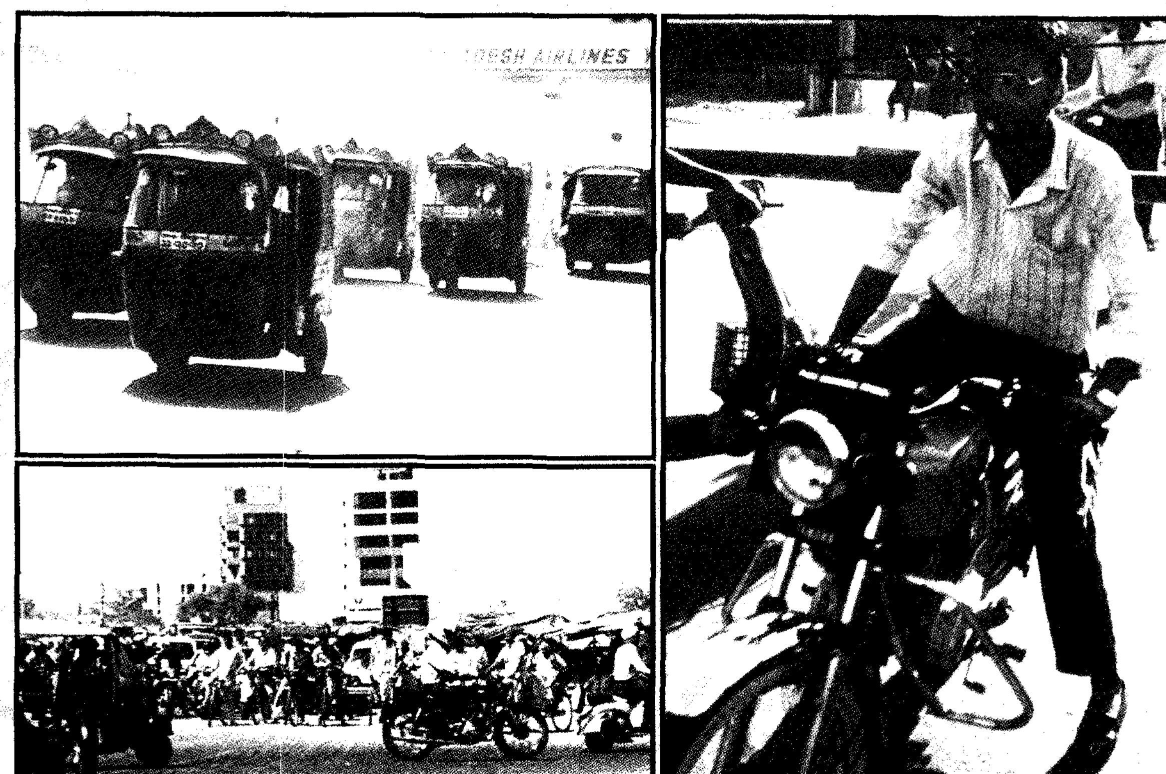
Improving Urban Air Quality in South Asia by Reducing Emissions from Two-Stroke Engine Vehicles

Masami Kojima, Carter Brandon, and Jitendra Shah



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Cover: Traffic images of South Asia. All images property of the World Bank.

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Foreword

Vehicles are one of the dominant sources of urban air pollution in South Asia. While this problem is common to growing metropolitan areas throughout the world, it is particularly severe in South Asia, where over half of all vehicles are two- and three-wheel vehicles operating on two-stroke engines.

This report analyzes different technical and policy options for reducing emissions from two-stroke engines. As the study emphasizes, it is important to understand not only the cost-effectiveness and feasibility of enforcing different mitigation measures but also the socioeconomic implications of those measures. We hope this report will stimulate the debate on these issues and help policymakers arrive at informed decisions about how to tackle this source of urban air pollution.

Richard Ackermann
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Abstract

While vehicular air pollution is common to growing metropolitan areas through out the world, it is particularly severe in South Asia, where about half of all vehicles are two- and three-wheel vehicles with two-stroke engines. This report analyzes different technical and policy options for reducing emissions from two-stroke engines. Precisely because two-stroke engine vehicles are so numerous and popular, an policy decision to address emissions from these vehicles must take into account the socioeconomic consequences of such a decision. While a large-scale immediate ban on gasoline-powered two-stroke engine vehicles would be extremely difficult and costly, numerous small and cost-effective improvements are available. Two immediate simple solutions—using the correct type and concentration of lubricant and carrying out regular maintenance—would significantly reduce emissions from two-stroke engines while saving drivers money and ultimately improving air quality. Promoting these "win-win" measures requires building public awareness by disseminating information on the health impact of emissions; the types of engines, fuel, and lubricant that reduce emissions; the importance of regular maintenance; and the advantages and disadvantages of various measures for mitigating air pollution. Partnerships among government, industry, and the public will continue to be crucial to bring about the changes required to achieve air quality goals.

Acknowledgments

This report summarizes the findings of the regional Two-Stroke Engine Initiative carried out by the South Asia Environment Unit. This initiative assessed the current state of pollution from two-stroke engines and evaluated different policy and technology options for curbing emissions from two- and three-wheel vehicles.

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Abbreviations

API	American Petroleum Institute
ARAI	Automotive Research Association of India
CNG	Compressed natural gas
CVS	Constant volume sampling
ECE	Economic Commission for Europe
ESMAP	Joint UNDP/World Bank Energy Sector Management Assistance Programme
FTP	Federal test procedure (in the United States)
IPIECA	International Petroleum Industry Environmental Conservation Association
ISO	International Organization for Standardization
JASO	Japanese Standards Organization
LPG	Liquefied petroleum gas
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of less than 2.5 microns
PM_{10}	Particulate matter with an aerodynamic diameter of less than 10 microns
RON	Research octane number
SIAM	Society of Indian Automobile Manufacturers
UNDP	United Nations Development Programme
VAPIS	Vehicular Air Pollution Information System

Executive Summary

Two-stroke engine vehicles are ubiquitous in South Asian cities, where they constitute approximately half of the total vehicle population—60 percent in India—and contribute significantly to urban air pollution. The serious health effects of this polluted air, breathed by 350 million people, make urban air quality management an important policy concern. This report addresses the technical, economic, and policy issues related to controlling air pollution from two-stroke engine vehicles.

In the past few years governments and vehicle manufacturers in the region have started to address the two-stroke engine issue. India, which has tightened its emissions control regulations, is investing in improved monitoring and enforcement programs and has taken steps to improve lubricants used in two-stroke engines. Delhi has provided financial incentives to owners to replace old three-wheel vehicles with new ones. Parallel to these government programs, two-stroke vehicle manufacturers, aware that the regional market for these vehicles is under threat, have contributed to programs to improve vehicle maintenance and have begun to bring alternative engine technologies to the market. This report pulls together some of the lessons learned to date across South Asia.

The Problem of Emissions from Two-Stroke Engine Vehicles

Emissions from the large and rapidly growing number of two- and three-wheel vehicles are a major source of air pollution in South Asia. Because they are less expensive than other vehicles, two- and three-wheelers play an important role in the transport market in South Asia and account for at least half of all vehicles in most countries in the region.

Two-wheel vehicles, which include mopeds, scooters, and motorcycles, are used mostly for personal transportation. Three-wheel vehicles, which include small taxis such as autorickshaws and larger vehicles that hold as many as a dozen passengers, are used commercially. Until this year, nearly all three-wheelers and the majority of the two-wheelers had two-stroke engines. Apart from emissions considerations, these two-stroke engine vehicles are much noisier than their four-stroke equivalents—an issue that draws much attention in South Asian cities, but is beyond the scope of this paper.

Emissions from two-stroke engines pose a danger to public health

The most critical pollutant in South Asia in terms of public health impacts is fine particulate matter.[1] Fine particles have been shown in studies in a number of cities around the world to have serious health effects, including premature mortality and such nonfatal effects as respiratory symptoms, exacerbation of asthma, and changes in lung function. Vehicle emissions of fine particles is particularly harmful because they occur near ground level, close to where people live and work.

Until recently new two-stroke engines 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 South Asia probably emit particulate matter at an even higher factor.

Two-stroke engines typically have a lower fuel efficiency than four-stroke engines, with as much as 15–40 percent of the fuel-air mixture escaping from the engine through the exhaust port. These "scavenging losses" contain a high level of unburned gasoline and lubricant, which increases emissions of hydrocarbons and organic lead if gasoline is still leaded.[2] Some of the incompletely burned lubricant and heavier portions of gasoline are emitted as small oil droplets, which in turn increase visible smoke and particulate emissions.

Poor vehicle maintenance, misuse of lubricant, and adulteration of gasoline exacerbate emissions

The age and poor maintenance of many two- and three-wheelers in the region increase emissions well above any applicable standards. In addition, many drivers use lubricants of poor quality, leading to two distinct but related problems:

- Many drivers in South Asia use widely available straight mineral oil or new or recycled four-stroke engine oil rather than the specially formulated 2T oil recommended by vehicle manufacturers. These oils build up in the engine, increasing emissions.
- Drivers also use excessive quantities of lubricant. Some drivers may 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 increases fuel economy and provides greater protection against piston seizure. To the extent that 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.

Finally, drivers are encouraged to buy too much lubricant by the filling station operators themselves, who earn higher margins on oil than on petrol. Furthermore, adulteration of gasoline with kerosene is widespread in some countries in South Asia 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 are emitted in the exhaust gas.

Reducing Emissions from Two-Stroke Engines

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) improving the quality of gasoline. For *new vehicles*, emissions can be reduced by (d) redesigning two-stroke engines to decrease scavenging losses and the amount of lubricant needed, and (e) installing catalytic converters to further reduce tailpipe emissions. Some of these measures can be achieved through regulation. Others require mass education of drivers, vehicle owners, regulators, and even the public, which has a role in bringing political pressure to bear on the problem.

Measures targeted at the existing fleet of two-stroke vehicles

Ensuring that drivers use the correct type and quantity of lubricant. In much of South Asia very few drivers of commercial three-wheelers use 2T oil. In Bangladesh the use of excessive amounts of straight mineral oil is the norm rather than the exception among three-wheeler drivers. The sale of straight mineral oil for use in vehicles is not illegal. Changing the behavior of these drivers to use the correct quantity of 2T oil, as well as raising the standards for the type of lubricant that must be used, would make an enormous difference in particulate emission levels. Preliminary tests show that reductions of particulate matter emissions of as much as two-thirds may be achieved through the use of the proper amounts of higher quality lubricants.[3]

At the technical level, metering the correct amount of lubricant directly into gasoline at the pump (the so-called premix in India) is one way of ensuring that the correct type and quantity of lubricant is used. Banning the sale of "loose" oil in favor of the sale of premeasured sealed packets would also help enforce adding the right amount at the petrol pump. *The use of higher-quality 2T oil represents cost savings to most two-stroke vehicle drivers.* Even though the oil itself is more expensive, analysis has repeatedly shown that 2T oil used in the proper amount costs less than drivers currently pay for larger amounts of lower-grade oils. In addition come nonquantified benefits of longer engine life and lower emissions.

Improving vehicle maintenance. The importance of an effective inspection and maintenance program cannot be overemphasized: proper maintenance is critical to both increasing fuel efficiency and reaping the full benefits of emission reduction investments. Simple servicing procedures—cleaning and adjusting the carburetor, adjusting the ignition system, cleaning and adjusting or replacing spark plugs, and cleaning air filters—can reduce exhaust emission levels significantly as well as improve fuel efficiency. Tying the frequency of inspection to the age of the vehicle and the annual number of kilometers traveled could also increase the effectiveness of inspection programs.

Improving the quality of gasoline. Eliminating the widespread practice of adulterating gasoline with kerosene would reduce emissions. Reducing the gum content and increasing the octane level of gasoline that does not meet the minimum specified by vehicle manufacturers could also cut emissions. High gum content can cause an engine to misfire, damaging the vehicle and significantly increasing emissions of hydrocarbons and particulate matter. Low octane can cause knocking and engine malfunction.

Measures targeted at the environmental performance of new two-stroke vehicles

Reducing scavenging losses. Substantial reductions in scavenging losses have been achieved by designing better port configurations. In India, for example, short-circuiting fuel losses have been reduced from 35 to 14 percent as a result of better engine designs. Several new technologies for reducing scavenging losses are also being tested, but all of these would require an electronic engine management system. While this system would add to the cost of the vehicle, this cost would be partially offset by improved fuel efficiency.

Installing catalytic converters. Installation of catalytic converters in two- and three-wheelers would reduce exhaust emissions by about half. Vehicles with catalytic converters must use lead-free gasoline, however, which is not widely available in some parts of South Asia. The durability of catalytic converters for two-stroke engines is also an issue. For commercial three-wheelers catalysts are likely to have to be replaced at intervals ranging from six months to a year to maintain reasonable emission levels. While essentially no data are available to quantify the impact of catalytic converters on reducing particulate emissions from two-stroke engines, estimates indicate that cost-effectiveness may be questionable.

