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Automotive Air Pollution

Issues and Options
for Developing Countries

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Automotive air pollution will intensify with increasing urbanization and the rapid pace of motorization in developing countries. Without effective measures to curb air pollution, some 300-400 million city dwellers in developing countries will become exposed to unhealthy and dangerous levels of air pollution by the end of the century. Administratively simple policies that encourage clean fuels and better traffic management are the most promising approach to controlling vehicle pollutant emissions in developing countries.

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This paper is the result of an informal collaboration between the Bank's Transport Division, Infrastructure and Urban Development Department, and the Industry and Environment Office of the United Nations Environmental Program on transport-related environmental issues. It is part of a larger effort in PRE to address environmental concerns in the Bank's operational work. Copies are available free from the World Bank, 1818 H Street NW, Washington DC 20433. Please contact Pamela Cook, room S10-063, extension 33462 (109 pages with tables).

Automotive air pollution, once largely a problem of developed countries, will spread to the developing countries in the next decade because of the rapid pace of urbanization and motorization there.

Rising incomes, combined with more desire for travel and personal mobility, will increase automobile ownership and bus transport in Asia, the Middle East, Eastern Europe, and parts of Africa. The need for fast, reliable distribution of goods, the increasing pace of containerization, and the selection of transport options on the basis of service rather than price alone will increase reliance on trucks for freight transport. As motor vehicle ownership approaches saturation levels in North America, Western Europe, and Japan, most growth will be in developing countries.

Automotive air pollution will be worst in big cities, particularly in Latin America and Asia — but also in Eastern Europe and the Middle East.

The growth in road transport is unlikely to be curbed in developing countries. Possible actions and countermeasures to control automotive air pollution encompass energy efficient and environmentally clean vehicles, clean fuels, traffic management, and a policy framework including regulatory, pricing, and taxation measures. The most promising approach in developing countries, however, is through clean fuels, sound traffic management, and administratively simple policy measures — such as a tax on leaded gasoline combined with a rebate on the use of ethers as octane boosters. This could encourage refineries to change their products and encourage users to substitute more appropriate vehicles. Owners of bus and taxi fleets could be given incentives to run vehicles on alternative fuels — such as LPG, GNG, or alcohol — and vehicle taxes and license fees could be designed to discourage the ownership and use of polluting vehicles.

Appropriate response measures should be based on sound information and cost-effective programs. They should be equitable in their impact on industry and consumers and introduced with enough lead time to give enterprises and consumers time to adjust — to reduce widespread evasion and gain public acceptance.

An emissions control policy should include an emissions inventory to assess the relative contribution of motor vehicles to overall pollution; emission standards based on a realistic evaluation of costs and expected compliance; identification of specific problems and appropriate countermeasures based on their cost-effectiveness; design of a policy framework to ensure success of control measures; an appropriate institutional set-up; and appropriate monitoring and evaluation.

Although there is a consensus on the need to reduce lead in gasoline and sulfur in diesel fuels, knowledge of the cost and effectiveness of various control measures is inadequate. More research is needed in the following areas:

- The characteristics and amount of automotive air pollution in urban areas in developing countries.

- The environmental characteristics of reformulated and substitute transportation fuels.

- The cost-effectiveness of various measures to control motor vehicle emissions.

- An evaluation of vehicle inspection and maintenance programs.

- The environmental management of urban buses and paratransit vehicles.

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SUMMARY AND RECOMMENDATIONS

The Scale of the Problem in Developing Countries

There is a direct relationship between transport energy consumption and pollutant emissions from transport sources. This relationship also offers the simplest approach to control transport emissions -- reduced consumption of fossil fuels and increased efficiency in transport energy use. There is another key relationship that is germane to the air pollution problem -- greater the concentration of population more severe is the exposure to air pollutants, as airsheds have a finite capacity to absorb emissions within acceptable air quality limits.

Developing countries together account for about 10% of the global automobile population, 20% of trucks and buses, and a little over 20% of the global transport energy consumption. In comparison, the United States alone consumes about 35% of the world's transport energy. The global distribution of pollutant emissions reflects the difference in the intensity of transport use between developing and industrialized countries. A comprehensive assessment of the scale and severity of transport-induced air pollution in developing countries is precluded by the complexity of contributory factors and the lack of reliable information. However, sufficient evidence is available to delineate the scale of the problem, identify the major issues, and formulate specific actions to mitigate the impacts of motor vehicle air pollution in developing countries.

It is estimated that transport sources in developing countries contribute about 4% to the global emissions of fossil carbon dioxide, versus 18% for industrialized countries. Except for lead and diesel particulates, the share of developing countries in the global emissions of harmful and toxic pollutants (e.g. CO, NOx, HC) by motor vehicles is no more than 30%, even allowing for higher emission rates for vehicles typically used in developing countries. The share of developing countries in emissions of lead and diesel particulates might be somewhat higher because of the poor quality of transport fuels and the more extensive use of diesel-powered vehicles.

These figures may lead one to conclude that air pollution from transport sources is primarily a problem of industrialized countries. While air pollution from motor vehicles may not be a serious concern in much of the developing world today, two factors point to a worsening of the situation over the next decade -- the rapid pace of urbanization and the even faster pace of motorization.

The world population is expected to increase from 4.8 billion in 1985 to over 6.0 billion in 2000. What is more significant is that almost one-half of the world's population will be living in urban areas by the end of this century. The growth in urbanization would be most pronounced in Africa, South Asia, and Latin America. The concentration of population in very large connurbations has led to some of the world's worst congestion and air pollution problems. Atmospheric pollutants commonly associated with motor vehicles (CO, NOx, SOx, particulate matter, and lead) often exceed the WHO Guidelines in many large cities in developing countries such as Mexico City, Sao Paulo, and Santiago in Latin America; Ibadan and Lagos in Africa; nearly all the megacities in Asia (notably Bangkok, Bombay, Jakarta, Manila and Seoul) and some of the second-order urban centers such as Medan in Indonesia and Klang in Malaysia; Ankara, Cairo, and Tehran in the Middle East; and most of the major urban centers in Eastern Europe, e.g., Belgrade, Budapest, Istanbul, and Sarajevo. Mexico City today is by far the most populous and the most polluted metropolis in the world.

The air pollution problem is sure to intensify with increasing urbanization in developing countries. In 1985, eight of the world's 12 urban agglomerations with a population of 10 million or more were in developing countries; their number will more than double (to 17 out of 23) by the year 2000, while an additional 18 metropolitan areas in developing countries will have populations between 5 and 10 million. Without effective measures to curb air pollution, some 300-400 million city dwellers in developing countries would become exposed to unhealthy and dangerous levels of air pollution by the turn of the century.

Motorization is inextricably linked to urbanization. The Latin America and Caribbean region, for example, is highly urbanized (70%) and is also the most motorized among developing regions, accounting for over 60% of the automobiles and about 30% of the buses and trucks in developing countries. In 1986, Brazil, Mexico, Argentina and Venezuela collectively had almost twice as many automobiles as all the developing countries in East and South Asia and sub-Saharan Africa.

Rising incomes combined with an increasing propensity for personal mobility and travel is likely to result in a pronounced increase in automobile ownership and bus transportation in much of Asia, Middle East, Eastern Europe and parts of Africa. The requirements for fast and reliable distribution of goods, the increasing pace of containerization, and the selection of transport options on basis of service rather than price alone will increase the reliance on trucks for freight transport. The global motor vehicle population crossed the half a billion mark in 1988 and is expected to double in the next 20 to 30 years. As motor vehicle ownership rates approach saturation levels in North America, Western Europe and Japan, much of the growth will be concentrated in developing countries. The motor vehicle growth trends of the late 1980's reflect what might be expected in the 1990's and beyond. Between 1984 and 1988, the annual growth in the motor vehicle fleet in the Republic of Korea was 30%, in Kenya 26%, China 14%, Brazil 11%, and Pakistan and Thailand 9% each, compared to about 2% in the United States and 3% in the United Kingdom.

As motorized travel in developing countries is concentrated in a few large cities, urban freight and passenger demand will increase at a rate well above the average growth in transport. Projections of emission levels from passenger transport for a sample of large cities in developing countries indicate a doubling or more of emissions by the year 2000, assuming modal shares remain unchanged from a 1980 base level. With the anticipated increase in automobile ownership and the heavy reliance on buses (often poorly-maintained) for public transportation, pollutant emissions from motor vehicles could well be higher by a wide margin. Extrapolating current trends to the year 2000, motor vehicle air pollution in many large cities in the developing world will be much worse than the projected levels for major cities in industrialized countries. The risk of exposure to dangerous levels of air pollution will be high given the dense concentrations of urban population and the life-styles in many developing countries.

How vulnerable cities in developing countries are to the adverse impacts of motor vehicle air pollution depends on a number of factors other than city size, population, and level of motorization. Altitude is an important factor; fuel combustion efficiency of motor vehicles declines with altitude resulting in increased pollutant emissions, particularly of carbon monoxide. Temperate zone cities located in valleys and basins surrounded by mountains commonly experience thermal inversions, which compress pollutants within a reduced ceiling height. Other meteorological factors include direction and speed of prevailing winds, amount of sunlight, precipitation, and humidity. Abundant sunshine is a critical factor in the formation of photochemical ozone and smog as in Mexico City.

The type of built-up environment also has a significant influence -- the canyon effect of tall buildings can cause elevated roadside levels of CO and NOx. On the other hand green spaces, forests and woodlands as well as urban precincts with prohibited or restricted motor vehicle use can help to mitigate the effects of air pollution. Concentration of stationary sources of pollution such as refineries, thermal power plants, and chemical industries within urban boundaries multiplies the level of air pollution and exposes a much larger population to health hazards. Motor vehicle emissions can aggravate the already elevated CO and SOx levels from domestic heating and cooking with coal, lignite, firewood, charcoal and animal dung, as in Seoul, Ankara, Warsaw, and numerous cities in South Asia and Sub-Saharan Africa. Diesel exhaust emissions also add materially to the existing particulate load from natural dust and mineral particles and ash emitted by industry (e.g., cement, steel, and coal-fired thermal power plants).

There are no straightforward generalized approaches to determine the contribution of land transport and particularly motor vehicles to pollutant emissions and ambient pollution concentrations. A case by case assessment is required based on detailed emissions inventories and air quality monitoring programs. But it can be stated with certainty that:

- the contribution of transport to air pollution in developing countries will increase substantially with the projected growth in motorization levels; and

- motor vehicle air pollution in developing countries is largely an urban problem confined mainly to very large cities with a high proportion of trip-making by buses, automobiles, motorcycles and other 2-3 wheeled vehicles such as autorickshaws.

Health and Welfare Effects

Health hazards commonly associated with air pollutants from motor vehicles are summarized in Exhibit A. There is, for example, a strong correlation between average blood lead levels and the lead content of gasoline. The fact that up to 70% of newborns in Mexico City have excessive lead levels at birth gives credibility to this link. Air pollutants also have pronounced welfare effects -- lead and heavy metals in motor vehicle exhaust are eventually deposited in soil and can be absorbed by vegetative growth. Diesel particulates absorb light and degrade visibility. They also cause soiling of city buildings and other materials. Nitrogen oxides have adverse effects on vegetation and on plastics and rubber. Photochemical oxidants, such as ozone, impair visibility and cause damage to thin-leaved vegetation and rubber products.

Beyond *localized health and welfare effects* in urban areas, NOx and SOx emissions from motor vehicles contribute to wind-borne *acid deposition* at the regional level. Acid rain is associated with extensive forest decline mainly at or above the cloud line in temperate zones, and contributes to corrosion of materials, structural damage to monuments and buildings, and impairment of sensitive aquatic ecosystems. Trace gases associated with motor vehicle use (CO_2, CFCs, HC, O_3, and N_2O) contribute to the *greenhouse effect* and the destruction of the protective ozone shield at the global level. The effects of acid deposition in Eastern Europe are well-documented. Other developing regions susceptible to acid deposition include southern China, parts of south-east Asia, south-western India, south-eastern Brazil, northern Venezuela, and southern Nigeria. By and large, the regional and global issues related to motor vehicle emissions are likely to be of lesser importance in developing countries than the more local urban concerns. It is primarily the more advanced and higher income developing countries (such as Brazil, Korea, Hungary, Yugoslavia) where air pollution from motor vehicles might reach a level to contribute significantly to regional or global environmental problems. These countries, fortunately, are likely to have the financial, technological, and administrative resources to address the problem.

Regional Priorities

The response to transport-induced air pollution in developing countries has to be differentiated by region and country. In the first instance, attention should focus on Latin America as it has the highest level of urbanization and motorization -- mostly the major urban

Exhibit A. Health effects of pollutants from motor vehicles

Pollutant	Health Effects
Carbon Monoxide	Interferes with absorption of oxygen by hemoglobin (red blood cells); impairs perception and thinking, slows reflexes, causes drowsiness, brings on angina, and can cause unconsciousness and death; it affects fetal growth in pregnant women and tissue development of young children. It has a synergistic action with other pollutants to promote morbidity in people with respiratory or circulatory problems; it is associated with less worker productivity and general discomfort.
Nitrogen Oxides	Can increase susceptibility to viral infections such as influenza; irritate the lungs and cause oedema, bronchitis and pneumonia; and result in increased sensitivity to dust and pollen in asthmatics. Most serious health effects are in combination with other air pollutants.
Hydrocarbons and other Volatile Organic Compounds	Low-molecular weight compounds cause unpleasant effects such as eye irritation, coughing and sneezing, drowsiness and symptoms akin to drunkenness; heavy-molecular weight compounds may have carcinogenic or mutagenic effects. Some hydrocarbons have a close affinity for diesel particulates and may contribute to lung disease.
Ozone (Precursors: HC and Nox)	Irritates mucous membranes of respiratory system causing coughing, choking, and impaired lung function; causes headaches and physical discomfort; reduces resistance to colds and pneumonia; can aggravate chronic heart disease, asthma, bronchitis, and emphysema.
Lead	Affects circulatory, reproductive, nervous, and kidney systems; suspected of causing hyperactivity and lowered learning ability in children; hazardous even after exposure ends. Lead is ingested through the lungs and the gastrointestinal tract.
Sulfur Dioxide	A harsh irritant, exacerbates asthma, bronchitis and emphysema; causes coughing and impaired lung functions.
Particulate Matter	Irritates mucous membranes and may initiate a variety of respiratory diseases; fine particles may cause cancer and exacerbate morbidity and mortality from respiratory dysfunctions. A strong correlation exists between suspended particulates and infant mortality in urban areas. Suspended particulates have the ability to adhere to carcinogens emitted by motor vehicles.
Toxic Substances	Suspected of causing cancer, reproductive problems, and birth defects. Benzene and asbestos are known carcinogens; aldehydes and ketones irritate the eyes, cause short-term respiratory and skin irritation and may be carcinogenic.

Source: OECD [1988a], French [1990], ECMT [1990], Walsh [1989c]
Note: There is growing evidence that the synergistic effects of these pollutants in combination may be far more serious than the adverse effects of individual pollutants. This is particularly the case where NOx and SOx coexist or occur in association with particulate matter.

centers in Brazil, Mexico, Argentina, Chile, and Venezuela and other cities with environmentally-sensitive locations (e.g. Bogota, La Paz, Guatemala City). East Asian cities with high levels of motorization such as Seoul, Bangkok, Manila, Kuala Lumpur, Jakarta also merit priority consideration, with initial efforts targetted at diesel-fueled vehicles and two-stroke engined vehicles (motorcycles and three-wheelers). Countermeasures would also be needed in the large urban centers of Eastern Europe and the Middle East (e.g. Ankara, Tehran, Budapest, Belgrade) but such measures should be balanced against other air pollution abatement priorities, for example those related to industry and domestic heating. Interventions in the megacities of Asia with low levels of motorization (e.g. Bombay, Calcutta, Beijing, Shanghai, Karachi) may be warranted because of the sheer number of vehicles and people involved, but other environmental issues such as water quality and solid waste disposal may deserve higher priority. Apart from a few major cities such as Cairo, Lagos, Ibadan and Nairobi, air pollution from motor vehicles is not likely to be a major environmental problem in much of Africa.

Vehicle Emission Control Strategies

Without excessive Government intervention and fairly draconian measures, it appears unlikely that the growth in road transportation could be curbed in developing countries. Fiscal and regulatory measures to restrict motor vehicle ownership, however, can impose a heavy economic burden. Reduction and control of pollutant emissions from motor vehicles, along with more efficient utilization of motor vehicles, should be the aim of air pollution abatement policies.

A wide range of options are available to combat air pollution from motor vehicles. Most of these options have been tried and tested over the past two decades in many developed and some developing countries. International experience in controlling air pollution can serve as an important guide for developing countries contemplating the implementation of air pollution countermeasures. A state of the art review of possible actions and countermeasures (Chapters VI to IX) suggests a four-pronged strategy encompassing:

- Energy efficient and clean vehicles: including use of lighter weight materials in manufacture of vehicles, and development of new power plants and aerodynamically efficient vehicle profiles; use of technological innovations to reduce emissions in new vehicles, such as exhaust treatment devices (catalysts and traps), fuel management systems, electronic engine controls, combustion chamber and engine modifications, and combustion advances (e.g., lean burn, thermal reactors, and exhaust gas recirculation); retrofitting on-the-road vehicles with emission control devices; and vehicle inspection and maintenance programs;

- clean fuels: in the first instance reduction or substitution of lead in gasoline and reduction of sulfur in diesel; then complete elimination of sulfur, aromatics, and heavy oils in diesel, and lead and other octane boosting additives such as benzene, toluene, and xylene in gasoline; combined with increased use of clean substitute fuels (oxygenated blends, GNG, LPG, and neat alcohols), particularly in captive vehicle fleets with high mileage and restricted range of operation, such as taxis and buses;

- traffic management: involving mostly traffic engineering and regulation measures aimed to improve traffic flow and manage transport demand. They range from simple traffic engineering interventions (coordinated signals, channelization, reversible lanes, one-way street pairs, and other traffic control devices) to traffic restraints (area licensing schemes, parking controls, exclusive pedestrian zones, vehicle bans, special bus and HOV lanes and so on), advanced traffic surveillance and control techniques, and provision of facilities and services to encourage modal shifts (such as sidewalks, bicycle lanes, busways, light and rapid rail transit, and commuter rail[1]); and

- a policy framework encompassing regulatory, pricing, and taxation mechanisms, and reinforced with effective enforcement, to encourage the use of clean vehicles and fuels, to restrict or ban the use of polluting vehicles and fuels, and to modify travel behavior and transport demand.

Apart from a handful of developing countries that have an indigenous motor vehicle industry, most of the developing world depends on the industrialized nations for supply of motor vehicles and accessories. The advances in vehicle emission control technology will invariably come from industrialized countries. The most developing countries can do is to adapt this technology to their circumstances by requiring that vehicle imports and locally-assembled vehicles meet specified fuel consumption and emission standards. As developing countries commonly have aging vehicle fleets with low vehicle turnover (10 - 15 years), it would take at least 10 - 15 years before the entire vehicle fleet could conform to a given set of standards. Scrapping non-conforming vehicles or retrofitting on-the-road vehicles with emission controls may not be an economical or technically feasible proposition in most developing countries.

The situation is further complicated by the poor standards of vehicle use and maintenance in developing countries. Overloading and poor vehicle maintenance, for example, are major causes of smoke and particulate emissions from diesel-powered vehicles. Without a rigorous

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[1] Air pollution from rail transport is quite small compared to road transport. In urban areas, trips by commuter rail and rapid or light rail transit account for a small share of urban travel and contribute a negligible amount to air pollution; non-motorized trips (bicycles, walking) are pollution free but can induce increased pollution from other modes by causing congestion.

inspection and maintenance (I/M) program, vehicle emission controls can be rendered ineffective because of misfuelling or tampering. In general the experience with vehicle inspection programs to promote road safety in developing countries is quite dismal and there is little to suggest that I/M programs for vehicle emission control would fare any better.

To a large extent, the use of sophisticated vehicle emission control technology will remain confined to the more technologically advanced and higher income developing countries (such as Brazil, Mexico, Korea, Taiwan, Yugoslavia). For others the most practical approach to reducing vehicle emissions and the only means to reduce CO_2 emissions would be to replace existing motor vehicles with highly fuel efficient vehicles (but without using octane boosters such as lead and aromatics in fuel). Such vehicles exist in prototype (gasoline mileage of 60 - 100 miles per gallon), and establishing an emissions standard for CO_2 (which does not exist at present) could hasten their production. For the U.S. vehicle fleet, a 20% reduction in fleet emissions of CO_2 would require a fuel efficiency of approximately 60 mpg by the year 2000 and 125 mpg by 2030, unless growth in vehicle miles of travel could be constrained.

A more promising approach to the control of vehicle emissions in developing countries, therefore, is via clean fuels, traffic management, and administratively simple policy measures (see Chapters VIII and IX). Policy instruments directed at changing vehicle use and fuel consumption patterns are not too difficult to formulate and implement. Motorized transport in developing countries, unless subsidized by the Government, is sensitive to fuel efficiency and prices, as clearly shown by the dieselization program implemented in the early 1980's in the Philippines. Appropriately designed taxes on vehicle ownership and use and on fuel consumption to internalize environmental externalities could significantly improve the environmental and efficiency characteristics of motor vehicles and the fuel they consume. For example, a graduated tax on gasoline in proportion to the amount of lead in it or a tax on diesel graduated by its sulfur or heavy oil content, combined with a rebate on the use of ethers as octane boosters could encourage refineries to change their product and encourage users to substitute more appropriate vehicles.

Where buses and taxis are a dominant mode of public transport, incentives could be provided to owners of taxi and bus fleets to convert their vehicles to run on alternative fuels such as LPG, GNG, or alcohol. Furthermore, vehicle taxes and license fees could be designed to discourage the ownership and use of polluting vehicles.

The starting point in the implementation of a program to control vehicle emissions is to establish an inventory of pollutant emissions by major sources, even if it is based on gross estimates and subjective assessments. Such an inventory serves as a baseline to assess the magnitude of the air pollution problem and the contribution made by mobile sources, particularly motor vehicles. Combined with an air quality monitoring program, an emissions inventory can help to target problem areas, define attainable emissions standards, identify cost-effective control strategies, and monitor their effectiveness. It must be emphasized that without an emission inventory and a reliable air quality monitoring program, it would prove very difficult to monitor the progress of a vehicle emissions control program irrespective of the merit of the control strategy and the technology adopted.

Implementing Vehicle Emission Control Programs

The introduction of vehicle emission controls imposes significant economic and social costs while the benefits are amorphous and often unproven, and the beneficiaries difficult to identify. The motor vehicle and oil industries may be required to develop or change their products while striving to maintain their competitiveness. In addition monitoring compliance with standards may add an extra administrative and financial burden on government resources. In many developing countries, the burden of adjustment for domestic oil refineries or small-scale motor vehicle manufacturing and assembly units may be so large that without Government support they might not be able to absorb the additional costs or compete with cheaper imports. In any event vehicles and fuels become more expensive and maintenance costs may also increase if inspection tests are to be passed.

To justify the added personal, business, and national costs, the environmental benefits from vehicle emission controls must be tangible and supported by incontrovertible evidence. Standards prescribed and regulated by the Government should therefore be equitable in terms of the impact on industry and consumers and should be introduced with sufficient lead time for enterprises and consumers to adjust to the new requirements. Where control measures are applied too quickly, they may have an initial shock effect but the control measures do not take root and result in widespread evasion. Measures that are not excessively costly and are preventive in nature are likely to gain the greatest public acceptance.

Devising an effective motor vehicle emission control program in developing countries is also hindered by institutional and technological constraints. Thus responses to the problem have followed a piece meal approach using mostly technological solutions borrowed from industrialized countries with little local experimentation and adaptation. Seldom have such responses been formulated in the context of a comprehensive policy framework to address overall air quality issues. In many instances, regulatory measures such as vehicle inspection and maintenance programs have been introduced, often with the support and assistance of external funding agencies, without an assessment of their expected impact in reducing emissions. Selection of appropriate response measures has been further complicated by the lack of reliable information on their cost-effectiveness in the developing country context. As a minimum, the implementation of a comprehensive vehicle emissions control program should be based on:

- an emissions inventory, even a crude one but based on a minimal level of physical tests and measurements, to assess the relative contribution of motor vehicles to overall pollutant emissions;

- emission standards that are derived from a realistic evaluation of costs and expected compliance by vehicle manufacturers and suppliers, oil refineries and fuel distributors, and users;

- identification of specific problem areas (for example diesel-fueled vehicles), selection of appropriate countermeasures based on their costs and likely effectiveness in the context of local technical and administrative capacities, and design of a policy framework -- regulations, enforcement, and fiscal measures -- to ensure the success of control measures;

- an appropriate institutional set-up -- legislation, organization, administrative procedures, funding sources -- to implement the selected measures;

- a monitoring and evaluation mechanism to assess progress and recommend adjustments in the control program.

Research Priorities

Establishing economically justified and socially acceptable motor vehicle pollution control measures is likely to prove problematic in developing countries, partly because the magnitude of the problem and its consequences are not well understood. Knowledge of the cost and effectiveness of various control measures is inadequate nor is it possible to establish the priority of reducing one pollutant relative to another, although there is a general consensus about the need to reduce lead in gasoline and sulfur in diesel fuels. Based on the findings of this study, further investigation is warranted in the following areas:

- <u>Role of motor vehicles in urban air pollution.</u> There is very little reliable data and empirical information on the nature and magnitude of air pollution caused by motor vehicles in developing countries. Emission inventories to assess the contribution of motor vehicles to air pollution are lacking, particularly data on vehicle kilometers of travel, speed, and vehicle emission rates. A cross-country assessment of air quality and vehicle emission standards is also needed to evaluate how these standards were determined and to propose a realistic framework for specifying standards. The proposed research would involve a cross-sectional analysis relating physical and transport characteristics to transport pollutant emissions for a representative sample of urban areas in developing countries. The main objective of this work would be to make a more accurate determination of the nature and scale of motor vehicle pollution in urban areas in developing countries and to identify typical urban and transport characteristics associated with elevated air pollution levels.

- Environmental characteristics of reformulated and substitute transportation fuels. Clean fuels offer the most promising approach to reducing harmful pollutant emissions from motor vehicles in developing countries. The proposed research would investigate the emission characteristics (from production to end-use) in motor vehicles of a variety of alternative transport fuels ranging from lead-free gasoline and low-sulfur diesel to LPG, CNG, alcohols, and various types of reformulated gasolines. The main objective would be to compare the end-use costs of these fuels and their cost-effectiveness in reducing pollutant emissions. A further objective of the research would be to document the experience of developing countries in using alternative fuels such as ethanol in Brazil and CNG/LPG in a number of Asian countries. The proposed study would also examine safety considerations in end-use and the institutional and other constraints affecting the distribution, marketing and acceptance of alternative fuels by users. The proposed research would be a useful complement to the earlier Bank work on alternative transport fuels from natural gas [Moreno and Bailey 1989].

- Cost effectiveness of measures to control motor vehicle emissions. This study has identified four key elements -- motor vehicles, fuel, traffic management, and fiscal instruments -- in terms of formulating a strategy to combat motor vehicle air pollution. A comprehensive framework for cost-effectiveness analysis of control measures related to these four elements is not available. Furthermore the control measures and their effects are not mutually exclusive; it is not clear whether the various control measures are mutually reinforcing or relative to the large array of pollutants emitted by motor vehicles. The first step will be to identify the cost of the control measures and their impact on the type and amount of pollutants emitted by motor vehicles. This information would be reduced to a common cost-effectiveness scale so as to provide a more systematic basis for formulating motor vehicle pollution abatement programs.

- Evaluation of vehicle inspection and maintenance programs. An effective vehicle inspection and maintenance (I/M) program is considered the basic cornerstone of vehicle pollution control, particularly where the emission control strategy relies on electronic engine control and exhaust treatment devices. The proposed research would review worldwide experience with I/M programs, their costs and actual benefits. The study would identify the institutional and technical characteristics of good I/M programs and provide recommendations for the planning, design, and operation of I/M programs in developing countries. The study would explore the possibility of private financing and management of I/M programs.

- Environmental management of urban buses and paratransit vehicles. Diesel-fueled vehicles are a major source of air pollutant in developing countries. The proposed study would investigate appropriate procedures for managing urban bus and paratransit fleets to reduce pollutant emissions. The research would establish standards for operation, maintenance and rehabilitation of urban buses and paratransit vehicles and specifically assess the cost-effectiveness of vehicle replacement, vehicle retrofit, and fuel conversion programs. A further objective of the study would be to identify policy instruments -- economic levers and regulations -- to make the proposed measures attractive to private bus and paratransit owners.

