing tool—whereby those judged to be visible smokers are sent to test centers with dynamometers—may help reduce the overall cost of the diesel emissions inspection program. While visual checks are subjective and potentially more prone to corruption, using them as a screening tool so that those who conduct the checks cannot fine motorists may help to minimize corruption.

- Inspecting underhood equipment, such as the air filter, or measuring manifold boost may be a relatively inexpensive way of identifying high particulate emissions.

Administrative Control

Even when all test centers are in the hands of the private sector, local authorities must dedicate significant resources, personnel, and effort in supervising and controlling I/M programs. More details are given in a recent publication (ESMAP 2004).

Supervision

In an environment where the requirement to possess current certificates is enforced, the black- market value of the certificate increases. Certificates and stickers should be issued to the inspection centers on a controlled basis and their use supervised. Both certificates and stickers should ideally incorporate antiforgery design elements similar to those used in banknote production. The stickers should incorporate a highly visual design and be easily visible at a distance of five meters, enabling enforcement personnel to determine whether certification is current or not.

To be effective, the test protocol must minimize the impact the test technician can have on the test's outcome. It is good policy not to make the test results available to the test technician in the test lane until the vehicle owner has been officially informed of the final decision (pass or fail). Otherwise, it is common for testers to prevent rejects from occurring by tampering with the lane computer, the test procedure, or the vehicle. The availability of real-time emissions measurements even helps the tester to generate a false pass for vehicles that would otherwise have failed the test. The computer should take the gas reading after a preestablished time. As long as this decision is left to the tester, there can be tampering until a pass result is generated.

Vehicle owners must sense a strong need to comply with I/M; that is, they must feel compelled to report to testing stations. This requires that stickers be controlled by the government and be difficult to falsify, and that the sticker have a highly visual design that enables any police officer to easily identify if the vehicle has a current certificate. It also requires that there be enough traffic police or their equivalent empowered to stop and fine vehicles without current stickers.

Centralized software development

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

Test protocol control and improvements

- **Better consistency and repeatability in the test results and control of false passes.** 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 otherwise-uncontrolled variables to be managed: the software is able to determine the characteristics of the diesel engine, particularly its low-idle speed, its rated maximum power 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 emissions readings.

- **Dynamic validation of all the test protocol constraints.** These 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, that the test equipment is not in a low-flow condition, and if the equipment has been 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 require that the test be restarted.
- **Differentiation of emission standards.** Reliable and consistent vehicle identification and test data in centralized databases are essential for performing the statistical analyses required to define the emission limits. These can be obtained only when the test process is computer controlled. 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 lean air–fuel mixture 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 adequate oxygen limits to be applied to both types of vehicle.

Proper equipment operation

- **Automatic computer-controlled random calibration audits.** These audits are needed to ensure that the instruments are within their correct specifications.
- **Automatic equipment calibration.** The software can improve the measurement accuracy by automatically calibrating the equipment at intervals that depend on each specific instrument's proven stability and usage pattern. Intensively used I/M 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 re-calibration is highly beneficial. Re-calibrations should also be considered after high emitters have been tested since there is a tendency to saturate the measuring circuits, which 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 bench 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

- **Correct identification of vehicle.** The identification of the specific vehicle and its owner can be improved by using computerized data entry software that automatically consults lookup 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 suboptimal because the standards are likely to be too lenient for those with newer technology and yet very stringent for other vehicle types.

- **Use of bar-code scanners to improve data entry accuracy.** When the centralized databases contain tests for a specific vehicle, registering the previous test certificate's barcode with a scanner allows the captured and validated data for that vehicle and its owner to be accessed. Thus the test technician only has to enter and validate any changes that might have taken place against other official documents. These include changes of ownership for that vehicle and changes of address for the owner.
- **Real-time electronic transmission of data.** 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 emissions distributions in all test centers and with all test technicians. If one center is found to have emissions 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

- **Improved equipment security measures and electronic detection of tampering attempts.** 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 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 emissions 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 activity that could have resulted in undue adjustments.
- **Automatic printing of digitally signed and validated certificates.** 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. Ele-

ments 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.[1] This allows the computer to validate, for example, when a vehicle is presented for testing that its current (or previous) certificate has not been fraudulently generated or modified.

- **Improved data and certificate security measures to control electronic tampering.** The electronic information also needs to be protected. This can require encryption (where the information cannot be read or deciphered without a specific key),[2] per-register and per-table[3] digital signatures and fingerprints (where the information can be read, but not modified without detection), and protected operating systems and database structures.