Replacing Two-Stroke Gasoline Engines

In addition to reducing emissions from two-stroke gasoline engines, both governments and vehicle manufacturers are finding cleaner alternatives to these engines. Options include four-stroke gasoline engines and engines powered by liquefied petroleum gas, compressed natural gas, and electricity. As cleaner vehicles come on the market, the share of the older, more polluting vehicles will fall. In addition, retrofit kits that take advantage of cleaner fuels and lubricants are becoming increasingly available for installation on older two-stroke engine vehicles.

Four-stroke engines

Replacing two-stroke engines with four-stroke engines (at the time of vehicle replacement) would significantly reduce hydrocarbon and particulate emissions, although emissions of nitrogen oxides would increase.

The cost difference between new two- and four-stroke engines is less than 10 percent. If operating and maintenance costs are taken into account—especially the 10–20 percent improved fuel efficiency over the life of the vehicle—*owning a four-stroke engine vehicle may be more economical than owning a two-stroke engine vehicle.* If the social benefits of reduced emissions are factored in, the net economic benefits are even higher. The negative socioeconomic effects of banning new two-stroke engines are small.

Vehicles powered by liquefied petroleum gas

Two-stroke engines powered by liquefied petroleum gas (LPG) typically produce lower levels of particulate emissions than two-stroke gasoline engines. Moreover, since lubricant cannot be premixed with LPG, it must be mechanically metered, eliminating the possibility of overlubrication. The main problems in introducing LPG into the transport sector in South Asia are the lack of sufficient domestic sources of supply and the inadequate distribution system. India, Pakistan, and Sri Lanka import about 30–40 percent of their LPG consumption. None of the countries in the region has made the necessary investments in LPG refueling stations, the lack of which constrains widespread LPG use. In fact, the use of LPG in vehicles is illegal in India and Sri Lanka today, although this situation is expected to change in the near future.

Vehicles powered by compressed natural gas

Compressed natural gas (CNG) is a potentially attractive fuel because it emits little particulate matter, volatile organic compounds, or sulfur oxides when burned. Bangladesh and Pakistan are piloting the use of CNG. Bajaj Auto in India has developed CNG-powered three-wheelers based on a four-stroke engine design and began to market these in 2000.

Although replacing two-stroke gasoline engines with vehicles powered by CNG would reduce emissions, providing substantial subsidies to promote such vehicles is not recommended. As New Zealand's unsuccessful promotion program shows,[4] adoption of CNG as an alternative fuel must be based on economic viability, not artificial inducements. The economic viability of CNG-powered vehicles depends on the local retail price of natural gas. Switching to natural gas would make economic sense only if the retail price of CNG were about 55–65 percent of the cost of the fuel being replaced. Without consistently lower gas prices, promotion of CNG-powered vehicles may not be sustainable.

Governments have a disincentive to reduce the price of CNG, however, since a consumer shift from (taxed) fuels to (essentially untaxed) CNG would reduce their tax revenues. In countries such as India that will soon begin importing liquefied natural gas on a large scale as a future source of natural gas, world crude prices could make it difficult to keep CNG prices much lower than gasoline prices. Bangladesh, however, with its large natural gas reserves and extensive networks of gas pipelines in large cities, might be able to introduce CNG into the transport sector without compromising other needs in the economy.

Electric vehicles

Electric three-wheel vehicles are estimated to cost nearly twice as much as gasoline-powered vehicles (based on market prices in India), have shorter ranges, and run on batteries that take up to 6–10 hours to recharge. Until technological changes make these vehicles more attractive, they are not expected to play an important role in South Asia except in extremely polluted traffic corridors. In Kathmandu, Nepal, for example, large electric three-wheelers known as Tempos have proved very popular with the government and passengers. In early 2000 about 500 of these vehicles were operating in Kathmandu, partly in response to the ban on diesel Tempos imposed by the government in 1999.

Standards and Enforcement

Emission-based standards tend to be more cost-effective than policies that dictate specific technologies. But enforcing emission standards requires effective inspection and maintenance programs. Policymakers can deal with pollution by setting emission targets that vehicles must meet or by mandating specific types of fuel or vehicle technology in the hope of achieving emission targets. Emission-based measures provide greater flexibility to suppliers of fuels and vehicles, who can choose the lowest-cost options for meeting the specified emission targets. Provided people comply with emission-based standards—and unfortunately their monitoring may be more difficult than that of technology-based measures—they generally represent a lower-cost option for society as a whole.

Regulations based on fuel and vehicle technologies mandate the minimum technology to adopt. Such measures include banning two-stroke engines, mandating the use of catalytic converters, and requiring that a percentage of vehicles run on gaseous fuels. This approach is not likely to be a low-cost solution unless rigorous cost-benefit analysis is performed to identify the optimal technologies for each specific situation.

At the heart of the policy debate concerning controlling emissions from new two- and three-wheelers is the level of emission limits, because the emission standards in turn may dictate the choice of vehicle technology and even fuels. Taiwan (China) will effectively ban new two-stroke engine motorcycles in 2003 by making emission standards so tight that only four-stroke engine motorcycles can meet them.[5] The emission standards that came into effect in 2000 in India can be met by two-stroke engine vehicles only if oxidation catalysts are installed. The result is an increasing move toward four-stroke engine two- and three-wheelers, although for very small engines (for example, 50 cubic centimeters), two-stroke engines will remain the technology of choice in the foreseeable future.

Banning all two-stroke engines is not the answer. Banning all existing two-stroke engines in urban areas would reduce emissions but eliminate point-to-point transportation for millions of South Asians. Women and families, who depend on the vehicles more than other groups, and the many people who use the vehicles commercially would be particularly hard hit by a ban. Taking two-stroke three-wheelers off the road in a precipitous manner would also affect the livelihoods of tens of thousands of drivers and invite widespread agitation. Moreover, banning existing two-stroke engines without putting in place a well-documented vehicle registration system, an effective traffic police force, and transport alternatives for the current users could lead to increased harassment of drivers and corruption by traffic police.

More viable options are to: (a) ban older (and typically more polluting) two-stroke vehicles from urban areas; (b) raise annual registration fees for older vehicles to incorporate environment-related factors as well as vehicle book value; and/or (c) ban new two-stroke engine vehicles. The first two approaches seek to encourage the removal of older and more polluting vehicles from polluted cities, either through their being scrapped or relocated to less populated areas.

These options are best pursued if the following conditions are met: (i) alternatives to the vehicles being removed are readily available and market-tested; (ii) these alternatives are affordable, which may require the lowering or elimination of import duties or other taxes on new vehicles; and (iii) sufficient credit exists for vehicle owners and drivers to be able to finance the purchase of the newer vehicles. In assessing each of these measures, policymakers need to weigh the socioeconomic cost of making it more expensive to own old vehicles against the public health benefits of reducing vehicular emissions.

In sum, two immediate simple solutions could significantly improve air quality. Using the correct type and concentration of lubricant and carrying out regular maintenance would significantly reduce emissions from two-stroke engines while potentially saving drivers money. Promoting these "win-win" measures requires building public awareness by disseminating information on the health impact of emissions; the types of engines, fuel, and lubricant that reduce emissions; the importance of regular maintenance; and the advantages and disadvantages of various measures to mitigate air pollution. In South Asia partnerships among government, industry, and the public will continue to be crucial to bringing about the changes required to achieve air quality goals.

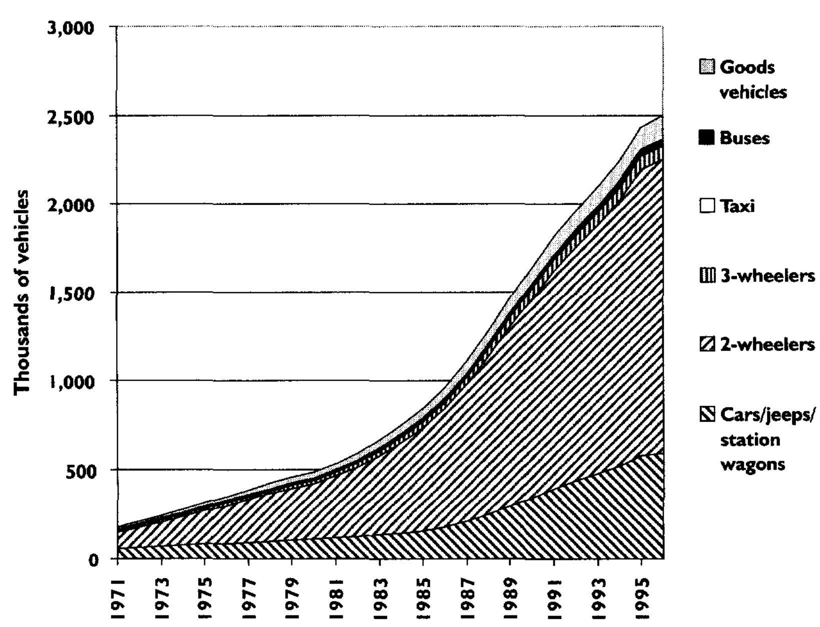
CHAPTER 1

Understanding the Problem of Two-Stroke Engine Emissions

Air quality is deteriorating in the cities of South Asia and is a byproduct of rapid urban population growth. Of the 1.3 billion people living in Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka in 1998, 350 million—27 percent of the combined population of these countries—lived in urban areas. The average population growth in urban centers, 3.2 percent a year between 1990 and 1998, was much higher than the 1.3 percent rate of growth for the population as whole.

A major source of air pollution is emissions from the rapidly rising number of vehicles. In India the number of registered vehicles tripled in 10 years from 10.6 million in 1986 to 33.6 million in 1996, an annual average rate of growth of more than 12 percent (figure 1). The number of vehicles grew rapidly in other countries in the region as well, increasing at an annual rate of 8.2 percent in Bangladesh (1990–96), 13.5 percent in Nepal (1990–99), 8.0 percent in Pakistan (1990–99), and 7.3 percent in Sri Lanka (1990–97). In the absence of cleaner technologies and stringent control measures, the level of vehicular emissions is expected to increase at similarly high rates.

Figure 1 Number of vehicles in Delhi by type, 1971–96



The Role of Two- and Three-Wheel Vehicles in South Asia

Two-stroke engine vehicles in South Asia fall into two categories, two-wheelers and three-wheelers. Two-wheelers include mopeds, scooters, and motorcycles and are used mostly for personal transportation. Three-wheelers include small taxis such as autorickshaws and larger vehicles such as Tempos in Bangladesh and Nepal, which carry as many as a dozen passengers.

Two- and three-wheelers play an important role in the transport market in South Asia. India has a very large number of two-wheelers, which are used for personal transport. Three-wheelers (called baby taxis in Bangladesh and autorickshaws in India and elsewhere) are typically used as short-distance taxis. In Sri Lanka some families are buying three-wheelers for private use, attracted by the lower price of the vehicles relative to passenger cars.

Because they are used commercially, three-wheelers are driven much more than two-wheelers and require frequent maintenance. But drivers often fail to maintain their vehicles properly. The problem of maintenance is particularly severe when drivers lease their vehicles, because neither the driver nor the owner feels solely responsible for the mechanical condition of the vehicle.

Three-wheel taxis are perceived as less compliant with traffic regulations and more accident prone than four-wheel vehicles. They are also more visible, because of their numbers, and contribute to congestion. For these reasons there is strong sentiment in some countries, notably Bangladesh, against two-stroke engine three-wheelers.

Two-stroke gasoline engine vehicles are estimated to account for about 60 percent of the total vehicle fleet in South Asia (table 1). The large

Table 1 Distribution of vehicles by type, selected South Asian countries

Vehicle type	*Bangladesh (1999)*	*India (1997)*	*Nepal (1999)*	*Pakistan (1999)*	*Sri Lanka (1997)*
Cars	92,000	3,500,000	49,000	670,000	122,000
Taxis	2,300	420,000	—	68,000	6,000
Light-duty gasoline	52,000	740,000	2,600	310,000	14,000
Heavy-duty diesel	55,000	5,200,000	46,000	750,000	235,000[a]
Two -stroke three-wheelers	68,000[b]	1,180,000	—	91,000	59,000
Four-stroke three-wheelers	7,600[b]	210,000	5,900[c]	—	—
Two -stroke two-wheelers	200,000[d]	21,800,000[d]	110,000[d]	1,700,000[d]	424,000[d]
Four-stroke two-wheelers	35,000[d]	3,900,000[d]	19,000[d]	250,000[d]	75,000[d]
Total	523,000	37,200,000	232,000	4,000,000	936,000
Percentage of two-stroke vehicles	51	62	47	45	52

— Not available.

Note: Because vehicle registration is by vehicle category and not by fuel type, these figures are based on assumptions about fuel use by each vehicle category. Breakdowns should therefore be taken as approximations. Totals may exceed the sum of the individual categories because of other categories not listed, such as tractors.

a. All diesel vehicles except diesel cars.

b. Ninety percent of three-wheelers are assumed to be two-stroke engine vehicles.

c. The total number of three-wheelers in Nepal is 5,900. No estimates could be made of the breakdown of three-wheelers because of the large number of four-stroke engine diesel three-wheelers.

d. Eighty-five percent of two-wheelers are assumed to be two-stroke engine vehicles.