I. INTRODUCTION

Air pollution constitutes an ominous threat to human health and welfare. Its adverse effects are pervasive and may be disaggregated at three levels --*local*, confined to urban and industrial centers, *regional*, pertaining to transboundary transport of pollutants, and *global*, related to build up of greenhouse gases. These effects have been observed globally but the characteristics and scale of the air pollution problem in developing countries are not known; nor has the problem been researched and evaluated to the same extent as in industrialized countries. Air pollution, however, can no longer be regarded as a local or a regional issue as it has global repurcussions in terms of the greenhouse effect and depletion of the ozone layer. At an international conference in Montreal [Wald 1989], experts from 91 nations identified urban smog, acid rain, and global warming as the three most critical environmental concerns of the future.

Mobile sources, particularly motor vehicles, are a major cause of air pollution. In 1988, the global automobile population exceeded 400 million for the first time in history. Including commercial vehicles, over one half billion vehicles are now on the world's roads -- ten times more than in 1950. While motor vehicles have increased mobility and flexibility for millions of people, created jobs, and enhanced many aspects of the quality of life, the benefits have been at least partially offset by the air pollution generated by motor vehicles.

Motor vehicles emit carbon monoxide, hydrocarbons, nitrogen oxides, and other toxic substances such as fine particles and lead. Each of these pollutants has adverse effects on human health and welfare. The growing vehicle population is a major contributor to air pollution problems; initially, these problems were most apparent in city centers but over the last two decades lakes and streams and even remote forests have experienced significant degradation. As evidence of anthropogenic impacts on the upper atmosphere accumulates, there is increasing concern over the role of the motor vehicle in global warming.

In an effort to reduce air pollution from mobile sources, emission rates from automobiles and other motor vehicles have been regulated by legislation in some industrialized countries for over two decades. As air pollution problems have spread in the wake of rapid motorization in the developing world, similar regulatory measures have been adopted in some developing countries, notably Brazil, Mexico, Republic of Korea, and Taiwan. However, the reduction in emissions per kilometer driven achieved through such measures is being more than offset by the rapid increase in the number of vehicles.

Longer term measures to reduce and maintain vehicle pollution at acceptable levels will require a multifaceted strategy comprising the following elements:

- standards for new vehicles which gradually approach state-of-the-art technologies;
- improved fuel quality which includes at a minimum reduced lead, lower gasoline volatility, and lower sulfur and aromatics in diesel fuel;
- inspection and maintenance strategies which maximize the effectiveness of existing and future technologies in lowering emissions;
- comprehensive programs in land use management, transportation planning, and traffic management;
- promotion of less-polluting transport modes (rail transit, buses, bicycles) through market incentives and eventually physical restraints on motor vehicle use; and
- in the longer term, fundamentally new power plants and fuels.

This paper discusses the contribution of motorized land transport to air pollution problems, with special reference to developing countries. It assesses the adverse effects of air pollution from transport sources, primarily motor vehicles, and reviews possible approaches to bring about improvements. The paper identifies key issues and research needs related to land transport and air pollution in developing countries.

II. AIR POLLUTION CHARACTERISTICS

Air pollution characteristics of a particular region are determined by:

- the type and amount of pollutants in the air and their sources of emission, both mobile and stationary;
- the topographical and meteorological conditions affecting dispersion, concentration, and transboundary transport of pollutants;
- the mix of factor inputs and technology applied in economic activities, and their impact on types and levels of emissions;
- the scale of economic activity and population density to assess exposure to pollutants; and
- estimated dose-response functions for various pollutants to assess health and welfare impacts.

Types and Sources of Air Pollutants

Air pollutants are classified in two categories: *primary*, if emitted directly into the atmosphere by a stationary or mobile source; and *secondary*, if formed in the atmosphere as a result of physical and chemical processes such as hydrolysis, oxidation, and photochemistry. Among primary pollutants are carbon monoxide (CO), hydrocarbons (HC) and other volatile organic compounds (VOCs), oxides of sulphur (SOx), oxides of nitrogen (NOx), particulate matter including dust and smoke, and compounds of lead. Secondary pollutants include nitrogen dioxide, the entire class of photochemical oxidants (including ozone), and acidic depositions. Carbon dioxide has no direct adverse effects on human health or public welfare but its build-up contributes to the greenhouse effect. Other greenhouse gases, such as nitrous oxides, methane, chloroflurocarbons (CFC) and ozone also trap heat and thus contribute to global warming and potential climatic changes. It is estimated that different greenhouse gases presently contribute to overall global warming roughly in the following proportions:

Carbon dioxide	49 to 55%
Chlorofluorocarbons	14 to 25%
Methane	12 to 18%
Nitrous oxides and other gases	13 to 19%

There are natural as well as anthropogenic sources of air pollutant emissions. Among natural sources are forest fires and volcanoes, as well as swamps, oceans, lakes, vegetative matter, and insects. Anthropogenic sources include industrial processes, power generation, commercial and domestic fuel use such as wood or coal burning, solid waste disposal (for example, incineration), slash and burn cultivation practices, and transport. Automobiles are by far the predominant contributor to air pollution among mobile sources.

Factors Affecting Emission and Concentration of Pollutants

The emission rate refers to the amount of a particular type of pollutant discharged in the air. The magnitude of emissions depends on the number of emission sources, the diversity of source types, the nature and scale of activity at the polluting source, and the emission characteristics. The emission characteristics of motor vehicles, for example, worsen with altitude because of inefficient combustion.

The emitted pollutant gets dispersed, diluted or transformed in the atmosphere. The resultant amount of a pollutant in terms of its mass or volume per volume of air is the concentration of the pollutant in the air. The atmospheric concentration of a pollutant is dependent on the magnitude of emissions, topographical features and altitude, meteorological conditions, and physical and chemical mixing in the atmosphere. Concentration levels are normally associated with harmful effects of air pollution.

Meteorological Factors

Meteorology plays an important role in the transport of air pollutants from source to receptor (person, animal, vegetation, or materials). Meteorological factors, which affect the dilution, dispersion or transformation of the emitted air pollutant, are wind speed, wind direction, atmospheric stability, amount of sunlight or intensity of solar radiation, precipitation and temperature [Bellomo and Liff 1984]. These factors account for temporal (hourly, daily, seasonal) and spatial variation in the resultant concentration of emitted pollutants. **(Box 1)**

The tendency of the atmosphere to either enhance or suppress vertical motion affects the atmospheric concentrations of pollutants. A stable atmosphere tends to increase pollutant concentrations while an unstable atmosphere tends to minimize pollutant concentrations. Stability is related both to the vertical temperature structure, i.e. change in temperature with increasing height and wind shear, i.e. variation of horizontal wind speed and its direction with height [Bellomo and Liff 1984]. Thermal inversion occurs when the normal vertical temperature profile (i.e. decrease in temperature with increasing height) is reversed, with layers of cold air trapped by higher warm air. Pollutants collect in the cold air and their concentration increases as the normal vertical flow of air is impeded.

Box 1. Meteorology and Concentration of Air Pollutants - Some Examples

- Sea breezes (water to land) prevail along a lake or seacoast during the day while land breezes (land to water) are more common at night. This cycle can cause pollutant concentrations to recur in coastal areas. A similar "recycling" of pollutants can occur when winds flow out of a valley in day time, and into the valley at night.

- Radiation fog sometimes occurs under clear skies at night. The ground loses heat because of outgoing radiation and the air in contact with the ground cools down. If, in such cases, the air is sufficiently humid, the cooling will bring the air to saturation point and a fog will form. This is the mechanism which produces radiation fog and is quite common in valleys and basins surrounded by mountains. The top layer of the fog radiates essentially as a blackbody and cools down further, thus forming an inversion layer directly above the fog. The normal vertical temperature profile of the atmosphere is altered, leading to *thermal inversion* and a heavy concentration of air pollutants in the lower atmospheric layers.

- Rain often acts as a natural cleansing agent, flushing particles out of the air. Rain and humidity, however, can react with some pollutants such as NOx and SOx to yield acids or acidic depositions which corrode metals, destroy stone buildings and sculptures, and degrade water bodies and forests.

- Solar radiation plays an important part in the formation of secondary pollutants, such as ozone, and also affects atmospheric stability near ground. The temperature of a region is related to the intensity of the solar radiation and its distribution with latitude, altitude, and cloud cover.

Ceiling height (mixing height or depth) is the height above which relatively vigorous vertical mixing occurs. There are significant differences in seasonal averages for ceiling height in temperate locations. The ceiling height also varies during the course of the day. During the summer daylight hours the ceiling height may reach several thousand feet, while in winter, less heat is received from the sun and the ceiling height may be as low as a few hundred feet [Bellomo and Liff 1984]. If the same amount of pollutants were found in each situation, one would expect a much higher concentration of pollutants in winter since there is a smaller volume within which the pollutants can disperse.

Topography and Urban Spatial Form

The topography of a region can modify wind speed and direction, and can also influence temperature, principally through the combined effects of air drainage and radiation. As a result the atmospheric dispersion of pollutants is affected. In addition, air pollution problems are aggravated in some cities by the street canyon effect created by tall buildings, whereby vertical mixing of the atmospheric layers is prevented [OECD 1975]. The influence of topography and urban spatial form on air pollution is discussed in **Box 2** using Mexico City and Bombay as case examples.

Box 2. Effect of Topography and Urban Form on Air Pollution: The Examples of Mexico City and Bombay

Mexico City is the world's most populous and polluted metropolis, having the world's worst smog problem. The city's thin and usually still air is contaminated by 5.5 million tons of pollutants a year -- 80% from the nearly three million motor vehicles, 15% from its 35,000 industries, and the remaining 5% from natural sources including fecal dust [Branigan 1988]. The metropolitan area of Mexico City lies on the southeastern part of the Mexico City basin at an altitude of 2240 meters above sea level. The combustion of gasoline at this altitude is only 66 percent as efficient as at sea level. The high altitude contributes to increased HC, CO, and particulate emissions from vehicles due to less efficient fuel combustion, and hence aggravates the air pollution problem. The basin is surrounded by mountains, with a pattern of winds blowing from the northwest and the northeast concentrating pollutants in the southwest part of the city, and is characterized by abundant sunshine, one of the key elements of photochemical smog. Because of the city's elevation and the surrounding mountains, winds rarely blow with enough force to clear the polluted air. In addition, thermal inversions that trap pollution are common, particularly in winter months [Walsh 1989b].

Air pollution is a serious problem in major Indian cities, although coal used in India is low in sulphur content, the motor vehicle population is relatively small, and the monsoon acts as an effective scrubber to clean the air. **Bombay's** predicament is probably the worst if only because of the city's geographical location: a number of heavy industries are crowded on the eastern coast of the island, overlooking the mainland across the Thane creek. The prevailing winds blow across the island from west to east. Unlike other Indian cities, where a large fraction of pollutants are generated in the home from fuel used for cooking, transport and industrial activities contribute far more to the air pollution in Bombay. For example, transport accounts for 12% of SOx, 32% of particulate matter, 28% of NOx, 69% of CO, and 46% of hydrocarbon emissions. The contaminants emitted by the city's industries and motor vehicles affect the eastern suburbs and then waft inland across the creek, since the winds, particularly during the monsoon, are from the south-west. This makes the so-called twin city of New Bombay on the mainland the unwilling recipient of air pollution generated on the island [CSE 1982].

The examples of Mexico City and Bombay suggest that there are no straightforward generalized approaches to tackle the air pollution problem in a given region. The diversity of polluting activities, meteorological conditions, topographic features and urban spatial form makes the evaluation of the magnitude and causes of air pollution very complex and necessitates a case by case assessment to identify appropriate countermeasures. It is clear, however, that increased urbanization, industrialization, and motorization are likely to lead to a worsening of the air pollution problem in developing countries.

Emission Factors

The large number of emission sources and the diversity of source types make it impractical to conduct field measurements of emissions on a source-by-source basis at the point of release. Hence, a practical method of determining pollutant emissions in a given area is to make generalized estimates of emissions from each of the source types using typical emission factors. An emission factor is an average estimate of the rate at which a pollutant is released into the atmosphere as a result of some activity, such as industrial production or use of motor vehicles, divided by the level of the activity. Emission factors relate the quantity of pollutants emitted to some indicator such as production capacity, quantity of fuel burned, or kilometers traveled by motor vehicles.

Measurement and Assessment of Air Quality

Monitoring programs and methods of measuring air quality constitute the first step in determining the magnitude, scale, and characteristics of the air pollution problem. Methods for sampling and measuring air pollutants must be chosen carefully and must take into account the purpose of the measurement as well as the resources available. The criteria used for selection relate directly to the degree to which a method meets the following requirements--(a) whether it is precise and sufficiently accurate, (b) whether it is sensitive to changes specific to the local region, (c) whether it is economical in time, material and instrumentation, (d) whether it is already widely accepted, and (e) whether its result could be used for interlaboratory comparison studies. Some of the common methods used for air quality assessment and monitoring are described in the literature [WHO 1976].

Assessment of air quality consists essentially of examining the prevalent air quality against the established ambient air quality standards, if such standards exist. If the air quality exceeds the standards, it signifies deterioration in the air quality to the point that it can harm human health, or cause damage to human welfare. The measured data have to be studied and analysed statistically and inferences deduced from such analysis. Air quality measurement techniques vary for different pollutants. In addition to the selection of appropriate measurement techniques, attention should be given to the siting of the sampling apparatus and the timing and frequency of sampling. These should be chosen such that the air sampled is representative of the air breathed by the affected population.

Ambient Air Quality Standards

Establishment of standards for ambient air quality (against which the current condition and the effects of any countermeasures to reduce air pollution can be assessed) is necessary for protection against potential adverse effects. The process of setting standards usually occurs in two stages -- the scientific stage and the political and administrative stage.

The *scientific stage* requires:

- knowledge of the air pollution problem;
- evaluation of the risk i.e. probability and severity of potential adverse effects on health and public welfare; and
- assessment of the problem viz. the source of the problem and the number of sensitive populations exposed.

The *political and administrative stage* involves:

- determination of acceptable risk;
- determination of target populations and ecologies to be protected;
- consideration of human ecology, i.e. man in balance with his environment;
- choice of control technology, i.e. both formulation and selection of appropriate control techniques;
- legislation and standards considering existing legal framework and identification of legal strategies; and
- economics i.e. striking a balance between costs and benefits [de Koning 1987].

In the U.S. there are two sets of air quality standards: primary and secondary. The primary standards are designed to protect human health and hence take into account the population groups that are sensitive to air pollutants, such as the elderly and children. The secondary standards are established to protect general human and public welfare. Human and public welfare includes effects on soil, water, crops, vegetation, man-made materials, animals, wildlife, atmospheric visibility, and climate; damage to and deterioration of property; hazards to transportation; and effects on economic values and on personal comfort and well-being [Cohn and McVoy 1982].

The ambient air quality standards of selected countries as well as those set by the World Health Organisation (WHO) are summarized in Table 1. China has detailed standards differentiated by regions; the allowable contaminants in congested and polluted cities being almost three times as high as those in virgin and conservation areas. However, it is not clear how these standards were obtained. Brazilian and Indonesian standards are quite similar to the U.S. standards but it is not known whether they reflect the socio-economic conditions in the respective countries.

Table 1. Selected ambient air quality standards

Pollutant	Country	Averaging Time	Standard	Remarks
Particulate Matter	U.S.A a1)	AGM d)	50-65 ug/cu. m j1)	Primary n)
		AGM d)	70-90 ug/cu. m j2)	Secondary o)
		24 hrs e)	150-250 ug/cu. m j1)	Primary n)
	Brazil a)	AGM d)	80 ug/cu. m	
		24 hrs e)	240 ug/cu. m	
	Indonesia a)	24 hrs e)	260 ug/cu. m k)	
	China a)	Daily Mean f)	150 ug/cu. m	First Class p)
		Daily Mean f)	300 ug/cu. m	Second Class q)
		Daily Mean f)	500 ug/cu. m	Third Class r)
		Not Once g)	300 ug/cu. m	First Class p)
		Not Once g)	1000 ug/cu. m	Second Class q)
		Not Once g)	1500 ug/cu. m	Third Class r)
		Daily Mean f)	50 ug/cu. m l)	First Class p)
		Daily Mean f)	150 ug/cu. m l)	Second Class q)
		Daily Mean f)	250 ug/cu. m l)	Third Class r)
		Not Once g)	150 ug/cu. m l)	First Class p)
		Not Once g)	500 ug/cu. m l)	Second Class q)
		Not Once g)	700 ug/cu. m l)	Third Class r)
	WHO Guidelines b)	Annual Mean	40-60 ug/cu. m m)	
		98 percentile h)	100-150 ug/cu.m m)	
		Annual Mean	60-90 ug/cu. m	
		98 percentile h)	150-230 ug/cu. m	
Sulfur Oxides	USA a)	AAM i)	80 ug/cu. m (0.03 ppm)	Primary n)
		24 hrs	365 ug/cu. m (0.14 ppm)	Primary n)
		3 hrs	1300 ug/cu. m (0.5 ppm)	Secondary o)
	Brazil a)	AAM i)	80 ug/cu. m (0.03 ppm)	
		24 hrs d)	365 ug/cu. m (0.14 ppm)	
	Indonesia a)	24 hrs	260 ug/cu. m (0.10 ppm)	
	China a)	ADM j)	200 ug/cu. m	First Class p)
		ADM j)	600 ug/cu. m	Second Class q)
		ADM j)	100 ug/cu. m	Third Class r)
		Daily Mean f)	50 ug/cu. m	First Class p)
		Daily Mean f)	150 ug/cu. m	Second Class q)
		Daily Mean f)	250 ug/cu. m	Third Class r)
		Not Once g)	150 ug/cu. m	First Class p)
		Not Once g)	500 ug/cu. m	Second Class q)
		Not Once g)	700 ug/cu. m	Third Class r)
	Mexico c)	Daily Mean	0.13 ppm	
	WHO Guidelines b)	Annual Mean	40-60 ug/cu. m	
		98 percentile h)	100-150 ug/cu. m	
		10 min	500 ug/cu. m	
		1 hr	350 ug/cu.m	
Carbon monoxide	USA & Brazil a)	8 hrs d)	10 mg/cu. m (9 ppm)	Primary & Secondary n) o)
		1 hr d)	40 mg/cu. m (35 ppm)	Primary & Secondary n) o)
	Indonesia a)	8 hrs	22.6 mg/cu. m(20 ppm)	
	China a)	Daily Mean f)	4 mg/cu. m	First Class p)
		Daily Mean f)	4 mg/cu. m	Second Class q)
		Daily Mean f)	6 mg/cu. m	Third Class r)
		Not Once g)	10 mg/cu. m	First Class p)
		Not Once g)	10 mg/cu. m	Second Class q)
		Not Once g)	20 mg/cu. m	Third Class r)
	Mexico c)	8 hr	13 ppm	
	WHO Guidelines b)	15 min	100 mg/cu. m	
		30 min	60 mg/cu. m	
		1 hr	30 mg/cu. m	
		8 hr	10 mg/cu. m	

Table 1. Selected ambient air quality standards (continued)

Pollutant	Country	Averaging Time	Standard	Remarks
Nitrogen oxides	USA a)	AAM i)	100 ug/cu. m (0.05 ppm)	Primary n)
	Indonesia a)	24 hr	92.5 ug/cu. m (0.05 ppm)	
	China a)	Daily Mean f)	50 ug/cu. m	First Class p)
		Daily Mean f)	100 ug/cu. m	Second Class q)
		Daily Mean f)	150 ug/cu. m	Third Class r)
		Not Once g)	100 ug/cu. m	First Class p)
		Not Once g)	150 ug/cu. m	Second Class q)
		Not Once g)	300 ug/cu. m	Third Class r)
	Mexico c)	Hourly Max.	0.21 ppm	
	WHO Guidelines b)	1 hr	400 ug/cu. m	
		24 hr	150 ug/cu. m	
Hydrocarbon (nonmethane)	USA a)	3 hr (6 a.m. to 9 a.m.)	160 ug/cu. m (0.24 ppm)	Primary & Secondary n) o)
	Mexico c)	Hourly Max.	0.24 ppm	
Lead	USA a)	Quarterly Avg.	1.5 ug/cu. m	Primary & Secondary n) o)
	Indonesia a)	24 hr	60 ug/cu. m	
	WHO Guidelines b)	Annual mean	0.5-1.0 ug/cu. m	
Photochemical Oxidants (Ozone)	USA a)	1 hr d)	235 ug/cu. m (0.12 ppm)	Primary & Secondary n) o)
	Brazil a)	1 hr	160 ug/cu. m	
	Indonesia a)	1 hr	200 ug/cu. m (0.10 ppm)	
	China a)	Hourly mean	120 ug/cu. m	First Class p)
		Hourly mean	160 ug/cu. m	Second Class q)
		Hourly mean	200 ug/cu. m	Third Class r)
	Mexico c)	Hourly max.	0.11 ppm	
	WHO Guidelines b)	1 hr	150-200 ug/cu. m	
		8 hr	100-120 ug/cu. m	

a1) Source: [JAPCA 1984]
a) Source: [Sinha et al. 1989]
b) Source: [WHO 1987, UNEP & WHO 1988]
c) Source: [Walsh 1989b]
d) Annual Geometric Mean
e) Not to be exceeded more than once a year
f) the mean concentration limit not to be exceeded by any day mean
g) the concentration limit not to be exceeded by any once of sampling and determination
h) 98% of the daily averages must fall below this concentration
i) Annual Arithmetic Mean
j) Annual Daily Mean
j1) This standard applies to PM10 (particles that are 10 micrometers or smaller) and is used as a primary health standard.
j2) Applies to total suspended particles (TSP)
k) standard for dust
l) standard for fly dust
m) standard for black smoke
n) standard designed to protect human health
o) standard designed to protect general public welfare such as effects on soil, water, crops, vegetation, man-made materials, etc.
p) at natural conservation areas, secnic spots, historical sites, and convalescent places
q) at residential areas, mixed areas of business cultural areas
r) cities, towns and industrial areas having serious air pollution problems

Note: 1. ug = $1x10^{-6}$gm; mg = 1 x 10^{-3}gm; ppm = parts per million; cu.m = cubic meter.
2. mg/cu.m = ppm * MW * 40.91, where MW = molecular weight; (H=1, C=12, N=14, O=16, S=32)

Trends in Emissions and Ambient Concentration of Pollutants

Table 2 shows trends in the overall emissions of SOx, particulate matter, NOx, CO, and lead in selected countries. Based on this sample of countries, there has been a decreasing trend in overall emissions of air pollutants in industrialized countries during the period 1973 to 1984, whereas in developing countries there has been an increasing trend. The share of transport in overall emisions is not well-documented, particularly in developing countries.

Air quality in major urban areas around the world has been monitored by the Global Environmental Monitoring System (GEMS/Air), which operates worldwide networks to monitor air quality under the auspices of World Health Organization (WHO) and United Nations Environmental Program (UNEP). The concentration levels in 1985 and trends from 1973 to 1988 in selected cities are shown in Table 3. There has been a decreasing trend in the concentration of sulfur oxides and particulate matter in many cities in industrialized countries, but urban areas in developing countries have experienced sharp increases in these contaminants. For example, New Delhi experienced a 20% increase in the concentration level of sulfur oxides from 1973 to 1985. Except for Singapore the concentration levels of NO_2 increased in all cities shown in Table 3, in both industrialized and developing countries.

The concentration levels of SOx in many cities such as Beijing, Sao Paulo, Rio de Janeiro, and Seoul exceeded the WHO guidelines of 40 to 60 ug/cu. m, in 1985. The particulate level in almost all the developing cities shown in the Table 3 exceeded the WHO guideline of 60 to 90 ug/cu. m. Although the average levels of NO_2 in most cities in developing countries were below the US national air quality standard of 100 ug/cu.m, in Sao Paulo this limit was exceeded in some years. Peak concentrations of NO_2, however, are more significant from a health standpoint than annual mean values, as intermittent exposure to high concentrations contributes more to toxicity of NO_2 than the total dose. Data on CO levels in cities in developing countries are generally insufficient; Bangkok had a level which is about one-half of the WHO guideline of 10 mg/cu. m. while ambient levels in Sao Paulo were almost twice as high. Lead level in Singapore was very close to the maximum limit of the WHO guidelines.

Table 2. Trends in emissions in selected countries (1000 tons per year)

Pollutant	Country	1973-75	1976-78	1979-81	1982-84
SOx	USA	25600	25670	23330	21100
	UK	5430	4990	4740	3750
	Japan	2620	1680	1640	1610
	China	..	..	14210	12920
	Hong Kong	160	200	220	240
	India	1610	1890	..	..
	Poland	2080	..	2600	3700
	Portugal	180	195	260	305
	Thailand	..	..	120 a)	310
	Turkey	..	710	..	..
Particulate Matter	USA	10400	9330	8470	6900
	UK	450	360	300	230
	China b)	..	..	16200	13740
	Hong Kong	15	20	20	15
	Poland	2230	..	2120	3350
	Portugal	75	90	120	..
	Thailand	..	..	40 a)	230
	Turkey	..	140	..	..
NOx	USA	19200	20870	20670	19500
	UK	1870	1890	1900	1770
	Japan	1800	1550	1340	1420
	China	..	..	4400	4130
	Hong Kong	40	45	50	80
	Poland	90	..	..	1770
	Portugal	105	170	210	190
	Thailand	..	..	30 a)	130
	Turkey	..	380	..	..
CO	USA	81200	83100	76030	69230
	UK	4820	4920	5090	5180
	Hong Kong	110	120	165	180
	Poland	590	..	..	3300
	Portugal	460	490	525	..
	Thailand	..	..	120 a)	..
	Turkey	..	..	3710	..
Lead	USA	147	141	78	47
	UK c)	7.9	7.4	7.2	7.0
	Mexico	..	..	19.6	8.4
	Thailand	..	..	..	1 to 5

a) for Bangkok only
b) fossil fuel combustion only
c) gasoline fueled road vehicles only

Source: [UNEP & WHO 1984, UNEP & WHO 1988]

Table 3. Ambient pollution levels in selected cities

Pollutant	Cities	Trend in 1973-1985 in %	Concentration Level 1985
SOx a)	New York	- 6	50
	London	- 7	55
	Tokyo	- 6	35
	Bangkok	..	18
	Kuala Lumpur	..	22
	Lisbon	..	25
	Bombay	..	30
	New Delhi	+ 20	40
	Hong Kong	+ 8	45
	Shanghai	..	50
	Santiago	0	60 c)
	Manila	..	65 c)
	Beijing	..	75 c)
	Sao Paulo	- 10	90 c)
	Rio de Janeiro	..	100 c)
	Seoul	..	105 c)
Particulate Matter a)	New York	- 3	61
	Tokyo	- 1	60
	Accra	..	100 d)
	Rio de Janeiro	..	101 d)
	Kuala Lumpur	..	105 d)
	Bombay	..	110 d)
	Bangkok	+ 13	110 d)
	Shanghai	..	111 d)
	Jakarta	- 3	115 d)
	Calcutta	0	130 d)
	Beijing	..	130 d)
	New Delhi	- 3	131 d)
NO_2 a)	New York	+ 2.5	65
	London	+ 7	61
	Bombay	+ 3	20
	Bogota	..	25
	New Delhi	+ 2	32
	Hong Kong	..	43
	Singapore	- 4	46
	Lisbon	+ 4	47
	Sao Paulo	+ 1	75
CO b)	New York	..	12 e)
	Los Angeles	..	13 e)
	Sao Paulo	..	19 e)
	Bangkok	..	5
Lead a)	Stockholm	..	1.1 f)
	Amsterdam	..	0.3
	Frankfurt	..	0.4
	Hong Kong	..	0.14
	Sao Paulo	..	0.22
	Bangkok	..	0.3
	Singapore	..	0.9

a) annual average concentration level in ug/cu. m for 1980-1984
b) maximum 8-hourly concentration level in mg/cu. m for 1980-84
c) exceeds WHO guidelines of 40 to 60 ug/cu. m
d) exceeds WHO guidelines of 60 to 90 ug/cu. m
e) exceeds WHO guidelines of 10 mg/cu. m
f) exceeds WHO guidelines of 0.5 to 1.0 ug/cu. m
Source: [UNEP & WHO 1984, UNEP & WHO 1988]

III. THE ROLE OF MOTOR VEHICLES IN AIR POLLUTION

Motor vehicles cause more air pollution than any other single human activity. The primary pollutants emitted by motor vehicles include hydrocarbons (HC) and nitrogen oxides (NOx), the precursors to ground level ozone, and carbon monoxide (CO).