Administrative measures

- **Remote lock-out.** 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.
- **Accounting.** There should be automatic certificate accounting and control procedures from government to test centers and to end users verified against 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, which were 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 emissions test altogether.
- **Checking compliance.** 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-test after having obtained a fail certificate. This information greatly helps the vehicle enforcement process.

Auditing

It is difficult for a salaried on-site inspector to adequately control an authorized testing station that is

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[1] A digital signature, a long chain of characters, uniquely defines the certificate. A fingerprint which is shorter for ease of entering into the computer is unlikely to be unique. For example, if one has to type it in, a string of 6 characters is a good fingerprint. If one uses only capital letters, the number of options in this string is 26 to the power of 6 which is unlikely to give a unique combination: 266 = 308,915,776 and a key that has only 300 million combinations is cryptographically speaking very weak and could probably be broken using a normal desktop computer in less than 24 hours. A signature (which does not need to be typed in) can contain more options per character and the string could be 254 characters long, which gives a unique combination. If the digital fingerprint is put on the certificate in the form of a barcode, a far greater number of combinations can be contemplated.

[2] There are many ways of encrypting data. In all cases, one uses a formula or a specific key (character string) to convert the plain-text message into its encrypted form. One then needs to use the same or another formula or key to convert the encrypted message back into its plain text form. Without the formula or character-string in one's possession the encrypted message cannot be converted into a readable format.

[3] Two things need protection in the database: (1) data in a specific test record should not modified (for example, ensure that the emissions readings that were reported by the test equipment have not been manually changed in the database); and (2) that records in the database should not deleted and that new records should 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).

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 monetary payments. The local authority needs to invest in remote, computer-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.

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.

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 the U.S. EPA Protocol G1 or G2 or other internationally recognized protocols. Similarly, a set of internationally traceable neutral filters should be used to evaluate the linearity of the opacity meters.

Experience in Mexico City

The I/M program in Mexico City is widely acknowledged to be one of the most successful in developing countries. The Mexico City government initiated an I/M program in 1982 as a voluntary exercise. The program has undergone a number of changes since, adopting more reliable and stricter testing procedures in order to reduce the number of vehicles obtaining false passes. An independent assessment of the program, including a detailed analysis of emissions data, was carried out in 1999–2000 (ESMAP 2001a). More recently, remote sensing was used in 2003 to collect independent data on the emission levels of vehicles as they are driven on the road. Data analysis is currently underway.

The 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, multilane, test-only "macrocenters" in which some of the lanes would be equipped with dynamometers (enabling dynamic loaded-mode testing). By 1993, 500 test-and-repair centers and 24 macrocenters, all privately owned, were in operation. This side-by-side operation allowed a direct comparison to be made between the test-and-repair centers and the test-only macrocenters.

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 the vehicle and a macrocenter that pronounced the vehicle to be in noncompliance. 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 macrocenters for the dynamometer test, which was unavailable at the test-and-repair centers.

From the point of view of quality control, the test-only macrocenters were far easier for the government inspectors to supervise. They also 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.

Over time, the quality of testing from the test-and-repair centers degenerated. There was surplus capacity of test centers, increasing the incentive to cheat. 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 emissions testing. The situation deteriorated to the extent that an estimated 50 percent of the vehicles that went through the test-and-repair centers eventually obtained their approval certificates fraudulently. Public opinion was that it was a highly faulted emissions control program, and it was very close to being shut down permanently.

These problems led to the program being completely restructured in 1995. Despite political opposition, the licenses were withdrawn from all 600 test-and-repair centers, while the number of test-only macrocenters was increased. A series of stringent quality assurance controls and technical changes were added to the multilane center operation and a new public identity was generated, repositioning them as test-only "verificenters."

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 proportion of failing tests increased several-fold.

In spite of these quality control measures, the system had serious shortcomings. It was estimated that during the first semester of 1997, 19 percent of vehicles obtained their certificate because of a loophole in the standards and test procedures. Garages would tune vehicles "late and lean" or disconnect air hoses from the inlet manifold. Once the test had been passed, the vehicle would be retuned. These techniques sometimes reduced the engine power during testing to an undriveable level and could also have increased NO emissions. However, they effectively, but temporarily, reduced HC and CO emissions and could not be detected by the test procedures in place.