Source: Bangladesh Road Transport Authority; Society of Indian Automobile Manufacturers; Department of Transport Management, Kathmandu, Nepal; Economic Adviser's Wing and *Economic Survey*, Government of Pakistan; Ministry of Transport and Highways, Sri Lanka.

number of these vehicles, their age, poor maintenance, low lubricant quality and excessive lubricant use, and traffic congestion in large cities make two-stroke engine vehicles a significant source of particulate emissions.

Two-stroke engines have several advantages over four-stroke engines. These include lower cost; excellent torque and power; mechanical simplicity (fewer moving parts and resulting ease of maintenance); lighter and smaller engines; greater operating smoothness; and lower nitrogen oxide emissions. They also have disadvantages compared with four-stroke gasoline engine vehicles, including higher particulate and hydrocarbon emissions, lower fuel economy, and louder noise.[6]

Types of Emissions

Gasoline engines contribute to air pollution by emitting high levels of particulate matter (in the case of two-stroke engines), lead if leaded gasoline is used, carbon monoxide, nitrogen oxides, and volatile organic compounds. Diesel engines emit high levels of particulate matter, nitrogen oxides, and sulfur oxides (if the level of sulfur in diesel is high).

The pollutant of special concern in South Asia is small particulate matter because of its high ambient concentrations and documented impact on morbidity and premature mortality. The level of particulate matter with an aerodynamic diameter of less than 10 microns (PM_{10}) exceeds internationally accepted standards by several times in a number of cities in South Asia. Two major contributors to high ambient concentrations of PM_{10} in the transport sector are two-stroke engine gasoline vehicles and heavy duty diesel vehicles.

Emissions are higher in two-stroke engines because of the design of the engine. Gas is exchanged through ports located in the cylinder, usually opposite each other. A fresh fuel and air mixture compressed in the crankcase enters through the intake opening, while exhaust gases exit through the exhaust port. While both the intake and exhaust ports are open some of the fresh fuel and air mixture escapes through the exhaust port. As a result of these "scavenging losses," which can amount to 15–40 percent of the unburned fresh charge, the exhaust contains a high level of unburned fuel and lubricant (MECA 1999). Nitrogen oxide emissions tend to be lower because a significant portion of the combustion products remains in the cylinder.

In two-stroke engines the crankcase is not used as an oil reservoir, as it is in four-stroke engines. Instead a small amount of lubricating oil is added to the fuel or introduced continuously mechanically. Because lubrication is on a total loss (once-through) basis, incompletely combusted lubricant and other heavy hydrocarbons are emitted as small oil droplets. These oil droplets increase visible smoke and particulate emissions, with serious impact on public health because of their well-documented link to morbidity and premature mortality (annex A).

Particulate emissions data from two-stroke engine vehicles in South Asia are scarce. Data on motorcycles in the United States from the 1970s may be representative of pre-1991 two-stroke engine vehicles in South Asia (table 2). More recent data (table 3), from tests done in the fall of 2000 at ARAI (the Automotive Research Association of India), indicate that particulate emissions levels of *in-use* three-wheelers from Dhaka (engine size of 150 cubic centimeters) are significantly higher than the data obtained in the 1970s. These tests also show that 7-year old vehicles using excess "straight mineral oil" emit particulate matter up to ten times, and that 4-year old vehicles using "straight mineral oil" emit particulate matter roughly two to three times, the typical values obtained in the United States in the 1970s. For both ages of vehicles, particulate emissions are much less if the correct amount of 2T oil, formulated specifically for use in two-stroke engine vehicles, is used.

Since two-stroke engine vehicles emit significantly more unburned gasoline than four-stroke engines, they emit more organic lead if leaded gasoline is used.[7] Organic lead is much more damaging to public health than inorganic lead formed by combustion of lead additives. Lead emissions are a problem in countries such as Pakistan that still sell only leaded gasoline. Fortunately, Bangladesh phased lead out of gasoline in July 1999, India in February 2000, and

Table 2 Emissions from uncontrolled motorcycles, 1970s (grams per kilometer except where otherwise indicated)

Model	*Type*	*Engine size (cubic centimeters)*	*Hydrocarbons*	*Carbon monoxide*	*Oxides of nitrogen*	*Particulate matter*
Honda SL100[a]	Four-stroke	100	1.3	13.7	0.21	0.02
Honda CL350K3[a]	Four-stroke	350	2.5	28.9	0.03	0.03
Kawasaki 125F-6[a]	Two-stroke	125	6.1	4.8	0.10	0.12
Suzuki T250[a]	Two-stroke	250	12.9	21.6	0.02	0.35
Yamaha DT1-E[a]	Two-stroke	250	10.3	16.3	0.03	0.15
Kawasaki KE100[b]	Two-stroke	100	5.6	20.5	—	0.34
Yamaha DT100[b]	Two-stroke	100	3.8	10.5	—	0.08

— Not available.
Note: Uncontrolled vehicles are those with no emissions control measures.
Source: a. Southwest Research Institute 1973; b. Danielson 1975.

Table 3 Emissions from selected Bangladeshi two-stroke three-wheelers (grams per kilometer)

Vehicle age	*Lubricant type*	*Percentage lubricant*	*Hydrocarbons*	*Carbon monoxide*	*Oxides of nitrogen*	*Particulate matter*
7 years	straight	8%	23	25	0.03	2.7
7 years[a]	2T	3%	16	17	0.09	0.9
4 years	straight	8%	9	8	0.08	0.6
4 years	2T	3%	9	10	0.09	0.2

Note: a. Data taken after performing simple maintenance procedures on the vehicle.
Source: ARAI (Automotive Research Association of India), November 2000. These measurements are preliminary and require further analysis.

Pakistan and Sri Lanka are considering strategies for eliminating lead in gasoline.

Factors Exacerbating Emission

Poor vehicle maintenance, the misuse of lubricant, the adulteration of gasoline, and the lack of catalytic converters exacerbate two-stroke engine emissions. The age and poor maintenance of many two- and three-wheelers in the region increase emissions well above any applicable standards. In addition, many drivers use lubricants and fuels of poor quality.

Misuse of lubricant

Both the quantity and quality of lubricant used affect the level of hydrocarbon and particulate emissions from two-stroke engines. Vehicle manufacturers recommend adding 2 percent lubricant for two-wheelers and 3 percent lubricant for three-wheelers. But many drivers of three-wheelers add considerably more lubricant for several reasons:

- Lack of knowledge about the correct amount to add
- Lack of knowledge about the adverse effects of excess lubricant
- Addition of excess lubricant to gasoline by filling station attendants at the point of sale
- Perception that more lubricant will provide greater protection against piston seizure
- Perception that more lubricant will increase fuel economy
- Lower miscibility of straight mineral oil and conventional motor oils with gasoline compared to 2T oil.

Excessive use of lubricant increases combustion chamber deposits and fouls spark plugs. When pistons and rings are badly worn, excess lubricant may postpone piston seizure for a while. But the adverse social effects of much higher emissions far outweigh the benefits to vehicle owners.

Lubricant requirements for two-stroke engines differ from those for four-stroke gasoline engines: good lubricity; piston cleanliness; low deposits, especially in the exhaust system; and low smoke emission. Two-stroke engine vehicles should use specially formulated 2T oil. Because polyisobutene of moderate molecular weight tends to decompose without leaving heavy deposits, polyisobutene thickener in a base stock is increasingly used in lubricant. Japan has taken the lead in developing new motorcycle oils referred to as low-smoke or smokeless lubricants.

Many three-wheelers in South Asia do not use the 2T oil recommended by vehicle manufacturers. Instead they use straight mineral oil or new or recycled engine oil, which results in greater deposit buildup and higher emissions (box 1). The principal reason for using these oils is their lower cost, although some drivers may be under the impression that these more viscous oils provide greater engine protection. In some countries, such as Bangladesh and Sri Lanka, 2T oil is not readily available at filling stations.

Conventional motor oils do not mix well with gasoline. Their use in two-stroke engine vehicles results in insufficient lubrication when oil does not reach the engine and high emissions when it does. Long-term use of conventional lubricants results in premature wear of the engine and higher maintenance costs.

> Box 1
>
> Reducing pollution while saving money
>
> Many drivers in Bangladesh use mineral oil instead of 2T oil because it is less expensive. But switching to 2T oil would actually save most drivers money. Straight mineral oil in Dhaka sells for about 50 takas a liter, while 2T oil sells for about 90 takas a liter. A driver of a baby taxi who uses 6 liters of gasoline a day and drives 280 days a year would typically spend 6,700 takas a year adding straight mineral oil at 8 percent concentration. A driver who switched to a 3 percent concentration of 2T oil would spend just 4,500 takas a year—an annual savings of 2,200 takas. The switch to 2T oil would also reduce emissions and help maintain vehicles.
>
> *Source:* Informal World Bank survey, 1999.

Inadequate vehicle maintenance

Vehicular emissions are exacerbated by the age of the vehicle fleet and the poor state of vehicle maintenance (ARAI, 1998). A study in the United States found that poorly maintained vehicles, which represented 20 percent of all vehicles on the road, contributed about 80 percent of total vehicular emissions (Auto/Oil Air Quality Improvement Research Program 1997). Recently three baby taxis in Dhaka, Bangladesh, from four to seven years old were randomly selected for mechanical inspection. The engineers inspecting the engines found evidence of considerable ad hoc, unauthorized repairs and modifications. A combination of inadequate or improper maintenance and repairs by poorly trained mechanics contributes to the poor mechanical state of many vehicles in South Asia .

Adulteration of gasoline

Emissions by all gasoline vehicles are exacerbated by the adulteration of gasoline with kerosene. Kerosene has a higher boiling point than gasoline and is thus more difficult to burn. As a result more deposits build up in the engine and more unburned hydrocarbons are emitted in the exhaust gas. Anecdotal evidence suggests that adulteration of gasoline is widespread in South Asia because of the significantly lower retail price of kerosene. Limited sampling and testing of gasoline by the World Bank in Dhaka in 1998 also indicated that a significant fraction of gasoline had been adulterated.

Lack of catalytic converters

Catalytic converters—installed in passenger cars in many parts of the world where unleaded gasoline is readily available—cannot be used to convert a high proportion of hydrocarbons in two-stroke engines because current designs result in greater exotherm (heat of reaction) and the sintering of precious metals, which deactivates the catalyst. The tendency of two-stroke engines to misfire under low load conditions further aggravates the problem of catalyst deactivation. Despite these limitations oxidation catalysts—which lower the emission levels of hydrocarbons and carbon monoxide and to some extent reduce the amount of fine particles emitted in the form of oil droplets—have been used in Taiwan (China) to meet increasingly tight emission standards. Beginning in 2000 these converters are installed in all new two-stroke engine two- and three-wheel vehicles in India.

Health Impact of Emissions

Research in various cities and countries has shown that PM_{10}, and especially $PM_{2.5}$ (particles with diameters of no more than 2.5 microns, called fine particulate matter), are extremely damaging to public health. These particles are associated with respiratory symptoms, exacerbation of asthma, changes in lung function, and premature death (Holgate and others 1999, chapter 13).

The health impact of particulate matter increases as the size of the particle diminishes. Very fine particles—such as those emitted by the combustion of transportation fuels—are believed to be particularly harmful. In addition, the fact that they are emitted near ground level, close to where people live and work, suggests that vehicular emissions are even more harmful than their share in total emission loads might indicate. (A detailed discussion of the health impacts of various pollutants is given in annex A.)

The health impact of oil droplet-based particles is not well understood. Most health impact studies have been carried out in countries that do not have large two-stroke engine vehicles, where the principal sources of fine particulate emissions are diesel vehicles and stationary sources. In all of these studies, sickness and death are regressed against the overall ambient particulate concentrations measured in terms of total suspended particles or PM_{10}, 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.

Effect of Emissions on Global Warming

Three greenhouse gases emitted by vehicles—carbon dioxide, methane, and nitrous oxide—are believed to have the potential to increase global warming. Two-stroke engines are not a major source of these emissions, however. The transport sector accounts for an estimated 13 percent of carbon dioxide emissions in South Asia, ranging from 10 percent in Bangladesh to 48 percent in Sri Lanka (International Energy Agency 1997). Emissions from two-stroke engine vehicles are relatively low because of their low fuel consumption. Two-stroke engine vehicles account for about 11 percent of vehicular carbon dioxide emissions (8 percent by two-wheelers and 3 percent by three-wheelers) and a very small share of methane and nitrous oxide emissions.