HC, NOx, and CO in OECD Countries

Europe -- Motor vehicles are the dominant source of these air pollutants in Europe. Road transportation is responsible for 50-60% of NOx emissions. Mobile sources, mainly road traffic, also produce around 50% of anthropogenic VOC emissions, therefore constituting the largest manmade VOC source category in all European OECD countries [OECD 1988a].

The key role of motor vehicles was reinforced in the EEC's Technical Annex to the NOx Protocol to The 1979 Convention on Long Range Transboundary Air Pollution, (signed in November 1988), which states:

> "Road transport is a major source of anthropogenic NOx emissions in many Commission countries, contributing between 40% and 80% of total national emissions. Typically, petrol-fuelled vehicles contribute two-thirds of total road transport NOx emissions."

United States -- In 1985, the U.S. Environmental Protection Agency (EPA) estimated that transport sources were responsible for 70% of CO, 45% of NOx, and 34% of HC emissions [USEPA 1987a]. If evaporative "running losses" are added, the HC contribution from vehicles may be substantially higher [USEPA 1988].

OECD Countries -- Beyond the US and Europe, for OECD countries as a whole, motor vehicles are the dominant source of carbon monoxide, oxides of nitrogen, and hydrocarbons [OECD 1987], as shown in Table 4.

HC, NOx, and CO in Developing Countries

While not as well documented, it is increasingly clear that motor vehicles are emerging as a major source of air pollution in the developing world, particularly in the major metropolitan areas. By way of examples, a few countries are considered below.

Table 4. Motor vehicle share of OECD pollutant emissions, 1980 ('000 tons)

Pollutant	Total Emissions	Motor Vehicle Share
HC	33,869	13,239 (39%)
NOx	36,019	17,012 (47%)
CO	119,148	78,227 (66%)

India

The motor vehicle related air pollution in India is already serious and worsening. While the problem of diesel smoke and particulates is the most apparent, carbon monoxide, nitrogen oxide, hydrocarbon, lead, and ozone levels exceed internationally accepted levels in several cities. The lead content in gasoline is very high and is the major source of lead contaminants in the air. The problem continues to worsen as the vehicle population, particularly motorcycles and three-wheeled autorickshaws, continues to grow and age; vehicles once introduced into use remain active much longer than in industrialized countries. The adverse consequences of air pollution are especially severe because the life style and climate are such that public exposure to high pollution levels is very high.

Thailand

Urban air pollution in Thailand, especially with regard to diesel particulates, is already quite acute and is reaching chronic levels, with the overall vehicle population increasing at a rate of 10% per annum. Carbon monoxide and ambient lead levels periodically exceed internationally accepted limits, although they are apparently stabilizing. Because of meteorological conditions, the ozone problem is not yet serious.

The emission characteristics of the gasoline-powered vehicle fleet is gradually improving as there is a tendency, when serious engine problems occur, to replace the old engine with a used one imported from Japan. The used engine is less polluting and costs about US$300, considerably less than the cost of a typical engine overhaul. In addition, taxicabs and tricycles have been largely converted to run on Liquified Petroleum Gas (LPG) which emits less CO (and no lead) compared to gasoline. As diesel fuel is about 25% cheaper than gasoline, its use is encouraged. So it is not surprising that diesel vehicles continue to increase rapidly, although the diesel fuel quality is believed to be poor.

The adverse consequences of air pollution are particularly severe in Bangkok because public exposure to elevated pollution levels is quite high. Smoke from diesel vehicles is palpable on the streets of Bangkok; it smothers pedestrians and motorists alike and occasionally creates a safety hazard in traffic, literally blinding motorists in a black fog.

Indonesia

The combination of densely congested traffic, poor vehicle maintenance, and large numbers of diesel vehicles and two-stroke engined (smoky) motorcycles has contributed to elevated air pollution levels in Jakarta and other large urban centers. While air quality data are not well documented, the carbon monoxide and ambient lead levels exceed internationally accepted standards.

Philippines

The air pollution problem in Manila is quite serious. A large proportion of the vehicles is diesel-fueled and most of these, especially the "Jeepneys", emit excessive smoke. Owing to a lack of instrumentation, actual air quality data do not exist at present. However, it appears, that particulate, lead, carbon monoxide and possibly ozone levels exceed internationally accepted standards. Based on an analysis of fuel consumption, motor vehicles are estimated to account for approximately 50% of particulates, 99% of carbon monoxide, 90% of hydrocarbons, and 5% of sulfur dioxide. Fuel quality is very poor as reflected by the sulfur content of as much as 1.0% by weight (compared to 0.3% in the US) and a lead content of up to 1.16 grams per liter (compared to 0.15 in the European Community).

Singapore

The motor vehicle related air pollution in Singapore is primarily related to diesel particulates, though the problem is clearly not as severe as in many other Asian cities. There is also concern with carbon monoxide and ambient lead levels, which exceed internationally accepted standards.

The overall vehicle population continues to increase with rising incomes (about 25% more vehicles were on the road in 1989 compared to 1980). The major problems are related to sub-standard maintenance of vehicles and the relatively high density of vehicles throughout the day in the city center. Authorities are concerned because surveys conducted by the Pollution Control Department in 1989 showed that the percentage of smoky vehicles on the roads had increased from 7% to 10% over a six-month period. Of the smoky vehicles stopped by enforcement officers on the roads, more than 87% were found to emit excessive black smoke as compared to 70% the previous year.

Mexico

The combination of high altitude, special meteorological conditions, and a rapid rate of motorization have transformed Greater Mexico City, the world's largest metropolis (with a population of 19 million) into a virtual 'gas chamber'. The number of automobiles in Mexico

City has grown dramatically in the past several decades; there were approximately 48,000 cars in 1940, 680,000 in 1970, 1.1 million in 1975 and 2.6 million in 1989. The Mexican government estimates that fewer than half of these cars are fitted with even modest pollution control devices. Virtually none are equipped with state-of-the-art exhaust treatment systems. Only recently has unleaded gasoline become available. The lead content of leaded gasoline was lowered during 1986 and 1987, but there are indications that it has increased since then [Walsh 1989b].

In addition, more than 40% of the cars are over 12 years old, and of these, most have engines in need of major repairs. The degree to which the existing vehicles are in need of maintenance is reflected by the results of the "voluntary" inspection and maintenance program run by the Federal District during 1986 through 1988. Of the over 600,000 vehicles tested (209,638 in 1986, 313,720 in 1987 and 80,405 in the first four months of 1988), about 70% failed the gasoline vehicle standards and 85% failed the diesel standards.

Although there are not as many commercial vehicles as automobiles in Mexico City, they are considered a serious pollution hazard because of the high levels of fine particles produced by diesel engines and the direct public exposure to these emissions. The contribution of mobile and stationary sources to emissions of primary air pollutants in Mexico City is summarized in Table 5; motor vehicles contribute the preponderant part of CO, HC, and NOx emissions.

Table 5. Source distribution of air pollutant emissions in Mexico City, 1987

Pollutant	**Total Emissions** (tons/year)	Distribution by Source (%)						
		Motor Vehicles					Industry	Natural Sources
		Cars	Taxis	Buses	Trucks	Total		
CO	3,549,000	54	13	1	31	99	1	0
HC	335,000	61	14	1	13	89	11	0
NOx	270,000	34	8	3	19	64	36	0
SO2	445,000	0	0	0	2	2	98	0
Particulates	428,000	0	0	1	8	9	30	61

Source: [Joumard 1989]

Despite the rapid growth in motor vehicles in Greater Mexico City over the last several decades, the number of cars licensed in the Federal District (city center) has stabilized since 1980, and the number of trucks and buses seems to have decreased slightly. This is probably to be expected at the center of a very large conurbation and follows the trend in other large cities, where a stage is reached after which the increase in vehicle population takes place largely in surrounding districts. In the metropolitan zone, outside the Federal District, the vehicle population has continued to increase rapidly, with the population of private cars and light vehicles almost doubling during the period 1980 to 1990, and the number of buses increasing by over 20%. These figures emphasize the need for a comprehensive plan to improve air quality in the entire metropolitan zone of Mexico City, with close and effective collaboration among the various metropolitan authorities.

In 1989 a comprehensive program to combat atmospheric pollution in Mexico City Metropolitan Area was established by presidential order, including:

- Rationalization and reorganization of the urban transport systems;
- Improvement of fuel quality;
- Introduction of alternative fuels;
- Installation of emission control systems for vehicles and industries; and
- Ecological recovery of deteriorated areas.

The program has attracted considerable international support and participation. The 1989-1990 winter season included a number of emergency measures: addition of oxygenated compounds to gasoline, a one-day ban on circulation of private automobiles (effectively removing about 20% of the private vehicle fleet from circulation) each weekday, and mandatory exhaust emission vehicle inspection. With these measures, the emissions have been reduced by an estimated 23% or by more than 2000 tons per day, while improvements in ambient air quality (CO, ozone) have ranged from 10-15%.

IV. ADVERSE IMPACTS OF AIR POLLUTION

Certain adverse effects of air pollution, such as odor, may be immediately apparent and easily traceable to transportation sources. Other effects (such as high lead levels at birth or the link between NOx emissions from automobiles and respiratory tract irritation) may occur in the short term but the precise contribution of vehicle emissions to these is not always clear. Still other effects may take long periods to become apparent, and drawing a causal link to vehicle emissions becomes difficult, complicated often by lack of complete scientific understanding of the process, as is the case with many carcinogens.

Health and Welfare Effects of Major Pollutants

Vehicle emissions of hydrocarbons, nitrogen oxides, and carbon monoxide cause or contribute to adverse health effects in humans; in addition these emissions are harmful to terrestrial and aquatic ecosystems, and contribute to crop damage and other welfare losses.

Tropospheric Ozone (O_3)

One of the most widespread auto-related pollutants is ozone, the principal ingredient in urban smog. Ozone, a photochemical oxidant, results from the reaction of nitrogen oxides and hydrocarbons in the presence of sunlight. Exposure to elevated levels of ozone can cause eye irritation, cough and chest discomfort, headaches, upper respiratory illness, increased asthma attacks, and reduced pulmonary function. Exposure to ozone even at levels below current air quality standards has been known to cause adverse effects among young children.

Based on the health effects of ozone, considered in relation to its high natural background level, the World Health Organization (WHO) in its air quality guidelines for Europe has recommended a 1-hour guideline in the range of 150-200 ug/m3 (0.076-0.1 ppm). To lessen the potential for acute and chronic adverse effects and to provide an additional margin of protection, an 8-hour guideline for exposure to ozone of 100-120 ug/cu. m (0.05-0.06 ppm) is recommended [WHO 1987].

These levels are frequently exceeded in Europe and North America. For example, in conjunction with a severe heat wave in the summer of 1988, the Northeast United States experienced worse levels of ozone in 1988 than in several preceding years. Similar problems occurred in Athens in mid- summer 1988, with hundreds hospitalized by the combination of heat and smog. Ozone levels in many parts of Europe frequently exceed internationally accepted health and environmental guidelines for short- and long-term ozone exposure, such as those recommended by WHO.

Photochemical pollutants inflict damage on forest ecosystems and seriously impact the growth of certain crops such as corn, wheat and soybeans [Mackensie and El-Ashry 1988] and thin-leaved vegetables. Visible symptoms of "Waldsterben", or forest decline, first appeared in Europe in 1979-80 and within four years the symptoms had spread over large areas of the continent. It is associated with a high frequency of damage from secondary stress factors such as insects, needle, and root fungi, and climatic stress such as frost, wind, and snow damage. It now affects virtually every tree species in Europe including the four most important conifers (spruce, fir, pine, larch) and six angiosperms (beech, birch, oak, ash, maple, alder). According to one analysis, damage in Western European countries is worst in the Federal Republic of Germany (FRG), where 55% of the trees are injured, followed by Switzerland, where 33% of the stands are affected by "Waldsterben" [Schutt and Cowling 1985]. The situation in Eastern Europe is not well documented but conceivably could be much worse.

There are reliable reports of extensive ozone damage to yellow pine, white pine, red spruce, fraser fir, sugar and yellow maple, beech, birch, red maple and a wide variety of other tree species throughout eastern North America [AFA 1987, Bruck 1987, Knight 1987, Zedaker et al. 1987, Wang and Borman 1986]. Field and other experiments have confirmed that levels of ozone commonly encountered throughout the eastern United States can cause significant reductions in growth and net photosynthesis [Wang and Borman 1986]. One study showed that in areas where known anthropogenic air pollution takes place, trees from polluted areas have been significantly more suppressed in terms of their growth rates over the past 25-30 years as compared to non-pollutant sites, and surface soils have in fact accumulated lead, often an order of magnitude above that of soils in non-polluted regions [Reich and Amundson 1985].

Photochemical oxidants accelerate the deterioration processes of plastics and rubber and significantly contribute to visibility degradation due to the formulation of aerosols in the light scattering range [OECD 1988a].

Tropospheric ozone is a greenhouse gas. Ozone absorbs infrared radiation and increased ozone concentrations in the troposphere may eventually contribute to global warming and climate modification.

Carbon Monoxide

Over 90% of the carbon monoxide in many urban areas is emitted by motor vehicles. Because the affinity of hemoglobin in the blood is 200 times greater for carbon monoxide than for oxygen, carbon monoxide hinders oxygen transport from blood into the tissues. Therefore, more blood must be pumped to deliver the same amount of oxygen. Scientific studies in humans and animals have demonstrated that subjects with weak hearts are placed under additional strain by the presence of excess CO in the blood. For example, an assessment by the Health Effects Institute indicated that low levels of COHb produce significant effects on cardiac function during exercise in subjects with coronary artery disease [Allred et al. 1989]. In addition, fetuses, sickle cell anemics and young children may also be especially susceptible to low exposure levels of CO.

There is also some evidence that CO may contribute to elevated levels of tropospheric ozone [Walsh 1990].

Oxides of Nitrogen (NOx)

NOx emissions from vehicles and other sources produce a variety of adverse health and environmental effects. They also react chemically with other pollutants to form ozone and other toxic pollutants. Next to sulfur dioxide, NOx emissions are the most prominent pollutant contributing to acidic deposition.

Exposure to nitrogen dioxide (NO_2) emissions is linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics, and decreased pulmonary function [Lindvall 1982]. Short term exposures to NO_2 have resulted in a wide ranging group of respiratory problems in school children (cough, runny nose and sore throat are among the most common) as well as increased sensitivity to urban dust and pollen by asthmatics [Orehek et al. 1976, Mostardi et al. 1981].

Oxides of nitrogen have also been shown to affect vegetation adversely. Some scientists believe that NOx is a significant contributor to the dying forests throughout central Europe [Whetstone and Rosencranz 1983]. This adverse effect is even more pronounced when nitrogen dioxide and sulfur dioxide occur simultaneously. Acid deposition results from the chemical transformation and airborne transport of sulfur dioxide and nitrogen oxides and is associated with corrosion of materials, structural damage to buildings and monuments, and impairment of sensitive aquatic ecosystems. Increasing acidity of fresh water bodies from acid deposition has resulted in a significant decline of fishery resources in Europe and North America. Areas in developing countries that are susceptible to acid deposition from increasing rates of motorization and industrialization include southern China, parts of southeast Asia, southwestern India, southern Nigeria, southeastern Brazil, and northern Venezuela [Rodhe and Herrera 1988].

Recent evidence suggests that the role of NOx may be of increasing significance:

- The nitrate to sulphate ratio in the atmospheric aerosol in southern England, for example, has shown a steady increase since 1954.

- The nitrate content of precipitation averaged over the entire European Air Chemistry Network increased steadily over the period 1955 to 1979.

- The nitrate levels in ice cores from South Greenland increased steeply from 1975 to 1984, whilst the sulphate content since 1968 has remained relatively stable. The 'Thousand Lake Survey' in Norway has revealed a doubling in the nitrate concentration of 305 lakes over the period 1974/75 to 1986, despite little change in ph and sulphate [Derwent 1988].

Several acid deposition control plans have targeted reductions in NOx emissions in addition to substantial reductions in sulfur dioxide. Furthermore, the ten participating countries at the 1985 International Conference of Ministers on Acid Rain committed to take measures to decrease effectively the total annual emissions of nitrogen oxides from stationary and mobile sources as soon as possible [ICM 1985]. One result has been the recent NOx protocol freezing emissions at 1987 levels by 1994; several European countries have committed to an additional 30% reduction.

Lead

Leaded gasoline is a major source of atmospheric lead in urban areas [Annest et al. 1983]. Several studies have shown that children with high levels of lead accumulated in their baby teeth experience more behavioral problems, lower IQs, and decreased ability to concentrate [Needleman et al. 1979]. A study by the U.S. National Academy of Sciences concluded that the evidence was convincing that exposures to levels of lead commonly encountered in urban environments constituted a significant hazard of detrimental biological effects in children, especially those less than three years old. Furthermore, a small fraction of this population experienced particularly intense exposures and was at severe risk [NAS 1980]. More recently, in a study of 249 children from birth to two years of age, it was found that those with prenatal umbilical-cord blood lead levels at or above 10 micrograms per deciliter consistently scored lower on standard intelligence tests [Bellinger et al. 1987]. Evidence of adverse health effects at lower levels of lead continues to grow [Bellinger et al. 1987, USDHHS 1988]. Statistical evidence has been found to link lead in adults to increased incidence of high blood pressure [Schwartz 1983].

Other Toxics

Mobile sources are a potentially significant source of toxic compounts and remain a substantial contributor to the overall health risks associated with air toxics. According to U.S. EPA, mobile sources may be responsible for between 629 and 1874 cancer cases per year in the United States [Wilson 1987]. Substantial improvements in certain toxics, however, have resulted as a by-product of the overall motor vehicle pollution control program, e.g., lower exhaust benzene and polynuclear aromatics (PNAs) from catalysts and lower diesel organics from particulate controls.

The control of exhaust and evaporative hydrocarbons generally lowers toxic emissions as well; catalytic converters tend to selectively eliminate a greater proportion of the more biologically active compounds and therefore are beneficial for toxic control. Metallic fuel additives are not desirable because of potential toxic effects and in some cases carcinogenicity. Alcohol fuel blends are of some benefit in reducing exhaust emissions, but they may actually increase aldehydes, as do neat alcohol fuels. A summary of significant toxics from mobile sources is given below, based on the work of Boyd [1986] and Carhart and Walsh [1987].

Diesel Particulates

Uncontrolled diesel fueled engines emit approximately 30 to 70 times more particulates than gasoline-fueled engines equipped with catalytic converters and burning unleaded fuel. Virtually all of these particles are small and respirable (less than 2.5 microns) and consist of a solid carbonaceous core on which a myriad of compounds adsorb. These include:

* unburned hydrocarbons;
* oxygenated hydrocarbons;
* polynuclear aromatic hydrocarbons; and
* inorganic species such as sulfates, sulfur dioxide, nitrogen dioxide and sulfuric acid.

Most of the toxic trace metals, organics, or acidic materials emitted from automobiles or fossil fuel combustion are highly concentrated in the fine particle fraction [Ozkaynak et al. 1986]. These emissions may cause cancer and exacerbate mortality and morbidity from respiratory disease [Clavel and Walsh 1984]. Health experts in FRG consider occupational exposure to diesel particulates a cancer risk in the workplace. A review by the Swedish National Institute of Environmental Medicine showed a statistically significant association between exposure to diesel exhaust and lung cancer among forklift truck drivers. The study indicated an excess risk of lung cancer among such truck drivers in the order of 30 to 50% [Per Camner et al. 1988].

Aldehydes

Formaldehyde and other aldehydes are emitted in the exhaust of both gasoline- and diesel-fueled vehicles, and are a major emission component in the exhaust of alcohol-fueled vehicles. Aldehyde exhaust emissions from motor vehicles correlate reasonably well with exhaust hydrocarbon (HC) emissions. Diesel vehicles generally produce aldehydes at a greater percentage rate of total HC emissions than gasoline vehicles. Formaldehyde is also generated by photochemical reactions involving other organic emissions. Formaldehyde is of particular interest both due to its high photochemical reactivity in ozone formation and its suspected carcinogenicity. Formaldehyde can also be a short-term respiratory and skin irritant, especially for sensitive individuals [Carhart and Walsh 1987].

Benzene

Benzene is present in both exhaust and evaporative emissions. Mobile sources (including refueling emissions) dominate the benzene emission inventory in most countries. For example, according to the U.S. EPA, roughly 70.2% of the total benzene emissions come from vehicles. Of the mobile source contribution, 70% comes from exhaust and 14% from evaporative emissions [Carhart and Walsh 1987]. Several epidemiology studies on workers have identified benzene as a carcinogen causing leukemia in humans [Carhart and Walsh 1987].

Non-Diesel Organics

Gasoline-fueled vehicles emit far less particulates than their diesel counterparts but the mutagenicity of the gasoline soluble organic fraction (SOF) per mass of particulate collected is greater than the diesel SOF. The overall impact from gasoline particulate matter might be quite significant as gasoline-fueled vehicles accumulate so much travel. It should be noted that the emission factors and unit risk estimates for gasoline particulate are far more uncertain than those for diesel-fueled vehicles.

Asbestos

Asbestos is used in brake linings, clutch facings and automatic transmissions. About 22% of the total asbestos consumption in the US in 1984 was used in motor vehicles. Health impacts of asbestos exposure are well known, including cancer, asbestosis, and mesothelioma [Carhart and Walsh 1987].

Metals

Toxicological effects of metals, especially heavy metals, have been known for some time [Carhart and Walsh 1987]. In addition, many are now being analyzed for their carcinogenic potential, including several for which unit risk values have been published. U.S. EPA has identified mobile sources as a significant contributor to nationwide metals inventories in the United States, including 1.4% of beryllium and 8.0% of nickel. The California Air Resources Board is evaluating these metals, as well as arsenic, manganese, and cadmium, as mobile source pollutants [Boyd 1986]. Because of a relatively high unit risk value, emissions of chromium may also be a concern although the health risk tends to be associated with hexavalent chromium which does not appear to be prevalent in mobile source emissions.

Motor Vehicles and Global Warming

Trace gases associated with motor vehicle use (e.g., CO_2, CFCs, HC, O_3, and N_2O) can contribute to global warming by changing the atmospheric chemistry in ways that either allow more of the sun's radiation to reach the surface of the planet or increase the ability of the atmosphere to retain heat [Arrhenius and Waltz 1990]. The release of chlorofluorocarbons used in vehicle air conditioning equipment can destroy the protective ozone shield. Increased ultraviolet radiation resulting from a depletion of the ozone shield may significantly influence local ozone air pollution episodes. An increase in ultraviolet B radiation resulting from even a moderate loss in the total ozone column can be expected to result in a significant increase in peak ground-based ozone levels. These high peaks would occur earlier in the day and closer to the populous urban areas in comparison to current experience, resulting in a significant though quantitatively unspecified increase in the number of people exposed to these high peaks [ALA 1988].

The role of motor vehicles in global warming becomes significant even if only HC and NOx emissions are taken into consideration, as these gases contribute to increased levels of tropospheric ozone. But motor vehicles also emit other greenhouse gases, including carbon monoxide (CO), carbon dioxide (CO_2) and chlorofluorocarbons (CFC-11, CFC-12). The amount of each of these gases in the atmosphere has been increasing on a global scale.

Carbon Monoxide

Through chemical reactions, an increase in even a radiatively inactive gas such as CO can increase the concentration of several greenhouse gases. For example, hydroxyl radicals (OH) which scavenge many anthropogenic and natural trace gases from the atmosphere are themselves removed by carbon monoxide [Ramanathan 1988]. The role of CO in global warming becomes significant in view of the evidence that global CO levels are increasing. As noted by Khalil and Rasmussen [1988], the average tropospheric concentration of CO is increasing at between 0.8% and 1.4% per year, depending on the method used to estimate the trend, and the 90% confidence limits of the various estimates range between 0.5% and 2.0% per year.

Chlorofluorocarbons (CFCs)

CFCs are the most radiatively active gases, and are estimated to account for about 14 to 25% of the total global warming effect, mostly through destruction of the protective ozone layer. About 30% of European production of CFCs and 40% of the United States' is devoted to refrigeration and air conditioning. According to U.S. EPA, mobile air conditioning accounts for 56,500 metric tons of CFCs, i.e., about 28% of the CFCs used for air conditioning and refrigeration in the United States, or about 13% of the total production. In contrast, home refrigerators accounted for 3,800 metric tons [USEPA 1987b]. Thus, approximately one of every eight pounds of CFCs manufactured in the United States is used, and eventually emitted, by motor vehicles, either through poor maintenance of the air conditioning system or when the vehicle is finally disposed. CFCs also find use as a blowing agent in the production of seating and other foamed products but this constitutes a considerably smaller application in motor vehicles.

Carbon Dioxide (CO_2)

Although inert and harmless in terms of direct human health and welfare effects, carbon dioxide is a major greenhouse gas. Worldwide CO_2 emissions from transport sources in 1985 were estimated at 1,152 million metric tons [Parson 1989]. A single standard tank of gasoline (16 gallons) produces between 300 and 400 pounds of CO_2 on combustion. Thus, motor vehicles are responsible for a significant amount of the global CO_2 emissions from fossil fuels; estimates range from 15-20% [DeLuchi et al. 1989; Lenssen and Young 1990]. This quantity is directly related to the quantity of energy consumed by motor vehicles. The United States contributes more than a third to the global CO_2 emissions from transport; an amount equivalent to the combined contribution from transport in all developing countries, including the oil-exporting countries in the Middle East. As use of conventional fuels in vehicles increases, it is likely that CO_2 emissions will increase. Since 1988, estimates of petroleum reserves have grown from 699 billion barrels to 887 billion barrels.

Motor vehicle emissions, therefore, not only contribute to adverse health and welfare effects resulting from ground level pollution but they are considered to have a significant and increasing role in global warming and destruction of the ozone shield. To deal with these problems in a coordinated fashion requires the simultaneous minimization of carbon dioxide, carbon monoxide, hydrocarbons, nitrogen oxides, and chlorofluorocarbons.

V. FACTORS INFLUENCING AIR POLLUTION FROM LAND TRANSPORT SOURCES

The major factors affecting air pollution from transport sources include:

- the amount of energy consumption by the transport sector;
- the magnitude and density of population;
- the degree of urbanization;
- transport modes and their share of travel;
- fuel consumption and emission characteristics of transport modes; and
- the aggregate emission levels associated with transport sources.

Energy Consumption

Air pollution is directly related to energy consumption. Statistically significant and positive relationships were obtained when data on energy consumption were regressed with data on air pollution for a sample of OECD countries (Table 6). Emissions of CO, NOx, and HC were highly correlated with energy consumption.

Table 6. Relation between energy consumption and air pollution for OECD countries

Pollutant	Regression Equation	df	F	R^2
CO	Y = -780.316 + 0.06548*X	8	1375	0.99
NOx	Y = -252.522 + 0.015306*X	14	1150	0.97
HC	Y = -593.935 + 0.018368*X	9	419	0.98

Note:
1. X is energy in 1000 tonnes of oil equivalent
2. Y is pollutant emission in 1000 tonnes
3. Source of data [OECD 1987]
4. 1 ton of oil equivalent is equal to 426.216 joules of energy

The estimated global energy consumption by transport in 1985 was approximately 56 quads of energy or almost one-third of the total energy consumed in the world [Parson 1989]. As shown in Table 7, there are large regional variations in the energy consumed by the transport sector. The United States is by far the largest consumer, using over 35% of the world's transport energy. A large share of energy consumption by the transport sector is characteristic of many developing countries, particularly in Africa and Latin America (Table 8).

Population and Urbanization

The world's population is estimated to increase to over 6 billion by the year 2000 with almost one-half living in urban areas. The population growth would be concentrated in the developing world (Table 9) -- Latin America and Asia would have a decreasing rate of population growth while Africa would continue to have a high growth rate, estimated at about 3% per annum in the 1990's. The rate of urbanization (percent change in the percentage of population living in urban areas) would be the highest in Asia, in particular South Asia, and Africa (Table 10). Urban population in the least urbanized countries in Africa is expected to quadruple between 1980 to 2000. In absolute terms, the largest growth in urban population would be in South Asia [United Nations 1987]. Increase in population, and more importantly the increase in urbanized population, will mean increased energy use (including transport energy) and in turn potentially increased emissions of air pollutants, if not controlled.