To address technical problems of the testing procedures, considerable work was done by the Mexico City government during 1995–96 to define a new protocol—acceleration simulation mode—from which a hybrid version went into effect for the second semester of 1997. The objectives of modifications in the test protocol were to generate more reproducible test results, reduce measurement uncertainties, permit the use of stricter test limits, and reduce false approvals. By 2001, a fine of up to US$40,000 was imposed on test centers located in the Federal District of Mexico City caught not following the test or administrative procedures. During the first semester of 2000, NO limits were established, eliminating the loophole in the I/M program whereby owners of polluting vehicles could still pass by tuning "late and lean."

The experience in Mexico City shows that for an I/M program to be effective, several conditions have to be met:

- The government must be willing and able to invest in the resources, staff, and effort in auditing and supervising the program to guarantee its objectivity and transparency. This includes remote-auditing and the development of centralized software that controls not only data entry, storage, and analysis, but also equipment calibration, zero-referencing, and test protocols.
- A legal framework has to be established that allows sanctions to be applied for failure to carry out the testing protocols correctly. The testing stations must be subject to monitoring by independent bodies, and in cases of noncompliance, sanctions must be applied.
- Testing protocols should be designed to minimize the chances of individual testers giving false passes.
- The certificate for passing the test has to be easy to monitor, and there should be sufficient monitors (for example, traffic police) to ensure a high probability of catching vehicles that do not display such a certificate.
- The fine for not displaying or not having a legal emissions test certificate must be high enough to act as an incentive to pass the test.
- The testing technology has to be able to prevent the use of temporary "tuning" that enables a vehicle to pass the test but cannot be sustained for regular driving. In the absence of such a technology, motorists and garages become adept at circumventing the purpose of the testing procedure—to identify high-polluting vehicles.
- All testing centers must be subject to equally rigorous implementation of protocols and inspection of their procedures; otherwise, owners of the highest-polluting vehicles easily identify the "softest" centers for passing the test.

- The optimal number of centers relative to the volume of traffic to be tested has to be licensed. If there are too many small centers, the rigor of the tests tends to be watered down as each garage tries to increase its market share.

ANNEX 8

Estimating the Health Impacts of Air Pollution

Air pollution has been associated with a variety of adverse health effects (see table A8.1). 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 (such as colds and sinus problems) and subclinical effects (such as itchy, watery eyes).

Selecting the Health Effects to Be Studied

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. Air pollutants have been associated with hospital admissions, respiratory infections, asthma attacks, 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—and days of work loss. SO_2 and NO_x do not have such significant direct effects, although 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.

How Are Health Effects Estimated?

Estimating the health impacts of air pollution reductions (World Bank 2003a) 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, and 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.

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 their number. Instead, cities typically transfer information on health impacts of pollutants on the susceptible demographic groups from existing studies conducted elsewhere. Box 6 gives an example

TABLE A8.1

Human Health Effects of the Common Air Pollutants

Pollutant	Quantified health effects	Unquantified health effects	Other possible effects
Ozone	Mortality Morbidity: Respiratory symptoms Minor RADs Respiratory RADs Hospital admissions Asthma attacks Changes in pulmonary function Chronic sinusitis and hay fever Centroacinar fibrosis Inflammation in the lung	Increased airway responsiveness to stimuli	Immunologic changes Chronic respiratory diseases Extrapulmonary effects (changes in the structure or function of the organs)
Particulate matter/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) Inflammation in the lung	Changes in pulmonary function	Chronic respiratory diseases other than chronic bronchitis
CO	Morbidity: Hospital admissions—congestive heart failure Decreased time to onset of angina	Behavioral effects Other hospital admissions	Other cardiovascular effects Developmental effects
NO_x	Morbidity: Respiratory illness	Increased airway responsiveness	Decreased pulmonary function Inflammation of the lung Immunological changes
SO_2	Morbidity in exercising asthmatics: Changes in pulmonary function Respiratory symptoms		Respiratory symptoms in non-asthmatics Hospital admissions
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 1997b.

of a CR function transferred in a health impact estimation study of Mexico City (Mexico Air Quality Management Team 2002). Similar functions are available for other health impacts from PM_{10} 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.

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.

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.

The estimated burden of disease from air pollution, such as 800,000 deaths annually in the world reported in a recent publication by the World Health Organization (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, PM_{10} concentration of 15 μg/m^3). 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.

The estimated avoided cases of illness or disease are calculated in the third step using the information collected in the first two steps. Box 6 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 PM_{10}. The avoided cases provide a concrete measure of health gains understandable to a wide range of policymakers.