Only 1–2 percent of total greenhouse gases in South Asia can thus be tied to two-stroke engine vehicles. This very minor contribution of two-stroke engine vehicles to greenhouse gas emissions suggests that efforts to reduce such emissions should target other types of vehicles, such as heavy-duty buses and trucks, and sectors other than transport. Nevertheless, mitigation measures that reduce local pollution from two-stroke engines may lead to reduced greenhouse gas emissions as well (see chapter 2). Examples of such measures include switching to more fuel-efficient four-stroke engines and switching to electric vehicles, especially where the electricity used to charge the vehicles is generated using a clean fuel such as natural gas.[8]

CHAPTER 2

Reducing Emissions from Two-Stroke Engine Vehicles

With the exception of India, countries in South Asia have not yet adopted measures used in other parts of Asia to mitigate emissions from two-stroke engines. These include use of low-smoke lubricants, installation of oxidation catalysts, and mechanical metering of lubricant. This section examines ways to improve the functioning of two-stroke engines. Chapter 3 looks at alternatives to two-stroke gasoline engines.

Declines in Emissions

Emissions from recent two-stroke models have decreased markedly as a result of technological improvements. In Taiwan (China)—which has the largest number of two-wheelers per capita in the world—emission standards have tightened significantly (table 4). The emission standards in Taiwan (China) also control visible smoke; smoke opacity is limited to 15 percent for new vehicles and 30 percent for in-use vehicles.

In India vehicle manufacturers faced the challenge of meeting more stringent emission standards in 1996 without using catalytic converters, which could not be used because unleaded gasoline was not widely available (table 5). Manufacturers had to rely solely on improvements in engine technology to meet the mandated emission limits. Today as a result of continuing technological advances, including the installation of catalytic converters, new two- and three-wheelers manufactured in India emit less than 16 percent of the carbon monoxide and less than 25 percent of the hydrocarbons and nitrogen oxides emitted by vehicles manufactured in 1991.

Emission factors of new and well-maintained two-wheelers using the correct amount of lubricant have declined in recent years. A scooter

Table 4 Emission standards for gasoline-powered two-wheelers in Taiwan (China), 1988–2003

Year	*Driving cycle*	*Catalyst durability requirement (kilometers)*	*Carbon monoxide (grams per kilometer)*	*Hydrocarbons and nitrogen oxides (grams per kilometer)*
1988	ECE 40[a] warm	None	8.8	5.5
1991	ECE 40 warm	6,000	4.5	3.0
1998	ECE 40 warm	15,000	3.5	2.0
2003	ECE 40 cold	15,000	7.0	1.0/2.0[b]

Note: Emissions of carbon monoxide and hydrocarbons are higher when the engine is cold, so that the increase in the carbon monoxide limit between 1998 and 2003 does not represent a relaxation in emission standards but in fact represents some tightening. a. Economic Commission for Europe Regulation 40 for two- and three-wheelers. b. 1.0 gram per kilometer for two-stroke engines and 2.0 grams per kilometer for four-stroke engines.
Source: Society of Indian Automobile Manufacturers.

Table 5 Emission standards for gasoline-powered two- and three-wheelers in India, 1991–2000 (grams per kilometer)

	Two-wheelers		*Three-wheelers*	
Year	*Carbon monoxide*	*Hydrocarbons and nitrogen oxides*	*Carbon monoxide*	*Hydrocarbons and nitrogen oxides*
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	2.0	2.0	4.0	2.0

Note: Tests of 1991 and 1996 vehicles were based on the warm Indian driving cycle. Tests of 1998 and 2000 were based on the cold Indian driving cycle. a. Emission standard depends on the reference mass of the vehicle. b. Limit applied to hydrocarbons only and not to the sum of hydrocarbons and nitrogen oxides.
Source: Society of Indian Automobile Manufacturers.

equipped with a catalyst, for example, emitted just 0.015 grams of particulate matter per kilometer in a recent test (table 6), but even this emission factor is many times greater than that of a comparable four-stroke scooter.

But data on emission factors for particulate matter must be interpreted with caution. No established methodology is accepted industry-wide for measuring particulate emissions from two-stroke engines. Nearly all the work carried out on two-stroke engine vehicles has focused on reducing hydrocarbons (or the sum of hydrocarbons and nitrogen oxides), carbon monoxide, and visible smoke. No in-depth study has been conducted on particulate emissions.

Measurement of particulate matter emissions from two-stroke engines is difficult because oil droplets from lubricant added to gasoline on a pass-through basis account for a large fraction of particulate matter in the exhaust gas. Depending on the dilution rate and the temperature to which the line downstream of the exhaust pipe (including the dilution tunnel) is heated, these droplets can condense before being collected on filter paper. Oil samples condensed on filter papers can also be lost as a result of the passage of gas through the filter.

A reliable and reproducible methodology for measuring particulate matter emissions from two-stroke engines should be developed and statistically significant data collected to enhance

Table 6 Particulate matter emission factors for two-wheelers in India

Vehicle type	*Odometer (kilometers)*	*Amount of lubricant*	*Lubricant type*	*Particulate matter emissions (grams per kilometer)*
Motorcycle[a]	215	Metering	API TC/JASO FC*	0.055
Scooter[a]	550	2%	JASO FB	0.032
Scooter with catalyst[a]	550	2%	JASO FB	0.015
Scooter, four-stroke[a]	650	n.a.	n.a.	0.0005
Motorcycle[b]	19,000	Metering	—	0.025
Motorcycle[b]	3,000	3%	—	0.012

n.a. Not applicable.
— Not available.
Note: All vehicles are two-stroke engine vehicles without catalysts unless otherwise indicated. All vehicles are well maintained. The Indian driving cycle is used. *American Petroleum Institute TC and Japanese Standards Organization FC (see the section "Improving Lubricant Use" in this chapter).
Source: a. Unpublished data from the Automotive Research Association of India and Bajaj Auto; b. Palke and Tyo 1999.

understanding of emissions from these vehicles and help policymakers select optimal measures for curbing emissions. (Annex B presents the results of recent tests of alternative hypotheses about measurement problems.)

Improving Gasoline Quality

The adulteration of gasoline with kerosene is likely to increase hydrocarbon and particulate emissions. Because some of the gasoline effectively bypasses the combustion chamber and is emitted uncombusted by the two-stroke engine, eliminating or reducing such toxic components as organic lead and benzene from gasoline—a worthwhile step under any circumstances—is particularly important to mitigate the health impact of toxic emissions from two-stroke engines.

The high gum content and low octane level of gasoline also increase emissions. If gasoline is unstable the gum content may become unacceptably high, leading to the deterioration of carburetor settings and increased deposits, which alter the air-to-fuel ratio. This in turn could cause the engine to misfire, damaging the vehicle and significantly increasing emissions of hydrocarbons and particulate matter comprising oil droplets.

While the minimum research octane number (RON)[9] requirement for two- and three-wheelers in South Asia is 87, Bangladesh still markets 80 octane gasoline widely. Depending on how the driver accelerates, 80 RON gasoline can cause knocking and engine malfunction—and hence higher emissions.

Improving Lubricant Use

Many drivers of two-stroke engine vehicles use excessive quantities of the wrong kind of lubricant (see chapter 1). Correct use of lubricant can go far to reduce emissions from these vehicles.

Standards for lubricants

In the mid-1980s the American Petroleum Institute (API) and the Coordinating European Council for the Development of Performance Tests for Transportation Fuels, Lubricants, and Other Fluids set up a provisional two-stroke lubricant performance and service classification list. API canceled the system in 1993, deferring to the International Organization for Standardization (ISO) global specification and the Japanese Standards Organization (JASO) system. Oil marketers continue to use the outdated test criteria established for API TC to certify air-cooled oils. The API TC classification is currently the lowest acceptable level of 2T oil quality.

In 1990 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. North America's API TC oil rating is equivalent to JASO FB.

Since April 1999 the Government of India has required all two-stroke engine oils sold in the country to meet both API TC and JASO FC specifications (that is, only low-smoke lubricating oils can be used in India). In the National Capital Territory of Delhi, 2T oil can be sold only in sealed packages or premixed with gasoline and dispensed through the pump nozzle. This ban on unsealed packages is intended to discourage the sale of recycled and other unsuitable engine oils. The sale of premixed gasoline is intended to encourage the use of not only the suitable quality but also the correct amount of 2T oil.

Using the correct concentration of lubricant

The use of the correct amount of 2T oil significantly reduces two-stroke vehicular emissions. New lubricant formulations even allow certain makes of two-wheelers to cut the lubricant requirement to just 1 percent. Table 7 shows indicative emission factors as a function of the amount of lubricant and type for well-maintained motorcycles without any advanced emission control technologies. Particulate matter emission factors in the table are approximations based on limited available data and indicative of general trends only. Since particulate emissions are not regulated in Asia, relatively little data are available.

Table 7 Relation between lubricant content and emissions by uncontrolled motorcycles

	Particulate matter emissions		*Hydrocarbon emissions*	
Lubricant content	*Grams per kilometer*	*Percent reduction*	*Grams per kilometer*	*Percent reduction*
6–8%, regular 2T	0.6–0.7	n.a.	8.5	n.a.
5% maximum, regular 2T	0.35	50	7.0	18
2–3%, regular 2T	0.25	64	6.5	24
1–2%, regular 2T	0.20	71	6.0	29
1% maximum, low-smoke	0.15	79	5.7	33

n.a. Not applicable.
Note: Based on an average speed of 20 kilometers per hour.
Source: Mario Camarsa, Enstrat International Limited, personal communication (1999).

Using low-smoke lubricant

The use of low-smoke lubricant significantly reduces emissions of visible smoke. The retail prices of lubricants in India in March 2000 are given in table 8. If drivers using 6 percent JASO FB oil cut back the amount of lubricant to 3 percent and simultaneously switch to JASO FC (low-smoke lubricant), they can realize savings of about 35 percent in lubricant costs.

In Bangkok, several motorcycles with varying levels of visible smoke emissions were selected to see if visible smoke was correlated with mass particulate emissions. Some of the test results are shown in table 9. The mass particulate emissions for all the three driving cycles showed weak correlations with opacity for two-stroke engine vehicles using regular 2T oil. One four-stroke engine vehicle is included in the table to illustrate its low opacity as well as mass particulate emissions. Limited data on the impact of switching from regular 2T oil to low-smoke lubricant on particulate emissions indicate that while low-smoke lubricant may reduce visible smoke, it may not reduce mass particulate emissions (Radian International 1998 and unpublished data from ARAI). Thus the public health benefit of using low-smoke lubricant is not clear.

Metering lubricant

A mechanical lubrication system, which adjusts the amount of lubricant metered into gasoline to the engine speed and load, can control the amount of lubricant added to gasoline. Such a system reduces emissions by making it impossible for drivers to add excess lubricant to gasoline. However, mechanical lubrication may not yield any greater benefits than drivers adding the correct amount of lubricant.

Improving Vehicle Design

In response to national standards more stringent than those of the European Union (see box 2), Indian vehicle manufacturers have made engine design changes that have reduced the level of

Table 8 Retail prices of lubricants in India, March 2000 (Indian rupees)

Lubricant	*Price of lubricant per liter*	*Price of 3 percent oil per liter of gasoline*	*Price of 6 percent oil per liter of gasoline*
Two -stroke oil meeting JASO FB standard	80–90	2.4–2.7	4.8–5.4
Two -stroke oil meeting API TC and JASO FC standards	100–120	3.0–3.6	6.0–7.2
Crankcase oil meeting API standard SC[a]	80–90	2.4–2.7	4.8–5.4

Note: a. API SC is a grade of crankcase oil for four-stroke engine gasoline vehicles.

Table 9 Particulate matter emission factors for motorcycles in Bangkok (grams per kilometer, except where otherwise indicated)

Type	*Opacity (percent)*	*Driving cycle*		
		ECE 40	*FTP 75*	*Bangkok*
Four-stroke	7	0.01	0.12	0.02
Two -stroke	20	0.26	0.26	0.04
Two -stroke	54	0.29	0.22	0.22
Two -stroke	77	0.19	0.18	0.13
Two -stroke	86	0.47	0.70	0.29
Two -stroke	100	0.41	0.23	0.14

Note: ECE 40: Economic Commission for Europe test cycle 40. FTP 75: U.S. Federal Test Procedure 75; Bangkok: Bangkok driving cycle developed by Radian International. Percent opacity was measured under free acceleration. All the motorcycles tested had built-in automatic lubrication systems and used regular 2T oil.
Source: Radian International 1998.