Air pollution is generated primarily in large metropolitan areas in both developed and developing regions. Thus rapid growth of urban agglomerations may have an indirect link to increased pollutant emissions. Moreover, an increase in population concentration in urban areas makes more people exposed to the adverse effects of air pollution. In 1985, there were 99 urban agglomerations of two million or more inhabitants; 12 of them had ten million or more inhabitants, and 18 had from five million to nine million. Eight of the 12 urban agglomerations with ten million or more inhabitants were in developing countries. By the year 2000, there will be 23 of that size, 17 of which are expected to be in developing countries [United Nations 1987]. Table 11 shows the urban agglomerations in developing countries that are expected to have a population of five million or more in 2000. The rapid increase in the number and size of urban agglomerations in developing countries is expected to lead to a major concentration of air pollution problems in developing countries, as presently exemplified by megacities such as Mexico City, Sao Paulo, Bombay, Shanghai, and Seoul.

Table 7. Global transport energy consumption, 1985

Region	Transport Energy in Quads[a]	Regional Share (%)
United States	20.0	35.4
Canada and Western Europe	13.0	23.0
Eastern Europe (including USSR)	8.4	14.9
Japan, Australia, New Zealand	4.4	7.8
Latin America and Caribbean	4.1	7.3
South and East Asia	2.5	4.4
Africa	2.0	3.5
Middle East	1.0	1.8
China	0.9	1.6
Global Total	**56.3**	**100.0**
• *Industrialized*	*44.6*	*79.6*
• *Developing*	*11.4*	*20.4*

[a] 1 Quad is equivalent to 1 trillion Btu of energy
Source: [Parson 1989]

Table 8. Share of transport in regional energy consumption, 1985

Region	Transport Share of Regional Energy Consumption (percent)
United States	35.9
Canada & Western Europe	31.4
Eastern Europe (including USSR)	17.8
Japan, Australia, and New Zealand	36.4
Latin America and Caribbean	33.3
South and East Asia	24.1
Africa	39.6
Middle East	16.9
China	6.7
Global Total	**27.5**

Source: [Parson 1989]

Table 9. Total population and its urban share (in millions)

Region	1970		1985		2000	
	Total	Urban	Total	Urban	Total	Urban
World	3693	1371 (37%)	4837	1983 (41%)	6122	2854 (47%)
Africa	361	81 (23%)	555	165 (30%)	872	340 (39%)
Asia	2102	503 (24%)	2818	791 (28%)	3549	1242 (35%)
Latin America	283	163 (57%)	405	279 (69%)	546	420 (77%)

Source: [United Nations 1987]

Table 10. Average annual growth rate of population and urbanization (percent)

	Total Population			Urbanization			Urban Population		
Region	1970 to 1980	1980 to 1990	1990 to 2000	1970 to 1980	1980 to 1990	1990 to 2000	1970 to 1980	1980 to 1990	1990 to 2000
World	1.9	1.65	1.55	0.65	0.75	0.9	2.5	2.4	2.4
Africa	2.8	3.00	3.00	1.80	1.80	1.8	4.5	4.8	4.7
Asia	2.1	1.70	1.50	1.10	1.10	1.6	3.2	2.9	3.0
Latin America	2.5	2.20	1.80	1.30	1.00	0.7	3.8	3.3	2.6

Source: [United Nations 1987]

Table 11. Major urban agglomerations in developing countries (with more than five million population in 2000)

Agglomeration	Country/Region	Population in millions		
		1970	1985	2000
Mexico City	Mexico/North America	9.12	17.30	25.82
Sao Paulo	Brazil/South America	8.22	15.88	23.97
Calcutta	India/South Asia	7.12	10.95	16.53
Bombay	India/South Asia	5.98	10.07	16.00
Shanghai	China/East Asia	11.41	11.96	14.30
Seoul	Republic of Korea/East Asia	5.42	10.28	13.77
Teheran	Iran/Middle East	3.29	7.52	13.58
Rio de Janeiro	Brazil/South America	7.17	10.37	13.26
Jakarta	Indonesia/East Asia	4.48	7.94	13.25
Delhi	India/South Asia	3.64	7.40	13.24
Buenos Aires	Argentina/South America	8.55	10.88	13.18
Karachi	Pakistan/South Asia	3.14	6.70	12.00
Beijing	China/East Asia	8.29	9.25	11.17
Dacca	Bangladesh/South Asia	1.54	4.89	11.16
Cairo/Giza	Egypt/Middle East	5.69	7.69	11.13
Manila/Quezon	Phillipines/East Asia	3.60	7.03	11.07
Bangkok	Thailand/East Asia	3.27	6.07	10.71
Tianjin	China/East Asia	6.87	7.89	9.70
Lima-Callo	Peru/South America	2.92	5.68	9.14
Lagos	Nigeria/Sub-Saharan Africa	1.44	3.65	8.34
Madras	India/South Asia	3.12	5.19	8.15
Baghdad	Iraq/Middle East	2.10	4.42	7.42
Bangalore	India/South Asia	1.66	3.97	7.96
Bogota	Colombia/South America	2.37	4.49	6.37
Pusan	Republic of Korea/East Asia	1.85	4.11	6.20
Lahore	Pakistan/South Asia	1.97	3.70	6.16
Shenyang	China/East Asia	3.14	4.08	5.35
Ahmedabad	India/South Asia	1.74	3.14	5.28
Santiago	Chile/South America	3.01	4.16	5.26
Ankara	Turkey/Middle East	1.27	2.90	5.20
Hyderabad	India/South Asia	1.80	3.12	5.13
Belo Horizonte	Brazil/South America	1.62	3.25	5.11
Alger	Algeria/North Africa	1.19	2.66	5.09
Kinshasa	Zaire/Sub-Saharan Africa	1.23	2.69	5.04
Caracas	Venezuela/South America	2.12	3.74	5.03

Source: [United Nations 1987]

Mobility and Motorization

Motor Vehicle Registrations

Since 1950, the global growth rate for automobiles has averaged 5.9% per annum; for trucks and buses, it has been only slightly less at 5.6% per annum. Although the overall rate of growth over this period declined slightly, commercial vehicles increased more rapidly than automobiles. For example, since 1970, automobile growth has averaged 4.7% per annum while truck and bus registrations have averaged 5.1%. As a result of this sustained growth, the total worldwide vehicle population now exceeds 500 million, with about 400 million automobiles [MVMA 1988].

A geographical distribution of the motor vehicle population (in 1986) is summarized in Table 12. Europe and North America each had a 40% share of the world's automobile population, with the remaining 20% accounted by Asia, South America, Oceania and Africa. Regarding trucks and buses, North America had a 41% share followed closely by Asia and Europe. Within Asia, Japan accounted for 70% of automobiles and 62% of trucks and buses. The developing countries, as a group, had a 10% share of the world's automobiles and about 20% of trucks and buses. The global population of motorized 2- and 3-wheeled vehicles (motorcycles, rickshaws) is not known, although they account for a substantial part of the motorized vehicle fleets in developing countries and contribute significantly to mobile emissions. In Taiwan, for example, motorcycles accounted for 76% of the registered motor vehicle fleet in 1988 and were responsible for 36% of total HC emissions and over 15% of CO emissions from all sources [Shen and Huang 1989].

Table 12. Global distribution of motor vehicles in 1986

Region	Automobiles (%)	Trucks & Buses (%)
North America	40.0	41.4
Europe	39.8	21.0
Asia	11.1	27.8
South America	4.8	3.7
Oceania	2.2	2.3
Africa	2.1	3.7

Source: [MVMA 1988]

The world motor vehicle fleet has been growing faster than the overall population. In global terms, automobiles per capita increased by over 20% during the last decade [MVMA 1988]. Short term projections suggest that the greatest gains in motor vehicle registrations will occur in the Asia and Pacific region (excluding Japan), Middle East and parts of Africa, and Eastern Europe. Only the United States is projected to show a decline in new vehicle registrations.

Looking to the longer term, vehicle population and use projections were developed based on historical trends and expected population and income growth rates. Such projections are inherently uncertain because of the inability to predict international crises, prolonged economic downturns, future oil prices, and other events affecting automotive transportation. Two methods were used to project the future vehicle fleet. Conservatively, vehicle growth can be expected to follow historical trends as reflected by a straight linear regression. This indicates a global vehicle population approaching 1 billion by the year 2030. If, on the other hand, per capita trends are regressed and then multiplied by population estimates, the global vehicle population would be substantially higher. Overall each projection indicates that the global vehicle population will increase at an average rate of about 2-3% per annum, over the time frame investigated. Individual countries in Asia and Latin America, however, are likely to experience higher growth rates. The global projections were compared with several individual country estimates [Matsunami 1988, Olsson 1986, SFIT 87, Gillingham 1988, Myers 1988, OECD 1983, ROV 1986, SASO 1987, Sjostrom 1988, Strategic Analysis Europe 1988, NZMTF 1987, TC 1987, Kroon 1988, TC 1988, Gospage 1985a, Gospage 1985b, Hartig 1988, Lenz 1985, DSA 1987]. In general, the estimated global growth rates compare reasonably with individual country estimates.

Urbanization, Economic Activity, and Motorization

The degree of urbanization is strongly influenced by the magnitude of economic activity, while the level of motorization is linked to economic activity and urbanization. Energy consumption is significantly influenced by both the degree of urbanization and the level of motorization. The regression analyses summarized in Table 13 suggest a reasonable positive correlation between income and motorization and between urbanization and motorization.

Table 13. Generalized relationships between urbanization, economic activity, and motorization

X	Y	Relationship	df	F	R^2
GNP per Capita[a]	Motor Vehicles per 1000 persons	$Y = 0.00879*X^{1.17062}$	24	108.1	0.82
Urban Pop.[b]	Motor Vehicles per 1000 persons	$Y = 0.0172683*X^{2.03898}$	24	30.64	0.57

[a] In 1985 US dollars; [b] percent

Basic indicators of urbanization, economic activity, energy consumption, and motorization and their historical growth rates are shown in Tables 14 and 15 for selected countries in different regions. Urban population growth in developing countries, as a result of both natural increases and migration from rural areas and small towns, has greatly expanded urban boundaries and resulted in increased travel and demand for urban transport services. The increase in vehicle kilometers of travel in many developing countries has averaged between 5-30% per annum since the mid-1980s [IRF 89]. Many developing countries, particularly in Asia, will continue to experience higher rates of economic growth (GNP per capita) than industrialized countries. Given the strong correlation between GNP per capita and the level of motorization (Table 13), the growth in motorization in many developing countries is expected to be considerably higher than the annual rate of 2-3% estimated for the global vehicle fleet. This would significantly increase the contribution of developing countries to transport-related air pollution.

Air pollution problems therefore are likely to worsen in many urban areas of developing countries because of rapid urbanization, the rising rate of motorization, increasing trip rates, and use of old and not so well maintained vehicles. Traffic growth has outpaced the increase in road space in the larger metropolitan areas in developing countries. The stop-and-go pattern of traffic flow resulting from traffic congestion increases fuel consumption and adds to the air pollution problem.

The lack of appropriate land use policies has aggravated the air pollution problem in many developing cities. For example, in Bombay there is a concentration of polluting sources such as refineries, thermal power plants, chemical industries within the highly congested urban boundaries [CSE 1982]. Similar conditions are noted in Santiago, Sao Paulo, and Mexico City. Such a clustering of emissions sources results in a high concentration of air pollutants and excessive exposure levels. Appropriate land use controls could have avoided the development and concentration of such polluting sources close to already congested areas.

Modal Share of Travel

Common modes of land transport observed in developing countries include: (a) automobiles and taxis, (b) motorcycles and three wheelers, (c) vans, pickups, light and heavy duty trucks, (d) buses and minibuses and various forms of paratransit, (e) trolley buses and trams, (f) light and rapid rail transit, (g) commuter and inter-urban trains, and (g) non-motorized modes (including human- and animal-drawn vehicles, bicycles and tricycles, and walking).

The number of motor vehicles in use is shown in Table 16 for selected countries. Brazil has by far the most number of motor vehicles among the developing countries. Although automobile ownership has increased rapidly in developing countries, notably in East Asian countries, trucks and buses constitute a large proportion of the vehicle fleet. The vehicle-kilometers of travel (VKT) by different modes in selected countries are shown in Table 17. A large part of passenger vehicle-kilometers (as high as 30-40%) is accounted by buses in developing countries. This proportion is even higher in many individual cities within a

Table 14. Basic socio-economic indicators for selected countries (1985)

	Population[a]		Energy consumption per capita[b] (kilograms of oil equivalent[d])	GNP per capita[b] (in 1985 dollars)	Motor vehicles per 1000 pop.[c]
	Total (million)	Urban (%)			
OECD Countries					
U.S.A	239.3	74	7,278	16,690	714
Japan	120.8	76	3,116	11,300	385
U.K.	56.5	92	3,481	8,460	345
Portugal	10.2	31	506	1,970	154
Turkey	50.2	46	258	1,080	30
Yugoslavia	23.1	45	898	2,070	152
Asia					
China	1,040.3	22	178	310	3
Hong Kong	5.4	93	424	6,230	56
India	765.1	25	100	270	5
Indonesia	162.2	25	91	530	12
Pakistan	96.2	29	136	380	5
Singapore	2.6	100	670	7,420	189
Korea, Rep.	41.1	64	237	2,150	26
Thailand	51.7	18	80	800	23
Africa					
Egypt	48.5	32	313	610	21
Tunisia	7.1	56	170	1,190	56
Kenya	20.4	20	114	290	6
Nigeria	99.7	30	34	800	12
South Africa	32.4	56	1,702	2,010	128
Latin America					
Argentina	30.5	84	975	2,130	172
Brazil	135.6	73	286	1,640	83
Chile	12.1	83	657	1,430	77
Colombia	28.4	67	269	1,320	77
Mexico	78.8	69	622	2,080	67
Peru	18.6	68	403	1,010	30

a) Source: [United Nations 1987]
b) Source: [World Bank 1987]
c) Source: [MVMA 1987]
d) 1 kg of oil equivalent is equal to 0.426216 joules of energy.

Table 15. Average annual growth in basic socio-economic indicators for selected countries (in percent)

	Population[a] Total	Population[a] Urban	GNP per[b] capita	GNP per[b] capita	Motor Vehicle Fleet[c]
	1985 -1990	1985 -1990	1980 -1988	1986 -1988	1984 -1988
OECD Countries					
U.S.A.	0.86	0.90	2.1	2.7	1.9
Japan	0.51	0.62	3.4	4.7	7.1
U.K.	0.02	0.15	2.8	3.8	2.7
Portugal	0.64	1.98	1.9	4.9	15.3
Turkey	2.06	3.12	3.0	3.1	7.2
Yugoslavia	0.63	2.26	-0.1	-2.2	1.7
Asia					
China	1.23	1.44	9.2	9.0	13.9
Hong Kong	1.68	1.81	5.7	9.2	3.2
India	1.72	3.58	3.3	4.2	6.8
Indonesia	1.74	4.30	1.7	1.6	4.5
Pakistan	2.23	3.65	3.0	3.4	8.9
Singapore	1.09	1.09	5.8	8.8	1.8
Korea, Rep.	2.36	3.45	7.7	11.1	30.0
Thailand	1.61	4.30	3.8	8.0	9.1
Africa					
Egypt	2.27	3.28	2.8	2.8	n.a.
Kenya	4.20	7.82	-0.2	1.5	26.1
Nigeria	3.49	5.97	-4.3	-3.6	n.a.
South Africa	2.53	3.45	-1.0	0.0	26.1
Tunisia	2.17	3.56	0.6	1.2	6.2
Latin America					
Argentina	1.46	1.84	-1.6	-2.0	3.0
Brazil	2.07	3.19	1.2	-0.3	11.5
Mexico	2.39	3.21	-1.4	0.8	4.0
Chile	1.52	2.00	-0.1	5.3	2.0
Colombia	2.05	2.89	1.2	2.3	3.3
Peru	2.51	3.32	-1.2	-n.a.	4.1

a) Source: [United Nations 1987]
b) Source: [World Bank 1987, 1989]
c) Source: [IRF 1989], [MVMA, 1988, 1989]

Table 16. Types and number of vehicles in use in selected countries

	Cars	Buses	Vans	2-Wheelers	Goods Vehicles	Tractors & Trailers
OECD Countries						
U.S.A (1987)[a]	135,323,632	602,055	..	4,885,772	41,118,762	..
Japan (1988)	30,776,277	238,021	..	11,450,266	21,440,494	75,034
U.K. (1988)	18,432,000	132,000	648,000	912,000	1,951,000	..
Portugal(1987)[a]	1,285,000	7,860	443,479	106,925	78,600	171,285
Turkey (1988)	1,406,387	63,853	124,357	411,126	590,809	683,577
Yugoslavia (1986)[b]	2,957,116	29,009..	102,223	203,011	208,082	
Asia						
China (1987)[c]	761,000	354,000	..	..	2,812,000	..
Hong Kong (1988)	201,775	13,853	..	17,323	108,479	14,671
India (1985)[d]	1,178,228	213,410	..	4,960,311	783,393	186,507
Indonesia (1986)[b]	1,059,851	256,576	..	5,115,925	876,684	..
Pakistan (1988)	278,506	39,219	34,303	635,888	80,301	232,584
Singapore (1985)[d]	225,034	8,717	..	127,564	66,694	..
Korea,Rep.(1988)	1,117,999	259,600	22,404	1,066,841	635,445	20,757
Thailand (1988)	816,693	428,366	..	3,894,824	1,422,773	..
Africa						
Egypt (1988)	791,245	31,590	184,358	263,389	318,478	39,942
Kenya (1984)[e]	122,300	7,001	64,805	17,944	24,769	29,791
Nigeria (1987)[a]	8,981	2,250	14,790	8,907	5,687	2,036
S. Africa (1988)	3,147,697	25,950	145,967	317,254	1,106,953	649,774
Tunisia (1988)	292,673	8,986	6,066	12,290	151,826	33,699
Latin America						
Argentina (1986)[b]	3,898,000	59,700	..	76,000	1,375,000	..
Brazil (1988)	14,995,837	193,683	..	1,666,407	1,416,081	..
Mexico (1987)[f]	5,282,200	..	..	..	2,193,300	..
Chile (1987)[a]	660,000	22,400	..	36,000	256,000	..
Colombia (1986)[b]	840,776	245,206	..	385,954	146,227	..
Peru (1987)[f]	388,788	..	..	..	214,863	

a) 1987 data [IRF 89]

b) 1986 data [IRF 89]

c) 1987 data from the Asian Development Bank Regional Seminar on Transport Policy, Manila, Feb. 1989 and [MVMA, 1989]

d) 1985 data [IRF 89]

e) 1984 data [IRF 89]

f) 1987 data [MVMA, 1989]; goods vehicles include trucks and buses

Table 17. Vehicle kilometers of travel in selected countries (in billions of vehicle-km)

	Cars	Buses	Two wheeler	Goods Vehicle	Avg. Annual Increase in Total VKT[a] (Percent)
OECD Countries					
USA (1987)	2183.7	8.57	15.86	888.10	4
Canada (1987)	135.7	n.a.	n.a.	6.90	5
Japan (1987)	308.1	6.63	n.a.	234.15	5
France (1988)	305.0	4.00	9.00	90.00	5
Germany, Fed.Rep.(1988)	376.5	3.50	7.00	36.50	4
Portugal (1985)	22.5	0.24	0.74	5.20	n.a.
Sweden (1988)	53.0	n.a.	n.a.	6.00	n.a.
Turkey (1988)	10.3	2.15	n.a.	9.92	9[b]
U.K. (1988)	270.0	3.60	4.60	53.90	5
Asia					
Thailand (1987)	10.62	5.65	n.a.	15.44	10
Jordan (1987)	4.94	0.17	0.11	2.32	5
Korea, Rep. of (1988)	8.85	3.71	n.a.	13.00	15
Hong Kong (1988)	3.66	7.17	0.16	2.37	5
Yemen A. Rep. (1988)	2.92	0.01	n.a.	4.18	28
Africa					
Tunisia (1988)	12.30	7.82	0.017	0.06	n.a.
South Africa (1987)	47.56	5.67	2.951	27.01	7
Latin America					
Colombia (1986)	12.29	2.65	n.a.	5.60	3
Chile (1987)	12.21	0.41	n.a.	1.89	30
Argentina (1986)	32.10	1.95	n.a.	15.97	1

[a] = Since 1984
[b] = Since 1986
n. a. = not available
Source: [IRF 89]

developing country. Attention to transport-related air pollution in developing countries, therefore, should not only concentrate on automobiles but also should consider buses and their travel characteristics. As indicated before the contribution of motorcycles and three-wheelers to total VKT also deserves careful assessment.

The modal share of motorized passenger trips in selected developing cities is given in Table 18. The total number of trips is closely related to city population. The relationship obtained by regressing city population with number of trips (sample size = 19) is given below:

$$Y = -1.28256 + 1.55429X \qquad (R^2 = 0.85) \qquad (1)$$

where, Y is number of trips per day in million; and
X is the population of urbanized area in million

Non-motorized trips, however, constitute a good portion of total trips made in major cities of developing countries. For example, in Bombay and Calcutta more than a fourth of the trips are by non-motorized modes, mostly walking [Pendakur 1988]. Of motorized trips, buses account for a significant portion as indicated in Table 18.

Table 18. Modal share of motorized passenger trips in selected cities, 1980

City	Modal Share (%)					
	Auto	Taxi	Bus	Para-transit	Rail or Subway	Other
Bangkok	25	10	55	10	-	-
Bombay	8	10	34	13	34	-
Calcutta	-	2	67	14	10	4
Hong Kong	8	13	60	-	19	-
Jakarta	27	-	51	-	1	21
Karachi	3	7	52	18	6	13
Manila	16	2	16	59	-	8
Seoul	9	15	68	0	7	0
Bogota	14	1	80	0	0	5
Mexico City	19	-	51	13	15	2
Rio de Janeiro	24	2	62	2	11	-
Sao Paulo	32	3	54	-	10	1
Abidjan	33	12	50	-	-	5
Nairobi	45	-	31	15	0	9
Cairo	15	15	70	-	-	-
Tunis	24	4	61	-	10	-
Amman	44	11	19	26	-	-
Ankara	23	10	53	9	2	2

Source: [World Bank 1986]

An estimated 600 million trips a day were being made in buses in cities of developing countries in 1980 and by the year 2000 that figure is expected to double [World Bank 1986]. These buses are not well maintained and they are kept in service long past their useful lives. Consequently, these vehicles are generally associated with high levels of emissions. A recent study conducted in New Delhi found that only 18% of the city buses conformed to the smoke intensity level standard. About 49% of the buses and 60% of trucks were much above the critical limit, and contributed to large quantities (945 mg/cu.m) of suspended particulate matter including dust and flyash [Chandra 1989].

Fuel Consumption and Emission Characteristics

Motor vehicles in many developing countries are not as fuel efficient as in industrialized countries. Many of the vehicles are old and poorly maintained because of lack of spare parts and other resources. For example, in India a major portion of the vehicle fleet is older than ten years [Pendakur 1988]. This is true not only for trucks, buses and automobiles, but also for motorcycles and autorickshaws. The use of autorickshaws is extensive in the Indian subcontinent and their contribution to air pollution is not insignificant.

Two-stroke engine motorcycles are also a major source of air contaminants. An investigation carried out in Taiwan found that the ratio of lubricating oil additive in gasoline was an important factor influencing the opacity of particulates emitted by two-stroke motorcycle engines. Since 1984, a major effort has been made to reduce the lubricating oil content in unleaded gasoline for 2-stroke motorcycles to less than 2% [Shen and Huang 1989].

Moreover, the gasoline used in most developing countries still has a high percentage of lead. In India the lead content in gasoline is considerably higher than the permissible limits in industrialized countries. The Indian Ministry of Petroleum, in response to environmentalists' demands, has recently asked the refineries to reduce the lead content [Chandra, 1989]. In Taiwan, the lead content in regular gasoline was reduced from 0.8 gm/liter in 1981 to 0.12 gm/liter in 1988; at the same time, unleaded gasoline was introduced. Diesel fuel supplied for buses and trucks in many developing countries has a very high sulfur content and is often contaminated and sometimes deliberately blended with heavier oil fractions.

The emission characteristics of transport vehicles depend on the characteristics of the power plant (the engine), the type of power source (fuel), the operating conditions (e.g. speed, congestion), and the physical environment (e.g. altitude, temperature). A comparison of emission characteristics for different modes on a vehicle-km or car-km basis is given in Table 19. Emission rates on a passenger-km basis, based on assumed vehicle occupancy, are estimated in Table 20.

The emission rates shown in Tables 19 and 20 are mostly representative of the U.S. vehicle fleet in the mid-1970's. For light duty gasoline vehicles and large diesel-powered buses, rates observed in Mexico City have been used. Given the paucity of data on emissions characteristics of in-use motor vehicles in developing countries, these rates serve as a reasonable overall representation of the emission characteristics of vehicles operating in developing countries, which mostly do not have strictly enforced emission standards and controls. In fact, the actual rates of emission could be considerably higher because vehicles in developing countries not only lack emission controls but are generally old and often operate in stop-and-go modes.

Several general conclusions can be drawn from the data presented in Tables 19 and 20:

- Road vehicles are more polluting than rail by a large margin.
- Gasoline vehicles emit more pollutants in the aggregate than diesel vehicles, for similar service characteristics.
- Gasoline vehicles emit large amounts of CO and HC whereas diesel vehicles, particularly diesel buses, are major contributors of SOx, NOx, and particulates.
- Emissions increase with altitude as combustion is not as efficient.
- Environmental performance of all vehicles generally increases with speed but up to a point.
- Pollutant emissions related to the rail transit operations depend on the type, age, emission control devices, and location of power generating plant producing the electric energy.
- Coal is the most polluting energy source while natural gas is the most energy efficient and environmentally clean energy source for rail operations. Coal burning to produce electricity for rail operations is a major contributor of particulate matter.
- Rail rapid transit operations are associated with more pollutants per car-kilometer than light rail transit possibly due to higher energy consumption.
- The magnitude of pollutants from rail operations is a function of the type of rail operation, age and condition of the rail, the speed of travel, and the sulfur and ash content of energy source, particularly coal. Moreover, the composite emission factors for the pollutants depend on the proportion of different energy sources used to generate power for the rail operations. For example, if the share of coal, natural gas, and residual oil for the electrical power generation to be used by light rail were 51.1%, 15.1%, and 10.7% respectively, then the composite emission factor for carbon monoxide would be as follows:

$$(0.5111)(0.211) + (0.1510)(\text{neg.}) + (0.1070)(0.003) = .1082 \text{ gms/car-km.}$$

The magnitude of pollutants emitted from automobiles in different driving modes is indicated in Table 21. The amount emitted is the highest for the acceleration phase, followed by deceleration, cruising, and idling phases. Thus frequent speed cycle changes as in stop-and-go traffic operations greatly increase the average emission rates. Emissions of carbon monoxide and hydrocarbons decrease while those of carbon dioxide and nitrogen oxides increase with increase in cruise speed. The amount of emissions from heavy vehicles also changes with the driving mode, as shown in Table 22.