BOX 6

Estimating a Health Impact of Lowering PM_{10} Concentrations

Estimating the impact of lowering ambient PM_{10} concentrations on avoided hospital admissions for respiratory problems is given below, taken from a study in Mexico City.

Step 1: Epidemiological study (transferred)

- Demographic groups: all
- Concentration-response relationship: 0.139 percent change in hospital admissions for a change in the daily average PM_{10} concentration of 1 μg/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 admissions: Population at risk × 0.00411 admissions/person = 77,218 admissions
- Current population-weighted annual average PM_{10} concentration: 64 μg/m^3
- Population-weighted annual PM_{10} concentration after policy implementation: 51.2 μg/m^3
- Change in PM_{10} concentration in response to policy implementation: 64 μg/m^3 – 51.2 μg/m^3 = 12.8 μg/m^3

Step 3: Calculation of estimated avoided cases

Avoided hospital admissions: 77,218 admissions × 0.00139 change/μg/m^3 × 12.8 μg/m^3 = 1,376 admissions

Note: Reduced hospital admissions are only one of the health benefits of reducing PM_{10} concentrations. Other impacts include premature death and less serious illnesses not requiring hospitalization.

Results from Existing Studies

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

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.

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 $\mu g/m^3$ 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 percent (Cohen and others 2003, Holgate and others 1999). The studies also indicate higher risk for the elderly with chronic heart and lung disease and infants.

Human health impacts of chronic exposure to particulate air pollution

Chronic exposure studies examine the impact of long-term exposure to particulate 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.

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.

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 $PM_{2.5}$ of 10 $\mu g/m^3$ 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 microns and premature death.

Estimating Health Effects in Developing Countries

Only a few studies based on measured ambient concentrations of PM_{10} or $PM_{2.5}$ 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.

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.

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 sufficiently 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.

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, quite 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.

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).

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 PM_{10} 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 PM_{10} 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.

ANNEX 9

Valuing Health Effects

Reductions in ambient levels of common air pollutants have been associated with reductions in premature mortality from heart and lung disease as well as reductions in chronic bronchitis, asthma attacks, and other forms of respiratory illness. This annex presents the methods 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. This is followed by illustrations of how the monetary value of health benefits associated with improvements in air pollution can be useful to policymakers (World Bank 2003b).

Valuing Reductions in Illness

What is being valued

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 guardians) 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).

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

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.

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

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 PM_{10} 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).[1]

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.[2]

Calculating the value of a reduction in risk of death

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).

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 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.

Compensating wage differential studies in the United States indicate that the VSL is approximately \$5 million (1990 US\$) (U.S. EPA 1999f). 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.

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.

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[1]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.

[2]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.

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 estimates of WTP 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

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).

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):

$$WTP_{DC} = WTP_{US}\,[Income_{DC}/Income_{US}]^{e} \quad (1)$$

where $Income_{DC}$ is the income in the developing country measured in U.S. dollars and *e* 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 parity[3] 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

To illustrate the usefulness of computing the monetary value of health benefits, the results of a study in Mexico City are given in table A9.1. 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.

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, giv-

[3]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 many developing countries are worth much more than the official exchange rate.

TABLE A9.1 Annual Health Benefits due to Ozone and PM_{10} Reductions in Mexico City (million 1999 US$)

Methodology for calculation		Air pollution reduction	
Morbidity	Mortality	10%	20%
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

Source: Mexico Air Quality Management Team 2002.

ing 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.

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 $300,000 in 1999 US$.

The values of reducing PM_{10} and ozone by 10 percent and 20 percent appear in table A9.1. 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 $\mu g/m^3$ reduction in annual average population-weighted PM_{10} will have approximately the same value, because the impact of a 1 $\mu g/m^3$ change is assumed to be independent of baseline concentrations. In this case a reduction of 10 percent is equivalent to lowering PM_{10} by 6.4 $\mu g/m^3$. This implies that, using the study's central case estimate, a 1 $\mu g/m^3$ reduction in PM_{10} is worth $100 million (1999 US$) annually (US$644 million for COI+WTP divided by 6.4 $\mu g/m^3$).

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 PM_{10} regardless of the approach used to monetize benefits. This is primarily because there are no studies, as yet, relating reductions in long-term exposure to ozone to premature mortality. This does not imply, however, that programs to reduce the precursors of ozone (NO_x and VOCs) 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

The estimates of health benefits, such as those computed in the Mexico City study in table A9.1, 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.

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 are 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 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.

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