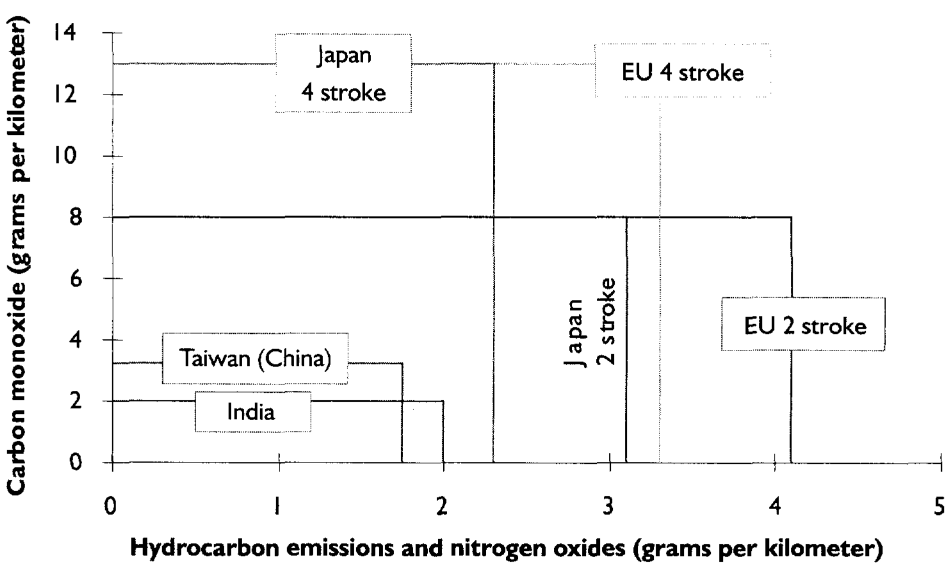
emissions and increased fuel economy. Scavenging losses have been reduced steadily, and in 2000 catalytic converters were installed for the first time.

Installing catalytic converters

Catalytic converters for two- and three-wheelers are oxidation catalysts, which reduce the level of carbon monoxide and hydrocarbon emissions but not nitrogen oxides, rather than three-way catalysts commonly installed in passenger cars, which also reduce nitrogen oxide emissions. Catalytic converters for two-stroke engines are not designed to achieve as high a level of conversion of carbon monoxide and hydrocarbons as those for four-stroke engine passenger cars because of the

Box 2
Emission standards from around the world

The emission standards for two-wheelers differ markedly. The emission standards in India and Taiwan (China) today rank among the most stringent in the world, reflecting the concern of the authorities with controlling emissions from vehicles that are numerous and popular because of their affordability and ease of maneuver. The emission standards shown below came into force in 2000, with the exception of those for Taiwan (China), which came into effect in 1998.



greater quantity of hydrocarbons and lubricant in the exhaust gas. They typically reduce exhaust emissions by half.

Catalysts deactivate more rapidly in two-stroke engine vehicles, partly because of higher exhaust gas temperature, and need to be replaced frequently. India is considering minimum catalyst durability requirements. Taiwan (China) has had catalyst durability requirements for motorcycles for some time, initially set at 6,000 kilometers and at 15,000 kilometers today. For three-wheelers in South Asia, which are often driven 120 kilometers a day, 15,000 kilometers is equivalent to less than six months of operation. For a vehicle driven 10 years or more, as many two-stroke vehicles in South Asia are, the catalyst might have to be replaced up to 20 times to maintain the original level of particulate emissions. This is clearly a problem.

In India the Society of Indian Automobile Manufacturers (SIAM) is offering the government a warranty of 30,000 kilometers for all two- and three-wheelers equipped with catalytic converters. Catalyst durability of 30,000 kilometers would enable drivers to replace their catalysts at the same intervals as they have their engines overhauled.

To meet year 2000 emission standards, the three-wheelers manufactured in India are equipped with catalytic converters for both two-stroke and four-stroke engine designs. The net-of-tax cost of the catalytic converter fitted in three-wheelers for both engines is approximately 1,100 Indian rupees, or US$25.

Reducing scavenging losses

A major area of research and development has been the attempt to reduce scavenging losses to increase fuel economy and reduce emissions (box 3). Substantial reductions have been achieved by designing better port configurations. In India, for example, short-circuiting fuel losses have been reduced from 35 percent in 1991 to as low as 14 percent in the year 2000 model as a result of design changes (Iyer 1999).

Improving Maintenance

The importance of an effective inspection and maintenance program cannot be overemphasized: proper maintenance is critical to reaping the full benefits of investments in emission mitigation. Simple servicing procedures, such as cleaning and adjusting the carburetor, adjusting the ignition system, cleaning and adjusting or replacing spark plugs, and cleaning air filters, can reduce exhaust emission levels significantly (ARAI 1998). Air filters should be cleaned or replaced every 3,000 kilometers. Carburetors should be tuned and cleaned every 3,000 kilometers for two-stroke engines and every 5,000 kilometers for four-stroke engines.

Because lubricant passes through the two-stroke engine on a once-through basis, there is considerably more deposition and accumulation of carbonaceous deposits in the combustion chamber, exhaust port, and silencer than in four-stroke engine vehicles. As a result more frequent decarbonization is needed. Bajaj Auto recommends decarbonization every 6,000 kilometers for three-wheelers and 9,000 kilometers for scooters. Four-stroke engines do not normally need decarbonization. Bajaj also recommends replacing spark plugs every 7,500 kilometers for two-stroke engines and every 10,000 kilometers for four-stroke engines. Decarbonization requires mainly labor, which is relatively cheap in South Asia, keeping maintenance costs low.

It is not clear whether long-run maintenance costs are higher for two-stroke or four-stroke engines. Four-stroke engines have many more moving parts (valves, camshafts, timing chains, oil pumps), which are relatively expensive because they tend to be sold by vehicle manufacturers. In contrast, parts for two-stroke engines are sold by a large number of parts suppliers. Labor costs for servicing four-stroke engines are also higher because of the higher level of skills required. Engine overhauls for two-stroke engines are more expensive, however. Minor engine overhauls, not normally required on four-stroke engines, are typically required every 30,000 kilometers for two-stoke engines. Major overhauls, which may also be needed on four-stroke engines, are required every 90,000 kilometers for two-stroke engine three-wheelers.

Box 3
Reducing scavenging losses in two-stroke engines

Several technologies are being tested to reduce emissions from two-stroke engines (see table below). The goal is to retain the advantages of the two-stroke engine while gaining control over the air-to-fuel ratio and eliminating the loss of air-fuel mixture through the exhaust port.

Injecting fuel into the engine instead of introducing it through the carburetor may dramatically reduce or eliminate scavenging losses. Direct injection of the fuel into the engine also makes it possible to use leaner air-fuel mixtures through charge stratification.

The effectiveness of a variety of systems that could be suitable for small engines has been demonstrated in laboratories, although none has yet been developed commercially. The technologies being tested include:

- Spraying pressurized fuel into the intake port or crankcase with controlled injection timing.
- Injecting a fuel spray into the transfer port or the piston.
- Injecting fuel into the cylinder as or after the exhaust port closes.
- Directing the in-cylinder injection toward the cylinder wall to improve fuel atomization, vaporization, and mixing.
- Using "skip firing" along with fuel injection to shut off fuel injection in some cycles to allow sufficient time for the exhaust gases to be purged from the combustion chamber.

All of these measures would require an electronic engine management system for precise control of the fuel injection timing and quantity, depending on the engine load and speed. They would thus add to the cost of the vehicle.

Emissions generated by various engine technologies (grams per kilometer)

Technology	*Hydrocarbons*	*Carbon monoxide*	*Oxides of nitrogen*
Carburetor system	3.8	3.7	0.03
Cylinder wall injector	2.9	3.4	0.06
Semidirect injection	0.8	0.8	0.1
Electromechanical direct injection	0.8	0.8	0.1
Loop-scavenged two-stroke engine with air-assisted direct injection	0.5	0.4	0.05
Air-assisted cylinder head injector with skip injection and catalytic converter	0.28	0.09	0.16

Source: Huang and others 1993; Kirchberger 2000.

CHAPTER 3

Alternatives to Two-Stroke Gasoline Engines

Vehicle and fuel alternatives to two-stroke gasoline engines can reduce exhaust emissions. Cleaner alternatives include four-stroke engines and engines powered by liquefied petroleum gas, compressed natural gas, and electricity.

Four-Stroke Gasoline Engines

If gasoline is retained as the fuel of choice, replacing two-stroke vehicles with four-stroke vehicles would significantly reduce hydrocarbon and particulate emissions. Emissions of nitrogen oxide would increase, however.

Because there are no scavenging losses in four-stroke engines, a much larger percentage of the fuel is combusted in the combustion chamber, resulting in 10–20 percent greater fuel efficiency (table 10). Savings from better fuel economy would easily offset the higher purchase price of four-stroke engine vehicles, making this a potentially strongly cost-effective way to reduce pollution.

Four-stroke engine two-wheelers have been on the market for some time. All motorcycles sold in the United States are of four-stroke design. Mishuk in Bangladesh has been selling four-stroke engine three-wheelers for a number of years. Four-stroke engine three-wheelers were not available in India until mid-2000, when Bajaj Auto began marketing them there. Year 2000 model three-wheelers are equipped with catalytic converters for both two-stroke and four-stroke

Table 10 Fuel economy of two-stroke and four-stroke engine vehicles

Vehicle type	*Engine type*	*Model year*	*Engine size (cubic centimeters)*	*Laboratory test fuel economy (kilometers per liter)*	*On-road fuel economy (kilometers per liter)*
Scooter	Two-stroke	Post-1996	150	55	52
Scooter	Four-stroke	Post-1996	150	62	59
Three-wheeler	Two-stroke	Pre-1996	150	24	20
Three-wheeler	Two-stroke	Post-1996	150	28	25–27
Three-wheeler	Four-stroke	2000	175	33	30–31

Source: ARAI test of Bajaj vehicles using the Indian driving cycle; Bajaj laboratory tests; ARAI and Bajaj estimates for on-road fuel economy.

engines. The ex-Delhi showroom prices are Rs.66,579 for two-stroke and Rs.70,463 for four-stroke engine three-wheelers, with a price difference of Rs.3,884 (US$88). This incremental cost is easily recovered in fuel savings in less than a year by operators of four-stroke engine autorickshaws (see chapter 4).

Diesel three-wheelers have even higher fuel efficiency than four-stroke engine vehicles. Moreover, because they are based on a four-stroke engine design, lubricant does not need to be added to the fuel. Diesel three-wheelers are also manufactured to meet particulate matter emission standards. However, diesel exhaust has recently been found to be more toxic than previously believed. And diesel three-wheelers are considerably noisier than gasoline three-wheelers. Diesel engines are thus probably not a good alternative to gasoline-powered two-stroke engines.

Vehicles Powered by Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) is a mixture of light hydrocarbons, mainly propane/ propene and butane/butenes. It is easier to distribute and store than compressed natural gas, liquefied at pressures of 4–15 bar.

LPG is a much cleaner automotive fuel than gasoline. If LPG (or CNG) vehicles are based on a two-stroke engine design, lubricant will still need to be metered and injected into the combustion chamber, thereby partially offsetting the emission reductions achieved as a result of replacing gasoline with a gaseous fuel. Since lubricant cannot be premixed with LPG, it is metered into the vehicle engine, eliminating the possibility of overlubrication. LPG also contains fewer highly reactive hydrocarbons and has a lower sulfur content than gasoline or diesel fuel. LPG does contains light olefins, highly reactive hydrocarbons that increase emissions and lower the knock-limited compression ratio, diminishing engine performance.

LPG three-wheelers are used widely in Thailand. Fueling vehicles with LPG is illegal in India, although this situation is likely to change in the near future. Three-wheelers have been illegally converted to LPG use in Bangalore. ARAI and Shakti Gas have jointly developed a conversion kit to run three-wheelers on LPG.

While not as good as CNG, LPG has superior antiknock characteristics compared to gasoline. Propane has an antiknock index (the average of research and motor octane numbers[10]) of 104, allowing LPG-powered engines to operate at slightly higher compression ratios than gasoline-powered vehicles. In India vehicle manufacturers have proposed a minimal motor octane number for automotive LPG of 89 to ensure that about 90 percent of LPG is propane.

The main problems in introducing LPG into the transport sector in South Asia are the lack of sufficient domestic sources of supply and the inadequate distribution system. India, Pakistan, and Sri Lanka import about 30–40 percent of LPG consumption. There is also a need to invest in refueling equipment required to transfer pressurized LPG from storage tanks to vehicles and to ensure that no LPG escapes during refueling. The lack of adequate investment in LPG refueling stations constrains widespread use of LPG in South Asia.

Vehicles Powered by Compressed Natural Gas

Switching to CNG reduces particulate matter and hydrocarbon emissions significantly. The combustion of CNG also yields essentially no volatile organic compounds or sulfur oxide emissions. Moreover, because natural gas is lighter than air, on escape it will not lie on the ground or enter sewage systems. CNG is expensive to distribute and store, however, requiring compression to about 200 bar.

Both Bangladesh and Pakistan are piloting the use of CNG vehicles. In Bangladesh a pilot program funded by the Canadian International Development Agency converted four three-wheelers in mid-2000; a larger demonstration involving 20–50 vehicles will follow. In Pakistan a donor-funded program plans to test 10–30 vehicles in Karachi, Lahore, and Quetta. In both programs one tank of CNG is estimated to have a range of about 100 kilometers. Bajaj Auto in India has developed CNG-powered three-wheelers based on a four-stroke engine design, which it launched in mid-2000.

Vehicles can be produced to run on either CNG or gasoline. Such vehicles make less efficient use of CNG, however, losing about 10–15 percent of their power output. Efficiency is also lost as a result of the extra weight of carrying two fuel systems.