Table 19. Emissions from different transport modes (per vehicle-km for road vehicles and per car-km for rail vehicles)

Mode	Fuel type or fuel source for electrical energy	Emission in grams					
		CO	HC	NOx	SOx	Aldehydes	PM
Motorcycle							
2-Stroke Engine[a]	Gasoline	17.00	9.9	0.075	0.024	0.068	0.21
4-Stroke Engine[a]	Gasoline	20.00	2.39	0.150	0.014	0.029	0.029
Light Duty Vehicle[b]	Gasoline						
Passenger Car							
Low Speed (30 km/hr)		33.66	2.63	1.05	0.21	..	0.33
High Speed (60 km/hr)		18.75	1.11	0.75	0.11	..	..
Van/Light Duty Truck							
Low Speed		84.19	7.61	1.48	0.37	..	..
High Speed		40.15	3.41	5.87	0.22	..	..
Small Bus/Combi							
Low Speed		47.18	5.81	1.88	0.26	..	..
High Speed		12.53	0.82	1.61	0.12	..	..
Light Duty Vehicle[a]	Gasoline						
Low Altitude		22.00	2.20	3.20	0.08	..	0.33
High Altitude		45.00	3.80	1.70	..	..	..
Light Duty Truck[a]	Diesel	1.10	0.28	0.99	0.45	..	..
Large Bus[b]	Diesel						
Low Speed		7.66	5.50	12.37	15.27	..	0.75
High Speed		6.77	4.76	11.61	11.55	..	..
Heavy Duty Vehicle[a]	Gasoline						
High Altitude		120.00	11.00	3.00	..	..	..
Low Altitude		81.00	9.90	5.70	0.16	..	0.52
Heavy Duty Vehicle[a]	Diesel	12.70	2.10	21.00	1.50	0.20	0.75
Commuter Rail Locomotive[a]	Diesel	18.44	13.17	19.76	17.13	1.08	6.58
Light Rail Transit (LRT)[c]	Coal	0.211	0.086	8.63	32.36	0.002	67.86
	Natural Gas	neg.	neg.	4.42	0.004	0.011	0.168
	Fuel Oil	0.003	0.253	8.21	6.32	0.05	0.8
Rapid Rail Transit (RRT)[c]	Coal	0.272	0.111	11.14	41.83	0.002	87.73
	Natural Gas	neg.	neg.	5.706	0.004	0.014	0.217
	Fuel Oil	0.004	0.326	10.59	8.15	0.062	1.032

a) Source: [EPA 1973]

b) Source: [Walsh 1989b]; representative of the vehicle fleet in Mexico City.

c) Source: [Reno and Bixby 1985]

Table 20. Emission characteristics of different modes for urban passenger travel (per passenger-km)

Mode	Fuel type or fuel source for electrical energy	Emission in Kilogram x 10^{-3}					
		CO	HC	NOx	SOx	Aldehydes	PM
Motorcycle	Gasoline						
2-Stroke Engine		17.0	10.12	0.075	0.024	0.068	0.21
4-Stroke Engine		20.0	2.39	0.15	0.014	0.029	0.029
Light Duty Vehicles	Gasoline						
Automobile							
Low Speed		16.83	1.32	0.55	0.10	..	0.165
High Speed		9.38	0.55	0.38	0.05	..	..
Van/Pickups							
Low Speed		21.05	1.90	0.37	0.09	..	..
High Speed		10.04	0.85	1.47	0.05	..	..
Small Bus/combi							
Low Speed		4.72	0.58	0.18	0.03	..	..
High Speed		1.253	0.082	0.161	0.012	..	..
Light Duty Vehicles	Diesel	0.26	0.07	0.25	0.10	..	..
Large Buses	Diesel						
Low Speed		0.19	0.14	0.31	0.38	..	..
High Speed		0.17	0.12	0.29	0.29	..	0.02
Conventional Commuter Diesel Rail		0.18	0.13	0.20	0.17	0.01	0.06
Light Rail Transit							
(LRT)	Coal	0.008	0.004	0.35	1.29	neg	2.70
	Natural Gas	neg	neg	0.18	0.0002	0.0004	0.007
	Fuel Oil	0.0001	0.011	0.33	0.253	0.002	0.03
Rapid Rail Transit							
(RRT)	Coal	0.01	0.005	0.40	1.47	0.0001	3.08
	Natural Gas	neg	neg	0.20	0.0002	0.0005	0.03
	Fuel Oil	0.0002	0.011	0.37	0.287	0.002	0.04

Note:
1. Emission values based on emission factors in Table 17
2. Average automobile occupancy assumed as 2
3. Average van/pickup/LDV diesel occupancy assumed as 4
4. Average small bus occupancy assumed as 10
5. Average large bus occupancy assumed as 40
6. Average occupancy of conventional diesel commuter train assumed as 100 (4 cars with 25 passengers)
7. Average occupancy of LRT and RRT car assumed as 25

Aggregate Emission Levels

An estimation of emission levels for a given area requires information on the vehicle fleet, its characteristics, and its usage. The proportional usage of automobiles, buses, and other vehicles plying on the transport network needs to be specifically determined and the emission characteristics of different types of vehicles in different operating conditions are also required.

An approximate estimation of emissions from road transport in selected countries is summarized in Table 23, based on the emission rates per vehicle kilometer given in Table 19 and the data on vehicle-kilometers of travel by different modes in Table 16. In all these countries automobiles account for most of the CO emissions. Buses contribute a significant portion to the HC, NOx, SOx, and particulates. The estimated values were aggregated and then compared to the reported data for some of the OECD countries for 1983, given in Table 24. The aggregate emission levels in developing countries such as Thailand, Republic of Korea, and Colombia are miniscule compared to those in the United States. However, if the size of the countries is taken into consideration, the emission density in developing countries could be quite high. Motorized travel in developing countries is concentrated primarily in a few large and densely populated cities; thus the potential for exposure to high concentrations of air pollutants in urban areas is quite high.

As transport-related air pollution is largely an urban phenomenon, a separate estimate of pollutant emissions from passenger vehicles was made for selected cities in developing countries. The data and assumptions underlying the estimation procedure are described in **Box 3**.

Using the procedure described in Box 3, the estimated number of motorized trips for the years 1980 and 2000 are tabulated in Table 25; the corresponding estimated emissions from automobiles (including taxis) and buses, in metric tons per day, are summarized in Table 26. Bus emissions are a serious environmental hazard and constitute a major portion of the estimated pollutant emissions in the selected set of cities. These results suggest that the emission levels in the selected cities will double by 2000 as compared to the 1980 levels, assuming a continuation of past trends in vehicle ownership and modal split. It is, however, quite probable that the estimated emission levels will be exceeded by a large margin given the rapid rate of motorization, increasing population and increasing income levels in many developing countries (e.g., compare the year 2000 estimates for Mexico City with the figures for 1987 shown in Table 5). By the end of the century, cities in developing countries may be expected to have comparable or even higher transport emission levels than cities in industrial countries if effective countermeasures are not adopted. As an example the projected daily emission levels for Munich for the period 1995-2000 are summarized in Table 27. These levels would be exceeded by a wide margin by year 2000 in most of the selected cities in developing countries, according to the estimates given in Table 26.

Box 3. Estimation of Pollutant Emissions from Automobiles and Buses in Selected Metropolitan Areas in Developing Countries: Data and Underlying Assumptions

- The number of trips were estimated using the relationship between number of trips and urbanized area population (Equation 1) and urban population data from Table 11.

- Non-motorized trips were assumed to constitute 25% of all trips made in the metropolitan areas. The estimated percentage of non-motorized trips may be high for Latin American cities, but is quite representative of Asian cities.

- The modal share of motorized trips was assumed to be the same as that given in Table 18, although this modal split may not be temporally stable. For example, the share of buses in motorized trips in Calcutta increased from 34% in 1970 to 67% in 1980 whereas the share of buses in motorized trips in Karachi decreased from 63% to 52% during the same period [World Bank 1975, World Bank 1986]. For the purpose of this exercise it was assumed that the modal split would be the same in 2000 as was observed in 1980. With the rapid increase in private vehicle ownership in developing countries, the assumption of a constant modal split may not be valid and may result in a significant underestimate of fuel consumption and also in the aggregate amount of emissions.

- An average trip length of 5 km was used to estimate passenger-kilometers by different modes. In many developing countries, such as in India, a trip length of 3-6 km is quite common [Pendakur 1988].

- The emission factors per passenger-kilometer shown in Table 20 were used to calculate emissions from automobiles, paratransit (minibuses, vans, and combi), and buses.

- Rail emissions were not estimated as reliable data is not available on rail operations. Furthermore, the proportional usage of different energy sources in the generation of power for rail operations in various cities is not known. For example, Bombay uses three sources, coal, natural gas and oil, whereas in Brazil water is the major source of power generation.

Table 21. Magnitude of pollutants generated by automobiles under different driving modes in the United States (in parts per million, ppm)

Driving Mode	Hydrocarbons (HC)	Carbon Monoxide (CO)	Carbon Dioxide (CO_2)	Oxides of Nitrogen (NOx)
Idling	1.34	16.19	68.35	0.11
Accelerating				
0-15 mph	536.00	2,997.00	10,928.00	62.00
0-30 mph	757.00	3,773.00	19,118.00	212.00
Cruising				
15 mph	5.11	67.36	374.23	0.75
30 mph	2.99	30.02	323.03	2.00
45 mph	2.90	27.79	355.55	4.21
60 mph	2.85	28.50	401.60	6.35
Decelerating				
15-0 mph	344.00	1,902.00	5,241.00	21.00
30-0 mph	353.00	1,390.00	6,111.00	41.00

Source: [Bellomo and Liff 1984]

Table 22. Representative composition of exhaust gases from heavy vehicles (in ppm by volume)

Pollutant	Idling	Accelerating	Cruising	Decelerating
Gasoline Engine				
Carbon monoxide	69,000	29,000	27,000	39,000
Hydrocarbons	5,300	1,600	1,000	10,000
Nitrogen oxides	30	1,020	650	20
Aldehydes	30	20	10	290
Diesel Engine				
Carbon monoxide	Trace	1,000	Trace	Trace
Hydrocarbons	400	200	100	300
Nitrogen oxides	60	350	240	30
Aldehydes	10	20	10	30

Source: [Holdgate et al. 1982]

Table 23. Estimated annual road transport emissions by mode in selected countries, 1988 ('000 tons)

Country	Automobiles					Buses					2 - 3 wheelers					Goods Vehicles				
	CO	HC	NOx	SOx	PM	CO	HC	NOx	SOx	PM	CO	HC	NOx	SOx	PM	CO	HC	NOx	SOx	PM
Asia																				
Thailand	337	28	11	2.2	3.5	43	31	70	86	4.2	n.a.	n.a.	n.a.	n.a.	n.a.	196	32	324	23.0	12.0
South Korea	298	23	9	1.9	2.9	28	20	46	57	2.8	n.a.	n.a.	n.a.	n.a.	n.a.	165	27	273	19.0	10.0
Hong Kong	123	10	4	0.7	1.2	54	4	9	11	0.5	2.7	1.6	0.01	-	0.03	30	5	50	3.5	1.8
Jordan	166	13	5	1.1	1.6	1	1	2	2	0.1	1.9	1.1	0.01	-	0.02	29	5	49	3.4	1.7
Africa																				
Tunisia	413	32	13	2.6	4.1	60	43	96	119	5.8	0.3	0.2	-	-	-	1	-	1	0.1	-
South Africa	1600	125	50	10.0	16.0	43	31	70	86	4.3	50.0	30.0	0.20	0.07	0.60	34	57	567	41.0	20.0
Latin America																				
Colombia	44	32	13	2.6	4.1	20	15	32	40	2.0	n.a.	n.a.	n.a.	n.a.	n.a.	71	12	117	8.4	4.2
Chile	41	32	13	2.6	4.0	3	2	5	6	0.3	n.a.	n.a.	n.a.	n.a.	n.a.	24	4	40	3.0	1.4
Argentina	1080	84	34	6.7	10.0	15	11	24	30	0.1	n.a.	n.a.	n.a.	n.a.	n.a.	203	33	335	24.0	12.0

n.a. = not available
- = negligible

Table 24. Annual aggregate transport emissions in selected countries, 1988 (in '000 tons)

	CO	HC	NOx
OECD Countries			
USA	47,700	7,200	8,800
Germany	5,330	624	1,692
UK	8,327	535	546
Asia			
Thailand	403	71	92
Jordan	198	20	56
South Korea	491	70	339
Hong Kong	210	21	63
Africa			
Tunisia	474	75	110
South Africa	1,727	243	687
Latin America			
Colombia	135	59	162
Chile	68	38	58
Argentina	1,298	128	393

Source: OECD countries; [OECD 1987], data for 1983.
Other countries; estimates from Table 23.

Table 25. Estimated motorized trips in selected metropolitan areas in developing countries

City	Motorized Trips per day (in millions) 1980	2000
Bangkok	4.50	11.52
Bombay	5.25	17.69
Calcutta	10.13	18.30
Hong Kong	5.60	6.46
Jakarta	3.38	14.48
Karachi	7.13	13.03
Seoul	11.63	15.09
Bogota	3.38	6.65
Mexico City	19.88	29.10
Rio de Janerio	9.78	14.50
Sao Paulo	14.25	26.98
Cairo	3.88	12.01
Nairobi	0.56	2.79
Tunis	0.44	1.60

Table 26. Estimated pollutant emissions by passenger cars and buses in selected cities (in metric tons per day)

	1980					2000				
Cities	CO	HC	NOx	SO_2	PM	CO	HC	NOx	SO_2	PM
Bangkok										
Auto	265	21	8	1.7	1.9	678	53	21	4.2	5.0
Bus	184	24	16	4.1	1.4	471	60	41	11.0	4.0
Bombay										
Auto	159	13	5	1.0	1.1	535	42	17	3.3	4.0
Bus	278	35	22	3.3	1.9	936	117	73	11.0	6.5
Jakarta										
Auto	153	12	5	1.0	1.1	658	48	20	4.0	4.7
Bus	1	1	2	2.6	0.1	6	4	9	11.0	0.6
Karachi										
Auto	120	9	4	0.1	1.0	219	17	7	1.4	1.6
Bus	522	66	41	6.7	3.6	955	119	75	15.0	6.6
Seoul										
Auto	470	37	15	3.0	3.0	609	47	19	3.9	4.3
Bus	6	4	10	12.0	0.6	8	6	13	16.0	0.8
Bogota										
Auto	85	7	3	0.5	0.6	168	13	5	1.0	1.2
Bus	2	2	3	4.1	0.2	4	2.9	7	8.0	0.4
Mexico City										
Auto	635	50	20	4.0	4.5	931	73	29	6.0	6.6
Bus	1054	133	86	17.5	7.5	1543	195	126	26.0	11.0
Rio de Janeiro										
Auto	427	33	13	2.7	3.1	634	50	20	3.9	4.5
Bus	84	13	13	9.4	1.0	124	19	19	14.0	1.4
Cairo										
Auto	195	15	6	1.0	1.4	606	47	19	3.8	4.3
Bus	2	2	3	4.0	0.2	6	5	10	13.0	0.6
Nairobi										
Auto	43	3	1	0.3	0.3	211	17	7	1.3	1.5
Bus	34	4	3	0.3	0.2	170	21	13	1.7	1.2

Note:
1. 'Auto' includes taxis; 'bus' includes paratransit vehicles.
2. Emission estimates for 1980 and 2000, based on assumptions and procedures given in Box 3, are intended to show the massive increase in pollutant emissions from motor vehicles over the 20-year period without emission controls. The actual emission levels may be significantly different from these estimates.

Table 27. Estimated pollutant emissions by passenger cars and buses in Munich, 1995-2000 (in metric tons)

Pollutant	Passenger Cars		Buses	
	Annual	Daily	Annual	Daily
Carbon monoxide	71535.8	195.98	262.1	0.72
Hydrocarbons	6935.5	19.00	31.4	0.09
Nitrogen oxides	3296.9	9.03	122.3	0.34
Sulfur oxides	178.3	0.48	43.7	0.12
Lead deposits	31.1	0.08	15.5	0.04

Note: Daily estimates obtained by dividing annual estimates by 365.
Source: [OECD 1988b]

VI. MOTOR VEHICLE EMISSION STANDARDS AND COMPLIANCE EXPERIENCE

Design of a comprehensive motor vehicle pollution control program begins with establishing standards for permissible levels of exhaust and evaporative emissions from motor vehicles. These standards should be based on a realistic assessment of costs and benefits keeping in view the technical and administrative feasibility of proposed countermeasures. The most practical approach to reducing emissions is to improve engine fuel efficiency. The less fuel burned, the fewer the emissions. Care must be exercised that measures to increase power plant efficiency are not achieved through the use of harmful and toxic fuel additives such as tetraethyl lead (TEL). Other countermeasures to achieve desired emission standards may include fitting new vehicles with emission control devices such as catalytic converters or particulate traps or requiring such devices to be retrofitted to existing vehicles (Chapter VII), modifying fuels or requiring the use of alternative fuels in certain vehicles (Chapter VIII), and traffic management and policy instruments (Chapter IX). These countermeasures must be buttressed with effective enforcement to ensure maximum compliance with standards.

Standards for Gasoline-Fueled Vehicles

Advances in automotive technologies have made it possible to dramatically lower emissions from motor vehicles. Initial crankcase HC controls were first introduced in the early 1960s followed by exhaust CO and HC standards later that decade. By the mid-1970s, most major industrial countries had initiated programs to control motor vehicle emissions. For a variety of reasons -- the nature and magnitude of air pollution problems, vehicle characteristics, economic conditions -- approaches to vehicle emission control have differed significantly among countries. Use of the existing state-of-the-art emission control technologies can substantially lower emissions from mobile sources. For example, automobile emissions in the United States currently are less than 20% of the hydrocarbons and carbon monoxide emitted by the uncontrolled vehicles of the 1960s.

During the mid to late 1970s, advanced emission control technologies were introduced on most new cars in the United States and Japan. These technologies resulted from a conscious decision to force the development of new approaches and were able to dramatically reduce CO, HC, and NOx emissions. The evolution of exhaust emission limits in the United States and Japan is traced in Tables 28 and 29. As knowledge of these technological developments spread, and as the adverse effects of motor vehicle pollution became more widely recognized, more and more countries began using these systems. During the mid 1980s, Austria, the Netherlands and the Federal Republic of Germany adopted innovative economic incentives to encourage purchase of low pollution vehicles. Since then, Australia, Austria, Canada, Denmark, Finland, Norway, Sweden, and Switzerland have all adopted mandatory requirements. Among developing countries, Brazil has established emission limits for vehicles running on alcohol and gasoline

Table 28. USA: exhaust emission control history for new gasoline-powered automobiles

	U. S. Federal pollutant standard (g/km)[a]		
Year	CO	HC	NOx
Uncontrolled	54	5.4	2.5
1968	32	3.7	3.1
1970	21	2.4	3.1
1972	17	1.9	3.1
1973	17	1.9	1.9
1974	17	1.9	1.9
1975	9.3	0.9	1.9
1977	9.3	0.9	1.2
1980	4.4	0.25	1.2
1983	2.1	0.25	0.6 (0.9)[b]

a) Applicable at 80,000 km.
b) Applicable at 100,000 km.
Source: [OECD 1988a, pp. 89]

Table 29. Japan: Exhaust emission control history for new gasoline-powered automobiles

	Pollutant standard[a]			Measurement	Test
Year	CO	HC	NOx	Unit	Cycle
1966	3	-	-	%	4 mode
1969	2.5	-	-	%	4 mode
1973	26.0	3.8	3.0	g/km	10 mode
1975	2.7[b]	0.39	1.6	g/km	11 mode
	85.0	9.5	11.0	g/test	11 mode
1976	2.7	0.39	1.20	g/km	10 mode
	85.0	9.5	9.0	g/test	11 mode
1978	2.7	0.39	0.48	g/km	10 mode
	85.0	9.5	6.0	g/test	11 mode

a) Applicable to all new model vehicles that are greater than 1000 kg equivalent inertia weight.
b) The figures show the maximum permissible limits of the standards applicable at 30,000 km durability and apply to new model vehicles only.
Source: [OECD 1988a, pp. 89]

Table 30. Brazil: emission standards for alcohol and gasoline-powered motor vehicles

			Emission Limits (g/km)		
Type of Emission	Effective Date	Remarks	CO	HC	NOx
Exhaust	Jan. 1st, 88	Brand new vehicle configurations	24.0	2.1	2.0
	Jan. 1st, 89	50% of sales is the minimum required	24.0	2.1	2.0
	Jan. 1st, 90	100% of sales except light duty trucks	24.0	2.1	2.0
	Jan. 1st, 92	Only light duty trucks	24.0	2.1	2.0
	Jan. 1st, 92	100% sales except light duty trucks	12.0	1.2	1.4
	Jan. 1st, 97	All light duty vehicles	2.0	0.3	0.6
Evaporative	Jan. 1st, 90	All light duty vehicles	-	(g/test) 6.0	-
Crankcase	Jan. 1st, 88	All light duty vehicles	emission shall be nil under any engine operating condition		

Source: [Szwarc and Branco 1987, pp. 24]

Table 31. Mexico: emission standards for gasoline-powered motor vehicles

Remarks	Emission Standards in g/mile		
	HC	CO	NOx
'89 Automobiles, no trucks	3.20	35.2	3.68
'90 Automobiles	2.88	28.8	3.20
GVW up to 6012 lbs[a]	3.20	35.2	3.68
GVW 6013 - 6614 lbs[b]	4.80	56.0	5.60
'91 Automobile	1.12	11.2	2.24
GVW up to 6012 lbs[a]	3.20	35.2	3.68
GVW 6013 - 6614 lbs[b]	4.80	56.0	5.60
'92 Automobiles	1.12	11.2	2.24
GVW up to 6012 lbs[a]	3.20	35.2	3.68
GVW 6013 - 6614 lbs[b]	3.20	35.2	3.68
'93 Automobiles	0.40	3.4	1.00
GVW up to 6012 lbs[a]	3.20	35.2	3.68
GVW 6013 - 6614 lbs[b]	3.20	35.2	3.68
'94 Automobiles	0.40	3.4	1.00
GVW up to 6012 lbs[a]	1.00	14.0	1.00
GVW 6013 - 6614 lbs[b]	1.00	14.0	1.00

a) Commercial vehicles (i.e., van & combis)
b) Light duty trucks
Source: [Walsh June, 1988]

(Table 30). In 1989, Mexico also introduced emission standards for light-duty vehicles (Table 31). Taiwan promulgated emission standards for new model automobiles in July 1987, based on standards enforced in Europe; it was further intended that by 1990, all new model automobiles would meet the more stringent 1983 U.S. standards (see Table 28). In addition, first-stage emission standards have been in effect for motorcycles since January 1988 (CO 8g/km; NOx + HC 5.5 g/km); second-stage standards to come into effect in July 1991 would be 50% lower than these limits [Shen and Huang 1989]. Republic of Korea is also known to have stringent emission regulations.

Standards for Diesel-Fueled Vehicles

Because of the problems associated with diesel smoke and particulates, control programs for diesel-fueled vehicles have been in progress for many years [Clavel and Walsh 1984]. In general, the initial focus was on smoke control because it was clearly visible and a nuisance. As evidence has grown regarding the serious health and environmental risks of diesel exhausts, more attention has focused on control of the particulates themselves.

United States

Emission control requirements for smoke from heavy duty trucks and buses were first implemented in the United States for the 1970 model year. These opacity standards were specified in terms of the percentage of light blocked by the smoke in the diesel exhaust, as determined by a light extinction meter. Heavy-duty diesel engines produced during model years 1970 through 1973 were allowed a light extinction of 40% during the acceleration phase of the certification test and 20% during the lugging portion; 1974 and later model years are subject to smoke opacity standards of 20% during acceleration, 15% during lugging, and 50% at maximum power.

The first diesel exhaust particulate standards were established for automobiles and light trucks by the U.S. EPA in March 1980. Standards of 0.6 grams per mile (0.37 g/km) were set for all automobiles and light trucks starting with the 1982 model year, dropping to 0.2 grams per mile (0.12 g/km) and 0.26 (0.16) for 1985 model year automobiles and light trucks, respectively. In early 1984, the U.S. EPA delayed the second phase of the standards from 1985 to 1987 model year to provide more time for manufacturers to comply. Almost simultaneously, California decided to adopt its own diesel particulate standards -- 0.4 grams per mile (0.25 g/km) in 1985, 0.2 (0.12) in 1986 and 1987, and 0.08 (0.05) in 1989.

Particulate standards for heavy-duty diesel engines were promulgated by the U.S. EPA in March, 1985. Standards of 0.60 grams per Brake-Horsepower-Hour (gm/bhph) or 0.80 grams per kilowatt-hour were adopted for 1988 through 1990 model years, 0.25 (0.34) for 1991 through 1993 model years, and 0.10 (0.13) for 1994 and later model years. Because of the special need for bus control in urban areas, the 0.10 (0.13) standard for these vehicles will go into effect in 1991, three years earlier than for heavy duty trucks. However, at the request of General Motors

(GM), the U.S. EPA revised the 0.26 grams per mile (0.16 g/km) diesel particulate standard for certain light duty trucks. Light duty diesel trucks (LDDTs) with a loaded vehicle weight of 3,751 pounds or greater were required to meet a 0.50 gpm (0.31 g/km) standard for 1987 and 0.45 gpm (0.28 g/km) level for 1988-1990. For the 1991 and later model years the standard would be tightened to 0.13 gpm (0.08 g/km).

Canada

In March 1985, in parallel with a significant tightening of gaseous emissions standards, Canada adopted the U.S. particulate standards for automobiles and light trucks (0.2 and 0.26 gpm, respectively) to go into effect in 1988. Since then, Canada has adopted U.S. standards for heavy-duty vehicles for 1988 as well. Canada intends to closely monitor developments in the United States as 1991 approaches; if technology advances sufficiently, and if the United States retains its existing standards, it appears likely that Canada will adopt them.

Japan

Japan does not currently regulate exhaust particulate emissions from diesel engines. However, smoke standards have applied to both new and in-use vehicles since 1972 and 1975, respectively. The maximum permissible limits for both are 50% opacity; the new vehicle standard, however, is more stringent because smoke is measured at full load, while in-use vehicles are required to meet standards under the less severe no-load acceleration test.

European Community (EC)

Smoke limits similar to those for the United States and Japan have been in effect in Europe for many years. Exhaust smoke levels are currently recommended by ECE Regulation 24 (equivalent to EEC Directive 72/306). Measurements are taken using light absorption type apparatus. However, recognizing that these requirements were not adequate, the Environmental Ministers of the European Community decided in December 1987 to adopt a particulate standard for light duty diesels, 1.1 grams per test (1.4 for conformity of production). In addition, the Ministers ordered the Commission to develop a second step proposal by the end of 1989, which would lower particulates to 0.8 (1.0 for conformity of production) unless it was determined that such levels were technically or economically infeasible. Approximate conversion rates between the U.S. and ECE tests are summarized in Table 32. As of 1989 there was no particulate emission legislation in force for heavy-duty diesel vehicles in the EC.

Table 32. Conversion between U. S. and ECE Tests

US Federal test procedures grams/mile	ECE test procedure grams/test
0.6	1.8
0.2	0.6
0.08	0.24

Other Western European Countries

Several other European countries have been cooperatively moving toward more stringent diesel particulate requirements. Sweden has already adopted the U.S. automobile standard to go into effect in 1989 and Switzerland and Austria are likely to do so in the near future. In Austria, a maximum permissible limit for particulate emissions of 0.373 g/km is already prescribed.

These countries are also considering more stringent requirements for trucks and buses. Sweden has announced its intention to adopt standards that will bring about the same degree of control as the U.S. by 1995. Specifically, the U.S. 1990 requirements (including diesel particulate) will be adopted by Sweden on a voluntary basis for 1990 light duty trucks, but will be made mandatory by 1992. Regarding heavy trucks, Sweden aims to introduce similar emission control technology and standards as in the U.S. The standards will be voluntary from 1991 but mandatory starting in 1995. In May 1988 Switzerland introduced new emission standards for heavy duty vehicles to go into effect on 1 October 1991; they include standards for CO, NOx, VOC, and particulates. The standards, based on the European Regulation ECE R 49, are summarized in Table 33.

Table 33. Emission control standards adopted by Switzerland

Pollutant	Current Standards (as of Oct. 1, 1989)		New Standards (by Oct. 1, 1989)	
CO	8.4	g/kWh	4.9	g/kWh
VOC	2.1	g/kWh	1.23	g/kWh
Nox	14.1	g/kWh	9.0	g/kWh
Particulates	---	g/kWh	0.7	

Compliance with Standards

A comprehensive compliance program should cover both new and in-use vehicles. It should assure that attention to emission standards is paid at the vehicle design stage before mass production begins. It should also ensure quality assurance on the assembly line. And through an enforceable warranty and recall system it should deter manufacture of non-conforming vehicles. Furthermore, vehicle owners should be encouraged to carry out maintenance on emission control devices as required by the manufacturer, and the service industry regulated to perform this maintenance properly. A comprehensive compliance program should include the items outlined in the following sections.

Certification or Type Approval

Most countries require some form of certification or type approval by vehicle manufacturers to demonstrate that each new vehicle sold is capable of meeting applicable emission standards. Usually, type approval requires emission testing of prototype vehicles representative of planned production vehicles; sometimes this will also require a mileage accumulation period of up to 80,000 kilometers (50,000 miles) to demonstrate that the vehicle emission control systems are durable. Mileage accumulation, maintenance, and testing are normally conducted by the vehicle manufacturers but national testing authorities will occasionally test some certification vehicles on a spot check basis.

The advantage of a certification program is that it can influence vehicle design before mass production. Obviously, it is more cost-effective if manufacturers identify and correct problems before production actually begins. As a practical matter, the certification process deals with prototype cars (sometimes almost hand-made) in an artificial environment (very careful maintenance, perfect driving conditions, with well-trained drivers using ideal roads or dynamometers). As a result, vehicles that fail to meet emission standards during certification will almost certainly fail to meet standards in use; the converse, however, is not true, i.e., it cannot be said with confidence that vehicles that pass certification will inevitably perform well in use.

Assembly Line Testing

The objective of assembly line testing is to enable national authorities to identify certified production vehicles that do not comply with applicable emissions standards, to take remedial actions (such as certification revocation or recall) to correct the problem, and to discourage the manufacture of noncomplying vehicles.

