ANNEXES

Annex I

PRIMARY AND SECONDARY POLLUTANTS FROM THE TRANSPORT SECTOR

Lead

The negative effects of lead are clear and well documented. Ingestion of lead aerosols has been linked to cardiovascular disease, brain and kidney failure in adults and children at 100 micrograms per decilitre (ìg/dL) and 80 ìg/dL respectively, premature death at 125 ìg/dL, and gastrointestinal symptoms. Chronic effects include behavioural and developmental problems among children, elevated blood pressure, problems with metabolizing vitamin D, and anaemia (EPA 2000). Exposure to lead has also been associated with decreased sperm count in men, and increased likelihood of spontaneous abortion among pregnant women. Within the transport sector, lead has also been linked to hidden maintenance costs of automobiles, such as frequency of spark plug, oil and filter, muffler, and exhaust pipe replacements. In the United States, the marginal costs to the economy of each 10 mg of lead per litre of gasoline have been estimated at about US$ 17 million per year (Schwartz 1994).

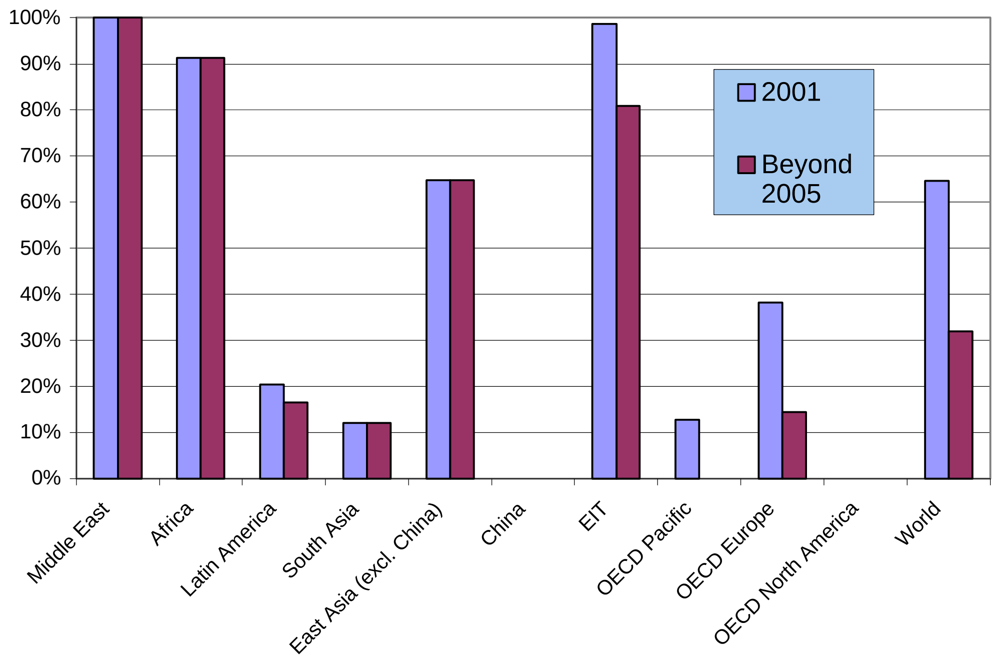
The lead industry projects that by 2005, lead will be completely phased out of the gasoline supply in 28 per cent of all countries, representing 68 per cent of the world's population (International Lead Management Center [ILMC] 2000). Nevertheless, after 2005, the burden on populations still living in countries with leaded gasoline will fall disproportionately on developing countries—particularly those in Africa and the Middle East—as shown in figure A.I below. This figure shows the proportion of population, for each world region, living in a country that has not phased out leaded gasoline by 2001 and 2005. The burden for Africa and the Middle East is even more marked than the figure implies, however, because allowable lead levels are significantly higher there than elsewhere, as table A.1 shows. Even where countries have not completely phased out lead, those with relatively low levels of permissible lead (under 15 mg per litre) tend to be medium- or high-income countries. The situation in sub-Saharan Africa is of particular concern, not only because no country in that region has completely phased out the use of leaded gasoline, but also because high lead levels in gasoline are tolerated; over one quarter of the countries there tolerate a standard of .84 grams per litre, and the median allowed lead content is .64, over four times higher than the world median.

Studies carried out by the World Health Organization have shown that children in developing countries have three times as much body lead content than children in the United States, Japan and the EU (Wijetilleke and Karunaratne 1995). The EPA (1999) has estimated that health damages from using lead in gasoline in a typical megacity in a developing country are approximately US$ 0.24 per gram of lead used, which is more than 10 times the savings to refiners from using lead as opposed to other octane-enhancing methods.

Particulate matter

Although quite harmful, lead is largely considered a highly manageable pollutant, because emitted lead is directly proportional to the amount of lead in the fuel, and technical and policy mechanisms for reducing lead content are well understood and documented. Among the various pollutants emitted by the transport sector, therefore, particulate matter, small solid or liquid particles or aerosols suspended in air, is the most daunting because the direct impacts on human health as far as they are understood today appear to be significant, and because reducing these emissions is tricky. Unfortunately, while the adverse effects on human health are well established, the precise chemical, biological, and physical mechanisms responsible for these effects are poorly understood.

Figure A.I. Proportion of population living in a country with leaded gasoline, by region



Source: Author's calculations based on statistics from the International Lead Management Center.

Notes: Regional definitions correspond to those used by the International Energy Agency, *World Energy Outlook* (Paris, 1998). Data for China include Hong Kong Special Administrative Region of China, Macao Special Administrative Region of China and Taiwan Province of China. EIT = economies in transition.

Table A.1. Tolerated levels of lead use in gasoline specifications, by world region

Status of unleaded gasoline specifications in world regions	**Median allowable lead content (*grams per litre*)**	**Maximum allowable lead content (*grams per litre*)**
Sub-Saharan Africa	0.64	0.84
South and East Asia	0.15	0.45
Western Hemisphere	0.03	0.85
Middle East/North Africa	0.60	0.84
Western Europe	0.15	0.15
Central and Eastern Europe	0.15	0.37
World	0.15	0.85

Source: Author's calculations, based on M. Lovei, "Phasing out lead from gasoline: worldwide experience and policy implications," *Environment Department Paper 28* (Washington, DC, World Bank, 1995), annex A.

Particulate chemistry

The term particulate matter refers generally to all particles suspended in air. Larger particles—those larger than 10 ìg in diameter—precipitate rapidly from the atmosphere, so are less likely to be inhaled, and they are filtered efficiently by the nasal system and upper respiratory tract if they are inhaled. Consequently, these particles, such as resuspended road dust, are not considered substantial health risks. However, many particles associated with fossil fuel combustion, and tyre and brake wear are small enough that they can be deposited deep in the lungs, and they take longer to precipitate out of the atmosphere. These respirable particles are produced as a result of fossil fuel combustion–not only in the combustion chamber itself, but also potentially minutes, hours, or even days later as gaseous pollutants react in the atmosphere in myriad complex ways. Aerosols produced from combustion that are of concern include carbonaceous particles (soot and soluble carbon compounds, both formed in different ways from carbon present in fuels and lubricating oils), sulphates (from sulphur present in fuels and lubricating oil), nitrate-based particles (from nitrogen present in air-fuel mixture), and ash (from trace amounts of metallic additives in lubricating oil).

Carbonaceous particulate matter. Carbon present in fuels can contribute to particulate matter by forming soot–particularly in compression-ignition engines–and through particle phase emissions of non-volatile and semi-volatile hydrocarbons (soluble organic fraction or SOF). Often, SOF adsorbs onto soot particles, adding both mass and volume to PM emissions. While these processes normally occur during combustion, semi-volatile hydrocarbons can transform in the atmosphere from gaseous to particle phase, contributing to secondary particulate formation often observed during ozone episodes. Because soot formation does not normally occur in spark-ignition engines, and hydrocarbons in gasoline are predominantly volatile, particulate matter is a more serious problem for diesel fuel than for gasoline (although adulteration or improper mixing of lubricating oils in gasoline can cause significant particulate emissions). Soot and SOF generally account for over 60 per cent of ambient particulate matter.

Sulphates. Sulphur is another important component of petroleum-based transport fuels that contributes to particulate matter, in the form of hydrated sulphates (for example, sulphuric acid or ammonium sulphate). Sulphur dioxide (SO_2), produced during combustion, will oxidize to form sulphate ions (SO_3^{+}), which, in turn, will hydrate to produce sulphuric acid. The oxidation may occur in or near the combustion chamber (normally about 2-5 per cent of SO_2

emissions), in the exhaust stream, or in subsequent atmospheric reactions. In particular, platinum catalysts used in exhaust aftertreatment systems can greatly increase the rate of SO_2 oxidation. Therefore, catalytic devices to reduce emissions of pollutants such as carbon monoxide, hydrocarbons (including SOF), carbonaceous particulates–for example, with particulate traps that regenerate the filter with catalytic technology–may exacerbate sulphate particulates. Ammonia-related compounds used in certain NOx control technologies, such as selective catalytic reduction, may also exacerbate ammonium sulfate emissions.

Because sulphur tends to remain in the heavier petroleum distillates during the distillation process, sulfur is generally more prevalent in diesel than in gasoline. What sulphur does come into gasoline, therefore, results from fluid catalytic cracking processes. Sulphate composition of ambient particulate matter can vary significantly, but is generally under 40 per cent.

Nitrates and ash. Sulphur and carbon compounds are the predominant constituents of atmospheric particulates, but nitrates and ash also tend to be present in urban particulate matter. Nitrates, formed from the reaction of nitric acid with alkaline minerals or ammonia, are of particular concern, because they generally are in the ultra-fine or nano-size range. Ash consists of primarily metallic or mixed particles from trace substances found in fuels, which are of some concern because they can absorb SOF particles, providing a conduit for potential human toxins.

Health impact of particulate matter

Particulate matter has been associated epidemiologically with cardiopulmonary disease, cardiovascular disease, respiratory disease, lung cancer, and other cancers (Krewski and others 2000). The precise nature of the mechanism for these diseases, however, is unclear. It is suspected that both particle size and particle composition play a role in these diseases.

Particle size. The size of particles is of increasing concern in the assessment of the impact of particulates on human health. Worldwide, most ambient air quality and emission regulations focus on particulates smaller than 10 microns in diameter. However, fine particles (below 2.5 microns) are increasingly identified as a potentially more serious source of health deterioration problems than larger ones. Most fine particulates are actually smaller than 1 micron, allowing them to penetrate deep in the lung. Regulations focusing on PM_{10} may therefore be relatively ineffective at, and insufficient for, protecting human health. These uncertainties, as well as the uncertainties concerning the number, rather than the mass, of SOF particulates produced by the different fuels reviewed above, leave open the possibility that excessive focus on diesel vehicles as the transport sector's primary culprit in particulate-related human health deterioration may prove to be misplaced.

It is believed that 60 per cent of all suspended particulate matter are fine particles (Lvovsky and others 2000). Direct combustion sources are typically 50-60 per cent, but including combustion sources for gases that contribute to indirect (secondary) fine particulate formation means that combustion is substantially responsible for particulate matter in urban areas with unhealthful levels. As indicated above, fine and very fine particles interfere with cardiovascular and respiratory function, because they are generally too small for the body's natural mechanism to filter, and can lodge in different parts of the respiratory system (depending on conditions at ingestion). In the United States, a 10 ìg increase per m^3 in short-term exposure to PM_{10} has been associated with a 1 per cent increase in mortality, a 1.1 per cent increase in hospital admissions for respiratory conditions, and a 3 per cent increase in symptom exacerbation among asthmatics (Romieu 1999). Some respiratory symptoms of fine particles do not go away when exposure is terminated. Both the State of California and the United States Federal Government maintain ambient air quality standards for both PM_{10} and $PM_{2.5}$, although courts only recently allowed the latter to proceed with enforcement.

Particle composition. The precise impact of particle composition on human health is unclear. It is likely that sulphate particles, because of their acidity, have a toxic, and possibly carcinogenic impact on the human body over time. The potential impact of soluble organic fraction and soot is even more uncertain. SOF particles condense onto or are adsorbed by soot particles; when these particles are lodged in the respiratory tract, therefore, it is thought that the SOF portion of the particle may enter the blood stream as a toxic–and possibly carcinogenic–hydrocarbon, leaving the soot core lodged to impair breathing function. Because of the multiplicity of possible permutations of the make-up of SOF, and the various ways they might interact chemically with the human body, the precise toxic effects of SOF are unclear.

Particle reactivity, ozone, and greenhouse effect. As with gaseous hydrocarbons, soluble organic fraction can also react photochemically in the atmosphere, contributing to the formation of tropospheric ozone. This SOF may be emitted directly from the engine during combustion, but it may also come from secondary particulates which are themselves formed from atmospheric reactions of gaseous hydrocarbons (which may or may not have come from combustion). The mechanism by which ozone and particulate matter are created in urban airsheds, therefore, can be both complex and highly fluid. For this reason, urban air pollution is frequently referred to as a "cocktail", making it difficult to understand completely the full impact of particulate emissions. Recently, air pollution researchers have begun to question the effect of this "cocktail" on radiative balances and global climate change. It may be that particulate cocktails spreading out over many cities at different times of the year are having an effect on the amount of solar radiation reaching the earth, as well as the earth's albedo. Recent research, for example, has suggested that soot, or black carbon, may be responsible for as much as 30 per cent of observed climate change, and be the most important anthroprogenic source after carbon dioxide (Jacobson 2001).