Methane, which constitutes the bulk of CNG, has an antiknock index of more than 120. Vehicles that run on CNG can thus take advantage of the 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 the year. As a result, not only does the fuel octane number vary but the heating value can vary by as much as 25 percent, affecting vehicle performance. Moreover, when used as fuel in vehicles, the heavier hydrocarbons in natural gas can condense and revaporize, affecting the level of fuel enrichment. Changes in fuel enrichment affect both emissions and engine performance. The water content of natural gas is also a concern because of its tendency to form solid hydrates and corrode transmission pipes, vehicle storage tanks, and refueling stations.

The long-term viability of CNG vehicles depends on a favorable legislative and regulatory atmosphere and fuel prices that are not distorted by subsidies. Efforts to encourage the purchase of CNG vehicles through subsidization are unsustainable—as New Zealand's failed attempt to jumpstart the conversion to CNG illustrates. New Zealand's aggressive program of financial incentives, including subsidies, led to the conversion of 110,000 vehicles to natural gas between the early 1980s and 1986. When the government withdrew its support, however, the market for CNG vehicles essentially died: today only about 10,000 such vehicles remain on the road. As the International Association for Natural Gas Vehicles put it, "Governments that believe that all they need is a two- to three-year kick-start are wasting their time and money" (Cumming 1997).

For converting to natural gas to make economic sense, the retail price of CNG needs to fall to about 55–65 percent of the cost of the fuel being replaced. Without consistently lower prices, promotion of CNG vehicles will not be sustainable. But governments have a disincentive to reduce the price of CNG since this would reduce their tax revenues as consumers shift from (taxed) fuels to (essentially untaxed) CNG.

In countries such as India that will soon start importing liquefied natural gas on a large scale (a source of natural gas in the future), it would be difficult to keep CNG prices much lower than gasoline prices if world crude oil prices were to fall markedly. In contrast, Bangladesh, which has large natural gas reserves and extensive networks of gas pipelines in large cities, might be able to introduce CNG into the transport sector without compromising other needs in the economy. However, natural gas is effectively subsidized in Bangladesh. In 1998 the price of natural gas was estimated to average about 25 percent less than its economic opportunity cost. Once the gas sector is restructured to reflect market prices, the economics of CNG vehicles will become less favorable than they are today—something that must be considered in assessing a CNG vehicle program.

Electric Vehicles

Electric three-wheelers cost much more than gasoline-powered vehicles, have shorter ranges, and run on batteries that take up to 6–10 hours to recharge. Until technological changes make these vehicles more attractive, they are not expected to play an important role in South Asia.

Electric vehicles currently operate on lead acid batteries.[11] When the batteries are charged indoors, good ventilation is necessary, because hydrogen is emitted as lead acid batteries recharge. Preliminary estimates in India price the batteries at about $40–$50 apiece for three-wheelers that operate on eight batteries. The eight batteries and required vehicle modifications are expected to increase the cost of electric three-wheelers by about $1,000, effectively doubling the price of the vehicles relative to gasoline-fueled three-wheelers in India.

The economic viability of electric vehicles depends in part on the price of electricity. The power sector in South Asia is being reformed and restructured. The long-term viability of electric vehicles should be evaluated based on market pricing of electricity.

Given the current state of technology, electric vehicles are not expected to have widespread applications in South Asia. They could play a useful but limited role, however, in extremely polluted traffic corridors. In Kathmandu, Nepal, for example, electric Tempos were introduced in 1994 (box 4). In 1995 the government reduced import duties on electric vehicle components from 60 to 5 percent, and duties on fully assembled electric vehicles from as much as 150 percent to 10 percent. In early 2000 about 500 electric Tempos operated in Kathmandu, partly in response to the ban on diesel Tempos imposed by the government in 1999. Seven plants assembled more than 200 electric Tempos in 1999. This is the world's largest fleet of electric road public passenger transport vehicles. The future is not secure, however, as the government approved in May 2000 the import of 300 15-seat vans with the same preferential import duties accorded to the electric vehicles.

Box 4

Converting diesel three-wheelers to electric Tempos in Kathmandu

An important mode of public transport in Kathmandu is the Tempo, a 10-passenger three-wheeler that operates as a minibus. Before the government banned diesel Tempos in Kathmandu in 1999, about 1,500 of the vehicles operated in the city.

A pilot program to convert diesel Tempos to electricity was conducted in 1994–96 by Global Resources Institute with the support of the U.S. Agency for International Development (Moulton and Cohen 1997). The electric Tempos in the pilot program, called Safa (*clean*) Tempos, had an operating range of 50 kilometers and a maximum speed of 45 kilometers an hour. Their batteries weighed 360 kilograms, so that when full the vehicle operated close to its maximum design load. The brakes also operated close to design limits.

To allow the vehicles to travel 150 kilometers a day, three sets of batteries were used. Specified stops loading and unloading passengers—a new concept in Nepal—were established so that the vehicles could operate on a schedule.

The Safa Tempos are cleaner and quieter than diesel Tempos, and public acceptance of the vehicles has been high. In fact, demand from passengers often exceeded available space during the pilot period.

CHAPTER 4

Policy Options

Policymakers can deal with pollution by setting emission targets that vehicles must meet or by mandating specific types of fuel or vehicle technology in the hope of achieving emission targets. Emission-based measures provide greater flexibility to suppliers of fuels and vehicles, who can choose the lowest-cost options for meeting the specified emission targets. Provided that compliance can be ensured, this approach is generally a lower-cost option for society. However, emission-based measures are usually more difficult to monitor than technology-based options. Technology based options are not likely to be a low-cost solution unless rigorous cost-benefit analysis is performed to identify the optimal technologies for each specific situation. (For a brief discussion of available software for evaluating emission sources, see annex C.)

The distinction between emission-based and technology-based policies is not necessarily sharp, because vehicular emission standards can be made so stringent that they effectively dictate the type of vehicle or fuel that must be used. An example is the year 2003 emission standards in Taiwan (China), which set tighter emission standards for two-stroke engines than for four-stroke engines, effectively banning two-stroke two-wheelers.

Emission-Based Policies

Emission-based policies set vehicular emission standards and allow the automobile and oil industries to seek the lowest-cost means of complying with the standards. Vehicle manufacturers prefer emission-based policies, which allow them to explore different technology options and select technologies themselves on the basis of market requirements and their research and development activities. Emission-based policies work well if the automobile and oil industries cooperate. Without cooperation, each industry has an incentive to unload capital-intensive activities onto the other.

Stricter emission standards are apparently pushing Indian manufacturers to build more four-stroke engine vehicles. Moving to a four-stroke engine appears to be cost-effective: an autorickshaw driven 120 kilometers a day 300 days a year would save about Rs.7,200 a year (based on the prices of 87 octane gasoline and lubricant for two-stroke engine vehicles meeting JASO FC standards in mid-2000). Since the ex-Delhi showroom price difference between a two-stroke and a four-stroke engine vehicle is Rs.3,900, the incremental cost of purchasing a four-stroke engine three-wheeler is recovered in a little over half a year. Assuming that maintenance costs are comparable, replacing old autorickshaws with new four-stroke engine autorickshaws is therefore a cost-effective way of reducing fine particulate emissions.

Monitoring emissions

While checking compliance of new vehicles may not be difficult, monitoring the performance of in-use vehicles is a far greater challenge. At a minimum, an effective inspection and maintenance program needs to be in place, together with an up-to-date vehicle registry. Even when implemented rigorously, however, inspection and maintenance have limited effectiveness because owners and mechanics can temporarily adjust vehicles, particularly older technology vehicles, so that they pass emissions tests.

One way to ensure that emissions consistently meet standards is to spot-check vehicles on the road. However, such tests are expensive to set up and administer and invite corruption.

To increase the effectiveness of inspection and maintenance programs, the frequency of inspection could vary with the age of the vehicle as well as the annual number of kilometers traveled. Commercial vehicles such as three-wheelers could be inspected more frequently than motorcycles driven for private use.

Frequent inspection is particularly important once oxidation catalysts are installed. If catalysts last about 30,000 kilometers and taxis are typically driven in two shifts for 150 kilometers a day, inspection and replacement of catalysts would be necessary twice a year.

Repairing vehicles that fail inspection

Vehicle inspection will be ineffective if vehicles that fail are not repaired promptly. The availability of adequately equipped and trained mechanics is a prerequisite for a successful inspection and maintenance program. Since four-stroke engine vehicles are more complex and require higher mechanical sophistication to service, training of mechanics should be given high priority in the coming years. There is currently a shortage of mechanics who can service four-stroke engine three-wheelers and vehicles with increasingly sophisticated technology in general, and of repair shops with diagnostic tools to service such vehicles.

Where vehicles are not driven by their owners, the incentives for regular inspection and maintenance, weak in the best of circumstances, are even weaker, since the vehicle owner who is responsible for passing inspection does not have the vehicle most of the time. This dilemma highlights the importance of finding ways to enforce emission standards and deal with noncompliance, given that neither the owners nor the drivers have an incentive to spend time having commercially operated vehicles inspected.

Technology-Specific Policies

Measures based on fuel and vehicle technology mandate the minimum technology to be adopted. Technology-specific policies include:

- Mandating higher-quality two-stroke engine lubricants
- Mandating premixing of gasoline and lubricant
- Mandating installation of catalytic converters
- Banning two-stroke engines
- Banning or providing incentives to scrap vehicles that have reached a certain age or number of kilometers traveled
- Mandating or providing incentives (tax credits, tax reduction, tax elimination, or subsidies) for replacing two-stroke gasoline engine vehicles with four-stroke engine vehicles
- Mandating or providing incentives for replacing two-stroke gasoline engines with alternative fuels such as liquefied petroleum gas, compressed natural gas, and electricity.

Where emission-based policies are difficult to monitor, it may make sense to adopt some of these policies. Before this is done, however, it is imperative that policymakers examine the cost-effectiveness of each option. Some measures make more sense to mandate than others. Banning the sale of unpackaged lubricant would prevent inferior quality lubricant from being added to gasoline (box 5). Requiring that all new three-wheelers use four-stroke technology may be reasonable given the fuel cost savings, provided that enough mechanics are trained to service four-stroke engine three-wheelers.

In contrast, the rationale for mandating catalytic converters is much weaker, since they can function efficiently only if several conditions are satisfied:

- Unleaded gasoline must be widely available. Ideally, leaded gasoline would be completely phased out to eliminate the chances of fueling catalyst-equipped vehicles with leaded gasoline.

- Gasoline must have a reasonably low level of sulfur, preferably less than 500 parts per million by weight.
- Emission levels and the length of time the catalyst system must meet those levels must be specified.
- An effective inspection and maintenance system must be in place to ensure that catalytic converters are replaced as needed.

If these conditions are not met, the benefits of catalytic converters may not justify the cost of installing them. Even if these conditions *are* met, it still makes sense to specify emission levels for new vehicles rather than mandate catalytic converters. Retrofitting in-use vehicles with catalytic converters is problematic because misfires, which are more common in two-stroke engines, can cause temperature runaway and catalyst sintering and damage the catalyst as a result. For this reason Bajaj Auto in India recommends that only two-stroke engine vehicles built after 1996 be considered for retrofitting.

Reducing particulate matter by mandating catalysts may not be cost-effective. It is difficult to estimate the impact of oxidation catalysts on particulate matter emissions because data are scarce. Assuming catalyst conversion efficiency of 50 percent, a particulate matter emission factor without catalysts of 0.1–0.2 grams per kilometer, and catalyst durability of 30,000 kilometers, the total amount of PM_{10} eliminated by the catalyst would be 1.5–3.0 kilograms. This translates to US$8,000–17,000 per ton of PM_{10} given the net-of-tax catalytic converter cost of US$25 apiece in India. This figure varies severalfold depending on the assumptions made about the durability of the catalyst and the amount of particulate matter reduced, but the cost figures remain on the high side compared with other PM_{10} reduction strategies.

Banning all two-stroke engines

Banning all two-stroke engines would eliminate point-to-point transportation for millions of South

Box 5

The role of the supreme court in air quality management in Delhi

In July 1998 the Supreme Court of India mandated several measures affecting two- and three-wheelers in Delhi to combat air pollution:

1. Banning the sale of loose 2T oils at filling stations and service garages, effective December 1998.
2. Mandating that filling stations mechanically meter lubricant to be mixed with gasoline at the point of gasoline sale for two-stroke engine vehicles, effective December 1998.
3. Mandating the replacement of all pre-1990 autos and taxis with new vehicles using clean fuels, effective March 2000.
4. Introducing financial incentives for replacing all post-1990 automobiles and taxis with new vehicles using clean fuels, effective March 2001.

The first three measures have been implemented. The third measure effectively requires that pre-1990 autorickshaws be retired from Delhi and replaced with autorickshaws powered by compressed natural gas. The only two "clean" fuel options, until the use of liquefied petroleum gas is legalized in India, are natural gas and electricity. No electric-powered autorickshaws are commercially available for sale in India today.