Assembly line testing provides an additional check on mass-produced vehicles to assure that the designs found adequate in certification are satisfactorily translated into production and that quality control on the assembly line is sufficient to provide reasonable assurance that cars in use will meet standards. The major advantage of assembly line testing over certification is that it measures emissions from "real" production vehicles. However, a substantial and inevitable shortcoming of an assembly line testing program is that it provides no measure of vehicle performance over time or mileage.

Recall or Conformity of Production

A recall program is invoked on the basis of emissions from "in-use" vehicles driven by consumers in the "real" world and is the ultimate test of how well manufacturers have designed and built durable emission controls. The primary purpose of the recall program is to provide an incentive to manufacturers to design and build vehicles properly so that the costs and burdens of recalls are avoided. No estimate can be made regarding how many potential violations are prevented by this measure, but the high cost and adverse publicity of recalls no doubt have encouraged manufacturers to design systems with an extra margin of safety.

Recall programs have had their difficulties, however. For example, in the United States, on average, only 55% of the vehicles recalled are actually brought in by their owners for repair. The lag time between identification of a nonconforming class and the manufacturer's recall notice has sometimes been well over a year. Mandatory recalls are possible only when a substantial number of vehicles in a class or category exceeds standards; this may preclude recalls of serious but less frequent failures.

Warranty

Warranty programs are intended to provide effective recourse to consumers against manufacturers when individual vehicles do not meet in-use standards, and as importantly to discourage the manufacture of such vehicles. Warranties attempt to assure that defects in design or workmanship that result in high emissions are remedied.

Inspection and Maintenance (I/M)

The inspection and maintenance program usually consists of a periodic emissions test of in-use vehicles, and is intended to detect and bring about the repair of in-use vehicles with excessive emission levels. A key objective is to encourage proper vehicle maintenance so as to maximize the benefits the public realizes from the emission controls installed on the vehicles.

Inspection and maintenance has a prominent role in many of the most important components of a motor vehicle emission control program. To the extent that I/M identifies vehicles which may be out of compliance, this information can be fed back to the 'Recall' and 'Assembly Line Test' programs to permit the regulatory authorities to focus investigations and test orders on the most critical vehicles. The I/M program helps to identify equipment defects and failures covered by vehicle warranty schemes. It is also a key element of measures designed to discourage or prevent tampering with emission controls or misfueling; the threat of inspection failure is considered a strong deterrent. Without effective I/M programs, compliance with standards is significantly weakened.

Onboard Diagnostics

The intent of an onboard diagnostic (OBD) system is to minimize the large increases in exhaust emissions when emission-related malfunctions occur in in-use vehicles equipped with three-way catalysts and feedback fuel control systems. Vehicles equipped with electronic engine controls incorporate a backup set of engine operating parameters in the on-board computers to maintain adequate vehicle driveability and performance characteristics in the event of a malfunction in the vehicle's emission control system (ECS). The vehicle operator may thus be totally unaware of an ECS malfunction since driveability is retained and the vehicle continues to operate under high emitting conditions. An OBD system visually alerts the operator to any detected malfunction and the need to repair it.

An additional benefit of an OBD system is in assisting the service industry to quickly and properly diagnose and repair malfunctions in the vehicle's ECS. Since the OBD system is an integral part of the vehicle's power plant, it senses computer electronic signals under a variety of vehicle operating speed and load modes and can thus detect and store intermittent faults which are very difficult to duplicate in the service garage. The OBD system also provides a relatively easy means for inspecting vehicles under the I/M program by simply monitoring the malfunction indicator lights.

Retrofit

Another approach to lowering in-use vehicle emissions is to retrofit vehicles with emission control devices. Several urban localities in the United States and Europe have evaluated retrofit controls on existing urban bus fleets and found it an attractive option as the public response to particulates from urban buses is high and it will be well into the next century before controls on new buses will have their full impact. Active test programs including hardware demonstrations are underway in several cities including Athens, Denver, Philadalphia, New York, and Toronto.

The most aggressive retrofit effort in recent times has been undertaken in the Federal Republic of Germany over the past few years. This program encourages retrofit installations on vehicles through tax incentives and has been a modest success. An approximate estimate of the overall reduction as a result of the program has been about 25,000 tons of CO, 3,000 tons of HC, and 4,200 tons of NOx.

Experience with Vehicle Inspection and Maintenance Programs

International Status of I/M Programs

Inspection and maintenance programs to reduce emissions have been an integral element of air pollution control programs in many industralized countries. The I/M program in the United States is administered by the states and consists of a periodic emission test of in-use vehicles. I/M has been required as a part of the State Implementation Plans (SIP) for those states unable to achieve compliance with the CO or ozone air quality standards. The history of motor vehicle emission standards in Japan including those for in-use vehicles, is similar to that of the United States. The Japanese inspection programs for CO have been in effect since 1970 and HC measurements and limits were added in 1975.

In Canada, the authority for regulating new vehicle emissions is restricted to the Federal authorities, whereas the provinces exercise control over in-use vehicles. Ontario, British Columbia, and several other provinces are currently in the process of evaluating various options of I/M programs for in-use vehicles in conjunction with safety inspection programs. One of the issues is whether the program would be voluntary or mandatory; some of the factors against a mandatory program in the sparcely-populated territories are:

- high costs of travel for inspection;

- anticipated negative public response to mandatory inspection; and
- possible lack of qualified personnel to perform inspection in some communities.

Sweden conducts an annual I/M program limited to measurement of CO emissions at idle with very lenient cut-off points or standards. However, a more comprehensive but non-sophisticated I/M program is being evaluated for implementation. The Federal Republic of Germany (FRG) has required biennial inspection of automobiles for many years. Recently, the program was expanded to an annual test. As the FRG introduces more and more rigorous emission standards with increased use of catalyst technology, it is evaluating a variety of techniques to improve its I/M test requirements. The FRG program, if finally implemented, will likely serve as a model for other European countries, especially for countries interested in reducing NOx and diesel particulate emissions. In Austria, all cars are currently subject to an annual safety and CO emission inspection. Since 1986, a manadatory I/M program has been in effect in Switzerland. This program requires compulsory testing at least once a year and it is administered by the local cantons.

In Singapore, cars are presently tested for idle CO and HC, but there is no requirement to pass the test because the Transport Ministry is not yet convinced that the I/M program can be implemented effectively. The test standards are quite lenient (800 ppm HC and 4.5% CO). Diesel smoke testing is carried out using the free acceleration test; mobile vans are employed by the police who stop smoking vehicles and administer a Hartridge smoke test. If the vehicle fails to meet a standard of 50 Hartridge Smoke Units (HSU), compared to 60 HSU in Hong Kong, the owner must pay a fine and repair the vehicle. In 1989, the government announced an increase in the fine for vehicles which fail, from Singapore $40 to $100. If the smoke level exceeds 85, the driver and owner must go to court and face the potential of higher penalties at the discretion of the judge. At a level of 70 and above, the vehicle cannot be driven until it is repaired.

The Republic of South Korea has an active air pollution control program including a system of random roadside inspections. As part of a study on motor vehicle pollution control, a task force has been organized to develop a set of recommendations to improve I/M. It should be noted that while currently there is an I/M program in place, the pass/fail standards are lax.

In Taiwan, random roadside inspections have been implemented by the local EPA bureaus. The number of violations dropped from 25.5% of vehicles tested in 1986 to 19.2% in 1988. A free motorcycle emissions test and maintenance program has also been promoted. In large cities buses are tested free of charge. The Environmental Protection Administration in Taiwan intends to set up state of the art government vehicle inspection and maintenance stations throughout the island. In addition testing licenses will be issued to qualified privately-owned garage stations.

In India the development of the first stages of a vehicle pollution control program have been completed. Major elements include:

- idle CO emissions limit for all 4-wheel gasoline-driven vehicles shall not exceed 3% by volume;

- idle CO emissions limit for all 2- and 3-wheel gasoline-driven vehicles shall not exceed 4.5% by volume;

- smoke density for diesel vehicles shall be restricted to 75 HSU at full load, 60 and 70% of maximum rated engine speed, for type approval; on the road, the limit on the free acceleration test is 65 HSU or equivalent.

The above standards went into effect on October 1, 1989. By April 1, 1991, automobile standards roughly equivalent to the EEC R 15-04, but tailored to Indian driving conditions will go into effect. Similarly, diesel vehicle requirements will be tightened at that time [Walsh and Karlsson 1990].

Thailand has a very modest vehicle pollution control program, including roadside checks of smoking diesel vehicles by the police. No I/M requirements exist for automobiles at present but plans exist to introduce idle test standards in the future.

In an effort to address the diesel particulate problem in Hong Kong, smoke observer teams issue citations to smoking vehicles, requiring such vehicles to report to a central testing station for instrumented (Hartridge) tests. Vehicles which fail must obtain necessary repairs or face fines. In addition, a large automated inspection facility is expected to open by September 1990. At that time, annual inspections will be required for all goods vehicles (currently only those over 11 years old are tested), taxis, and buses. Private cars at present are only tested for roadworthiness in private garages if they are six years old or more but this has very little if any impact on emissions.

In Philippines, the diesel smoke control has three key elements: information, education, communication -- coupled with strong enforcement. Teams operate on key routes in Metro Manila and on the basis of Ringlemann chart readings issue citations and strip offending vehicles of their registration plates. To reclaim their plates, vehicles must be presented to the central testing facility for a more technically sound Hartridge instrument test. This test must be passed (67 HSU or less) to avoid a fine (200 pesos for the first failure, 500 for the second and 1000 for the third). The citation rate has risen to 5000 vehicles per month. Vehicles passing this test still emit visible smoke because the limits are so lenient [Walsh and Karlsson 1990].

In many developing countries, weak administrative and regulatory arrangements could result in massive evasion of I/M programs or worse lead to corrupt practices on part of I/M officials and inspectors. In general, the experience with enforcement of traffic and safety regulations in developing countries is not encouraging and I/M programs for vehicle emission control may prove equally ineffective [Harral 1990].

Emission Improvements and Fuel Economy

Based on U.S. data, it is estimated that a well run I/M program is capable of significant emissions reductions, on the order of 25% for HC and CO and about 10% for NOx. The NOx reductions are less significant and are mostly the result of lower tampering rates, as at present there has been no focused effort to specifically design I/M programs to identify and correct NOx problems. If FRG proceeds with implementation of its low-NOx I/M proposal, it will be the first major exception.

It is important to note that emission reductions start out slowly and gradually increase over time because I/M programs tend to retard the overall deterioration rate of fleet emissions. Maximum benefits are achieved by adopting the I/M program as early as possible.

Fuel savings have been attributed to improved vehicle maintenance practices associated with an effective I/M program. Values reported in the literature range from 0 - 7%. In calculating cost effectiveness the U.S. EPA uses a figure of 3.5%.

Impact On Tampering and Fuel Switching

Over the last few years, the U.S. EPA has been collecting data on the occurrence of tampering and misfueling to assess the magnitude of the problem as these activities can increase hydrocarbon emissions tenfold and carbon monoxide emissions twentyfold. As a result, it would only take a small percentage of the vehicles with these problems to greatly increase average fleet emissions. Surveys by the U.S. EPA have shown that nearly one in five vehicles had at least one emission control disablement and that a significant number of vehicle owners switched fuels. Fortunately, many European countries have adopted tax policies which make prices of unleaded gasoline equal to or less than leaded variety; this should restrain the tendency for fuel switching which occurred in the United States.

Investigations by the U.S. EPA suggest that I/M programs can significantly reduce tampering and misfueling rates (Table 34). With the exception of Exhaust Gas Recirculation (EGR) system disablements, I/M can cut tampering and misfueling rates virtually in half. As I/M programs in the United States have mostly addressed HC and CO problems, it is not surprising that these programs had no significant effect on tampering of EGR systems, which are designed to reduce NOx emissions. By minimizing tampering and misfueling of newer model cars which use catalysts to control NOx emissions, I/M programs should prove effective in reducing NOx emissions. Tampering surveys conducted by various state agencies in the United States suggest that older vehicles exhibit higher rates of tampering than newer vehicles. Furthermore, the underhood visual inspection portion was found to be effective in identifying many elements of a vehicle emission control system which may have been tampered with or modified.

Table 34. **Tampering and misfueling rates - 1982**

Type	No I/M	With I/M	Percent change
Overall tampering	16.7%	13.9%	-17%
Catalytic converter	4.4%	1.7%	-61%
Inlet restrictor	5.9%	3.1%	-47%
Air pump System	4.6%	2.3%	-50%
Exhaust Gas Recirculation System	9.8%	10.1%	+3%
Fuel Switching	15.1%	6.2%	-59%

Costs

There are *two* major costs associated with an I/M program, the cost of operating the program, which generally applies to all inspected vehicles since it tends to be a function of the total number of vehicles examined, and repair cost which only applies to vehicles which fail the inspection test. There are wide variations in the operating costs of I/M programs, which is to be expected since local conditions, such as land and labor costs, existence of safety inspection stations, and the type of inspection carried out can be quite variable.

In general, a centralized program is likely to have higher start-up costs than a decentralized program. This can be attributed to the costs associated with constructing centralized inspection stations. For example, in Maryland (USA), a private contractor was selected through a competitive bidding process to construct ten new inspection stations, with an average of five lanes each, to inspect approximately 1.6 million vehicles annually. The contractor retained US$7.50 of the US$9 inspection fee to recoup his investment in inspection stations and to cover his operating costs while US$1.50 was returned to the state to cover the administrative costs of the program. In some instances, implementation of a centralized program may not result in high construction costs. In New Jersey (USA), the emission testing program was incorporated as part of an existing, centralized safety inspection program, thus avoiding the cost of constructing completely new facilities.

Decentralized, garage-type programs are less costly than centralized programs but are usually not as effective in reducing emissions, especially without sealed and computerized analyzers. Cost elements include:

- licensing procedures for numerous inspection stations;
- certification of repair facilities;

- emission test equipment;
- audit vehicles; and
- program management (data processing, quality assurance, public information, training, supplies, etc.).

Historical repair cost data are available from several functioning I/M programs in the United States and these results are summarized in Table 35. A major difficulty in obtaining reliable and accurate repair cost data is related to non-uniform reporting methods and the inability to segregate the costs of I/M related repairs. Finally, an important factor which can substantially distort repair costs is the warranty coverage provisions which can require the vehicle manufacturer to pay for all repairs necessary to pass the I/M test. The warranty coverage remains in effect, however, under the condition that the vehicle has not been tampered with or misused, and that the vehicle owner follows the maintenance practices prescribed by the manufacturer.

Table 35. Average cost of repairs associated with I/M programs in the United States

I/M Program	Period Covered	Average Repair Cost (US$)
New Jersey	1979	$28.00
	1980	18.71
Arizona	1979	30.00
	1980	29.74
Portland	1980	17.00
	1986	50.68
California	1979	32.00
	1980 (July-Sept.)	29.09
	1980 (Oct.-Dec.)	28.82
Washington, D.C.	1985	95.00
EPA	1986	
Pre-1981 Vehicles		37.50
1981+ under 50,000 miles		47.50
1981+ over 50,000 miles		55.00

VII. VEHICLE EMISSION CONTROL TECHNOLOGY

Gasoline-Fueled Vehicles

Before emission controls were mandated, fumes from the engine crankcase were vented directly into the atmosphere. *Crankcase emission* controls involved closing the crankcase vent port, and were introduced on new automobiles in the early 1960s. Control of these emissions is no longer considered a significant technical issue.

Evaporative emissions of hydrocarbons result from distillation of fuel in the carburetor float bowl and evaporation of fuel in the gas tank. The control of these emissions generally requires feeding the HC vapors back into the engine to be burned along with the rest of the fuel. When the engine is not in operation, vapors are stored, either in the engine crankcase or in charcoal canisters, which absorb these emissions to be burned off when the engine is started.

By far the most difficult emission control problem is the one related to *vehicle exhaust emissions*. Fortunately, much progress has been made during the last decade in the development of control technologies which are capable of dramatic reductions in the exhaust pollutants. These involve the physics of combustion, changes in engine design, and exhaust treatment devices.

Combustion and Emissions

Emissions of hydrocarbons, which include thousands of different chemical compounds, are largely the result of incomplete combustion of the fuel. The amounts emitted are related to the air/fuel mixture inducted, the peak temperatures and pressures in each cylinder, whether lead is added to the gasoline, and such hard to define factors as combustion chamber geometry.

The oxides of nitrogen are generally formed during conditions of high temperature and pressure and excess air (to supply oxygen). Peak temperatures and pressures are affected by a number of engine design and operating variables and so are the concentrations of nitrogen oxides in the exhaust.

Carbon monoxide also results from incomplete combustion of the carbon contained in the fuel and its concentration is generally governed by complex stoichiometry and equilibrium considerations. The only major engine design or operating variable which seems to affect its concentration is the air/fuel mixture: the leaner the mixture or the more air per unit of fuel, the lower the carbon monoxide emission rate.

Finally, lead compounds (and their associated scavengers) are exhausted by an automobile almost directly in proportion to the amount of fuel used by a vehicle and the concentration of lead in it.

Engine Design Parameters

Certain engine design parameters are capable of inducing significant changes in emissions. Most notable among these are air/fuel ratio and mixture preparation, ignition timing, and combustion chamber design and compression ratio.

Air/Fuel Ratio and Mixture Preparation

The air/fuel ratio has a significant effect on all three major pollutants (CO, HC and NOx) from gasoline engines. In fact, CO emissions are almost totally dependent on air/fuel ratio whereas HC and NOx emissions rates can be strongly influenced depending on other engine design parameters. CO emissions can be dramatically reduced by increasing air/fuel ratio to the lean side of stoichiometric. HC emissions can also be reduced significantly with increasing air/fuel ratio, until flame speed becomes so slow that pockets of unburned fuel are exhausted before full combustion occurs or, in the extreme, misfire occurs. Conversely, NOx emissions increase as air/fuel mixtures are enleaned up to the point of maximum or peak thermal efficiency; beyond this point, further enleanment can result in lower NOx emission rates.

Ignition Timing

Ignition timing is the second most important engine control variable affecting "engine out" HC and NOx from modern engines. When timing is optimized for fuel economy and performance, HC and NOx emissions are also relatively high (actual values depending of course on other engine design variables). As ignition timing is delayed (retarded), peak combustion temperatures tend to be reduced thereby lowering NOx and peak thermal efficiency. By allowing combustion to continue after the exhaust port is opened (thereby resulting in higher exhaust temperatures), oxidation of unburned hydrocarbons is greater and overall hydrocarbon emissions are reduced.

Compression Ratio and Combustion Chambers

According to the fundamental laws of thermodynamics, increases in compression ratio lead to improved thermal efficiency and concomitantly increased specific power and reduced specific fuel consumption. In actual applications, increases in compression ratios tend to be limited by available fuel octane quality; over time, a balance has been struck between increased fuel octane values (through refining modifications and fuel modifications, such as the addition of tetraethyl lead to gasoline) and higher vehicle compression ratios.

Compression ratios can be linked to combustion chamber shapes and in combination these parameters can have a significant impact on emissions. Higher surface to volume ratios will increase the available quench zone and lead to higher hydrocarbon emissions; conversely, more compact shapes such as the hemispherical or bent roof chambers reduce heat loss, thus increasing maximum temperatures. This tends to increase the formation of NOx while reducing HC. Further, combustion chamber material and size and spark plug location can influence emissions. In general, because of its higher thermal conductivity, aluminum engine heads lead to lower combustion temperatures and therefore to lower NOx rates, but at the expense of increased HC emissions. Since the length of the flame path has a strong influence on engine detonation and therefore fuel octane requirement, larger combustion chambers which can lower HC emissions tend to be used only with lower compression ratios.

Emission Control Technologies

Tighter emission standards have required more specific attention to the treatment of vehicle exhaust emissions. Commonly used technologies to control exhaust emissions include recirculation of exhaust gases, electronic control of engine performance, exhaust after-treatment devices, and advanced combustion techniques.

With the current state of the art, engine modification alone cannot reduce emissions to the same extent as with a three-way catalyst. Compared to a carburetted engine, an electronically controlled engine equipped with a 3-way catalyst can reduce CO emissions from a mean rate of 7.5 g per km to 1.5 g per km; HC emissions from 1.5 g per km to 0.25 g per km; and NOx from 2.0 g per km to 0.25 g per km. Electronic fuel injection and ignition systems (EFI) without a catalytic converter are effective in reducing CO and HC emissions but have only a minor effect on NOx emissions [ECMT 1990].

Exhaust Gas Recirculation (EGR)

Recirculating a portion of the exhaust gas back into the incoming air/fuel mixture is frequently used as a technique for lowering NOx. The dilution of the incoming charge reduces peak cycle temperature by slowing flame speed and absorbing some heat of combustion.

Charge dilution of homogeneous-charge engines by excess air and/or by exhaust gas recirculation (EGR) has been used for many years. The use of excess air alone results in relatively small NOx reductions, in the order of 35-40%. When EGR is incorporated, substantially higher NOx reductions have been demonstrated. Excessive dilution, however, can result in increased HC emissions, driveability problems or fuel economy losses.

Fuel consumption can be modified when EGR is utilized. Brake specific fuel consumption and exhaust temperature decrease with increasing EGR because dilution with EGR decreases pumping work and heat transfer, and increases the ratio of specific heats of the burned gases. Improvements in mixture preparation, induction systems, and ignition systems can increase dilution tolerance. The latest technique for improving dilution tolerance is to increase the burn rate or flame speed of the air-fuel charge. Dilution can then be increased until the burn rate again becomes limiting. Several techniques have been used to increase burn rate including increased "swirl" and "squish", shorter flame paths, and multiple ignition sources.

Electronics

With so many interrelated engine design and operating variables playing an increasingly important role in the modern engine, the control system has become increasingly important. Modifications in spark timing must be closely coordinated with air/fuel ratio changes and amount of EGR lest significant fuel economy or performance penalties result from emissions reductions or NOx emissions increase as CO goes down. In addition, controls which can be more selective depending on engine load or speed have been found beneficial in preventing adverse impacts.

To meet these requirements, electronics have begun to replace more traditional mechanical controls. The conventional combination of carburettor and distributed ignition systems can now be replaced by electronic fuel injection (EFI) and ignition to provide more precise control [ECMT 1990]. Furthermore, electronic control of ignition timing has been shown to optimize timing under all engine conditions and has the added advantage of reduced maintenance and improved durability compared with mechanical systems. When both ignition timing and EGR are electronically controlled, it has been demonstrated that NOx emissions can be reduced with no fuel economy penalty and in some cases with an improvement.

Exhaust After-Treatment Devices

The use of catalytic converters and thermal reactors, generically known as exhaust after-treatment devices, becomes necessary in order to achieve a quantum reduction in exhaust emissions, beyond those feasible with engine design modifications. The catalyst comprises a ceramic support, a washcoat (usually aluminum oxide) to provide a very large surface area, and a surface layer of precious metals (platinum, rhodium, and palladium are most commonly used) to perform the catalytic function. The catalyst is housed in a metal container forming part of the vehicle exhaust system. For effective operation, the catalyst temperature must exceed the light-off value (about 300° C), which takes one to three minutes to achieve in typical urban driving conditions [ECMT 1990]. The cost of a catalytic converter and its accompanying equipment ranges from US$250 to US$750 per automobile (1981 prices) equivalent to a 4 - 20% increase in the cost of the vehicle [OECD 1988a]. Small inexpensive vehicles bear the brunt of the cost increase in relative terms. These devices can reduce HC emissions by an average of 87%, CO by 85% and NOx by 62% over the life of a vehicle [French 1990].

- Oxidation Catalysts: Quite simply, an oxidation catalyst is a device which is placed on the tailpipe of a car and which, if the chemistry and thermodynamics are properly maintained, will oxidize almost all the HC and CO in the exhaust stream to carbon dioxide and water vapor. Starting with the 1975 model year automobile, catalysts have been placed on upwards of 80% of all new cars sold in the United States. In 1981, they were placed on 100% of the new cars. A major impediment to the use of catalysts is lead in gasoline. Existing, proven catalyst systems are poisoned by the lead in vehicle exhaust. One of the unique advantages of catalysts is their ability to selectively eliminate some of the more harmful compounds in vehicle exhaust such as aldehydes, reactive hydrocarbons, and polynuclear hydrocarbons.

- Three-way Catalysts: So called because of their ability to lower HC, CO and NOx levels simultaneously, they were first introduced in the United States in 1977 by Volvo and subsequently became widely used when the U.S. NOx standard was made more stringent (1.0 grams per mile) in 1981. For three-way catalysts to work effectively, it is necessary to control air/fuel mixtures much more precisely than is needed for oxidation catalyst systems. As a result, three-way systems have indirectly fostered improved air/fuel management systems such as advanced carburetors, throttle body fuel injection, and electronic controls. Three-way catalyst systems also are sensitive to the use of leaded gasoline. An occasional tankful of leaded gasoline will have a small but lasting effect on the level of emitted pollutants.

- Thermal Reactors: They are well insulated vessels with internal baffling to allow several passes of the exhaust gas to maintain high temperature and extend the residence time. They thus promote oxidation of CO and HC emitted from the engine. To maintain high temperatures, they are often used in conjunction with exhaust port liners which reduce heat losses. In spite of this, a major problem with these systems is the difficulty in maintaining exhaust temperatures sufficiently high to promote combustion. Measures to increase exhaust temperatures such as retarded ignition, richer air/fuel ratios or valve timing delays result in increased fuel consumption. Because of these problems, systems of this type have gradually faded from use.

Lean Burn

At one point, it was believed that combustion advances, especially lean burn, might ultimately allow the catalyst to be eliminated. Recent experience, however, indicates that low HC and NOx levels are not attainable across the range of normal driving conditions through the use of advanced combustion technology alone. At least an oxidation catalyst is needed to control HC emissions. Also, under higher speeds and higher load driving modes, such as those reflected in the recently agreed upon European extra urban driving cycle, supplemental NOx control may also be needed. Recent European studies under high speed driving conditions have demonstrated that three-way catalysts are necessary to minimize NOx emissions. In addition, as concern with toxic pollution increases, it appears that lean burn engines would not be as effective as conventional catalyst-equipped engines in lowering polynuclear organics and other noxious compounds from motor vehicle exhausts unless they are also equipped with catalytic converters.

Emission Control and Energy Conservation

Many technologies which exist today and which could be placed on automobiles to improve fuel economy -- e.g., advanced air/fuel management systems such as fuel injection, electronic controls of spark timing, advanced choke systems, improved transmissions -- can also result in significant exhaust emissions benefits. In fact, some of the advances in fuel efficient vehicle power plants were made as a direct result of increasingly tighter emission control requirements. Furthermore, it is likely that in the absence of tight emission requirements these advanced technologies would not have been placed on automobiles. In many cases, once these technologies have been introduced, fuel economy has been even better than when emission requirements were less stringent.

Lead has been added to gasoline as it is an inexpensive way to increase octane values for improved vehicle fuel efficiency. In fact, a halt to the addition of lead to gasoline does entail a small (less than 1% in the United States) fuel penalty at the refinery. However, the greatest potential impact and the one that has generated the most serious debate is the impact on vehicle fuel efficiency - does it improve or deteriorate?

Attainment of the emission standards through 1987 in the United States has been accompanied by improvements in fuel economy, from a sales weighted fleet average of 14.9 miles per gallon (mpg) in 1967 to 27.3 mpg in 1987, an increase of 83%. Correcting for vehicle weight reductions, the improvements compared to pre-controlled cars are still about 47%. The introduction of unleaded fuel and catalytic converters in 1975 coincided with very substantial fuel economy gains. At a minimum, this demonstrates that tight emission standards are quite compatible with substantial fuel economy gains because unleaded gasoline provides design freedom to automotive engineers.

As vehicle technology is pushed harder and harder to achieve low pollution levels, whether it be in Europe, North America or the Pacific Rim, common elements are emerging. First, in every case, the least polluting vehicles is equipped with catalytic converters. As these systems are poisoned by lead and by phosphorous in most engine oils, they inevitably foster the introduction of unleaded gasoline and cleaner engine oils, with the result that overall lead pollution is also reduced. Further, to optimize the effectiveness of these systems, better air/fuel and spark management systems have evolved leading to a much greater use of both electronics and fuel injection. These advances, in turn, increase the prospects of better fuel efficiency and lower CO2 emissions.

Cost of Exhaust Emission Controls

Implementing tighter emission control standards has three cost implications:

- the increased cost of the vehicle, including the cost of additional or more advanced components;

- the increased cost of vehicle maintenance; and
- the cost of additional fuel if emission control measures result in higher fuel consumption.