Prevalence of particulate matter

Despite the uncertainties associated with particulate matter, especially its chemical formation and impact on human health, it is clear that PM is highly damaging to human health, and prevalent in many cities around the world, especially in developing countries. A recent study has estimated the benefits of PM reduction in Buenos Aires at about US$ 230,000 per ton of PM eliminated (Weaver 2001b). The World Health Organization reported that in 1992, ambient concentrations of particulate matter were very high for many cities, in both developing and developed countries, as shown in figure A.II below.

Volatile organic compounds

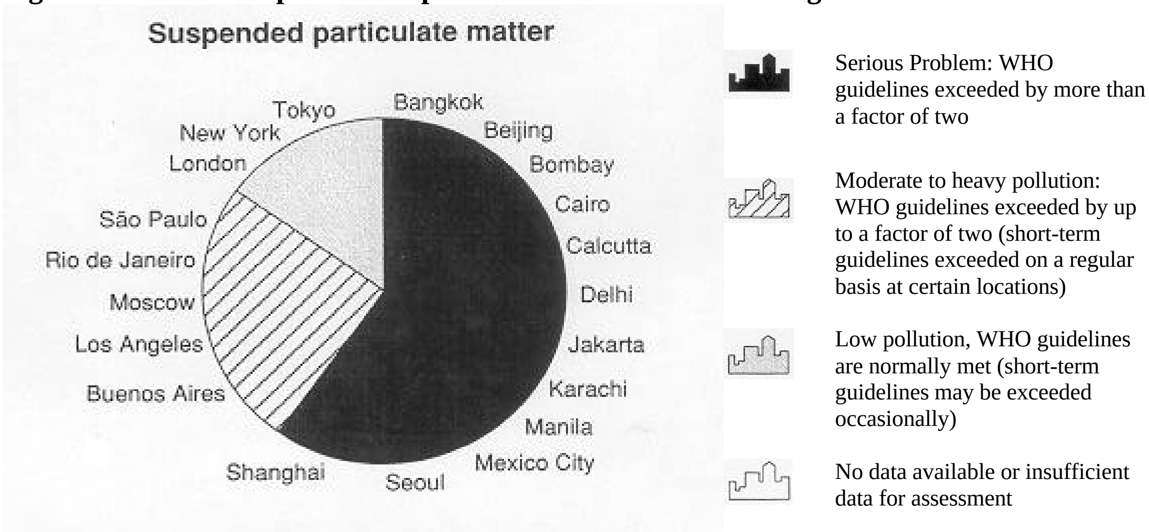
Volatile organic compounds are usually regulated collectively as a group in emissions standards. The term refers to those hydrocarbons susceptible to evaporation, and in common usage excludes methane, which is relatively unreactive. Lighter petroleum distillates tend to have higher volatility content, but reformulation and blending can reduce this somewhat. VOCs are released either directly from unburned portions of gasoline (either during combustion or immediately after combustion in the case of two-stroke engines or through evaporation at any time during the fuel delivery chain) or indirectly, as intermediate products of incomplete combustion. Higher flame temperatures, longer residence times, or greater oxygen content in the combustion chamber will reduce the chance of incomplete combustion, thereby reducing hydrocarbon emissions in the exhaust stream.

VOCs represent an air quality concern for two reasons. First, they are an important precursor to ozone formation. Secondly, many VOCs are themselves toxic.

Ozone-forming potential

Hydrocarbons react with NOx in sunlight to form ozone (O_3) through complex atmospheric reactions. Because ozone is an unstable molecule, it requires energy to form and remain intact, and can break down easily into normal oxygen molecules (O_2). For this reason, ozone is dangerous to human health; it interferes with respiratory function, leads to reduced lung capacity and increases the intensity of lung infections. An increase of 80 ìg per m^3 of ozone over a one-hour exposure, or 30 ìg per m^3 in an eight-hour exposure, has been associated with a 100 per cent increase in respiratory symptoms. An increase of 12 ìg per m^3 over an eight-hour exposure has also been associated with a 20 per cent increase in hospital admissions for respiratory conditions (Romieu 1999). The impact of long-term and chronic exposure to ozone is unclear, but some evidence suggests reason for concern (Romieu 1999).

Figure A.II. Relative problem of particulate matter in world megacities



Source: WHO/UNEP (United Nations Environment Programme, *Urban Air Pollution in Megacities of the World* (Oxford [United Kingdom], Blackwell, 1992).

Unlike other pollutants, ozone is a problem associated with cities in wealthy and poor countries alike, as figure A.III shows.

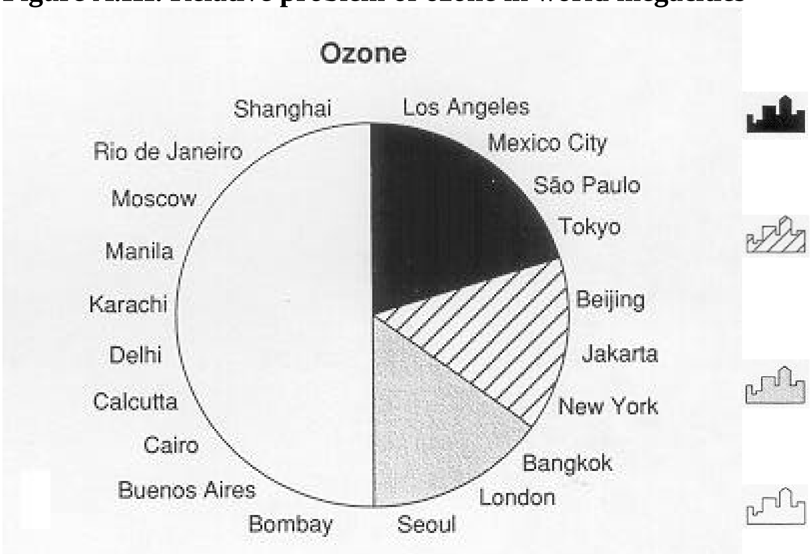
In the formation of ozone, some hydrocarbons are more reactive than others, depending on the complexity of molecular structure and the strength of the molecular bonds. For example, complex aromatics and olefins tend to be more reactive than straight chain paraffins. For this reason, some jurisdictions have moved towards emission restrictions targeting the more reactive VOCs, as opposed to simply non-methane hydrocarbons (NMHCs). California's NLEV regulations, for example, target a "reactivity adjusted" non-methane organic gas standard, under which different VOC species are weighted by photochemical reactivity.

VOC toxicity

Many hydrocarbons are known or suspected to have significant toxic effects on human health, as well as vegetation and animal life. Finding an effective mechanism to enact policy regarding these effects, however, has been tricky, because dose-response relationships are specific to particular hydrocarbons, while the relative content of any particular hydrocarbon in exhaust or evaporative emissions is highly variable. The toxic chemicals of most concern from the transport sector include benzene, 1,3 butadiene, various polycyclic aromatic hydrocarbons (PAH), and various aldehydes.

Benzene, the simplest and most basic component of gasoline, has been shown to have harmful effects on the immune system, the neural network, and hemoglobin. It is also a known carcinogen (Romieu 1999). Weaver and Balam (1999) estimate that benzene represents about 4 per cent of gasoline VOC exhaust, and about 6 per cent of diesel VOC exhaust in Mexico City. PAH are complex molecules based on simple aromatic rings such as benzene, and tend to be particularly prevalent in diesel fuel. The potential permutations of PAH are enormous, each with its own potential particular impact on human health. The most prevalent in diesel are toluene and various xylenes, although in toxicology studies, benzo[a]pyrene is often used as an index compound. PAH, which have been shown to be mutagenic and carcinogenic, can bind to soot particles, and be delivered deep into lung tissue.

Figure A.III. Relative problem of ozone in world megacities



Source: WHO/UNEP, *Urban Air Pollution in Megacities of the World* (Oxford [United Kingdom], Blackwell, 1992).

1,3 butadiene and aldehydes (acetaldehyde and formaldehyde) are all products of incomplete combustion of fossil fuels and subsequent atmospheric reactions. It has been estimated that 1,3 butadiene constitutes about 2.4 per cent of gasoline, and 1 per cent of diesel VOC emissions in Mexico City (Weaver and Balam 1999), but these emissions are highly dependent on the gasoline blends used. Aldehydes are particularly prevalent as a by-product from alcohol (methanol or ethanol) combustion, either when used as directly as a fuel, or as an additive, oxygenate, or octane enhancer (such as ETBE [ethyl tertiary butyl ether] or MTBE). 1,3 butadiene is a known carcinogen and mutagen. It has been shown to cause defects in fetal development, but these effects have been proven only on laboratory animals. Sensory irritation in humans, however, particularly to eyes, has been proven (Calabrese and Kenyon 1991). Acetaldehyde and formaldehyde are known irritants and are suspected of being carcinogenic to humans.

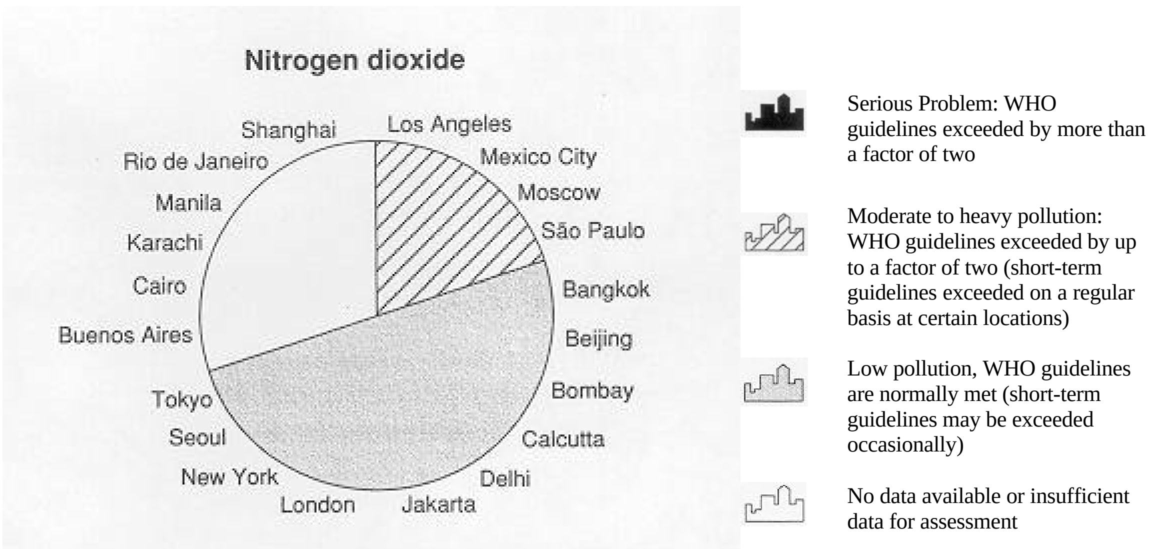
In addition to its contribution to aldehyde formation, MTBE has also recently been the subject of some concern as a water toxic, from groundwater contamination through seepage. In tests near refilling stations in California and Mexico City, MTBE contamination of groundwater has been found, raising fears about the impact on human health. California has banned the use of MTBE as a fuel additive—not without controversy—and the United States Environmental Protection Agency is currently considering such a ban.

NO_x

Oxides of nitrogen constitute another important category of regulated pollutants. Like VOCs, these pollutants are of concern both because of their direct effects on human health, and because they react in the atmosphere (with VOCs) to produce ozone. Nitric oxide (NO) and nitrogen dioxide (NO_2) are released in combustion because molecular nitrogen (N_2) present in the air/fuel mixture splits and is oxidized. Because molecular nitrogen is relatively stable, the proportion that splits and becomes involved in the combustion reaction is directly related to the flame temperature and duration of the combustion (residence time). Consequently, high flame temperatures and/or long residence times–precisely the kinds of engine changes that might reduce VOC or PM emissions–will increase NO_x emissions.

NO_2 has been shown to have toxic effects on human health, including altered lung function, respiratory illness, and lung tissue damage (Shah and others 1997). NO_2 has also been shown to exacerbate asthmatic symptoms. At the tailpipe, the volume of NO_x is about nine parts NO to one part NO_2. While NO is considered more benign to human health, it frequently oxidizes in atmospheric reactions to NO_2. This reaction is a key component of ozone formation, so reduction of NO_x emissions is a crucial element in resolving ozone problems. A WHO/UNEP survey of megacities throughout the world, conducted in the early 1990s, found NO_2 a prevalent problem in cities in both developed and developing countries, as shown in figure A.IV.

Figure A.IV. Relative problem of NO_2 in world megacities



Source: WHO/UNEP, *Urban Air Pollution in Megacities of the World* (Oxford [United Kingdom], Blackwell, 1992).