The fourth measure has had an interesting history. The Delhi government offered financial incentives until March 2000 to replace autorickshaws 15 years old or older with new vehicles meeting the April 1996 emission standards. Although both two-stroke and four-stroke engines were permitted in principle, only two-stroke engine autorickshaws were available during this period. The incentive package consisted of complete exemption from sales tax (6 percent until 2000, when it was raised to 12 percent) and subsidized loans from the Delhi Finance Corporation. The loan repayment period, ranging from three to five years, could be negotiated. As of April 2000, the financial package is offered only for the replacement of old autorickshaws with new autorickshaws running on compressed natural gas or electricity.

Autorickshaw owners' response to the measures has been overwhelming. By March 2000 nearly 20,000 old autorickshaws had been replaced by new ones. While the order allows owners to sell their old vehicles outside the National Capital Territory of Delhi, most owners chose to scrap their vehicles. Pollution is thus not transferred to other parts of the country, and there is no possibility of these old vehicles migrating back to Delhi.

Asians and cause hardship until there are enough buses and four-stroke engine taxis to replace the large existing stock of two-stroke engine three-wheelers. Women and families, who depend on the vehicles more than other groups, and the many people who use these vehicles commercially would be particularly hard hit by a ban. Taking two-stroke three-wheelers off the road precipitously would also affect the livelihoods of tens of thousands of drivers and invite widespread agitation. Moreover, banning existing two-stroke engines without putting in place a well-documented vehicle registration system, an effective traffic police force, and transport alternatives for the current users could lead to increased harassment of drivers and corruption by traffic police. Thus rather than banning these vehicles, policymakers should consider other lower-cost options for reducing their emissions.

More selective bans

Lower cost and politically more viable options to banning all two-stroke engine vehicles are to:

(a) Ban only older (and typically more polluting) two-stroke engine vehicles from urban areas. This approach has already been taken in Delhi, with widespread popular support (box 5); and/or

(b) Ban new two-stroke engine vehicles. This is likely to have less socioeconomic impact than banning all such vehicles, since the cost difference between new two- and four-stroke engines is not significant. If operating and maintenance costs are taken into account, owning a four-stroke engine vehicle may be more economical than owning a two-stroke engine vehicle. Removing financial disincentives for replacing two-stroke engine three-wheelers with four-stroke engine vehicles is a high-priority.

Either of these two options would be best pursued if the following conditions are met: (i) alternatives to the vehicles being removed are readily available and market-tested; (ii) these alternatives are affordable, which may require the lowering or elimination of import duties or other taxes on new vehicles (see below); and (iii) sufficient credit exists for vehicle owners and drivers to be able to finance the purchase of the newer vehicles.

Fiscal and Trade Policy Options

Whether or not the technology-specific measures are adopted, economic policy options exist to encourage the removal of older and more polluting vehicles from polluted cities. These options include providing tax incentives for renewing vehicles, offering cash for older vehicles to get them off the road, ensuring credit for purchasing new vehicles, and liberalizing the trade in new vehicles. Not all options are equally recommended.

Tax incentives for vehicle renewal

The structure of taxes and other vehicle charges, such as annual registration fees, should be carefully reviewed and revised if necessary where such structures do not capture the cost of pollution. For example, the import tariffs or sales taxes on cleaner alternatives to autorickshaws (whether new vehicles or parts for vehicle retrofitting) should not be so high as to discourage their purchase—since the public health benefits to be gained are high. Similarly, annual registration fees based solely on the market value of the vehicle, rather than on market value and pollution emitted, would be too low to discourage the use of older vehicles in urban areas. In assessing each of these measures, policymakers need to weigh the socioeconomic cost of making it more expensive to own old vehicles against the health benefits of reducing vehicular emissions.

Offering cash payments for older vehicles to remove them from the road

Government purchase of older vehicles can distort the market and have the perverse effect of keeping older vehicles in use. If the government offers to buy older vehicles, the price of those vehicles, many of which may be on the verge of being scrapped, will rise. A vehicle is typically scrapped when the cost of repairing it exceeds the market value of the vehicle after repair. The higher prices of older vehicles may have the unwanted effect of inducing some owners to keep and repair their old vehicles rather than scrapping them. Moreover, because vehicle prices are typically higher inside urban centers than outside, nonurban owners of old vehicles would have an incentive to bring their vehicles to urban centers and sell them there. These problems indicate that cash payment by the government for old vehicles is not the best use of limited public resources.

Ensuring adequate credit

In lieu of offering cash payments, the more valuable role for government is helping to ensure the availability of credit through regular credit and micro-credit markets to urban public transport vehicle owners and drivers. This would facilitate their replacing older autorickshaws—as well as larger vehicles, such as diesel and two-stroke engine gasoline Tempos—with cleaner ones.

Liberalizing trade in new vehicles

Liberalizing trade in new vehicles could also help reduce emissions. Making the technology available in the rest of Asia readily available to consumers in South Asia would allow them to meet tighter emission standards at lower cost. Rules such as local content requirements, based on the infant industry argument, often result in inefficiency. High import tariffs, rigid licensing schemes, and quotas on foreign-made vehicles are all likely to slow the rate of vehicle renewal, preventing a decline in emissions.

Public Education

Emissions from two-stroke engines and repair costs can be reduced by encouraging owners to carry out regular maintenance and use lubricant specifically manufactured for use in two-stroke engines at concentrations recommended by the vehicle manufacturer. Mass public education will be needed to induce vehicle owners to adopt these "win-win" measures.

Governments, donors, and nongovernmental organizations have sought to raise public awareness about emissions in South Asia.

- The Hydrocarbon Development Institute of Pakistan has distributed pamphlets and stickers containing basic information on the quality and quantity of gasoline and lubricant.
- In Dhaka, Bangladesh, the joint United Nations Development Programme–World Bank Energy Sector Management Assistance Programme (ESMAP) carried out a series of training sessions for mechanics and auto clinics for three-wheeler taxi drivers in late 2000. The program was based on the idea that the first step toward adoption of good practice is dissemination of accurate information by mechanics to taxi drivers.
- A major public awareness campaign in Delhi, India, in late 1999 led to more than 66,000 vehicles participating in free inspection and maintenance clinics for two-wheelers (Iyer 2000) (box 6).

Although public awareness initiatives have been taken throughout the region, many drivers continue to maintain their vehicles inadequately. Much more needs to be done to improve public understanding of the importance of proper vehicle maintenance.

Future Directions

Two-stroke engines make up much of the total vehicle fleet because they are relatively inexpensive, perform well in terms of power and speed, and are easy to repair. Precisely because two-stroke engines are so numerous and popular, any policy decision to address emissions from these vehicles must take socioeconomic consequences into account. A large-scale immediate ban on gasoline-powered two-stroke engine vehicles would be extremely difficult and costly, but fortunately numerous small and cost-effective improvements are available. Public education and awareness raising—about the health impact of emissions, the engine/fuel/lubricant parameters that increase emission levels, simple steps drivers can take to reduce emissions, and the advantages and disadvantages of various measures tabled for mitigating air pollution—make emissions reduction easier even with the existing vehicle fleet.

Two-stroke engine vehicles may eventually be phased out in South Asia, to be replaced by comparable but cleaner alternatives that still meet

Box 6

Reducing emissions and improving performance through free inspection and maintenance clinics in Delhi

To reduce emissions, the Society of Indian Automobile Manufacturers (SIAM) and other Indian companies sponsored voluntary inspection and maintenance clinics for two-wheelers in Delhi in 1999. The clinics, funded in part by the U.S. Agency for International Development, were held simultaneously in four locations in three phases over four weeks. SIAM member companies provided 45 instruments and 200 staff. Major vehicle manufacturers staffed and ran repair and information booths. Instrument manufacturers were on site to check instrument calibration and ensure the accuracy of emission measurements. The government of Delhi authorized SIAM to issue "Pollution under Control" stickers and stationed traffic police personnel at the clinic sites. The clinics were widely publicized in the media, with appeals made by dignitaries, celebrities, and top-ranking government officials. The cost of this highly successful program was about US$2.50 per driver.

Simple maintenance tasks were performed at the clinic, and booklets on maintenance and fuel-saving driving tips were distributed. Vehicles were first checked for carbon monoxide and hydrocarbon emissions while idling. If the vehicle failed (that is, if carbon monoxide emissions exceeded 4.5 percent of the exhaust gas or hydrocarbon emissions exceeded 9,000 parts per million) it was taken to a repair booth where the carburetor was adjusted and emissions measured again. If the vehicle failed the second emissions test, the spark plugs were cleaned and adjusted and the air filter cleaned. A third emissions test was then run. After testing the vehicle was taken to the safety booth, where the driver received a booklet of safety and maintenance tips.

About 80 percent of participating vehicles passed the idle carbon monoxide test; 95 percent of the remaining 20 percent passed the test after minor repairs. Seventy-five vehicles that initially failed the emission tests were tested for fuel consumption. Fuel economy improved from an average of 39 to 47 kilometers per liter after minor repairs, demonstrating the benefits of performing simple maintenance tasks. One of the four clinics had a smoke meter, and smoke measurements were taken of failing vehicles before and after the minor maintenance. Smoke emission levels fell after minor repairs.

the social and economic needs of the public. Dynamic partnerships among government, industry, and the public will be crucial in the development of, and commitment to, achieving air quality goals. A transition period is likely, probably a number of years, during which in-use two-stroke engine vehicles in large urban centers are phased out. Under these circumstances, the importance of promoting good practice in lubricant use in in-use two-stroke engine vehicles cannot be overemphasized. In this "win-win" situation vehicle emissions can be dramatically reduced and vehicle maintenance made easier at virtually no cost.

ANNEX A

Health Impact of Air Pollution

Nearly all vehicular particulate emissions are extremely damaging to public health. Concentrations of total suspended particles and particulate matter with an aerodynamic diameter of less than 10 microns (PM_{10}) have been found to exceed internationally accepted guidelines and standards severalfold in several South Asian cities. Even more damaging is fine particulate matter smaller than 2.5 microns ($PM_{2.5}$). Other air pollutants from vehicular emissions that affect public health are lead (where leaded gasoline is used), carbon monoxide, sulfur oxides, nitrogen oxides, ozone, and airborne toxins.

Particulate Matter

PM_{10} and $PM_{2.5}$ remain in suspension in the air for hours or days and can travel significant distances from the source. These particles enter the respiratory tract, reaching deep into the lungs. PM_{10} includes all particles likely to pass through the nose and mouth. $PM_{2.5}$ includes particles able to reach the deeper parts of the respiratory tract, especially the alveolar regions of the lung. Animal studies indicate that ultrafine particles (with diameters of less than 0.05 microns) are cleared from the lungs only very slowly and can penetrate the pulmonary interstitium, where they cause inflammation.

The largest source of fine particulate formation is the incomplete combustion of fossil fuels and biomass. Low fuel quality, inefficient combustion processes, and poor vehicle and equipment maintenance all contribute to particulate emissions. Most particles generated from the combustion and condensation of vapors are $PM_{2.5}$. Most particles emitted from vehicles have diameters of less than a micron. Moreover, these particles are emitted near ground level, close to where people live and work.

Primary particles are those emitted directly from a source. Secondary particles are formed within the atmosphere, mostly from the chemical oxidation of atmospheric gases. Vehicles contribute to secondary particulate formation when oxides of sulfur and nitrogen in the exhaust gas are transformed into sulfate-based and nitrate-based fine particulate matter in the atmosphere.

Isolating the effects of different types of particulate matter is difficult because other pollutants—as well as other factors in the environment, such as changes in temperature or epidemics of infections—also affect health. But a series of extensive studies, mainly in the United States, has tied changes in particulate concentrations to changes in a wide range of health indicators, including deaths, changes in lung function, emergency room visits, exacerbation of asthma, hospital admissions, respiratory symptoms, and time off from school or work (Holgate and others 1999).

These associations are stronger for particulate concentrations than for other pollutants. The measurement of particulate-related death has been particularly well studied, and the results are more consistent than those for other indicators. Although the composition of PM_{10} can vary widely from area to area and over time, the size of the estimated effects, particularly the effect on death rates, does not vary greatly with location. On the basis of these studies, the impact on public health may be considerably higher in South Asia than in the United States because the quality of medical care is lower and people in urban areas spend more time outdoors.

PM_{10} has much more serious effects on health than total suspended particles, which include particulate matter of all sizes. Coarse windblown particles, for example—common in Delhi—are not believed to have a significant impact on health. Recent studies have indicated that the number of particles to which a person is exposed could be more important than the aggregate mass.

Lead

In cities where leaded gasoline is still used, airborne lead poses a serious health threat. The worst effects appear to be on the intellectual and behavioral development of children. There has been much public health interest in this issue because of mounting evidence that continual exposure to even low levels of lead, previously considered safe, could have a negative impact on children's intelligence.