Estimated increase in the cost of vehicles and changes in fuel consumption for various low-emission engine and exhaust treatment configurations are given in Table 37 [ECMT 1990].

Table 37. The costs to consumers of various emission control technologies

Technologies	Price increase (%)	Fuel consumption increase (%)
Lean burn engine with carburetor and conventional ignition	1.0	-2
Pulsair and EGR	4.5	+3
Lean burn engine with carburetor and programmed ignition	2.0	+1
Recalibrated conventional engine with EFI	8.0	+2
Lean burn engine and EFI	9.0	-7
Lean burn engine oxidation catalyst	4.5	-3
Open loop 3-way catalyst carburettor	4.1	+2
Lean burn engine - closed loop - EFI variable intake system-oxidation catalyst	15.0	-7
Closed loop - EFI - 3-way catalyst	13.0	+3

Baseline = small vehicle, 1.4 litre conventional carburettor engine meeting ECE 15/04 standard.
Source: ECMT [1990]

In the United States, a cost model was developed by U.S. EPA to arrive at estimates of the initial cost paid by consumers to comply with the U.S. emission standards. The cost estimates were based on an analysis of the retail price equivalent of each component in the emission control systems used in gasoline-fuelled vehicles. The list of emission control components on each car was obtained from the Application for Certification submitted to the U.S. EPA by automobile manufacturers. Prices and price estimates were obtained from three sources: a study conducted for U.S. EPA, a price survey of dealer parts departments, and direct request to the manufacturers for parts price information. Based on the above, new automobile price increases as a function of increasingly tighter U.S. emissions standards were estimated and are summarized in Table 36. All emissions standards have been converted to the U.S. 1975 test procedure (CV5-75) along with the U.S. compliance programme.

Table 36. Progression of U.S. emission standards for automobiles (in grams per mile)

Model Year	HC/CO/NOx	Initial cost increase (in 1981 US$)
1968-69	5.9/50.8/N.R.*	30
1970-71	3.9/33.3/N.R.	50
1972	3.0/28.8/N.R.	70
1973-74	3.0/28.0/3.1	100
1975-76	1.5/15.0/3.1	150
1977-79	1.5/15.0/2.0	175
1980	0.41/7.0/2.0	225
1981	0.41/3.4/1.0	350
1990 (proposed	0.25/3.4/0.4 (by 1995/96)	n.a.
legislation)	0.125/3.4/0.2 (by 2003)	n.a.

* N. R. = not required.
n. a. = not available.
Source: U.S. EPA [1988]; OECD [1988a]

Technological Advances on the Horizon

The technology to reduce vehicle emissions continues to evolve and develop. Lower trace lead levels in unleaded gasoline and more advanced emission control components, particularly more durable catalysts, better air fuel management systems, and electronics will be key elements of future control. California (USA), still plagued by severe smog conditions in Los Angeles, continues its worldwide leadership in extending the pollution control requirements. While it already has the most stringent NOx requirements in the world, 0.4 grams per mile, it has indicated its intention also to adopt more stringent hydrocarbon levels as well as extending the mileage over which the standards apply.

More stringent control of passenger cars and light trucks is feasible and is actually being achieved by conventional vehicles, at least at the design stage. This is illustrated by an analysis of 1987 U.S. certification data which shows that the average gasoline-fueled vehicle emitted about 0.2 gpm HC, 1.91 CO, and 0.37 NOx, compared to standards of 0.41, 3.4, and 1.0, respectively.

Based in part on such data and the critical need for more NOx control, the California Air Resources Board (CARB) in 1986 determined that a 0.4 gpm NOx standard for automobiles was necessary, feasible, and cost effective. It adopted this standard, to be phased in starting in 1989 and estimated the costs to be about US$25 to 30 per vehicle. The incremental costs are modest because the technology necessary is basically the same as that needed to achieve 1.0 gpm NOx standard, although calibrations must be modified and precious metal loadings increased in catalytic converters in some cases. CARB has also determined that a 0.25 gpm standard is feasible and cost effective for HC. The incremental cost per vehicle to achieve this standard is estimated at US$25, with an overall cost effectiveness of about US$ 1600 per ton reduction in emissions.

As noted by CARB, the technology, which automobile manufacturers are expected to utilize for lowering non-methane hydrocarbons (NMHC) emissions, includes more durable and efficient close-coupled catalytic converters. These single bed converters are located in or close to the engine exhaust manifold and "light off" quickly to effectively reduce cold start HC [and CO] emissions. The advanced technology fostered by the tighter standards should make it easier to achieve low in-use emission levels. Several organizations have made estimates of the costs associated with these advanced controls as shown in Table 38.

Table 38. Costs associated with advanced vehicle emission controls in the United States (Beyond 0.41 HC and 1.0 NOx standards for 50,000 miles)

	Source of Estimate			
	EPA	CARB (in US$ per vehicle)	OTA[1]	CRS[2]
Automobiles				
0.25 HC	46.75	25	60	
0.40 NOx	36.75	25-30	80	
Light Duty Veh. Full Life[3]	Minor			
Idle Standard[4]	Minor			
10% Air Quality Level[5]	Minor			
No Averaging[6]	Minor			
Total				100

[1] U.S.Congressional Office of Technology Assessment

[2] U.S. Congressional Research Service

[3] Requires standards to be achieved for 100,000 miles instead of 50,000 miles.

[4] Requires the addition of an idle test along with the Federal Test Procedure.

[5] Requires all vehicles to meet standards as they come off the assembly lines.

[6] Prohibits any averaging of emissions results for individual cars to determine compliance.

Diesel-Fueled Vehicles

Except for particulate matter, exhaust emissions (particularly HC and CO) from diesel engines are quite low compared to gasoline engines. Thus much of the attention on diesel exhaust emissions has focused on particulate and NOx emissions. The particulate matter from diesel exhaust consists of soot, condensed hydrocarbons, sulphur-based compounds, and other oil-derived material. Smoke represents the immediately visible portion of particulate emissions and its opacity depends on the number and size of carbon particles present. The main cause of black smoke is poor maintenance of air fillers or fuel injectors. Fuel quality can also affect smoke emissions, the main factors being fuel density, aromatic content and certain distillation characteristics [T. J. Russell, 1989, ECMT, 1990].

Most of the techniques for reducing particulate and HC emissions from diesel engines improve the combustion efficiency and are fuel efficient but result in higher NOx levels in the exhaust. Common approaches to emission control require a series of diesel engine modifications, including fuel injection, electronic engine controls, combustion chamber modifications, air handling characteristics, reduced oil consumption, turbocharging, injection retard, exhaust gas recirculation, and reduced heat rejection [ECMT 1990].

Efficient combustion through improved mixing of air and fuel results in low emissions of hydrocarbons and smoke. Electronic control of fuelling levels and timing combined with high pressure fuel injection systems can be quite beneficial in this respect. Turbocharging increases NOx emissions but reduces particulates. Charge cooling (cooling the intake air after the turbocharges) directly reduces NOx emissions by reducing peak cycle temperatures and pressures. Injection retard is the most effective way of reducing NOx emissions but it increases fuel consumption and smoke and HC emissions, particularly under light loading. EGR can significantly reduce NOx but may double particulate emissions. Effective control of lubricating oil through engine design to prevent it from entering the engine piston rings, valve guides or turbocharges has been shown to reduce HC emissions by about 50% [ECMT 1990].

In order to achieve low levels of particulate emissions, manufacturers also have turned to the development of exhaust treatment devices, that is, devices added to clean up the exhaust after it leaves the engine. Several types of devices are being evaluated. First, a flow-through catalytic converter designed to operate on low sulfur fuel could reduce the soluble organic fraction (SOF) of particulates by as much as 90% and may also reduce the carbon portion. Second, and probably the most promising of these aftertreatment devices is the trap oxidizer control system. Trap oxidizer systems have demonstrated particulate control efficiencies in some instances of over 90%.

Trap Oxidizer Operating Characteristics

The trap oxidizer system consists of a filter positioned in the exhaust stream designed to collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system. Since the volume of particulate matter emitted is sufficient to fill up and plug a reasonably sized filter over time, some means of disposing of this trapped particulate must be provided. The most promising means of disposal is to burn or oxidize the particulate in the trap, thus regenerating, or cleansing the filter. A complete trap oxidizer system consists of three components, the filter itself, the regeneration system, and the controls which bring about regeneration.

Filter Material

A number of filter materials have been tested, including ceramic monolithic, wire mesh, ceramic foam, mat-like ceramic fibers, and woven silica fiber coils. Collection efficiencies of these filters range from 50% to over 90%.

The cellular ceramic monolithic filter is similar in construction to monolithic catalyst supports used in most gasoline-powered vehicles. It is modified by blocking alternate channels in a checkerboard fashion on the entrance face. The opposite or exit face is similarly blocked but one cell removed so that the gas cannot flow directly through a given channel. The entering exhaust gas is thus forced through porous walls to exit through an adjacent cell. The ceramic walls forming the cells serve as the filter medium.

The wire mesh trap oxidizer filter design is composed of knitted stainless steel mesh to which a high surface area alumina supported precious metal catalyst coating is applied. The presence of a catalyst oxidizes the gaseous HC and CO and facilitates the regeneration of the filter by promoting oxidation of the collected material at lower exhaust temperatures.

Another filter type is composed of sintered mullite fibers and silica alumina clay in a nearly 80% porous body. It is formed in a honeycomb configuration with plain and corrugated sheets joined together. Alternate cells are plugged similar to the ceramic wall flow design described above to form a filter element.

Silicon carbide fibers can be adapted to serve as a filter in a densely packed tube form. Using radial flow from the outside to the inside, the particles are trapped in the body of the tube as well as on the outside surface. Yet another trap oxidizer system consists of treated fiber yarn wound and placed in a series of porous metal tubes. The exhaust gas flows into the container and exits through the center of the tubes depositing its particulate content on the yarn. Finally, ceramic foams such as those used as filters in the processing of metals are being examined as filter material for trap oxidizers.

Excellent filter efficiency has rarely been a problem with the various filter materials described above but further development work has continued in order to optimize filter efficiency with accompanying low back pressure, improve the radial flow of oxidation through the filter during regeneration, and improve the mechanical strength of filter designs.

Regeneration

The temperature of diesel exhaust is not always sufficient to initiate regeneration in the trap. A number of systems are being developed to bring about trap regeneration based on the following techniques:

- Throttling the air intake to one or more of the cylinders thereby increasing the HC and CO concentration in the exhaust as well as increasing the temperature;
- Using a catalyst-coated trap. The application of a base or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary for thermal oxidation of the particulate;
- Using fuel additives to catalytically reduce the temperature required for ignition of the accumulated material;
- Throttling the exhaust gas downstream of the trap. This method consists of a butterfly valve with a small orifice in it. Manually operated, the valve restricts the flow adding back pressure to the engine thereby causing the temperature of the exhaust gas to rise. Special controls of fuel input to the engine are also made at time of regeneration; and
- Using burners or heaters to heat the incoming exhaust gas to a temperature sufficient to ignite the particulate.
- Bleeding predetermined amounts of scavenger air has shown very encouraging regeneration results with two cycle engines frequently found in transit buses.

To protect the filter from overheating and possibly being damaged, some trap systems incorporate a bypass for exhaust gases which is triggered and used only when exhaust temperatures reach critical levels. The period during which the bypass is operating is very short and relatively infrequent. Increasingly, systems are being designed with dual filters in which one filter collects while the other is being regenerated.

Despite substantial progress in the development of trap systems, the task of developing and optimizing regeneration systems which are simple, reliable, and reasonably priced remains the single greatest engineering challenge to the commercial application of trap oxidizers.
Heavy duty application of trap oxidizers presents special engineering challenges. While the basic technology to ensure a high trap collection efficiency has been established, the durability of a trap system in heavy-duty application -- longer useful life requirements, rugged use, heavier volume of emitted particulate, and higher exhaust temperatures -- has yet to be demonstrated. The status of trap oxidizer development in the United States is described in **Box 4**.

Effect on Fuel Consumption and Costs

Fuel economy of diesel-fueled vehicles is likely to suffer significantly as a result of stringent exhaust emission limits, with an overall increase in operating costs of about 2%. The techniques available for reducing NOx emissions (primarily ignition retard and EGR) will lead to poor economy while other engine improvements such as increased use of turbocharging and charge cooling, and better control of injection rates and timing may offset some of the fuel efficiency losses [ECMT 1990].

Additional equipment (for example, charge coolers or particulate traps) needed to comply with exhaust emission requirements are likely to increase vehicle costs. The use of more advanced equipment (such as electronic fuel injection systems or variable geometry turbocharges) will increase costs initially but the costs would go down when such equipment becomes standard. Vehicle maintenance costs are not likely to increase except for particulate traps which have not yet been shown to be durable. Table 39 shows estimated cost increases for individual engine modifications likely to be needed to meet future emissions standards.

Evaporative Emissions

Unburned gasoline emitted from a vehicle other than from the tailpipe is an increasingly substantial contributor to overall hydrocarbon emissions. Evaporative standards, onboard refueling systems, and lower volatility fuel are all important elements of an overall evaporative emission control strategy. In motor vehicles, fuel related evaporative emissions originate in two parts of the fuel system - the fuel tank and the fuel metering system. Significant evaporation occurs during episodes of increased temperature in these parts of the fuel system; they are known as *hot-soak* and *diurnal* emissions.

Hot soak emissions are generated by the continued heating of the fuel by the engine after it is shut off. During this period, fuel in the fuel line, the carburetor or the fuel injection system, and in the fuel tank rises in temperature. The purpose of evaporative control systems is to capture the released vapors in a sealed system which feeds to the charcoal canister, where they can be adsorbed and retained on the charcoal granules. Diurnal emissions are caused by the daily heating of the fuel tank by outside air. Again, in a properly designed and operating system, the vapors released are channeled to the charcoal canister.

The capacity of evaporative canisters to store gasoline vapors is limited by canister size, and they must be purged each time the engine is operated. To achieve this, vehicles are equipped with a purging system which draws air across the carbon granules and carries the purged vapors to the engine to be burned. This flow must be carefully controlled so that exhaust emissions are not adversely affected or driveability impaired. Properly designed and operating systems should have no difficulty meeting tight evaporative requirements when running on the fuel for which the systems were designed.

Box 4. Status of Trap Oxidizer Development in the United States

As the United States currently has the most stringent particulate emission standards in the world and is likely to implement them in the most rapid timeframe, the most rigorous efforts to develop advanced controls are focused on the U.S. market.

- **Light Duty Vehicles**

Compared to an average particulate emission rate of 0.6 grams per mile (gpm) in 1980, current engine out emissions now average under 0.2 gpm. The cleanest vehicles sold to date have been equipped with the first generation trap oxidizer systems, which are designed to capture and burn the particles. Daimler Benz introduced two models equipped with these systems in California and the neighboring Western states for 1985 Model Year. Over 20,000 vehicles equipped with these systems entered commercial service with emission levels below 0.08 gpm. However, during 1987, Daimler Benz suspended U.S. sales of light duty diesel vehicles equipped with trap oxidizers because of durability problems. With availability of cheap oil in the 1980's, interest in fuel efficient vehicles in the United States has dramatically diminished. Corporate Average Fuel Economy (CAFE) standards have been relaxed, speed limits have been raised and diesel automobile sales have almost disappeared. Therefore, there has been very little interest in pursuing advanced diesel particulate controls for the U.S. automobile market.

- **Heavy Duty Vehicles**

1991 U.S. Standards: Diesel engine manufacturers most likely will meet the 1991 heavy-duty truck particulate standard without traps, particularly if the sulfur content in diesel fuel is reduced. While every manufacturer has a trap development program, most of their efforts to meet emission standards have focused on engine modifications such as: fuel injection (higher injection pressure using a unit injector and reduced injector nozzle sac and orifice volumes); electronic engine controls to optimize operating parameters; air handling characteristics (turbocharging and aftercooling); and reduced oil consumption (e.g. improved piston design). Some manufacturers are looking at flow-through catalytic converters as well.

Only one major U.S. transit bus engine manufacturer has publicly stated it will meet the 1991 particulate standard (0.10 gm per brake horsepower hour) for buses with a methanol-fueled engine. The U.S. Engine Manufactures Association and the American Petroleum Institute have proposed that U. S. EPA establish a sulfur standard for diesel fuel of 0.05% by weight and a minimum cetane index of 40, beginning October 1, 1993. These standards would apply to diesel fuel for on-highway use only. If U.S. EPA agrees, it is expected that manufacturers would be able to achieve the interim 1991 through 1993 heavy truck particulate standard of 0.25 grams per brake horsepower hour without the use of traps.

In 1988, the California Air Resources Board adopted regulations limiting the sulfur content of diesel fuel to 0.05% by weight and the aromatic hydrocarbon content to 10% by volume for large refiners and 20% for small refiners. Refiners have the option of developing alternative fuel specifications that would achieve emission benefits comparable to those expected from the new limits, which are expected to add anywhere from US$0.12 - 0.24 to the price of a gallon of diesel fuel.

1994 U.S. Standards: Some manufacturers may be able to meet the 1994 particulate standard (0.10 grams per brake horsepower) using flow-through catalytic converters with low sulfur fuel, but a number of engine models probably will need trap oxidizers. Most manufacturers have a trap system concept which is out of the laboratory and being tested. The most prevalent systems consist of a wall-flow ceramic monolith filter with an active regeneration system. The cost and safety aspects of the systems being developed are the major problems at this time.

Table 39. Cost of diesel engine exhaust emissions control technology

Technology	Estimated extra cost as percentage of engine first cost (excluding development costs)
Baseline engine, no emissions control equipment. Developed for performance only	Nil
Injection timing retard	Nil
Low sac volume/valve covering orifice nozzle	Minimal
Turbocharging	3 - 5%
Charge cooling	5 - 7%
Improved high pressure fuel injection	13 - 15%
High pressure fuel injection with electronic control	14 - 16%
Variable geometry turbocharging (assuming it is already applied to the engine)	1 - 3%
Particulate trap	4 - 25%

Source: [ECMT 1990]

Excess evaporative emissions can also result from disabled systems, either as a result of tampering or defective components. A recently discovered source of vehicle evaporative emissions are *running losses* which occur when a vehicle's fuel tank heats up while the vehicle is running. Recent investigations suggest that a lot of these vapors escape through the gas cap or evaporative canister while the vehicle is running. This is especially a problem with tampered vehicles. Overall emissions will increase from these vehicles with higher volatility fuel. The U.S. EPA has estimated that running loss HC emissions could be about 2 gpm on hot summer days from vehicles using gasoline with a high volatility.

There are two sources of hydrocarbon evaporative emissions associated with vehicle refueling operations, displacement and spillage. *Displacement losses* refer to the gasoline vapors in the fuel tank of the vehicle that are displaced by the incoming liquid fuel and directly emitted to the atmosphere. *Spillage losses* refer to gasoline that is unintentionally spilled during refueling, which then evaporates.

About 90% of all refueling emissions consist of vapors displaced from the vehicle fuel tank by the incoming gasoline. The mass of these emissions depends on the volume of vapor displaced and its density, which in turn are determined by the temperature of the fuel being dispensed and of that already in the tank, the tank size and geometry, the volatility of the fuel, and a number of other minor factors.

Two- and Three-Wheeled Vehicles

Two- and three-wheeled vehicles, such as motorcycles and auto rickshaws constitute a large portion of motorized vehicles in developing countries, particularly in East and South Asia. While they are responsible for a relatively small fraction of the total vehicle kilometers of travel (VKT) in most countries they may make a substantial contribution to air pollution from mobile sources, in particular motorcycles/auto rickshaws with two-stroke engines running on a mixture of gasoline and lubricating oil. For example, it has been estimated that uncontrolled motorcycles in industrialized countries emit 22 times as much hydrocarbons and 10 times as much carbon monoxide as automobiles controlled to U.S. 1978 levels [OECD 1988a]. In Taiwan, HC emissions from two-stroke engine motorcycles were 13 times higher than the emissions from new four-stroke motorcycles and over 10 times higher than the emissions from in-use passenger cars. The CO emissions from two-stroke motorcycle engines were similar to those from four-stroke engines [Shen and Huang, 1989].

Technologies available to control emissions from two- and three-wheeled vehicles are similar to those available for other Otto cycle powered engines. Reducing the content of lubricating oil in the fuel is one possible approach. Refining the fairly simple type of carburetors used would help significantly reduce HC, CO, and smoke emissions. Even catalytic converters are technologically feasible for these engines [OECD 1988a].

VIII. ALTERNATIVE FUELS AND ADDITIVES

Alternative fuels include methanol (made from natural gas, coal or biomass) ethanol (made from grain), vegetable oils, compressed natural gas (CNG) mainly composed of methane, liquefied petrolem gas (LPG) composed of propane, butane, electricity, hydrogen, synthetic liquid fuels derived from hydrogenation of coal, and reformulated gasoline and diesel, including oxygenated blends. Additives (like lead compounds in gasoline) are introduced in small quantities to improve storage, distribution, or performance characteristics of fuel.

The characteristics of alternative fuels vary significantly with respect to engine design and performance and exhaust pollution. Hydrogen, methane and methanol burn efficiently and are intrinsically low polluting fuels. Hydrogen, furthermore, does not produce CO_2 as a product of combustion and therefore does not contribute to the greenhouse effect. Others, such as vegetable oils, have poorer combustion quality compared to petrochemical fuels and their emissions must be carefully controlled. It appears likely that the use of fuels derived from renewable plant and biomass sources will remain confined largely to regions where they have proven to be economically competitive; environmental gains from the use of such fuels will remain a secondary objective. Problems with storing hydrogen make it difficult to use it as a fuel for road vehicles. Its production requires electricity, and if this is generated from fossil fuels the use of hydrogen as a vehicle fuel would probably increase overall air pollution [ECMT 1990]. Environmental assessment of alternative fuels should not be based solely on vehicle end-use emission characteristics but should account for pollutant emissions associated with the production, storage, and distribution of these fuels. .

Partly in response to environmental pressures to eliminate lead in gasoline and partly in response to energy needs, increasing amounts of alcohols and ethers are being used either as high octane blending components or as substitutes for gasoline. Other likely changes will involve catalytic processing (cat cracking) of heavier crude and a decline in residual fuel demand. These changes could significantly influence vehicle emission characteristics.

Reformulated and Blend Fuels

Gasoline

Lead is the cheapest means of improving the octane level of gasoline and has been used since 1922. The required octane number[1] may also be achieved by increasing the severity of refinery processing but this entails additional energy consumption, increased refining costs, and less gasoline per barrel of crude oil. The effect of decreased octane levels is to lower vehicle fuel economy due to the need for lower compression ratio. The energy penalty is about one percent weight increase in gasoline consumption for each unit reduction in octane number. Some of the increased costs associated with reduction or elimination of lead in gasoline can be lowered by blending gasoline with high octane oxygenates such as methyl tertiary butyl ether (MTBE), tertiary butyl alcohol (TBA), methanol and ethanol.[2] But the investment costs for retooling to increase the severity of the refining process or for producing oxygenates can be high -- for Mexico the cost is estimated in the order of US$1.0 to 2.0 billion.

The addition of oxygenates (low level blends of approximately 6% oxygenates or less) to gasoline, however, alters the stoichiometric air/fuel ratio compared to pure gasoline. The leaner mixture may either reduce or increase the level of pollutants in the exhaust gas, depending on the carburetor setting. The leaning out effect, provided the carburetor setting is unchanged, reduces the emissions of CO with necessary amounts of oxygen. If the mixture becomes too lean, the HC emissions could increase considerably due to misfiring. There is also a tendency towards increased evaporative emissions and photochemically reactive aldehydes. Other performance characteristics of oxygented gasolines are reviewed in **Box 5**.

Colorado (USA) has initiated a program to mandate the addition of oxygenates to gasoline during winter months when high ambient CO tends to occur. The mandatory oxygen requirement for the winter of 1988 (January to March) was 1.5% by weight, equivalent to about 8% MTBE. For the following years, the minimum oxygen content required was 2% by weight equivalent to 11% MTBE. These oxygen requirements are expected to reduce CO exhaust emissions by 24-34% in vehicles already fitted with 3-way catalyst systems. The success of this program has encouraged other areas to consider oxygenate blends as a CO control strategy.

Diesel

Probably the most important characteristic of diesel fuel is its sulfur content (typically 0.15 to 0.5% by weight); increased sulfur content results in higher levels of sulfur dioxide (SO_2) and exhaust particulates, 10 - 15% of which consist of sulfates. Fuel desulfurization is the only

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[1] Gasoline octane values are measured in terms of RON - research octane number, and MON - motor octane number. A gasoline may have a RON of 94 and a MON of 88; in the United States, the two numbers are averaged and expressed as (RON + MON)/2 or RM/2. Thus, in the U.S. a pump octane rating of 91 (expressed in RM/2) would be comparable to a European rating (usually RON) of 94.

[2] Alcohol blends/fuels are commonly designated as M15, M50, M100 and so on or as E15, E50, E100; the symbols "M" and "E" designate the percentage of methanol or ethanol in the fuel.

Box 5. Use of Oxygenates in Motor Gasolines

Oxygenated supplements, covering a range of lower alcohols and ethers can substitute for lead additives in gasoline. While these supplements have high octane numbers, they are not as effective as lead in raising base fuel octane numbers nor do they offer valve seat protection. The behavior of oxygenates in terms of blending and vehicle performance is different from HC-only gasolines. The commonly used oxygenates in gasoline blends are methanol, ethanol, isopropanol, tertiary butyl alcohol (TBA), methly tertiary butyl ether (MTBE), and iso-butyl alcohol. Tertiary amyl methyl ether (TAME) has also been used in small amounts. The volume of oxygenates in gasoline blends varies from 3-10%. The oxygen content of the blend is generally about 1-2% by weight. Oxygenates serve three basic objectives: extending the gasoline stock or serving as a fuel substitute (e.g., ethanol in Brazil), boosting octane value, and providing an effective means of reducing harmful emissions. Some of the important vehicle performance characteristics of oxygenated fuels are summarized below:

Anti-knock Performance. Oxygenated fuels perform better than hydrocarbon-only fuels at low olefin levels. They give better anti-knock performance in unleaded gasolines; this is particularly the case with increasing MTBE content. MTBE has proven to be an effective substitute for lead in gasoline as it has a high octane rating (RON 119, MON 101) and is less water-sensitive than alcohol. It is, however, not clear if oxygenates give better anti-knock performance under lean-burn conditions.

Driveability. Vehicles fitted with fuel-injection systems have better tolerance in cold weather conditions for low-volatility fuels containing oxygenates. At high altitudes and in hot weather conditions, oxygenated fuels (except for certain methanol blends), give similar or better handling performance compared to wholly hydrocarbon fuels.

Exhaust Emissions. CO levels are progressively reduced as oxygen content is increased whilst NOx and HC emissions are marginally affected. Ethanol blends increase aldehyde emissions with increasing concentration; with other oxygenates, there is only a marginal increase, which may be corrected by exhaust oxidation or three-way catalysts. Oxygenates are particularly useful in lowering emissions from older vehicles.

Fuel Economy. In case of commercial oxygenated gasoline (which must comply with existing gasoline specifications), fuel economy is essentially unchanged with increasing amounts of oxygen. There could be marginal benefits in terms of reduced energy consumption with increased fuel oxygent content.

Source: C.J. Lang and F. H. Palmer. "The Use of Oxygenates in Motor Gasolines," in Gasoline and Diesel Fuel Additives, (Editor: K. Owen), John Wiley and Sons (1989).

technique currently available to reduce sulfur emissions. The aromatic content of diesel fuel is also important as an increase in aromatics increases particulate, HC, and NOx emissions. Another important characteristic is the ignition quality which is characterized by the cetane number. Maintaining current cetane number levels may prove difficult in the future because of the expected reduction in the quality of crude oils and the increasing demand for diesel fuel.

Kerosene and heavy oil fractions are sometimes added to diesel as fuel extenders, but they impair the quality of diesel fuel.

Other fuel considerations for diesel engines center around fuel purity and its relationship to diesel particulate control. Impurities in diesel fuel are a source of concern, particularly metals like chromium, because of the potential for direct emission in the exhaust. Fuel additives may also be important with respect to diesel particulate control. A number of fuel additives, mostly derivatives of barium, calcium or managanese that act as catalysts to convert carbon particles to CO_2, have been used to suppress smoke emissions. A class of trap oxidizer systems includes self regeneration by means of metallic fuel additives. Such additives could be a source of unregulated pollutants. Environmentally benign materials such as cerium are less problematic in this respect than metals such as lead or copper.