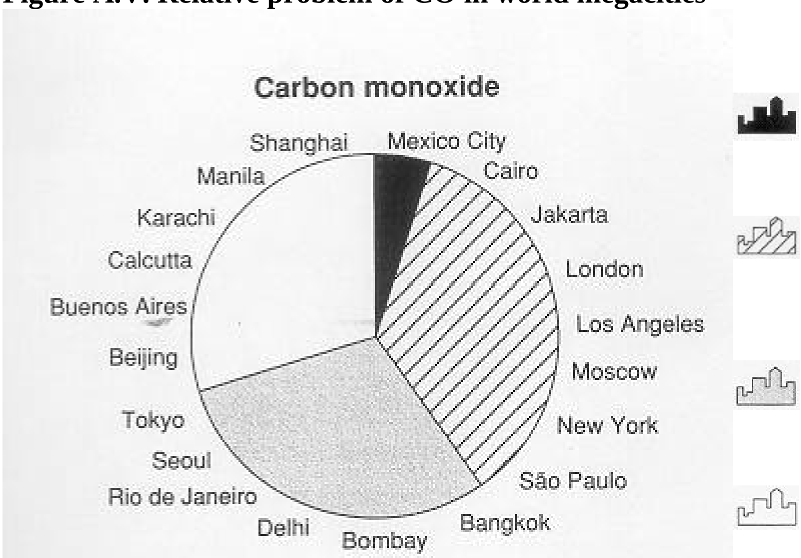
CO

Carbon monoxide is an interim gas in combustion, resulting from incomplete combustion–meaning the flame temperature is too low, the residence time too short, or oxygen too scarce (fuel-rich condition). Consequently, CO emissions are often highly correlated with HC emissions. In the human body, CO can cause oxygen deprivation (hypoxia) displacing oxygen in bonding with hemoglobin. This can cause cardiovascular and coronary problems, increase risk of stroke, and impair learning ability, dexterity and sleep. The above-mentioned WHO/UNEP survey of megacities found CO a problem in a wide range of cities, but a serious problem only in Mexico City, as shown in figure A.V; CO levels in that city have fallen since the WHO/UNEP survey in the early 1990s, however.

SO_x

Although particulate sulphates are released in fossil fuel combustion, most of the sulphur tends to be released in gaseous form (sulphur dioxide or sulphuric acid). Because of the quantities of sulphur found in heavy oil and coal, as opposed to gasoline or diesel, the transport sector’s relative contribution to SO_x in many areas, especially coal-burning areas, is actually quite low. In general, the lower the measured ambient concentrations of SO_x, the higher the proportion from transport is likely to be. For this reason, concern about sulphur in transport fuels has tended to focus much more on sulphur’s contribution to particulate matter concentrations, as noted above, than on SO_2. In metropolitan regions where SO_2 is a major health concern, it may often be more cost-effective to address the non-transport sources of ambient concentrations. SO_2 is associated with various bronchial conditions, which can be acute even at relatively low levels of exposure for children or asthmatics. Sulphuric acid has also been shown to have respiratory effects. As figure A.VI indicates, SO_2 is a serious problem in Beijing, Mexico City, and Seoul.

Figure A.V. Relative problem of CO in world megacities



Serious Problem: WHO guidelines exceeded by more than a factor of two

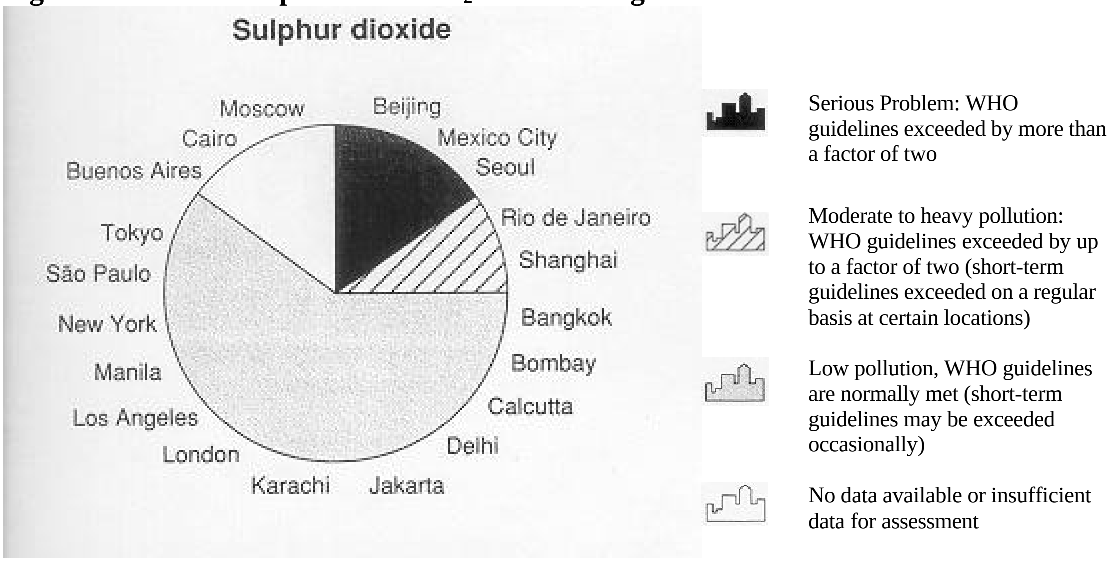
Moderate to heavy pollution: WHO guidelines exceeded by up to a factor of two (short-term guidelines exceeded on a regular basis at certain locations)

Low pollution, WHO guidelines are normally met (short-term guidelines may be exceeded occasionally)

No data available or insufficient data for assessment

Source: WHO/UNEP, *Urban Air Pollution in Megacities of the World* (Oxford [United Kingdom], Blackwell, 1992).

Figure A.VI. Relative problem of SO_2 in world megacities

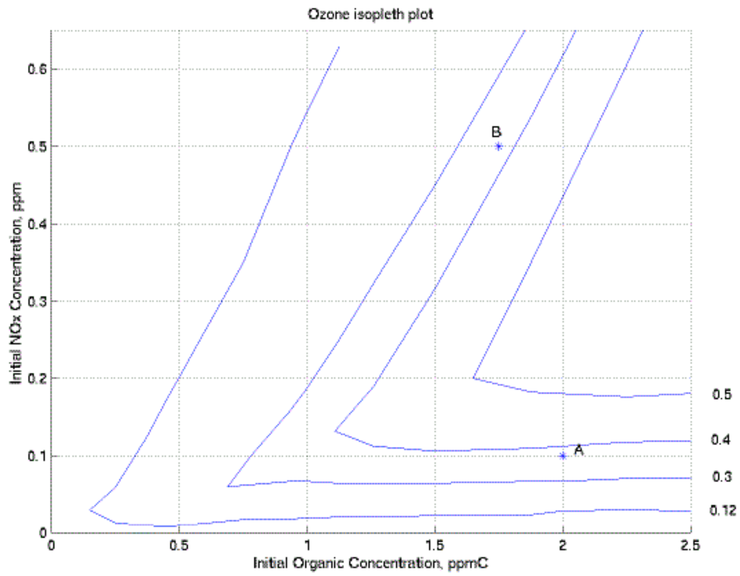


Source: WHO/UNEP, *Urban Air Pollution in Megacities of the World* (Oxford [United Kingdom], Blackwell, 1992).

NO_x and VOC standards

Because NO_x and VOCs both contribute to ozone formation, but respond differently to different technological interventions, early emissions regulation focusing on ozone reduction often established a combined NO_x/VOC standard, particularly for diesel vehicles. The difficulty of any strategy targeting ozone reduction is in knowing precisely what the NO_x/VOC composition of ozone for a given urban airshed actually is. Figure A.VII shows a typical NO_x/VOC isopleth for an urban area. Points A and B both reflect the same level of ozone pollution produced by different amounts of NO_x and VOCs. A strategy of reducing NO_x if the initial NO_x/VOC concentrations are represented by point B will be ineffective and, in this example, would actually increase ozone concentrations. Similarly, reducing VOC concentrations if the NO_x/VOC concentrations are represented by point A will also be ineffective. Consequently, no single ozone reduction strategy is appropriate for all urban airsheds. In practice, most urban airsheds tend to be located toward the lower right portion of the diagram, where NO_x strategies would be more effective than VOC strategies (Weaver 2001b). However, without local information, an inappropriately targeted strategy could prove costly.

Figure A.VII. Isopleth of NO_x and VOC contribution to ozone formation



Source: D. Daescu, *A Generalized Reaction Mechanism for Photochemical Smog,* University of Iowa, http://www.math.uiowa.edu/~ddaescu/task3.html

Annex II

EXCESSIVE VEHICLE USE

For any given level of economic development or aspired-to quality of life, a certain amount of travel by motorized vehicle can be considered necessary simply to achieve that aspiration or level of development. Above this amount, vehicle use can be considered to be "excessive". In microeconomic terms, it can be thought of as the difference between actual car use, and that which would occur if all marginal social costs were included in the costs seen by users. The phenomenon of excessive car use is linked to two important and interrelated factors: the controversial concept of "car dependence"[1] and the prevalence of price distortions favouring car use.

Despite its prevalence in recent policy discussions, the concept of car dependence remains poorly defined in the literature (Gorham forthcoming). Gorham (forthcoming) characterizes car dependence in developed economies as afflicting households for whom "sustained abstinence from regular car use would impose so high a social or economic burden on itself that such abstinence either is considered intolerable, or is inconceivable in the first place." The factors contributing to such a condition of car dependence are rarely adequately enumerated. Land-use and urban settlement patterns are frequently cited (Litman 1999; Newman and Kenworthy 1989; Newman and Kenworthy 1999), but there are a number of other factors contributing to this sense of powerlessness in the absence of car transportation. Gorham (forthcoming) suggests two other categories of factors: (a) psycho-social factors, in which the car and the transportation it provides take on psychological and social meanings that reflect deficits in individual lives; and (b) circumstantial factors, in which whole lifestyles change in response to a car, changes which cannot easily be undone once made.

The second factor creating conditions of excessive car use is pricing (and land-use) policy that creates price distortions favouring car use over other forms of accessibility. These distortions might include subsidies to road users through the road financing mechanism, unperceived costs through land-use policies that "hide" certain costs or taxing policy that masks the relationship of fixed to variable costs, a possible subsidy hidden embedded within the concept of induced travel, and secondary or feedback loops, through the capitalization of existing subsidies into land values.

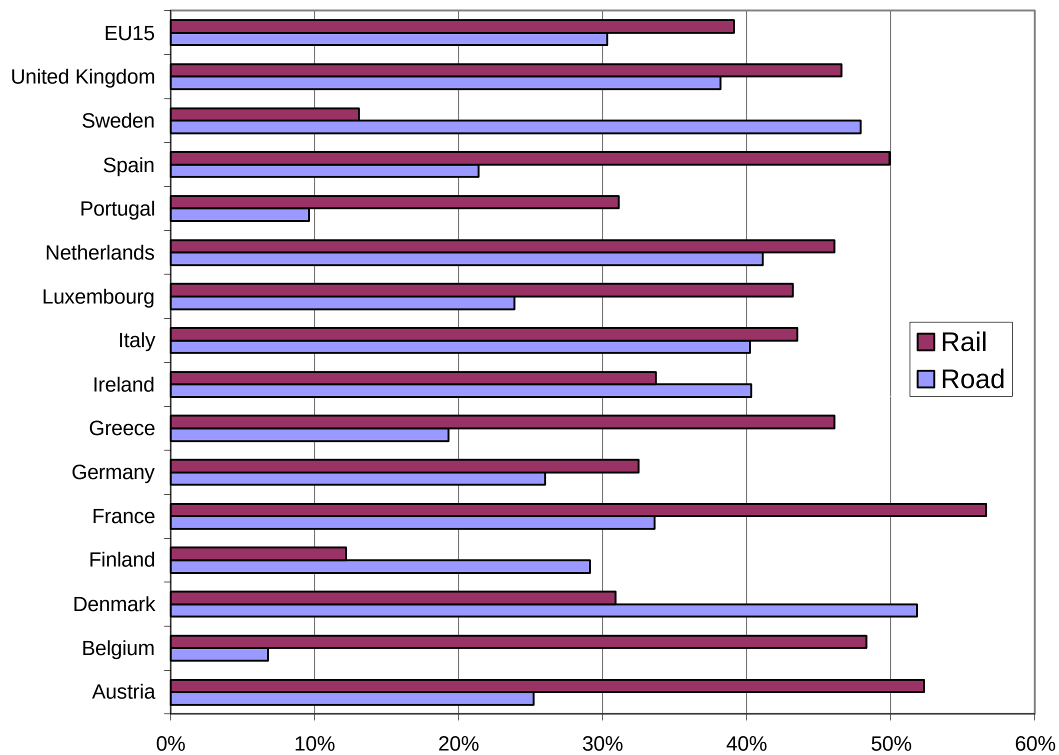
Fuel subsidies. Many countries, particularly in the developing world, maintain fuel subsidies that keep out-of-pocket costs lower than border prices. In many cases, these subsidies are not intended for the transport sector, but rather for the agricultural or household sectors in the form of price supports to diesel and kerosene, or propane, respectively. The perverse effect of such subsidies is that these subsidies may artificially create demand from the transport sector—demand that drives up prices for the very sectors for which they are intended.

General subsidies to road users. A number of studies in the United States and Europe suggest that road users are not exposed to the full range of costs they impose. A well-known and highly regarded study of transport cost recovery in the United States found that, in 1991, users paid only between 43 and 60 per cent (depending on certain assumptions) of the total costs of road use, including externalities such as congestion, pollution and traffic accidents (Delucchi 1997). A similar analysis of 15 European countries for the same year concluded that road users

[1] For example, as reviewed in Litman 1999 or Newman and Kenworthy 1999.

there on average pay only about 30 per cent of total costs, although with considerable variation between European Union (EU) States, as shown in figure A.VIII (EEA 1999). (Belgians covered only 7 per cent, while Danes covered 52 per cent of total road costs.)