The absorption of lead from the environment depends on the chemical and physical characteristics of the lead as well as age, nutritional status, and physiological status. The amount of lead absorbed by the body increases significantly when the stomach is empty. The rate of absorption is also higher for children than for adults. Some evidence also suggests that more lead is absorbed by people with low dietary calcium intake or iron deficiency (World Health Organization 1995). These findings indicate that poor, malnourished children are particularly susceptible to lead poisoning.

Carbon Monoxide

Carbon monoxide is a colorless, odorless gas that inhibits the capacity of blood to carry oxygen to organs and tissues. High levels of carbon monoxide can cause people with chronic heart disease to experience chest pain. Very high levels of carbon monoxide can impair vision, manual dexterity, and learning ability and cause death.

Carbon monoxide is a product of the incomplete combustion of fossil fuels. In most cities gasoline-fueled vehicles account for most carbon monoxide emissions. The level of carbon monoxide emissions can be reduced by incorporating oxygenates in gasoline for old vehicles and by using oxidation catalysts in new vehicles.

Sulfur Oxides

Sulfur dioxide, one of the oxides of sulfur, causes changes in lung function in asthmatics and exacerbates respiratory systems in sensitive individuals. Sulfur oxides are formed when fossil fuels containing sulfur are burned. These oxides contribute to acid rain and to the formation of secondary particles. The amount of sulfur emitted is directly proportional to the amount of sulfur in the fuel. It can be reduced by treating the fuel, for example, through hydrotreating, or by installing sulfur removal devices at the point of emission, such as flue gas desulfurization units at power plants.

Nitrogen Oxides

Nitrogen dioxide, one of the oxides of nitrogen, causes changes in lung function in asthmatics. Nitrogen oxides are formed during combustion as nitrogen in the air reacts with oxygen at high temperature. Like sulfur oxides, these oxides contribute to both acid rain and secondary particulate formation. Nitrogen oxides are also precursors of ground-level ozone.

Power plants and diesel- and gasoline-fueled vehicles emit nitrogen oxides. The amount of nitrogen oxide formed can be reduced by controlling the peak combustion temperature—for example, by recirculating exhaust gas in vehicles; reducing the amount of oxygen available during combustion; or converting nitrogen oxides to oxygen-containing inorganic compounds and nitrogen—for example, by installing three-way catalytic converters.

Ozone

Ozone causes photochemical smog and has been associated with transient effects on the human respiratory system, particularly the decline in pulmonary function during light to heavy exercise. Gasoline-fueled vehicles are a significant source of volatile organic compounds, which along with nitrogen oxides are precursors of ozone. Ozone abatement is complicated by nonlinear interactions among ozone precursors—the amount of ozone formed is not directly proportional to the ambient concentrations of volatile organic compounds and nitrogen oxides but is a complex function of a number of factors that include the ratio of these two precursors. It is therefore important to collect relevant data and understand the chemistry of ozone formation before selecting mitigation measures.

Toxic Airborne Emissions

Toxic emissions from vehicles include benzene; polycyclic aromatics; 1,3-butadiene; and aldehydes. All of these are carcinogens, according to the World Health Organization, which provides guidelines for ambient concentrations.

ANNEX B

Improving Particulate Sampling of Two-Stroke Engine Vehicles

AEA Technology in the United Kingdom conducted an experimental program to find a more reliable particulate sampling technique (Smith 2000). The experiment investigated two aspects of particulate sampling:

- Whether passing gas through a filter coated with liquid deposit causes any loss of that liquid.
- Whether significant amounts of oil are lost in the sampling pipes into and including the constant volume sampling (CVS) system.

To try to answer the first question, AEA compared the use of an Andersen impactor—in which particles are deposited on filter papers without gas passing through the paper—with the standard regulatory filter method. The second question was investigated by taking particulate sample from raw exhaust very close to a motorcycle under steady state conditions and comparing the results with CVS measurements.

A 1974 twin-port, two-stroke, single-cylinder Jawa 250 cubic centimeter motorcycle manufactured in Czechoslovakia was used for the experiments. The vehicle had 39,500 kilometers on the odometer and no emission control. It operated with unleaded gasoline at a ratio of 30 to 1 with Castrol Super TT two-stroke oil that met JASO FB and API TC specifications. The lubricant and gasoline were premixed.

A Horiba microdilution system (MDLT-1300) was installed very near the motorcycle's exhaust to capture sample from the hot exhaust gas before it had a chance to cool to ambient temperature. The flow to the microtunnel was constant; the remaining flow to the CVS depended on engine conditions.

The exhaust gases were mixed with filtered dilution air in the dilution tunnel (internal diameter 21.5 centimeters), with the CVS pump providing a constant volume flow through the dilution tunnel. A standard regulatory filter sample for particulate matter was taken from the dilution tunnel onto 47 millimeter diameter Pallflex type TX40HI20-WW filters.

In addition to this method, an Andersen impactor was used to measure particulate emissions. The Andersen II Cascade Impactor is designed to measure the mass-weighted size distribution of aerosol particles up to an aerodynamic diameter of about 10 microns. The instrument is a multistage, multijet device that separates particles into size classes based on their inertia. An impactor stage consists of a series of jets over a flat collection medium (filter) at a preset distance. Aerosol passing through each jet is directed against the filter, causing the fluid streamlines to be deflected through 90°. Particles with high inertia are unable to follow the streamlines and impact on the collection medium; particles with a sufficiently low inertia follow the streamlines and miss the collection plate.

The investigators used two impactor stages. The first collected particles with diameters of

0.3–10 microns. The second collected particles with diameters of less than 0.3 microns. This method differs significantly from the standard regulatory method because the gas flows around the paper instead of through it, eliminating the possibility of liquid droplets being bubbled through the paper because of the gas flow.

Because the total exhaust volume flow rate fluctuates, steady state experiments were conducted to be able to use the data obtained using the Horiba filters. The motorcycle was driven until reasonably stable conditions were obtained, and an average over 10 minutes was taken.

The motorcycle itself caused the greatest problem for obtaining reproducible results. Because the engine was unstable, it was not feasible to use the equivalent of a dead man's foot on the motorcycle. The steady states thus had to be manually driven.

Data were also taken at idle, at 30 and 50 kilometers per hour steady states, and at an Economic Commission for Europe (ECE) transient driving cycle. The ECE cycle could not be followed exactly because the motorcycle was unable to drive the cycle with the required gear changes. The cycle was run as an example exercise only.

Data were collected over three days (table A1). Deposits on the filter papers were gray-brown in color, typical of oil deposits. Solvent extraction on a selection of filter papers removed 98–99 percent of deposits.

The data from the regulatory and Horiba microtunnel systems were similar, particularly when the uncertainty in the microtunnel measurements was taken into account. The results suggest that condensation along the sampling lines and CVS is not a major problem and that the Andersen impactor yields masses about 60 percent higher than the other two techniques.

The CVS flow did not have a significant impact on the results within the experimental reproducibility of the driving conditions. At the end of the experiments the CVS system was taken apart. There was no evidence of significant fouling by oily deposits in the dilution tunnel, although there was a little oily soot in the heat exchanger. Fuel consumption from the transient cycle was calculated to be about 23 kilometers per liter using a carbon mass balance.

The relation between the particulate emissions measured by the Horiba microtunnel and regula-

Table A1 Experimental particulate emission results

Run	*Constant volume sampling flow (cubic meters per minute)*	*Road speed (kilometers per hour)*	*Regulatory particulate (grams per kilometer)*	*Andersen impactor particulate (grams per kilometer)*	*Horiba microtunnel particulate (grams per kilometer)*	*Smoke opacity (percent)*	*Percent of particles larger than 0.3 microns*
1	9.0	30	0.098	—	0.080	15	—
2	4.4	30	0.116	0.167	—	20	90
3	2.9	30	0.112	0.184	0.100	23	90
4	9.0	30	0.123	0.186	0.126	—	95
5	9.0	30	0.141	0.223	0.129	25	89
6	4.4	30	0.128	0.200	0.117	19	87
7	2.9	30	0.125	0.224	0.108	21	84
8	9.0	30	0.081	0.129	0.075	13	82
9	4.4	30	0.101	0.149	0.092	17	83
11	9.0	0	0.014[a]	0.026[a]	0.021[a]	28	84
12	9.0	50	0.056	0.093	0.054	14	78
13	9.0	ECE cycle	0.611	0.984	—	—	91

— Not available.
a. Emission expressed in grams per minute.
Source: Smith 2000.

tory techniques suggests that little sample is lost to condensation. Uncertainties in exhaust flow determination mean the two measurements are not identical, but the ratio between the two measurements is constant. The absence of sample loss is confirmed by the lack of fouling of the CVS dilution tunnel by oil droplets. However, there was evidence that the heat exchanger, with its much smaller diameter tubes, does cause droplet condensation. In the dilution tunnel, whose diameter is 21.5 centimeters, the interaction with the walls is minimized; in the heat exchanger, however, the interaction with the walls causes droplet condensation. This does not affect particulate measurements, which are made before the heat exchanger.

The higher results from the Andersen impactor seem to suggest loss of sample from the regulatory filter. However, under the conditions under which the system was operated, the relation between the Andersen and regulatory data is linear. Therefore, even if some systematic losses did occur, the use of the regulatory method would provide a satisfactory comparative method: the absolute values may not be exactly correct, but the correlation between vehicles and oils would be valid.

The Andersen data imply that about 90 percent of the particulates (by mass) have diameters of more than 0.3 microns. These are likely to be oil droplets, as suggested by the color of the deposits and the solvent extraction results, which imply that 98–99 percent of the deposits are from oil.

Annex C

Analytical Tools for Cost-Benefit Analysis

Regulatory decisions for the management of urban air quality should be based on objective assessment of scientific and technical evidence and thorough cost-benefit analysis of alternative air quality improvement strategies. Timely information about air quality, emissions, and health and other benefits of reducing emissions is needed to conduct cost-benefit analysis.

Air quality monitoring and reporting need to be upgraded to internationally acceptable standards and made available to the public daily. Reliable and complete inventories of emissions from different sources (domestic, industrial, different transportation modes, resuspended dust) are crucial for identifying priority areas for interventions. Air quality modeling then needs to be conducted based on the monitoring and inventory data to identify the main sources of ambient pollution in the areas where the largest number of people are at risk. The health and other benefits of reducing emissions then need to be computed and compared for different mitigation measures.

The reliability of the emissions inventory depends on the accuracy of the data on emission factors and consumption of fuels used in different sectors. But reliable data on emissions by the transport sector are scarce in developing countries. Vehicular emission factors are a function of fuel quality—for example, the level of sulfur in gasoline and diesel fuel—and vehicle technology—for example, the level of maintenance and the nature of exhaust treatment devices. The U.S. Environmental Protection Agency's highway vehicular emission factor model contains a fairly comprehensive list of vehicular emission factors, but the data do not reflect the condition of vehicles in developing countries.

Several software programs are available to build emissions inventories for both mobile and stationary sources. The Decision Support System for Integrated Pollution Control is based on the World Health Organization's emission factors. The International Petroleum Industry Environmental Conservation Association's Urban Air Quality Management Toolkit is one of only a few models that takes into account the effects of fuel composition on emission factors. It is linked to a model that calculates incremental costs for different mitigation options.

The World Bank has recently built an Excel spreadsheet–based transport emissions inventory program, VAPIS (Vehicular Air Pollution Information System). The program computes past and future vehicular emissions as a function of vehicle type, year, and fuel used for several pollutants. It projects future vehicle growth and emissions.

Annex D

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Notes

1. Another pollutant of concern is lead, although lead in gasoline has been phased out in Bangladesh and India. Pakistan and Sri Lanka are two countries where leaded gasoline is still widely used.
2. If leaded fuel is used, two-stroke engines emit organic lead, which is much more damaging to public health than the inorganic lead formed by the full combustion of lead additives.
3. Tests done at ARAI (the Automotive Research Association of India) in the fall of 2000 indicate emissions reductions of this magnitude, but require further analysis.
4. As the size of the program—and subsidy—grew, the government could not afford to continue bearing the cost. When the subsidies were reduced the use of CNG fell dramatically. Without subsidies CNG use proved to be unsustainable.
5. This is also because the standards for hydrocarbon emissions in 2003 are twice as stringent for two-stroke than for four-stroke two-wheelers.
6. Two-stroke engine vehicles produce more noise than four-stroke gasoline engine vehicles, but four-stroke diesel engines are noisier than either type of gasoline engine.
7. Lead is added to gasoline as an organic compound to improve its combustion characteristics.
8. In India most electricity is generated by burning coal, which emits about twice as much carbon dioxide as natural gas per unit of electricity generated. Thus where coal is burned, switching to electric vehicles will not necessarily reduce greenhouse gas emissions.
9. The research octane number is a measure of a gasoline's resistance to self-ignition (knocking) when vehicles are operated at low speed corresponding to city driving conditions.
10. The motor octane number is a measure of a gasoline's resistance to self-ignition (knocking) when vehicles are operated under highway driving conditions.
11. There is no consensus on the best type of battery for the future.

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