Alternative Fuels

Petroleum supply disruptions and cost increases in the 1970s and early 1980s accelerated interest in alternative fuels for motor vehicles. The need for these fuels became a high priority for many countries and investigations were initiated into possible use of coal, oil shale, natural gas, uranium and biomass. As oil prices dropped, interest in these alternatives from an energy conservation standpoint dwindled. From an environmental standpoint, alternative fuels hold promise for solving the diesel particulate problem (especially in city buses), reducing the overall toxic emissions problem from vehicles, and helping to reduce urban CO and ozone levels. A comprehensive technological and environmental assessment of alternative fuels for road transport is provided in IEA [1990].

Compressed Natural Gas (CNG)

It has been estimated that the use of CNG would reduce HC emissions by 40% in the exhaust and virtually eliminate HC emissions through evaporation; at the same time CO emissions would be reduced by about 50%. NOx emissions, however, could increase by about 40% [U.S. EPA 1988]. In the aggregate, U.S. EPA estimates CNG would substantially lower tropospheric ozone (the HC reductions more than offsetting the NOx increases) and CO, both of which are greenhouse gases. Recent studies indicate that the NOx increase may not be as high as previously estimated [Bruestch 1988; IEA 1990]. It seems likely that further optimization of emission controls will enable CNG vehicles to achieve low levels of CO, HC and NOx as well as toxic pollutants. However, it should be noted that the use of CNG has certain adverse safety and vehicle performance implications that need to be carefully evaluated. These and other technological aspects of alternative transport fuels from natural gas have been assessed by Moreno and Bailey [1989].

Alcohol

Exhaust emissions from neat alcohol engines have fewer components compared to gasoline or diesel fuel. Generally hazardous aromatic hydrocarbons including benzene are not formed and PAH emissions are very low. The characteristic emission components are carbon monoxide, unburned alcohol, nitrogen oxides and aldehydes. Engines designed for neat methanol tend to have low emissions of CO, NOx, and unburned fuel. Evaporative emissions are also low. Methanol is also expected to significantly reduce the reactivity of exhaust and evaporative VOC's, thereby lowering tropospheric ozone levels. EPA estimates the ozone reduction potential to be on the order of 35% [USEPA 1988]. Aldehyde emissions, however, can be four to eight times higher than for gasoline vehicles. These compounds tend to be highly photochemically reactive and to contribute directly to eye irritation. There is significant evidence that formaldehyde is a human carcinogen. It is, however, important to note that most aldehydes including formaldehyde, which exist in ambient air are formed photochemically in the atmosphere and are not directly emitted. Fortunately, these compounds are effectively reduced by catalysts. Emission characteristics of alcohol fueled diesel engines are also good. They feature low emissions of NOx and PAH and virtually no particulates. Both concepts can be used together with an oxidation catalyst to effectively reduce the unburned fuel and aldehydes. Data comparing emissions from different fuel types are summarized in Table 40.

Table 40. Emissions per kilometer from combustion engines

	LPG Gas	Leaded catalysts	Gasoline	Gasohol 95%	Diesel	Methanol
Particulates mg.	-	50-100	5-10	-	750-1500	-
Benzene mg.	1	50-150	1-15	50-150	10-20	1
Ethylene mg.	75-100	75-100	5-10	75-100	25-75	10-15
Formaldehyde mg.	20-40	20-50	1-3	30-60	10-15	100
Benzo(a)pyrene ug.	0.1	1-10	0.1-1	1-10	1-10	0.1
Methyl nitrite ug.	100-300	100-300	0-50	100-300	100-300	5-6x10^3
PAH ug.	2-9	35-170	3	35-170	500-1000	2-9

Source: [CAAP 1983]

Alternative Fuels and Global Warming

Carbon dioxide and chloroflurocarbons are considered to be significant contributors to global warming. Studies [Jackson et al. 1987] have demonstrated that natural gas has about 30% lower CO_2 emissions per equivalent volume of oil; methanol produced from natural gas has about 10% less; while methanol from coal produces twice as much CO_2 in the aggregate. It has been estimated that the use of natural gas either directly or as a feedstock for methanol could gradually lower CO_2 emissions. The benefits would be quicker using natural gas directly, assuming no difference in fuel economy. However, some evidence indicates that at the same power output and NOx emission levels, methanol-fueled vehicles would achieve better fuel economy than vehicles fueled with natural gas. Methanol from coal, however, would quickly lead to increases in CO_2 because of the aggregate emissions. It is unrealistic that methanol from coal would make a significant penetration in the marketplace unless energy prices were dramatically higher than today.

The Economics of Alternative Fuels

The economics of alternative transport fuels depends on the cost of production and the additional cost of storage, distribution, and end-use. Production costs are a function of abundance or scarcity of the resources from which the fuel is produced, as well as the technology available to extract those resources. The additional costs of storage, distribution and end-vehicle-use is important since gasoline and diesel fuel made from heavy oils or natural gas require relatively minor changes to existing distribution and end-use systems, whereas CNG and alcohol fuels require major modifications.

The estimated cost ranges (inclusive of production, distribution and end-use) of alternative fuels based on current oil and gas prices and the technology are shown in Table 41. According to OECD's International Energy Agency, CNG and Very Heavy Oil (VHO) products may be economically competitive with conventional gasoline at present. Methanol and synthetic gasoline made from natural gas may be close to competitive, under optimistic assumptions about gas prices. Methanol from coal or biomass and ethanol from biomass have a cost at least double that of gasoline at current oil prices and with current technology [IEA 1990].

A study by the World Bank [Moreno and Bailey 1989] has shown that at crude oil prices of $10 per barrel or lower (in 1988 prices) alternative fuels are generally uncompetitive. Between $10 and $20 per barrel custom-built propane-fueled high mileage vehicles and retrofitted vehicles using CNG trickle-fill refueling (mostly applicable to captive vehicle fleets -- urban buses, taxis, and delivery trucks -- with a relatively high annual mileage but restricted range), become competitive. Between $20 and $30 per barrel, CNG fast fill and propane-fueled low mileage vehicles would be competitive. Methanol from natural gas becomes competitive above $50 per barrel while synthetic gasoline and diesel guel do not become competitive until the price of crude oil reaches $70 per barrel. For CNG-fueled vehicles, the high cost of fuel transport in tube trailers suggests that CNG would become competitive at the crude oil prices indicated above only if filling stations are located close to a high-pressure pipeline.

Table 41. Comparative costs of substitute fuels, 1987

Fuel	Overall Cost (1987 US dollars per barrel-gasoline energy equivalent)
Crude Oil (assumed price)	$18
Conventional Gasoline	$27
Compressed Natural Gas	$20-46
Very Heavy Oil Products	$21-34
Methanol (from gas)	$30-67
Synthetic Gasoline (from gas)	$43-61
Diesel (from gas)	$69
Methanol (from coal)	$63-109
Methanol (from biomass)	$64-126
Ethanol (from biomass)	$66-101

Source: [IEA 1990]

Factors Influencing Large Scale Use of Alternative Fuels

The introduction of alternative fuels requires changes in distribution, marketing and end-use systems. Irrespective of the economics, inadequate supply of fuel or unreliable distribution systems could adversely affect consumer acceptance of alternative transportation fuels. Experience with the use of ethanol in Brazil and CNG in New Zealand and elsewhere suggests that the main factors influencing large-scale introduction of CNG and alcohol fuels are price competitiveness, availability and cost of feedstock (e.g., sugarcane for ethanol, or natural gas for CNG), fuel safety and quality standards, reliable system of distribution, and technical quality of vehicles (driveability, durability, safety). The Brazil experience with ethanol and the New Zealand experience with CNG clearly show that it is possible to develop a large market for alternative fuels within a reasonable time frame if the financial incentives are favorable and efforts are made to overcome uncertainty on part of industry and consumers [Sathaye, Atkinson, and Meyers 1989]. In both instances, substantial subsidies had to be offered to private motorists to persuade them to convert to alternative fuels [Moreno and Bailey 1989].

IX. TRAFFIC MANAGEMENT AND POLICY INSTRUMENTS

Control of pollutant emissions at source should be given the highest priority in any air pollution control and abatement program. But such measures by themselves will not eliminate the problem in developing countries because of increasing population and urbanization, rising vehicle ownership, and increasing trip rates. These measures may include urban and regional planning, urban design, transport facility design, traffic control and management, and regulatory and pricing policies.

Urban Growth and Transport

The increase in urban transport demand in developing countries has been caused by dramatic increases in urban population and mostly uncontrolled urban sprawl. The result has been a large increase in the number and length of trips, and worsening traffic congestion leading to falling traffic speeds and increased emissions. The linkages between urban growth and transport should be a central element of a rational urban development strategy. The control of urban leap-frogging and promotion of new residential and commercial developments close to existing transport facilities should help to minimize the number and length of automotive trips. As urbanization evolves into megacities such as Mexico City, Sao Paulo, Shanghai, Jakarta, Calcutta, Cairo, and Lagos, and particularly where the larger metropolitan area is subordinate to a well-defined historical business center, accessibility becomes a critical issue for the majority of the inhabitants because the time spent and costs incurred in work trips affect the quality of life, household incomes, the efficiency of productive sectors, and the delivery of social services.

The air pollution problem is directly associated with land use and transportation. Increased transport-related air pollution is often associated with changes in urban form in the direction of lower inner city densities combined with decentralization of employment, a shift from manufacturing to services, and higher rates of work and leisure trips. Changes in urban growth and land use, however, cannot be solely guided by the objectives of air pollution abatement, as the social and economic consequences of urban growth control and guidance can be profound and costly. Land use and urban planning policies should seek a commonality between the goal of air pollution abatement and the goals of congestion reduction, safety improvement, energy conservation, and reduction in the costs of transport and various municipal services.

Many opportunities exist in the area of urban design to reduce the impact of air pollution. High concentrations of carbon monoxide, for example, commonly occur in congested narrow roads and streets, garage forecourts, tunnels and other confined spaces, but are less likely to occur in wide streets with free-flowing traffic and good ventilation. Congested urban centers in developing countries with crowded streets and limited parking often have a high concentration of carbon monoxide and exhaust particulates along the main thoroughfares. Traffic management techniques can help to alleviate such problems [Holdgate 1982]. The design and location of streets and highways and the orientation of buildings with respect to them offer another range of possibilities to reduce the exposure of people to vehicle emissions. Major road alignments may be depressed or even tunnelled through areas where there are large concentrations of people.

Public transport options that could be considered in the context of an environmentally sound urban transport system include:

- building new public transport facilities;
- major overhaul and improvement of the existing transit lines;
- effective bus and rail transit fleet operation and maintenance programs;
- use of clean fuels for buses and taxis;
- electrification of commuter rail lines; and
- provision of exclusive roadways for non-motorized modes e.g., bicycles, rickshaws.

Traffic Management

Measures aimed to improve traffic circulation can result in substantial fuel savings and reduced pollutant emissions. They include a wide range of interventions such as:

- signalization and intersection improvements, including use of computerized areawide traffic control (ATC) systems;
- prohibition of turning movements;
- use of one-way street pairs and reversible lanes;
- designation of special lanes or exclusive facilities for buses and other high-occupancy vehicles (HOV);
- segregation of motorized and non-motorized traffic through provision of exclusive facilities for pedestrians, bicycles, and human- and animal-drawn vehicles;
- designation of truck routes, time and space restrictions on urban goods movement, and use of peripheral break-bulk and transfer freight centers (such as Garonor on the outskirts of Paris);
- use of staggered work hours;
- parking controls and restrictions; and

- controlling access to congested inner city areas.

The appropriateness of these interventions depends on the physical layout of the urban area, the density of street space, and the characteristics of the urban transport system. A detailed discussion of urban traffic management approaches to minimize air pollution impacts is provided in the ECMT report on transport policy and the environment. For example, different forms of bus priorities can reduce exhaust emissions from 7% for priority turns and other minor measures to as much as 60% for exclusive bus streets and freeway privileges. Emissions can also be reduced by increasing the proportion of the traffic in 30 kph to 70 kph range and reducing the proportion in the ranges above and below these limits. Thus, maximum speed limits, if effective, can reduce emissions significantly [ECMT 1990]. The elements of a comprehensive and environmentally-sound traffic management system implemented in Singapore are outlined in **Box 6.**

On-street and roadside parking is a common practice in major cities in many developing countries. Since roads are not wide enough, on-street parking interferes with traffic, often causing stop-and-go operations that result in increased vehicle emissions. A program of off-street parking would greatly improve traffic flow in many of these cities.

Lack of coordinated traffic signal systems is quite common in cities in many developing countries, resulting in prolonged stop-and-go traffic operations which in turn cause increased pollutant emissions (Tables 20 and 21). Centrally computerized control systems can greatly enhance the efficiency and timing of traffic signals to help maintain uniform speed and stable traffic flows. Even mechanical traffic signal synchronization and individual sign control arrangements can help to improve traffic circulation. For example, the progressive and simple linking of signals along arterial roads can minimize the number of acceleration/deceleration operations, while maintaining the cruising traffic speed within a range at which emission rates are lowest [UNEP 1981, UNEP 1986].

Other measures may be needed to reduce obstructions to smooth traffic flow caused by construction and maintenance works and the presence of non-mechanized forms of transport such as bicycles, and human- and animal-drawn crafts, which often serve as major means of personal and goods transport in some developing countries. Such obstructions slow the general traffic stream and lead to increased fuel consumption and emissions. In simulated urban traffic operations, a comparison between free-flowing and heavily congested peak-hour traffic flows indicated a 31% saving in fuel consumption and a reduction of 54%, 52%, and 2% in HC, CO, and NOx emissions for hot start [UNEP 1981, UNEP 1986].

Auto Restrictions and Vehicle Free Zones

Auto restriction measures include the designation of selected streets or areas in central cities as auto-free zones or zones that only allow high occupancy automobiles and public buses. In some cases, certain areas may be designated as pedestrian precincts and kept free of all

Box 6. Singapore: Elements of an Environmentally-Sound Traffic Management System

Singapore is an island city-state with a total land area of 623 sq. km and a population of 2.65 million. Its population density of 4,250 per sq. km is one of the highest in the world. Singapore is classified as a high income, advanced developing country.

Land transportation in Singapore is largely road based and a cornerstone of the domestic transportation policy has been to control road congestion. The integrated planning approach has included four key elements: systematic town planning, systematic road planning, priority for public transportation, and careful management of the growth and use of private vehicles. This has led to innovative traffic management practices such as the introduction of area licensing scheme in 1975 to manage the use of private road vehicles during peak hours in the central business district.

Singapore's comprehensive traffic management strategy has been quite effective in maintaining journey times and aggregate vehicle pollutant emissions within acceptable limits. The core elements of the traffic management system are:

- *Street usage strategies* - one-way schemes, bus-bays with designated pedestrian areas, and bus lanes;
- *Signalized traffic control* - computerized areawide traffic control (ATC), green link determining system (GLIDE);
- *Road pricing and car pools* - area licensing scheme (ALS), car pools, park-and-ride;
- *Car parking and management of traffic disturbances* - parking space control, variable parking fees, compulsory vehicle inspection systems, incentives for replacing old automobiles;
- *Public transport management* - encouraging use of public bus and rail rapid transit systems, discouraging auto ownership through high taxes on private vehicles and gasoline.
- *Other measures* - such as provision of grade-separated pedestrian crossings, speed limits, and driver information systems.

Source: B.W . Aug. "Traffic Management Systems and Energy Savings: the Case of Singapore." Department of Industrial and Systems Engineering, National University of Singapore.

automotive traffic. Vehicle free zones usually result in considerable reduction of CO concentrations. The central areas of cities often include many roadways near which CO concentrations are excessive. These areas are usually too large to be converted into vehicle-free zones. However, if a bypass route is available or can be established, then it may be possible to achieve significant reductions in the central area CO concentrations by diverting the through traffic to the bypass. One way of effecting this diversion is to divide the central area into traffic cells, or zones that are accessible to vehicles only from the bypass route. Direct vehicular travel between cells is discouraged or prevented by means of systems of one-way streets, restrictions on turns, or physical barriers. However, the diversion of through traffic to bypass roads that occurs when a traffic cell system is established is likely to increase the lengths of through trips. The lengths of local trips may also increase owing to the need to use bypass roads for travel between cells. This increased circuity of travel may cause aggregate HC and NOx emissions to increase.

Traffic cell systems have been implemented in several cities in Europe and Japan [Gakenheimer 1978, OECD 1988b]. Experience with these systems indicates that they can achieve substantial reductions in central area CO concentrations. In Gothenburg, Sweden, implementation of a central area traffic cell system is reported to have reduced half-hour average CO concentrations in the central area to less than 5 ppm from 60-70 ppm [Horowitz, 1982].

Emergency traffic management measures to alleviate air pollution often include area traffic bans based on license plate numbers. The main feature of the scheme introduced in Athens in 1981 is a ban on the use of private automobiles on and within the inner ring road. The ban is in operation on weekdays during business hours and on any given day only cars with license plates ending in an odd or even number are allowed to circulate. Violations receive fines ranging from US$50 to US$1000 [OECD 1988b]. Florence converts its downtown area into a pedestrian mall during daylight hours and Budapest bans motor traffic from all but two streets in the downtown area during particularly polluted spells [French 1990]. In Mexico City, a scheme banning use of private automobiles one day a week was introduced during the winter of 1989-90. Offenders can be fined US$100 and have their cars impounded for a day if they violate the ban. Traffic reductions in the order of 12-20% have been attributed to these measures. In Santiago, a similar ban based on license-plate numbers keeps one-fifth of all automobiles off the street each weekday. The ban is extended to two days a week during periods of excessive air pollution.

Economic Instruments and Other Policy Measures

As distinct from the regulatory approach, financial incentives and disincentives can be used to ensure compliance with air pollution control policies. These measures are sometimes referred to as "economic levers" or market/price mechanisms and are designed to induce a change in the behavior of producers and consumers. A wide variety of such mechanisms are possible; the commonly used measures include subsidies, taxes/emission charges and fines and emission credits and quotas [ECE 1987]. Several of these "economic levers" can be used to promote the production and use of environmentally cleaner vehicles and fuels. These may include an environment tax on fuel (as imposed in Netherlands to combat noise and air pollution); lower tax on unleaded fuel, higher tax on leaded fuel (as in Germany, Switzerland and the United Kingdom); and tax incentives for clean vehicles (as in Germany and Singapore). These measures can play an important role in accelerating the introduction and use of environmentally clean vehicles and fuels. Moreover, the net revenues collected from these charges can be rolled back to finance air pollution abatement programs.

Ultimately, it is the road user who pays the total cost of a vehicle emissions program through higher vehicle and fuel prices. In a program where there is a choice to pollute, the "polluter pays" principle should govern. In case of vehicle emissions, those who use clean vehicles and fuels should not pay more and ideally less than those who continue to use duty vehicles and fuels. Adjusting taxes so that the revenue impact is neutral is not easy and has to be considered over the time span that it takes users to adjust to cleaner vehicles and fuels. The cost of adjustment in Yugoslavia if half the road users switched to unleaded gasoline would require a 15% increase in the price of premium leaded fuel [Dickerson 1990].

A variety of pricing measures can be used to bolster clean air policies. For example, parking fees can be used to restrict the use of automobiles, differential fuel and vehicle taxation can be imposed according to the vehicle size and other characteristics, and area licensing schemes or more precise electronic road pricing schemes may be considered to impose real or surrogate congestion and environmental tolls. Most incentives and pricing measures aimed to promote the use of public transportation also serve to reduce aggregate air pollution from transport sources. Other measures may include a program of education and public information, labelling of vehicles in terms of their air pollution characteristics and preferentialtreatment for cleaner and quieter vehicles. Many such measures could be implemented at low cost and short lead time [OECD 1988a]. A menu of economic policy instruments to reduce air pollution through market incentives is provided in **Box 7.**

Box 7. Economic Policy Measures to Control Motor Vehicle Air Pollution

Economic policy instruments used to bring about a reduction in motor vehicle air pollution commonly consist of market incentives to influence consumer behavior. These measures promise to be effective in reducing air pollution while increasing the efficiency of road transport. They include:

- differential taxation for leaded and lead-free gasoline to promote the use of unleaded fuel and reduce the risk of misfuelling vehicles equipped with emission control devices.
- fuel price surcharges based on the lead content of gasoline or the sulfur/heavy oil content of diesel to encourage refiners to produce clean fuels.
- lower taxes on clean fuels such as compressed natural gas (CNG) and alcohol to encourage use of cleaner alternative fuels.
- lower duties and taxes on fuel-efficient vehicles.
- lower duties and taxes on purchase of low polluting vehicles to offset the cost of emission controls and to promote the sale of such vehicles.
- higher license fees and taxes on older non-conforming vehicles and other tax incentives to scrap older polluting vehicles.
- taxes to restrain the ownership and use of private automobiles, particularly the "gas guzzlers."
- tax deductions to retrofit vehicles with emission control devices or to modify vehicles to run on cleaner fuels.
- mandatory use of low or non-polluting vehicles in Government fleets to expand the market for such vehicles and reduce unit manufacturing/assembly costs.
- import ban on non-conforming used and reconditioned vehicles and vehicles above a specified age (e.g. five years).
- tax on CFC-based air-conditioning systems in automobiles, buses and trucks, and rebates for installing non-CFC based systems.
- taxing businesses and employers to help pay the transit cost of employees.
- taxing employee benefits such as free parking, company vehicles, and fuel allowances with such benefits treated as income.

X. IMPLEMENTATION ISSUES

There are several issues that require careful attention while considering implementation of a motor vehicle pollution control program in a developing country. They include the availability and more importantly the reliability of data on vehicle emissions and ambient air quality, the costs and effectiveness of adopting a set of air pollution abatement strategies, and the legal requirements and institutional responsibilities for implementing an air pollution control program.

Information Requirements

The evaluation of appropriate strategies to deal with transport-induced air pollution problems requires a well-maintained database on emission sources, the types and amounts of pollutants emitted and their spatial and temporal distribution. In most developing countries, a major implementation issue is the availability of reliable data. The database needed to develop a cost-effective program to control air pollution from land transport sources should include the following elements:

- *Air quality data* - including ambient concentration and spatial distribution of various pollutants at different time periods; wind speed and wind rose data for wind direction; stability of atmosphere including ambient temperature, precipitation, cloud cover and amount of sunlight; ceiling height for pollutant dispersion, and frequency and duration of temperature inversions; and other relevant meteorological information.

- *Transportation system characteristics* - including peak hour traffic, traffic mix, hourly traffic volumes (for 8-hour CO on major arterials), intersections and interchanges in the area, number of lanes for each direction of movement, lane capacities, traffic lights and stop sign locations, signal phasing, and traffic speeds; rail and bus corridors, type of rail facility, and location and type of power generating source for rail operations; and modal share of trips.

- *Vehicle data* - including types of vehicles and their age, condition and emission characteristics; the type of motive power and amount of fuel used by different modes; and information on vehicle and railcar occupancy rates.

- *Sensitive receptors* - including information on distribution of sensitive population groups (children, people with heart and lung diseases), sensitive aquatic and terrestrial (forest) ecologies, and historical and culturally significant monuments and buildings.

- *Cost data* - on emission control devices, switching to cleaner fuels, making transportation system changes, enforcement, air quality monitoring, applying emission standards, inspection and maintenance compliance, and making changes in the manufacturing processes, as well as other private and public costs related to alternative control strategies.

Economic Considerations

For developing countries to make a serious commitment of resources to combat air pollution, economic impacts of the environmental pollution have to be much greater than the cost of abatement. Only if it can be clearly demonstrated that environmental pollution is in fact a serious drag on the economy including the damaging effects on health and public welfare, can major ameliorative actions be expected.

There is a wide variation among developing countries (i) in the severity of the impact of air pollution (health effects, acid deposition, deterioration of lakes and forests, and so on), (ii) in the assimilative capacity of the environment, (iii) in public attitudes, (iv) in degree of urbanization, (v) in transportation systems, and (vi) in economic conditions. Consequently, the policies and their method of implementation will also vary, along with the urgency for tightening air pollution standards and pursuing attendant strategies.

A major constraint against meaningful programs to control air pollution in developing countries may be the economic and financial costs of abatement programs. The types of strategies pursued and the timing of their implementation would depend greatly on the financing implications of various actions. The question of how much and how soon to abate transport-related air pollution in developing countries will be resolved not only on the basis of the severity of the pollution problem and its direct health and welfare impacts, but more importantly on the basis of expected consequences of various control strategies including "do-nothing", on the economic sectors.

The basic issue is represented by the question: What strategies should be adopted, how soon, and at what cost? The answer to this question can be approached by assessing the marginal cost of allowing the emission of a given quantity versus the marginal cost of abating that amount of air pollution. The optimal approach to pollution abatement programs and timing of implementation should be to select the strategy that equates the two marginal costs. Some of the financing options for air pollution abatement programs include mobilization of funding from the private sector, joint property developments, differential taxation schemes and various tax concessions, and public bonds.

Costs and Effectiveness of Alternative Strategies

A careful cost-effectiveness analysis would be necessary before a particular set of strategies is adopted. Environmental problems related to land transport vary in severity from country to country depending on geography, climate, social and economic conditions, infrastructure facilities, and resource availability. Appropriate solutions will therefore depend on overall priorities set by the countries concerned and their determination to tackle specific environmental problems. The cost effectiveness of the various control measures should account for the full range of related factors such as energy and technological development, impact on public and private expenditure and on cost of living. Balance and trade-offs among conflicting objectives may be required in the evaluation, depending on the priorities adopted. A major obstacle in choosing cost-effective options to combat transport-related air pollution is the paucity of information on the costs of various control measures and their effectiveness in the institutional and administrative context of developing countries. Without such information, developing countries could end up investing scarce resources in pollution abatement programs without reaping the expected benefits.

Institutional Arrangements

In many developing countries environmental pollution abatement responsibilities are generally shared by both the central and local governments. A mechanism for close coordination between different levels of government is necessary in developing and implementing effective environmental policies. Central government commonly establishes air quality standards and emission limits for new and in-use vehicles while local (municipal) governments exercise control and ensure compliance. Central and local governments also cooperate in traffic management, transport pricing, control of land use, and research. Since road transport movements and their impacts on health and well-being are largely concentrated in urban areas, municipal authorities should reinforce national policies by taking proper steps to control the use of vehicles and transport infrastructures [OECD 1988a].

A comprehensive approach is necessary in planning appropriate strategies to address air pollution caused by motor vehicles. This approach should consider all possible measures including land use and infrastructure related actions; new motor vehicles and emission standards; inspection and maintenance programs of in-use vehicles; alternative fuels; retrofitting existing vehicles, particularly urban transit vehicles; traffic management programs; and regulatory and pricing measures in terms of their implementation costs and both short-term and long-run impacts. Strategies to combat localized pollutants may be drawn by local governments under the guidance of the central government, while the central government may take the leadership for mitigating those pollutants affecting the regional environment. It should be recognized that an effective implementation will not only require comprehensive planning, but also a continued execution of the plan and strict enforcement of the standards. Strong interagency coordination thus becomes vital for the successful implementation of environmental pollution abatement efforts.

The air quality and emission standards should be established considerating the ability of industry and consumers to comply. Experience in industrialized countries suggest that it takes industry and motor vehicle users a long time to achieve full compliance with standards. Enabling legislation and regulations should be consistent with the country's air pollution problem and its economic ability. The standards should be phased in gradually and improved over time taking into consideration the absorptive capacity of the economy and other limiting factors.

A government-industry-university cooperative approach can be taken in planning and implementing air quality improvement programs. The resources of the local universities should be effectively utilized in understanding air pollution characteristics and impacts in a given region or country. University research should also be encouraged in areas such as meteorology, atmospheric chemistry, monitoring of air environment and analysis, and interpretation of data collected for developing ambient air quality standards. Research on transportation and traffic and urban planning could also contribute to the improvement of the land use and transportation linkages and their impact on air pollution. In addition, the universities would provide appropriate educational and training programs for the development of qualified personnel to plan and manage the environmental programs.

Jurisdictional Responsibilities

There are few problems that require multi-country efforts more than the air pollution abatement problem. Although some air pollutants have localized effects and can be mitigated by appropriate local actions, the problems of acid rain and global warming do not follow jurisdictional boundaries. An effective regional approach is essential where several countries in a region would work cooperatively to combat air pollution problems. In fact, the issue is an international one, because motor vehicles are internationally traded goods, they cross national boundaries (trade and tourism) and generate pollutants that cause transboundary damage.

Within a particular country, regional and local programs should be coordinated with each other as well as with the national program. The responsibility of the relevant agencies should be defined and clearly understood. Jurisdictional cooperation among different agencies as well as area governments becomes critical for both transport system development and development of environmental programs, particularly in very large metropolitan areas and capital cities.

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