Figure A.VIII. Proportion of infrastructure and external costs recovered by European rail and road sectors



Source: European Environment Agency, *Are We Moving in the Right Direction? TERM 2000* (Copenhagen, 1999) (http://reports.eea.eu.int/ENVISSUENo12/en/page025.html).

Willoughby (2000a) has compiled estimates of the net road transport costs as a percentage of GDP, including infrastructure and land costs, externality costs such as congestion, pollution and accidents, and receipts, from a number of different studies and sources. These are shown in table A.2. Willoughby's numbers suggest that in developing countries, as in developed ones, road users pay little of the total costs they incur; in Buenos Aires, only between 14 and 18 per cent of costs are recovered by road users, and in Santiago, only about 20 per cent of costs are recovered.

If externalities such as costs of congestion, air pollution, noise and accidents are ignored, road users still generally do not pay the full costs they incur, although the cost-recovery proportion is quite high. Delucchi (1997) shows that users in the United States covered between 89 and 95 per cent of monetary costs for road use (again, depending on assumptions), with the remainder paid by taxpayers.

Unperceived costs. A second factor constituting a distortion in prices favouring excessive car use is the extent to which unperceived costs are built into the urban and pricing policy. Unperceived costs include "fixed" or "sunk" costs, as well as hidden costs inherent in many aspects of automobile ownership and use. A sunk cost is one which vehicle owners pay regardless of the amount they use their vehicles. This can include one-time and periodic, time-dependent costs. Examples include the purchase cost of the vehicle, registration fees, taxes and, conventionally, insurance premiums. Technically, depreciation of a vehicle is not a fixed cost, but most vehicle users perceive it as one.

Hidden costs are incremental costs of other goods that are, in fact, used to pay for transportation or infrastructure services provided. The classic example is “free” parking at a retail establishment or a site of employment. The hidden cost increment may be a slightly higher price for goods or services purchased, or income forgone because of the parking benefit (Shoup and Breinholt 1997). These costs may, of course, be borne by vehicle users, often unknowingly, but non-vehicle-users may also have to bear these costs as well. In the case of both fixed and hidden costs, the ability of motorists to express the true marginal value of using their vehicle for a given particular trip is suppressed, resulting in “excess” consumption, and an inefficient allocation of resources.

Inducement subsidy. Expansion of infrastructure capacity is associated with “induced” demand for transportation–that is, an increase in volume of transport demand that would not have occurred in the absence of the capacity expansion (DeCorla-Souza and Cohen 1999; Lee and others 1999). Annex VII to this report reviews this phenomenon in detail. It is also noted briefly here, in that induced travel may constitute a subsidy leading to excessive car use. Unfortunately, most of the theoretical work on the subject to date has focused on trying to identify and describe it adequately, while the empirical work has tried to identify how significant induced demand actually is. Relatively little attention has focused on evaluating the distributional implications of induced demand.

The portion of overall demand increase that can be attributed to facility expansion occurs because of a real or perceived time savings as a result of the change, the economic value of which translates into an income or substitution effect for the traveller. In the absence of facility-specific pricing to offset these price effects, the mechanism to finance the infrastructure facility can be thought of as a transfer of resources, from those paying for the new infrastructure (general taxpayers or current road users, depending on the finance mechanism) to motor vehicle users undertaking the new, incremental vehicle kilometres. In other words, potential travellers are subsidized by the system to undertake new travel by car. The actual assessment of the size of this subsidy is probably quite complex, because it is difficult to know which travellers would otherwise be willing to pay for induced trips. For infrastructure provision, therefore, the most efficient allocation of resources is effected through facility-specific pricing regimes, such as tolls or electronic road pricing (ERP). The real world trade-offs between optimal social-cost pricing and pricing for cost-recovery probably means that, in practical terms, an inducement subsidy can never be completely eliminated, but it can be substantially reduced.

Feedbacks: capitalization of subsidies into land values. Fuel subsidies, general subsidies to road users, unperceived costs, and inducement subsidies can create conditions in which motor vehicle users do not pay for the full costs they impose on society, particularly when externalities such as air quality deterioration and noise are taken into account. These implicit subsidies can become absorbed and capitalized into the relative distribution of land values and real estate prices (Willoughby 2000a; Lee 1997). Because of the price distortions, travellers perceive the use of private motor vehicles to be relatively less expensive than if they were facing the true costs. Consequently, other modes, and other forms of accessibility (for example, proximity) become relatively costly. These assessments of relative costs are taken into account in medium- and long-term decisions about location, lifestyle, and building patterns, which in turn are reflected in land values in a competitive market. Thus, underpricing of the transport system, in the long run, distorts land markets. This distortion of land markets towards car-intensive lifestyles becomes an important feedback factor in inducing further car dependence, potentially triggering a vicious circle of ever-escalating excessive car use.

Table A.2. Estimates of external costs of road transport as a percentage of national/regional GDP

Country/City	Year	Source	Road costs	Land and parking	Congestion	Accidents, net of insurance	Noise pollution	Local air pollution	GHG a/	Other	Subtotal	Revenue from road users	Net subtotal	Others
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)	(xiii)	(xiv)	(xv)
USA1	1989	WRI	1.64 b/	1.56	-	1	0.16	0.18	0.5	-	5.04	b/	5.04	0.46
USA2 c/	1990	NRDC	1.25 b/	0.43-1.74	0.19	1.71	0.05	2.09-3.83		0.07	5.69-8.84	b/	5.69-8.84	0.78-2.61
USA3	1991	Lee	1.76	2.41	-	0.24	0.19	0.73		0.26	5.59	0.88	4.71	0.87
EU1	Early 1990s	ECMT	1.75	-	0.75	2.4	0.3	0.6	0.5	-	6.3	1.67	4.63	-
EU2	Early 2000s	ECMT	1.49	-	0.75	1.2	0.3	0.15	0.47	-	4.36	1.67	2.69	-
UK	1993	CSERGE	0.24	-	3.03	0.46-1.49	0.41-0.49	3.12	0.02	-	7.28-8.39	2.6	4.68-5.79	-
Poland	1995	ISD	1.14	-	0.3	1.6	0.1	0.3	-	-	3.44	2.81	0.63	-
São Paulo	1990	IBRD	-	-	2.43	1.11	-	1.55-3.18	-	-	-	-	5.09-6.72	-
Buenos Aires	1995	FIEL	-.73	-	3.42	0.5-2.00 d/	-	0.97	-	-	5.62-7.12	1.01	4.61-6.11	-
Bangkok	1995	Misc.	-	-	1.00-6.00	2.33		2.56	-	-	5.89-10.89	-	5.89-10.89	-
Santiago	1994	Zegras	1.37	1.92	1.38	0.94	0.15	2.58	-	-	8.35	1.64	6.71	-
Dakar	1996	Tractebel	-	-	3.37	0.16-4.12	-	5.12	-	-	8.65-12.61	-	-	-

Sources: C. Willoughby, *Managing Motorization*, TWU Working Paper No. 42 (Washington, DC, World Bank, 2000), based on the following: (a) J.J. Mackenzie, R.C. Dower, and D.D.T. Chen, *The Going Rate: What It Really Costs to Drive* (Washington, DC, World Resources Institute, 1992); (b) P. Miller and J. Moffet, *The Price of Mobility: Uncovering the Hidden Costs of Transportation* (New York [New York], Natural Resources Defense Council, 1993); (c) D.B. Lee, "Uses and meanings of full social cost estimates" in D.L. Greene, D.W. Jones, and M.A. Delucchi, *The Full Costs and Benefits of* Transportation (Heidelberg, Springer, 1997); (d) European Conference of Ministers of Transport, *Efficient Transport for Europe: Policies for Internalization of External Costs* (Paris, OECD/ECMT, 1998); (e) D. Maddison, D. Pearce, O. Johansson, E. Calthrop, T. Litman, and E. Verhoef, *The True Costs of Road Transport*, Blueprint No. 5 (London, Earthscan for CSERGE, 1996); (f) Institute for Sustainable Development, *Information Package No. 2 on Alternative Transport Policy in Poland* (Warsaw, ISD, 1997); (g) World Bank, Draft Staff Appraisal Report for Brazil: São Paulo Integrated Urban Transport Project (Washington, DC, 1994); (h) Fundación de Investigaciones Económicas Latinoamericanas, *Financiamiento del Sector Transporte de la Región Metropolitana de Buenos Aires* (Buenos Aires, FIEL, 1995*);* (i) K. Lvovsky, G. Hughes, D. Maddison, B. Ostro, and D. Pearce, Environmental Costs of Fossil Fuels: a Rapid Assessment Method with Application to Six Cities (draft) (Washington, DC, World Bank, 1999); (j) Swedish National Road Consulting AB (SweRoad) and Asian Engineering Consultants Corporation, Consulting Services for Developing a Road Safety Master Plan and a Road Traffic Accident Information System for the Ministry of Transport and Communications, Kingdom of Thailand (1997); (k) V.S. Pendakur, "A tale of two cities: Bangkok and Mexico" *in* OECD, *Towards Clean Transport* (Paris, OECD, 1996); (l) D.E. Dowall, *Making Urban Land Markets Work: Issues and Policy Options*, Working Paper 702 (Berkeley, Institute of Urban and Regional Development, University of California, 1998); (m) C. Zegras, "The costs of transportation in Santiago de Chile: analysis and policy implications," *Transport Policy 5*, 1998; and (n) SSATP (World Bank Sub-Saharan Africa Transport Program), *Transport en Afrique—Note Technique*, SSATP note 19 (1999).

Notes: For USA1, see source (a); for USA2, see source (b); for USA3, see source (c); and for EU1 and EU2, see source (d).

a/ GHG = greenhouse gases.
b/ Road costs given net of revenues from road users.
c/ Car only.
d/ Calculation for nation as a whole and gross of insurance compensation.

Annex III

Conventional vehicle technology improvements

Technological improvements to internal combustion engine (ICE) vehicles–whether gasoline, diesel, or CNG–address one of five areas of vehicle operation, as shown in table A.3.

Table A.3. Areas of application of vehicle technology for ICE vehicles

Focus	*Affects*
Engine and fuel system	Tailpipe emissions of local pollutants, engine energy intensity (moderate evaporative reduction possible)
Transmission system	Vehicle energy intensity and GHG emissions
Aftertreatment of exhaust	Tailpipe emissions of local pollutants (can cause moderate increases in vehicle energy intensity)
Fuel-supply and crankcase treatment	Evaporative emissions
Vehicle/tyre design for friction reduction[a/]	Vehicle energy intensity and GHG emissions

a/ Can include improvements to transmission system, aerodynamic design, tyre design, reduction in weight of vehicle, and reduction in power loading of the engine.

Engine and fuel system

Pollutant emissions can be substantially reduced by carefully controlling the characteristics of engine operation, particularly combustion. A number of parameters affecting engine performance can influence the amount of emissions:

- The air-fuel ratio;
- Rate of air-fuel mixing;
- Flame temperature;
- Combustion lag;
- Residence time.

These, in turn, can be strongly influenced by the following:

- The fuel delivery system (including carbureted versus injected and sophistication of injection/carburetion technology);
- The size and shape of the cylinders and pistons;
- The nature of the exhaust gas path (direct versus recirculated).

In addition, high compression ratios in the cylinders can increase fuel efficiency, decreasing directly the amount of CO_2 emissions and, indirectly, HC and CO emissions.

Applying technologies that affect the above features in order to reduce tailpipe emissions of local pollutants, however, is tricky, because of an inherent trade-off between CO, NMHC, and PM_{10} (in the case of diesel and two-stroke gasoline engines) on the one hand, and NO_x and engine performance on the other hand. Car and truck manufacturers in industrialized countries have developed sophisticated technical mechanisms for balancing these trade-offs to minimize overall emissions over a range of pollutants, while maintaining engine performance to meet both consumer needs and fuel-efficiency or carbon-dioxide emissions standards. These technical mechanisms involve "lean-burn" combustion, in which the combustion occurs in an oxygen-rich environment. The state of the art uses sophisticated computer controls on a range of engine functions, controls that can be expensive to install and maintain. Given the limited resources, trying to bring these technologies to developing countries may be of limited value; only a relatively small number of vehicles could be fitted with them and properly maintained.

However, a number of intermediate engine technologies are available to help improve various factors of engine design and move towards lean-burn combustion in developing country contexts, including the use, design and timing of fuel-injection systems, the physical design of the combustion chamber and pistons (particularly important for diesel emissions reduction), and exhaust-gas recirculation techniques. This last technique, which is particularly important for two-stroke engines, where unburned hydrocarbons can be plentiful in the exhaust, contributing to both VOC and PM emissions, also helps to boost overall energy efficiency. For diesel engines, turbocharging and aftercooling are also effective ways of increasing oxygen content in the air-fuel mix, especially at steady-state conditions. Improvements in emissions performance can be achieved with even more basic improvements to engine design, including modification of carburetor design to optimize air/fuel mixture while controlling NO_x through retarding ignition timing and recirculating exhaust gas. It is estimated that even these modest changes can reduce NMHC and CO emissions by about two thirds, and NO_x emissions by about 10 per cent over unregulated emissions, assuming proper maintenance (Faiz and others 1996).

Exhaust aftertreatment

Aftertreatment of exhaust applies additional technology to engine exhaust to reduce the amount of pollutants, usually through thermal oxidation (uncatalysed), catalytic conversion (oxidation or oxidation and reduction catalysts), and/or filtration (in the case of diesel particulates). Thermal oxidation involves injecting air into the exhaust gases while they are still very hot (over 600°C) immediately after they leave the combustion chamber. With enough exposure to oxygen, the carbon monoxide and hydrocarbons will continue reacting under these conditions. While it is possible to use the exhaust manifold to pump the requisite air, it is more effective to use an external pump. Air injection as a retrofit strategy must use an external pump, which can be relatively expensive (between $60 and $100 per car).

For gasoline vehicles, three-way (oxidation-reduction) catalysts are effective in reducing NMHCs, CO and NO_x. Costing between $250 and $300 per catalyst, their use with closed-loop carburetion or, even better, direct injection technology can reduce NMHC and CO emissions by over 95 per cent of unregulated emissions, and NO_x by over 70 per cent.[2] A number of logistical problems render the use of catalysts problematic in many developing countries though. The first problem is cost. Although the catalyst itself costs less than US$ 300, other changes required in manufactured cars can push costs to over US$ 650 per vehicle. For retrofits, these required changes usually render the installation of a catalyst on previously uncontrolled gasoline cars economically infeasible.

---

[2] Two-way (oxidation) catalysts are no longer cost-effective compared with three-way catalysts for use in four-stroke gasoline engines under stoichiometric conditions. Three-way catalysts are only about US$ 50 to US$ 75 more than two-way, and few metropolitan areas with excessive ozone can afford to forgo the NO_x controls. However, two-way catalysts have been, and continue to be, used with moderate success in two-stroke applications (where NMHC and CO emissions overwhelm NO_x output). Three-way catalysts cannot be used with gasoline engines calibrated for lean-burn, but new "lean-NO_x" catalyst technology developed for NO_x control of diesel engines might be used for lean-burn gasoline applications.

The second problem is that, in many developing countries, fuel specifications remain incompatible with catalyst use. Sulphur and lead in fuels can degrade or neutralize the catalyst, and the latter can destroy it completely. Even in countries where unleaded fuel is available, if leaded fuel is still available, motorists may misfuel. A single tank of leaded fuel could permanently disable the catalyst. Therefore, mechanisms need to be in place to ensure that such misfuelling, intentional or otherwise, does not occur. The third problem is that, without the use of additional technology such as fuel injection, catalysts will generally degrade the fuel-efficiency of gasoline vehicles. Consequently, vehicle owners will have an economic incentive to disable the catalyst, absent adequate monitoring and controlling facilities. In addition, for lean-NO_x catalytic devices, higher levels of sulphur in the fuel can induce more frequent regeneration, further degrading fuel-economy (and increasing CO_2 emissions).[3]

For diesel vehicles, a number of exhaust aftertreatment techniques have been developed, but their effectiveness is less straightforward than those developed for gasoline vehicles, because of the inherently lean conditions of compression-ignition and the relatively higher prevalence of sulphur in diesel fuel than in gasoline. Two-way catalysts are being used with increasing frequency in light and heavy-duty vehicles, but deployment is limited by sulphur quantities in fuel. These catalysts do oxidize hydrocarbons, including the SOF portion of particulate mass. However, these SOF reductions may be offset by increased sulphate emissions caused by catalyst oxidation of SO_2 to SO_3 (Weaver and Chan 1999). In addition, some research has suggested that oxidation catalysts may limit SOF mass, but not the number of SOF particles emitted, suggesting that oxidation of hydrocarbons in diesel aftertreatment may merely reduce the size of emitted particles (Bagley and others 1996). The aggregate effects on human health of such a treatment are poorly understood at present.

Particle traps have been increasingly and more effectively used in diesel vehicle applications, but it is difficult to regenerate filters once they have become saturated with particulates. Various solutions exist, mostly involving oxidizing the soot particles, but, as with oxidation catalysts, the effectiveness of the process may be compromised by the presence of sulphur in the fuels, and the benefit offset by increasing emissions of sulphates. In addition, sulphuric acid vapour may escape the filter, only to condense later to form sulphate particulate. Some advanced solutions, such as continuously regenerating filters, are not even feasible at present sulphur levels, even in developed countries (Weaver and Chan 1999).

Three-way catalysts cannot be used in diesel vehicles because, as for lean-burn gasoline vehicles, oxygen in the air/fuel mixture reduces the effectiveness of the reductant. A number of de-NO_x catalytic technologies have emerged recently, however, to address NO_x emissions. Lean-NO_x catalysts use hydrocarbons as a reductant; since these are not available in sufficient quantities for diesel engines, it is expected that these catalysts, still under development, will involve the injection of fuel into the exhaust stream, degrading fuel efficiency somewhat and increasing hydrocarbon emissions. NO_x traps convert NO_x emissions into barium nitrate, which is periodically catalysed under rich conditions to release the nitrogen as N_2. This would require use of a diesel burner system distinct from the (normally lean) engine, entailing significant technical and economic costs. The catalyst for the conversion of barium nitrate would also be sensitive to the presence of sulphur in the fuel. Like particulate aftertreatment technologies, both of these de-NO_x techniques are highly sensitive to the amount of sulphur in the fuel. They require sulphur content under 50 particles per million (ppm), the purpose of a late Clinton administration

[3] This fuel-economy degradation is the driving force behind current efforts in the United States and the EU to reduce sulphur content to 10 particles per million (ppm), even though lean-NO_x technologies will still be operable at up to 50 parts per million (ppm) (CONCAWE [European oil industry organization for environment, health and safety] 2000).

rule on diesel fuel, and one tenth the current United States standard for sulphur (Weaver and Chan 1999).

A third de-NO_x catalytic technique, selective catalytic reduction, involves the injection of ammonia or ammonia-related compounds into the exhaust. Depending on the particular catalyst used, use of very low sulphur fuels may not be required. Low sulphur fuels, however, may allow certain catalytic materials to be used which also oxidize particulates and hydrocarbons, enhancing the effectiveness of the entire system (Weaver and Chan 1999).

Many of the exhaust aftertreatment technologies reviewed here are still under development, and many of those that are available are too cost-prohibitive for immediate implementation in many developing countries. Nevertheless, they must be taken into account in a strategic assessment of possible technologies, because they may become cost-feasible during the working life of an investment made in the near future.

Transmission system

Improvements to transmissions systems are primarily technical measures to improve fuel efficiency of vehicles and reduce CO_2 emissions, but they can also help to reduce VOC, CO and PM emissions somewhat, by helping to reduce engine loads in actual drive cycles, and also through reduction in fuel consumption, with which these pollutants are correlated. Advanced techniques include optimized transmission control, for both manual and automatic transmissions, five-speed automatic or other increases in gearing, and continuously variable transmission (CVT). Most of these are state-of-the-art technologies that may not work their way into general use in developing countries for some time. A more viable short-term "transmission" approach to improving fuel economy in developing countries may simply be better education for drivers about how to use their existing transmissions more efficiently (for example, by upshifting earlier).

Fuel supply/crankcase treatment

A number of other system-wide improvements to vehicles can affect evaporative hydrocarbon emissions. On-board vapour recovery systems involve specific improvements to the fuel tank, pipework and connectors. Treatment of crankcase sealers can also help with evaporative emissions. For developing countries with a source of vehicle supply primarily from second-hand European or North American markets, however, the ability to undertake aftermarket retrofits or treatments that address evaporative emissions is limited. Because of climate considerations in many developing countries, evaporative hydrocarbon emissions may be a significantly greater problem than in the countries where the vehicles originated. Consequently, changes to fuel specifications, introduction of vapour recovery systems in refuelling stations, and shaded parking areas may be even more important in cities in developing countries than they are in cities in developed countries with significant ozone problems.

Annex IV

ALTERNATIVE VEHICLE TECHNOLOGY

Alternative vehicle (fuels and propulsion) strategies generally involve the use of alternative combustible by-products of petroleum extraction and refining (such as LPG or CNG), alcohol-based fuels, electric propulsion (either fully dedicated or as a hybrid with another fuel), or synthetically produced fuel from various types of feedstocks. The potential for these fuels and propulsion systems to reduce emissions relative to conventional fuels, however, is dependent on much more than mere technical relationships of observed tailpipe emissions rates with current patterns of travel. Different alternative vehicles are likely to be used differently, depending on fuel prices and performance characteristics of the vehicle. In addition, not all alternative fuels are equally effective at reducing all regulated and greenhouse pollutants; some may decrease emissions of some pollutants, while increasing others. Some, such as alcohol-based fuels, may exacerbate emissions of unregulated pollutants like aldehydes. Consequently, the potential of alternative vehicles to contribute to an environmental objective depends on local circumstances, and must be analysed in context. The present annex reviews some of the most important factors that need to be taken into account in a contextual assessment of alternative fuels, and then surveys some of the most commonly discussed alternative vehicle strategies.

Factors affecting appropriateness of an alternative vehicle strategy

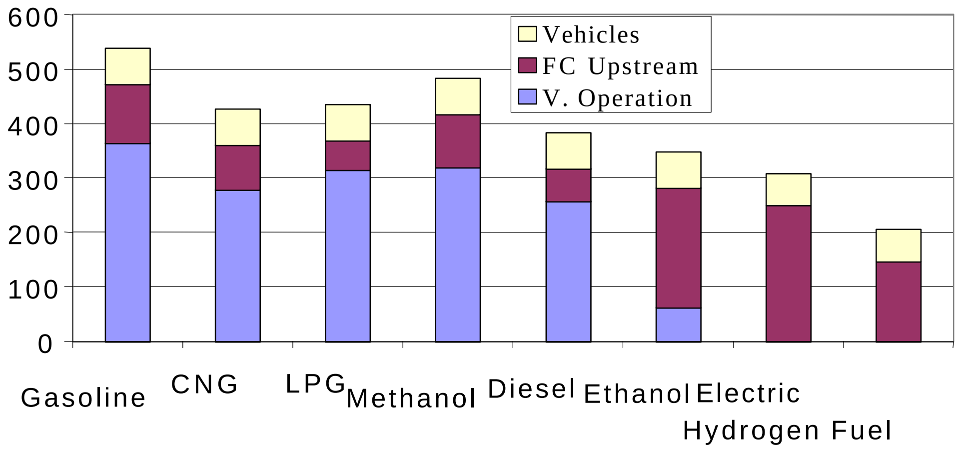
Objective of alternative vehicle strategy. Alternative vehicle strategies can have multiple objectives, but the extent to which emissions reductions can be expected will probably be linked to the importance attached to emissions reduction as an objective. Other objectives might be to reduce dependency on foreign petroleum, utilize a particular national resource (for example, natural gas reserves or surplus corn production), or incubate a particular industry. Each of these objectives may be legitimate, and each will have its constituents in an advocacy role. The important part of policy formulation is to understand the emissions implications of a particular strategy independently of any other objectives of such a programme. Advocates of alternative vehicle strategies whose primary motivation is one of these other objectives may be inclined to overstate the emissions reduction potential of a particular alternative vehicle strategy.

Availability and reliability of feedstock sources. Fuels that are loaded into the fuel tanks of alternative fuel vehicles can have their ultimate origin from any number of primary feedstocks, and be derived from them through a multiplicity of means, as figure A.X below shows. Each of these pathways represents a different set of costs of production of the ultimate fuel, and the initial input costs of the primary fuel stock constitute a significant part of these costs. Unlike petroleum, many of these alternative feedstocks (particularly corn, biomass, sugar, and soybeans) compete not only in energy markets, but also on other world markets, such as food or pharmaceutical feedstocks. In some cases, these markets could create long-term volatility in prices that might make some investors reluctant to put resources into development of the needed technology or infrastructure. In others, even short-term volatility in prices might destabilize an alternative fuels programme, if it entails large-scale shortages of fuel supply.[4]

Consequently, a successful alternative-fuel strategy needs to look not only at the emissions reduction potential of the use of a particular fuel, but also the likelihood that such a fuel would be produced and made available in significant amounts as to not constrain the penetration of the vehicle fleet using the fuel, and allow for enough of a penetration to make an impact on overall emissions levels.

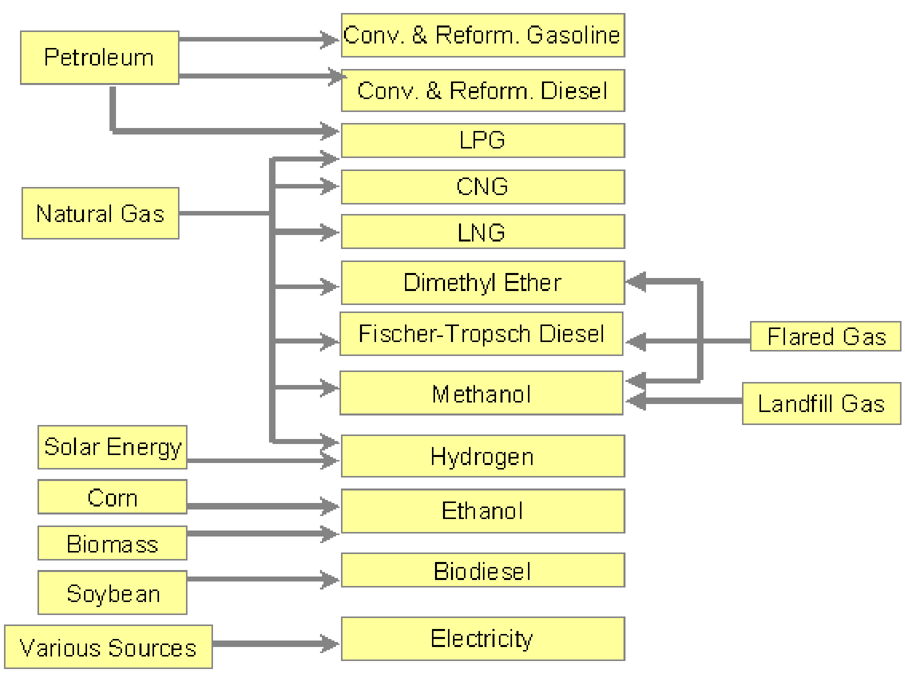
[4] In this regard, the Proalcohol programme in Brazil was brought down by volatility in world sugar prices.

Figure A.IX. GHG emissions of various fuels from different points of the energy cycle



Source: Argonne National Laboratory, *Transportation Fuel-cycle Model*, ANL/ESD-39, vols. 1 and 2 (Argonne [Illinois], 1999).

Figure A.X. Alternative production pathways for various fuels



Source: M.Q. Wang, *Development and Use of GREET* (Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation) *1.6 Fuel-cycle Model for Transportation Fuels and Vehicle Technologies*, Working Paper ANL/ESD/TM-163 of the Center for Transportation Research (Argonne [Illinois], Argonne National Laboratory, 2001).

The long-run potential for alternative vehicle penetration. Widespread alternative fuel or propulsion system use in developing countries will depend on the ability of the vehicles built or altered to use those fuels or propulsion systems to compete with ICE vehicles running on conventional gasoline or diesel fuel, both in terms of price and performance, over the service life of the vehicle. Future costs of both conventional and alternative fuels, the ability of alternative vehicles to perform according to the needs and expectations of consumers, the costs of acquisition and maintenance of alternative vehicles, and the ability of alternative vehicles to hold resale value at vehicle turnover are all important factors in the success of a strategy. The latter is particularly important for acquisition financing. In large urban transport fleets of many countries, new vehicle procurement hinges on the ability of the transit company to resell the vehicles to smaller markets part-way through the useful life of the bus. Alternative fuel vehicles may not be as competitive as conventional (diesel) buses in these markets, because of the absence of refuelling infrastructure in smaller-sized cities.

Perfect or imperfect substitution of alternative vehicles for conventional ones. An underlying assumption of many alternative vehicle strategies is that a kilometre driven by an alternative vehicle replaces a kilometre that would have been driven by a conventional vehicle. How different vehicle owners and operators actually use their vehicles may frame the choice set of alternative vehicles. For example, urban niche vehicles may be more adaptable to certain limited-range technologies (such as battery-electric or CNG) than vehicles used for longer distances. Long-range choices for technological development (for example, on-board or off-board reformulation for hydrogen production in fuel cells) may be similarly influenced. Perhaps more important than how vehicle owners actually use their vehicles, however, may be how they think they will use them. In developed countries, for example, particularly in the United States, there is evidence that a mismatch exists between car buying and car usage behaviour; consumers purchase cars using criteria for the occasional, long-distance trip, even though, for the United States and at least six European countries, 90 per cent of all car trips are under 30 kilometres (Schipper and others 1995). However irrational the expectations of consumers in developed countries, these expectations drive the product development strategies of the major car companies, including their alternative vehicle product development approaches. Car-purchasing criteria, as well as expected vehicle usage patterns, in developing countries may be quite different from those in developed countries, and these differences need to be taken into account in defining particular alternative vehicle approaches to specific countries.

Speed and nature of technology adoption. The speed with which alternative vehicles replace conventional ones, or conventional vehicles are converted to alternative fuel use is another important consideration. As with conventional vehicles, this is affected not only by the speed with which vehicles are converted or purchased, but also by the rate at which old vehicles are retired from the fleet, which affects aggregate demand. For this reason, demonstration projects of alternative vehicle technology in developing countries may be of little consequence in terms of overall emissions.

Supply-side constraints can also significantly affect the speed of technology adoption; the lag time between development of a roadworthy prototype and economically competitive assembly-line productive capability can be five years or more (Sperling 1995). The length of the product cycle needs to be taken into account in the adoption of standards or other specific measures designed to encourage alternative vehicle use.

How alternative or new technology is incorporated into the vehicle fleet is another important consideration. Retrofits of existing vehicles may not maximize the potential of a given technology. For example, newly built engines using CNG can take full advantage of the fuel's properties by using high compression ratios and lean-burn stoichiometry; retrofits generally cannot take full advantage of the fuel’s property in the same way, resulting in significantly less energy and emissions advantage over conventional fuels. CNG retrofits of diesel vehicles, furthermore, must continue to use small amounts of diesel fuel in the air-fuel mixture to ensure combustion, resulting in particulate and NO_x emissions significantly higher than standard CNG emissions.

Full-fuel (and vehicle) cycle comparisons. Emissions of local and global pollutants occur at the point of combustion, but they can also occur during fuel extraction/production, refinement, transportation, and storage, as well as during vehicle production, disposal and recycling. Any comparison of fuel emissions among fuel and vehicle mixes, therefore, must take this full fuel-cycle into account, particularly for global pollutants. Figure A.IX above shows greenhouse gas emissions per mile from various alternative vehicles, allocated by point of emissions in the energy cycle, as calculated by the Argonne National Laboratory for the United States under a given set of assumptions (Argonne National Laboratory 1999). Under this set of assumptions, (corn) ethanol emits about 76 per cent less greenhouse gases than diesel when only in-use emissions are taken into account. However, if full energy cycle emissions are taken into account, ethanol emits only 9 per cent less GHG than diesel. In addition, where emissions occur might be an important motivation for a particular alternative vehicle policy, because a ton of non-greenhouse pollutants emitted near population centres may be more costly than the same amount emitted elsewhere. Full fuel-cycle comparisons, therefore, need to not only quantify lifecycle emissions, but also to identify how much are produced where.

Dynamic assessment of competing technologies and scaling of baseline to resources and timeframe. Product cycle is also an important factor strategically because conventional technologies are (or could be) evolving in the meantime. Fuels could be reformulated to include higher oxygen content and lower sulphur content, vehicles can adopt multi-pollutant catalytic technology, direct-injection or more sophisticated air/fuel metering technology, sophisticated engine design, or any number of other innovations. An evaluation of an alternative vehicle strategy, therefore, needs to be made against this baseline of technological innovation. Since public and private resources will be channelled as a result of policy actions taken by local and/or national governments, an assessment should be made of how conventional gasoline and diesel would perform if similar resources were devoted to improving them and the vehicles that use them. This assessment needs to be evaluated in the context of the market penetration of alternative vehicles reviewed above. Relatively modest gains in emissions characteristics of conventional vehicles may in the long run be more cost-effective than dramatic improvements by alternative-fuelled vehicles, if the rate of market penetration of the latter is slow or if the ultimate penetration level is likely to be limited. Similarly, alternative fuel and propulsion technologies are developing at different paces, and require different amounts of up-front investment—in storage facilities, fuel handling and reformation facilities, distribution networks and refilling stations. Extensive investments in one technology may preclude or hinder the development of another.

Appropriate role for the public sector. In an ideal context, competition between technologies should be natural and healthy. The extent to which the public sector is insulated from potential losses resulting from technology competition, however, depends on how wisely alternative fuel strategies are devised and carried out. Experience worldwide in the transport, as well as other sectors, such as telecommunications, suggests that governments and large monopolies are ill-equipped to select from among competing technologies; a wise alternative-fuel strategy, therefore, may be for the government not to have one, but rather simply to send clear signals to the market about the kinds of emissions performance to be expected. To be sure, public actors can be highly influential in the adoption of one technology over another, but at the risk of rendering the sector or domestic industry uncompetitive in the international marketplace—thereby raising overall costs—if it guesses wrong. The approach in California, and more recently, at the Federal level in the United States with respect to cars and light trucks, has been to establish performance expectations—albeit with a clear sense of what is technically possible with different technologies—and let the private sector figure out how to meet those expectations, with whatever combination of vehicles and fuels that manufacturers believe is the most competitive.

Survey of alternative vehicle technology

While the best option for policy makers may be to favour no technology in particular, understanding the feasible near- and long-term options is crucial. Near-term alternative vehicle technologies include CNG (in certain applications), LPG, hybrid-electric and, in some countries, ethanol and methanol. Longer-term options include CNG in more general applications, battery and fuel-cell electric vehicles, and various synthetic diesel and diesel-substitute fuels. These technologies are reviewed below. In the very long term, solar-powered—or, more likely, fuel-cell—vehicles fuelled by hydrogen electrolysed by solar energy, are also envisioned. This section makes reference to the output from Argonne National Laboratory's GREET (Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation) model to indicate the orders of magnitude of the expected reductions. These results are based on Wang's assumptions in the GREET model (Argonne National Laboratory 1999) and should not be taken as indicative of any inherent emissions reduction potential of the fuels themselves. As noted above, many local, context-based factors need to be taken into account in assessing the reduction potential of a particular fuel applied in a particular context with particular technology.[5]

CNG

Natural gas can be compressed or liquefied for use in transport applications, but compression has proved to be the better method in terms of practicality and performance. CNG engines, when factory-built, generally have good performance characteristics, with energy efficiencies comparable to diesel engines, and low emissions of NMHCs, NO_x, and PM_{10} compared with both gasoline and diesel. Emissions characteristics for retrofits, however, are not as good in terms of performance, for a number of reasons that are examined below.

Three variants of natural gas (NG) engines have been developed: spark-ignition stoichiometric, spark-ignition lean-burn, and compression-ignition. Spark-ignition stoichiometric engines are the easiest to convert from existing gasoline engines. Because CNG has excellent anti-knocking characteristics, factory-built spark-ignition CNG engines tolerate a much higher compression ratio than equivalent gasoline engines, and are consequently more fuel-efficient. Most retrofits, however, cannot economically effect an increase in compression ratio; in practice, therefore, retrofitting of gasoline vehicles to CNG may result in no efficiency improvement whatsoever, or even a loss. Consequently, different CNG strategies have different implications for CO_2 emissions.

Lean-burn CNG engines with high compression ratios, turbocharging and aftercooling produce performance and efficiency characteristics similar to diesel in heavy-duty applications, but with significantly reduced particulate emissions. A number of problems, however, limit the attractiveness and viability of lean-burn CNG applications, in developed as well as developing

[5] The GREET assessment reports indicate emissions rates in terms of relative reduction from a BAU technology–standard, spark-ignition car running on conventional gasoline, or a standard compression-ignition truck running on conventional diesel fuel. Pollutants evaluated include local pollutants (VOCs, CO, NO_x, SO_x, PM_{10}), and global pollutants (CH_4 [methane], N_2O, CO_2, and total GHGs–using IPCC weights). For the local pollutants, emissions are reported as both lifecycle and tailpipe (urban) differentials in per kilometre emissions rates. In addition, it should be noted that the GREET model provides heuristic relationships between fuel and vehicle combinations based on observed baselines of vehicle use. Consequently, it is not an economic assessment of the "best" (most cost-effective) alternative vehicle strategies.

countries. If poorly calibrated, lean-burn engines can emit significant amounts of unburned fuel—largely methane—a greenhouse gas significantly more potent than CO_2. In addition, lean-burn calibration for CNG, as with gasoline, requires sophisticated anti-NO_x technology, such as de-NO_x or selective catalytic reduction to limit NO_x emissions. These technologies are not widely available even in the developed world, and are unlikely to be widely available in developing countries in the near future, limiting the potential of lean-burn CNG applications in these locations for the foreseeable future.

Finally, compression-ignition CNG engines are primarily used for dual fuel applications, where availability of CNG is uncertain, or in retrofits of existing diesel vehicles. Instead of a spark, the gas/air mixture is ignited by a small amount of injected diesel, which combusts from pressure. Because of the rapid burn-rate of diesel fuel, there is some concern that a significant portion of the NG in the mixture may remain uncombusted at the end of the cycle, potentially resulting in methane emissions.

As a nearly sulphur-free, spark-ignited fuel, CNG in fully dedicated heavy-duty applications produces significantly lower PM_{10} emissions than diesel. A number of uncertainties, however, call into question what had generally been perceived as the clear advantages of CNG over gasoline and diesel. Some evidence suggests, for example, that the number of SOF particles below 1 micron produced by CNG combustion is similar to that of diesel and gasoline; as epidemiological research concentrates on the health impact of these fine particles, it may turn out that the PM advantage of CNG may be somewhat less than is currently believed. In addition, the use of natural gas in the transport system has also raised concern about methane emissions, a greenhouse gas between 25 and 50 times as potent as carbon dioxide, depending on the period of evaluation. Emissions from individual, well-maintained vehicles have been well documented (Wang 2001; International Energy Agency 1999), but the unknown factors are leakage in the storage, distribution, and refuelling system, and emissions from poor maintenance or calibration. Finally, the process of compressing natural gas may also be associated with NO_x emissions in certain circumstances (Wang 2001).

The success of a CNG strategy naturally depends on access to a reliable, inexpensive supply of natural gas. This inexpensive access implies either proximity to a natural gas source, or the existence of an extensive (pipeline) distribution network. Application of natural gas to a CNG programme alone would probably not economically justify the development of such a network, so, for practical purposes, CNG is only realistic where other (non-transport) uses of natural gas is or will be demanded. Even then, the opportunity cost of using natural gas in the transport sector, rather than in other sectors or as an export commodity, needs to be fully evaluated.

CNG has been recommended as a strategy and is being implemented in a wide range of contexts; in the early stages, however, it is most applicable in urban contexts where access to CNG refuelling stations is not constrained by distance. Egypt has aggressively pursued a policy of CNG for the Greater Cairo region, targeting first taxicabs, and then micro-buses. The vehicle conversions are provided by the private sector–natural gas distributors–who are licensed by the government (currently, there are two licensees) on certain conditions, not least of which is that they maintain a strict limit on the number of vehicles they convert relative to the amount of refuelling capacity distributed around the city. Thus, a natural profit motive increases the pace of conversion, and limits the need for public resources. This strategy has been particularly well-suited to Cairo, since a relatively large supply of nearby gas–at the Red Sea–would otherwise be flared.

GREET assessment. In both the near and the long term, CNG shows good across-the-board reductions in all assessed pollutants, with the notable exceptions of NO_x and methane

(CH_4), as shown in table A.4. NO_x emissions from CNG might be significantly higher than those of gasoline cars, because of NO_x production during natural gas compression. Because such an assessment is based on the expectation of relatively low NO_x emissions levels from the United States gasoline fleet in the future, it is possible that the NO_x performance of CNG in other countries would be substantially better.

Table A.4. GREET assessment of reduction in emissions from CNG relative to conventional gasoline ICE automobiles

(range of percentages)

	VOC	CO	NO_x	SO_x	PM_{10}	CO_2	CH_4	N_2O	GHGs
Short term	49-71	43-35	19-27 increase	37-40	36-38	14-17	205-211 increase	19-38	8-11
Long term	56-63	2-18	26-68 increase	34-77	3-34	27	84 increase	48	24

LPG

LPG has similar combustion characteristics to CNG, apart from a lower octane rating. In combustion, it produces significantly lower emissions of local pollutants than gasoline and diesel vehicles. Like CNG, LPG engines can be built stoichiometric or lean-burn, but because of its high-knocking characteristics, LPG cannot be used in high-compression ratio spark engines (so the potential for energy efficiency gains is minimized). As a result, emissions of greenhouse gases, therefore, are only slightly lower than gasoline, and not as low as diesel. As with CNG, retrofits with LPG are more likely to be stoichiometric than lean-burn, so the HC and CO emissions of retrofits tend to be somewhat higher than for factory-built models. LPG is modestly compressed for use as a liquid in transport applications and, like all other transport fuels, is consequently, sold and metered by weight rather than volume. Handling LPG is significantly easier and cheaper than CNG.

LPG consists predominantly of propane and butane, mostly produced during petroleum distillation, as the lightest petroleum product. Consequently, it is a low-sulphur fuel with low particulate emissions. LPG can also be distilled from natural gas containing high amounts of ethane. Because of supply constraints associated with these two sources, widespread transport-sector adoption of LPG in the long run–that is, significant enough to displace gasoline sales–is generally not feasible. Recently, however, supplies of LPG have exceeded demand in petroleum-refining countries, suggesting room for growth in LPG use (OECD/UNEP 1999). It is well suited in urban areas for niche applications, such as taxis, urban delivery vehicles, or paratransit. Italy, the Netherlands and Japan have significant experience with such applications. Until very recent model years in the United States and Europe, no manufacturer has produced LPG vehicles on a commercial basis; consequently, almost all LPG vehicles on the road are retrofits. It should be noted that many countries are reluctant to introduce LPG into the transport sector, for fear that it would destabilize the supply of propane and butane to the household sectors. Propane and butane are subsidized in many developing countries as a cooking and heating fuel, in order to assist the poor; introducing LPG vehicles might deplete the source of this fuel for the very groups the subsidy is intended to benefit.

GREET assessment. For most pollutants, emissions characteristics for LPG are roughly in the same range as those for CNG, as shown in table A.5, except that NO_x and CH_4 emissions are significantly lower. In the short run, methane emissions for LPG may increase slightly if LPG is reformed from natural gas, rather than being distilled from petroleum.

Table A.5. GREET assessment of reduction in emissions from LPG relative to conventional gasoline ICE automobiles
(range of percentages)

	VOC	CO	NO_x	SO_x	PM_{10}	CO_2	CH_4	N_2O	GHGs
Short term	58-64	40	18-22	57-77	34-43	13-14	6 decrease 3 increase	2	12-14
Long term	49-56	21	32-40	72-91	31-39	21-23	22-29	2-3	21-22

Alcohol-based fuels

Vehicles can be built or altered to run on alcohol-based fuels, namely ethanol or methanol, although in practice these remain limited to light-duty applications. Alcohol fuels have poor starting characteristics in cold weather–not a problem in Brazil, where their use is most widespread, but in colder climates, they must be mixed with up to 15 per cent gasoline. Vehicles developed to run on these fuels are generally "flexible fuel vehicles" (FFV), since they can run on any mix of alcohol/gasoline, from 0 to 85 per cent. Production of a (methanol) FFV has been estimated to add an increment of US$ 300-US$ 400 to the cost of mass production per vehicle in the United States, while the conversion of an existing vehicle to an ethanol FFV costs about US$ 500 (Faiz and others 1996).

Ethanol is produced from fermentation of grains or sugar, and is consequently attractive to countries with surplus stocks of one or both of these resources. Costs of production can be high, however, particularly when competition for stock use is high, as it was in Brazil in the early 1990s. Countries that have maintained ethanol production programmes–notably Brazil and the United States–have needed to do so with substantial subsidies to production at predominant world oil prices. Methanol is produced from natural gas in a controlled oxidation process. It can also be produced from any number of other feedstocks, including crude oil, biomass or coal, but it is most economically produced from natural gas in remote sources with no natural markets (Faiz and others 1996). Because of the differing feedstock sources, methanol strategies have been pursued as a response to regulatory pressure to reduce emissions, while ethanol strategies have been favoured in order to reduce dependence on foreign oil.

The most extensive experience to date with alcohol fuels–indeed, with any alternative fuel–is the Proalcohol programme in Brazil, which was in effect from 1975 until the end of 1998. Under this programme, farmers received a premium for producing sugar, and private ethanol distillers received fixed prices and guarantees of purchases from Petrobras, the national petroleum company. Roughly two thirds of the cane produced in Brazil was used for production of ethanol, first as an additive to gasohol mixtures and then, beginning in the early 1980s, for use in 100 per cent ethanol vehicles. At the height of the programme, 95 per cent of all new light-duty vehicles in Brazil were ethanol vehicles. The large subsidy needed to maintain the programme, however, as well as the pressure to guarantee adequate supply of the fuel, came to be an increasing burden on the financially strapped Brazilian Government. In 1990, the government relaxed the 95 per cent requirement and, several years later, began limiting the subsidy to producers in the northern and north-eastern parts of the country, and shifted ethanol use back towards gasohol blends to provide budget relief. The resulting large stocks of ethanol occurred at a time of rising world prices for refined sugar, and the devaluation of the Brazilian real in early 1999. As a result, sugar producers began selling their sugar on the raw sugar market in large numbers. The outcome of all of these changes has been sharp spot shortages of 100 per cent ethanol in many regions, and an overall loss of credibility for the programme.

In the United States, too, alcohol fuels are no longer as viable as previously believed. Major manufacturers—which in the early 1990s were actively researching, producing and marketing methanol FFVs for the California market in response to low-emission vehicle sales mandates there—are now pursuing other strategies; current model year productions do not include any methanol vehicles.[6] However, a number of manufacturers are actively engaging in R and D on methanol as a fuel for on-board reformulation of hydrogen for use in fuel cells. Whether or not current high petroleum prices will create new niche markets for alcohol, particularly ethanol, remains to be seen.

GREET assessment. More than any other alternative fuel, the overall emissions performance of alcohol-based fuels depends crucially on the feedstock and the fuel path, as shown in table A.6. For example, the emissions characteristics of ethanol can vary substantially depending on whether it is produced from corn, herbaceous biomass, woody biomass or sugar cane. In general, methanol's local emissions characteristics are better than those of ethanol, and are comparable with reductions expected from CNG and LPG (indeed, better for NO_x), particularly when land-fill gases are used in the production of methanol. Ethanol and land-fill methanol also reduce methane and carbon dioxide emissions substantially.

Table A.6. GREET assessment of reduction in emissions from ethanol and methanol relative to conventional gasoline ICE automobiles

(range of percentages)

	VOC	CO	NO_x	SO_x	PM_{10}	CO_2	CH_4	N_2O	GHGs
Short term	120 decrease 54 increase	30-46	36 decrease 140 increase	152 decrease 169 increase	250 decrease 615 increase	3-135	434 decrease 1 increase	2 decrease 608 increase	2-140
Long term	156 decrease 74 increase	15 decrease 12 increase	84 decrease 228 increase	90 decrease 120 increase	266 decrease 409 increase	12-147	19-63	3 decrease 338 increase	12-15

Electric propulsion

Electric vehicles (EV) use an electric motor to drive the wheels. When, where, and how this electricity is created and stored distinguishes the various types of electric vehicles, and also serves to articulate changes in thinking on the economic potential of electric vehicles. In developed economies, recent focus on EV development has shifted from off-board production of electricity (stored on the vehicle via a battery, flywheel or some other mechanism) to dynamic, on-board production, either via a conventional, internal combustion engine (serial hybrid electric vehicle) or via a fuel-cell which causes gaseous hydrogen to react with oxygen to produce electric energy and steam. Automobile manufacturers have increasingly perceived off-board production of electricity to be too technically difficult to meet the near-term needs of car buyers in developed countries in an economic manner.

Hybrid electric vehicles. The electric motor of an electric vehicle can be powered either by a battery or an on-board source of electric generation, such as an internal combustion engine, running on gasoline, diesel, natural gas or any number of alternative fuels. Vehicle

[6] California's emission mandates allow individual companies to decide how best to meet the proportional fleet sale requirements. Presumably, the manufacturers have decided that methanol is not an economically productive way to meet those requirements.

manufacturers have focussed recently on hybrid vehicles that take advantage of both electricity storage and ICE production of electricity on-board. Systems have also been developed in which the vehicle's drive train is powered both by the electric motor, and power transmission directly from the on-board ICE engine (parallel hybrid electric systems). A number of Japanese manufacturers have hybrid electric vehicles on the market in Japan and the United States. These have been priced competitively with conventional ICE vehicles, but are probably not profitable at present. Since hybrid electric vehicles can function on widely available conventional fuels, and since they are capable of producing all their own energy needs, they require minimal capital investment on new fuel distribution or electric charging infrastructure. For this reason, they are an attractive near-term application of electric power.

Hybrid electric vehicles provide a number of potential environmental benefits over conventional gasoline and diesel vehicles. At lower loads and speeds, all the power can be provided by the electric motor with stored electricity, minimizing emissions in highly congested conditions. Because the electric motor is providing a large portion of the motive power, the overall fuel intensity of the ICE portion is also substantially reduced, resulting in a reduction in CO_2 emissions. In addition, breaking power can be regenerated to the battery and stored for later use, reducing fuel use. Because of all of these factors, however, developing emissions factors for hybrid vehicles is particularly tricky, since such factors are strongly dependent on local driving conditions and how the vehicles are put to use.

As market penetration of hybrid electric technology in developed countries is still unclear, even at industry-subsidized prices, applicability of hybrid electric technology to developing country contexts is probably some years off. Their role in developing countries, however, is important and immediate, in that they can serve as a benchmark technology against which to evaluate other alternative vehicle strategies, particularly those involving significant capital investments. As experience with hybrids in developed countries grows, costs will come down, and the anticipated level of those costs can be a criterion against which the costs of other investments need to be justified.

Fuel cells. Another benchmark technology for policy makers in developing countries is hydrogen fuel cells. Fuel cells combine hydrogen and oxygen dynamically to produce the electricity that powers an electric motor. The three biggest technical challenges to fuel cell development have been the development of an affordable catalytic membrane, the identification of cheap and practicable sources of hydrogen, and the development of a practicable system to store hydrogen on board. Recent advances in the Proton Exchange Membrane have significantly advanced a solution to the first of these challenges, but the latter two remain daunting. Storing of hydrogen in tanks is challenging, expensive and potentially dangerous. In addition, refuelling of storage tanks is time-consuming (although, with urban fleet vehicles, like delivery trucks or public transport vehicles, this may not be a problem), and storage tanks do not have much storage capacity in terms of energy density. Hydrogen-absorbing materials have recently emerged as a potentially more effective and economic means of storing hydrogen, but these are still under development.

Car manufacturers actively pursuing fuel cell vehicles are most actively looking into some kind of on-board reformulation of liquid fuel into hydrogen as an interim solution to the problem of both hydrogen source and storage. Under these systems, hydrogen would not be stored; rather it would be produced as needed from a hydrocarbon fuel such as gasoline or methanol. Daimler/Chrysler and Ford are both working to develop low-cost fuel reformers that can extract hydrogen from conventional fuels. Because of the high energy density of extracted hydrogen, and because these reformers will operate using recycled heat from the fuel-cell itself, it is anticipated that fossil-fuel-based fuel-cell vehicles would be significantly less energy-intensive than ICE vehicles running on an equivalent fuel.

The focus on on-board reformulation techniques is arguably a response of the industry to one of its prime potential markets: North American consumers. However, prototypes for urban fleet vehicles, using compressed hydrogen in storage tanks on the roof, will be put into urban service in the near future in several cities around the Americas, including Chicago, Vancouver, Oakland and São Paulo. In many cases, however, the source of the hydrogen is still unclear (Peeples 2000). Ballard/Daimler have developed a fuel cell bus based on a standard diesel chassis at about six times the cost of a conventional diesel bus, but sources in the industry estimate that production costs of this vehicle in the near term would be about two and a half times the cost of a conventional diesel bus[7] (Peeples 2000).

The specific emissions benefit of fuel cell vehicles depends both on the primary fuel used, and where the fuel is reformed. In principle, a fuel cell using stored hydrogen produced during electrolysis from solar, wind or hydropower would produce no in-use emissions, and virtually no fuel-cycle emissions, depending on location of hydrogen production and means of transport. Other sources of hydrogen, however, would produce both local and global emissions, although potentially minimizing human exposure, and at lower rates per vehicle kilometre.

Battery-electric cars. The future of battery-electric vehicles is uncertain at present. Although more than 25 years of research have been carried out since the energy crisis of the early 1970s initiated a flurry of interest in electric vehicles, no economically significant breakthroughs on battery storage capacity and size reduction have been made, except, perhaps, the realization that other means of delivering energy to an electric motor on a vehicle may be more viable–hence the interest in hybrid and fuel-cell technology. Even if significant long-range capacity is developed for batteries, it is unclear whether they can be made small and lightweight enough to compete, given the anticipated sizes of fuel cells for in-vehicle use.

Electric two- and three-wheelers. One potential niche for battery-electric technology is in two- and three-wheeler applications in countries where these modes are particularly important, for example, in South and East Asia. A recent assessment found the annualized cost of electric three-wheelers in Dhaka to be about 12 per cent more than that of traditional three-wheelers. The unit costs of reduction of particulates were actually found to be higher than other, more incremental measures on existing vehicles and technology. The primary advantage of electric two- and three-wheelers in these applications, therefore, is a displacement in the source of particulate emissions from dense, centre city environments, to more remote areas where coal-based power plants generate electricity. It is unclear, however, whether electric two- and three-wheelers are cost-effective relative to other technologies such as CNG or four-stroke ICE engines. A more promising application of electric technology, therefore, may be the battery-assisted bicycle. This uses a low-level electric generator to assist an otherwise human-powered vehicle. The primary niche advantage of such technology would be to provide a low-cost alternative to motorization for bicycle users who need more power to carry heavier loads, go farther distances, or climb hills.

GREET assessment. The potential for electric vehicles to reduce transport emissions depends on a number of complex factors: whether the vehicle is a hybrid, and whether the hybrid is of serial or parallel construction; what the ultimate energy source for the electricity is, whether fuel cell, grid-connected hybrid, or grid-independent hybrid; and what the energy source for the

[7] In comparison, a CNG bus based on the same standard diesel chassis was estimated to be about one and a half times the cost of a diesel bus.

non-electrical components of the vehicle is, if there are any. Table A.7 shows the short-term and long-term changes that can be expected in automobile applications of various electric propulsion technologies in the United States. For countries still using a significant amount of coal or petroleum in electricity production, emissions of SO_x, PM_{10}, and perhaps NO_x might be significantly worse than other alternative fuel choices.

Table A.7. GREET assessment of reduction in emissions from electric propulsion cars relative to conventional gasoline ICE automobiles

(range of percentages)

	VOC	CO	NO_x	SO_x	PM_{10}	CO_2	CH_4	N_2O	GHGs
Short term	34-95	36-99	51 decrease 65 increase	63 decrease 463 increase	32 decrease 148 increase	24-71	15-58	2-93	25-70
Long term	155 decrease 47 increase	99 decrease 22 increase	70-83 (99 if pure methanol)	102 decrease 377 increase	171 decrease 350 increase	46-113	177 decrease 33 increase	99 decrease 206 increase	45-136

Synthetic fuels

A number of synthetic fuels with potential application in compression-ignition engines have been shown to have significant emissions performance advantages over conventional diesel, while maintaining the performance and efficiency characteristics associated with diesel. These include various bio-diesels, Fischer-Tröpsch (FT) diesel, and di-methyl ether (DME). They are most commonly considered for heavy-duty applications, but they might also have potential light-duty applications. They can be produced from various feedstocks, contain virtually no sulphur, and have high cetane numbers. Consequently, they emit substantially lower particulate emissions than conventional diesel without loss of performance or increase in greenhouse gas emissions. In addition, many of these synthetic fuels are usable directly in existing diesel engines, reducing the need for significant up-front investment, and producing a more immediate impact on the environment.

Bio-diesel can be produced from a range of vegetable oils, including canola, sunflower, sesame, peanut, rapeseed and other oils. Handling problems prevent these oils from being used directly for combustion in engines, but reacting them with methanol or ethanol produces a fuel with diesel-like qualities. The potential availability of feedstocks can be an attraction for small-scale applications but, on larger scales, price, availability and competing resource use might lead to unacceptable levels of volatility for long-term investments. Diesel fuel can also be synthetically produced from natural gas or coal, through a process known as Fischer-Tröpsch. FT diesel is currently prohibitively expensive, but it has the advantage of having handling qualities superior to bio-diesel, more immediate, abundant and consistent feedstocks, and only trace amounts of sulphur. Some energy is lost in the transformation process, however, making life-cycle FT diesel less energy-efficient than direct use of natural gas in other applications.

DME is a synthetic fuel that can also be produced from renewable raw materials or methanol, but is more commonly produced directly from natural gas. Because it is a gas at room temperature, DME would require a modified storage and injection design, and is thus a synthetic "diesel" fuel that could not be used on existing vehicles without modification. It is anticipated that heavy-duty vehicles could be retrofitted for DME much in the way that gasoline vehicles have been retrofitted for LPG, at moderate cost. Nevertheless, like LPG or CNG, widespread DME use would require significant investment in refuelling infrastructure, which is its primary drawback. Fuel advantages of DME include not only lower tailpipe emissions compared with diesel, but also potential for large-scale production at costs competitive with diesel, and with lower life-cycle (production and distribution, as well as use) emissions and intensity than conventional diesel. A number of manufacturers are considering DME as part of a strategy to meet Euro IV standards (the European regulations for new heavy-duty diesel engines), which come into effect in 2004-2005.

Table A.8. GREET assessment of reduction in emissions from synthetic fuels relative to conventional gasoline ICE automobiles

(range of percentages)

	VOC	**CO**	**NO_x**	**SO_x**	**PM_{10}**	**CO_2**	**CH_4**	**N_2O**	**GHGs**
Long term	38-193	0-3	23-90	36-48	33-83	50-54	35-47	32-95	33-92

Annex V

ADDRESSING THE IN-USE FLEET

The prevalence of old vehicle technology is a significant contributing factor to overall emissions of local and global pollutants, particularly in developing countries. This excessive age is, to some degree, due to the slowness of new vehicles to replace old ones in the fleet, but primarily because old vehicles are held for a long time, for economic reasons. Consequently, new, relatively low-emission, high-efficiency cars do not replace high-emission, old ones, but rather supplement them. The prevalence of old cars and technology has two particular effects that lead to high emissions: (a) the deterioration of performance of ageing technology and componentry in in-use vehicles; and (b) the obsolescence of the technology (since more advanced technology is not used.) In the terminology of the ASIF framework (Schipper and others 2000), old technology tends to increase the emissions intensity of vehicles–the grams of pollutant emitted per kilometre driven. These impacts are magnified in locations where, for economic reasons, drivers of old vehicles tend to make more extensive use of their vehicles than drivers of new vehicles, and where old vehicles tend to be concentrated in city centres. Such high mileage and concentrated use of older vehicles is frequently the case with the taxi and informal transport sectors in many cities in developing countries. Emissions of pollutants and poor fuel economy performance are affected by fleet age because of performance deterioration and the continuation of the use of obsolete technology.

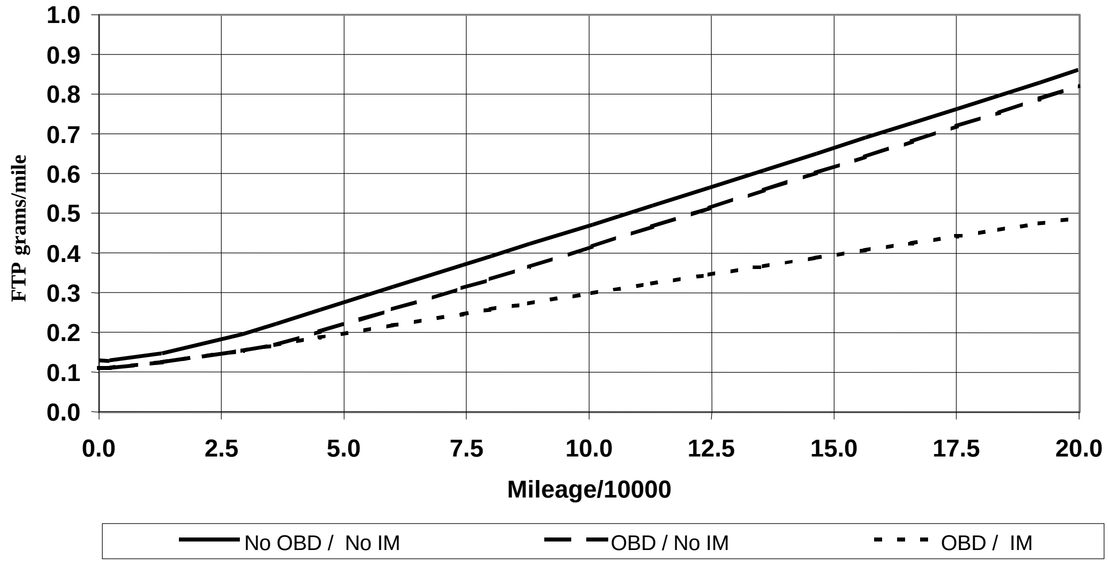
Performance deterioration

Emissions characteristics and fuel economy of a vehicle deteriorate with age. As a result, older vehicles tend to contribute a disproportionate amount of transport-sector-originating pollution than newer ones. For example, a study in Bangkok found that vehicles over 10 years old contributed about 70 per cent of all HC and CO emissions, and about 55 per cent of all NO_x emissions, even though these vehicles were only driven for 50 per cent of all the vehicle kilometres travelled (OECD 1999).

The causes of age-related emissions performance deterioration are varied. For local pollutants such as VOCs, CO, and NO_x, age affects catalytic technology more than the emissions performance of engines. Catalysts can lose efficiency as they age from exposure to high temperatures and gradual poisoning by oil additives; they are also susceptible to malfunction because of poor maintenance and misfuelling, the probability of which increases with age. Effective inspection and maintenance (I and M) programmes, such as those described below, can reduce the rate of this deterioration. In addition, fuel economy generally deteriorates with age as various elements of the fuel and engine system wear out, increasing CO_2 emissions.

Figure A.XI, from the EPA MOBILE6 model, shows the deterioration in NMHC emissions factors for tier I light-duty vehicles as they age. MOBILE6 emissions factors, derived from laboratory tests on actual vehicles, show an average deterioration of about 5.5 per cent per 10,000 vehicle miles travelled (VMT) for tier I vehicles with no inspection and maintenance programme, and about 4 per cent per 10,000 VMT with such a programme. For "tier 0" vehicles, that is, older vehicles more similar to fleets in developed countries, the rate of deterioration averages about 3 per cent per 10,000 VMT. Deterioration of NO_x is even more marked–7 per cent for I and M tier I vehicles, 8 per cent for non-I and M tier I vehicles, and about 5 per cent for older (tier 0) vehicles (EPA 1999).

Figure A.XI. Deterioration of NMHC emissions factors for tier I light-duty vehicles



Notes: FTP stands for Federal Test Procedure; and OBD stands for on-board diagnostics.

Obsolete technology

In many developing countries, both the vehicle fleets and the technology in use are old and obsolete from the point of view of air pollutant reduction. In many parts of the world, the prevalence of vehicles with no emission control equipment whatsoever and relatively rudimentary carburetion systems is still common, even among newly registered vehicles in national fleets. The obsolescence of the equipment used is in part simply a function of the age of the cars; in most developing countries, cars are kept in useful life on average longer than in developed countries. In some countries, however, particularly those with a highly protected automobile manufacturing industry, old technology may still be used in the production or assembly of new vehicles. These assembly or manufacturing operations may use “knock downs” of energy-intensive, obsolete models from North American, European, Japanese, or Soviet manufacturers which have long since been abandoned by their manufacturers. In addition, in the absence of adequate regulatory requirements and emissions control monitoring, many manufacturers may simply choose to not use available emissions control technology.

Inspection and maintenance

Inspection and maintenance (I and M) programmes are critical components of a metropolitan air quality control programme where the transportation sector is an important contributor to pollution and catalytic technology of some kind is in widespread use. I and M programmes are in widespread use in North and South America, Europe and Asia, although the specifics can vary significantly between programmes. In general, a mature I and M programme involves periodic (annual or biannual) testing of vehicles at a testing centre, usually using a chassis dynamometer (a device that allows the wheels on the drive axis to rotate) and exhaust analysers of varying sophistication. Vehicles of different sizes and model years are usually held to different standards, but those not passing must be repaired and retested.

A critical function of an I and M programme is to ensure that sensitive catalytic technology is maintained in working order. Catalytic converters can deteriorate or fail through negligence–for example, improper fuelling with leaded fuel–or through deliberate tampering, a temptation because catalytic converters can degrade efficiency, power, or both. It should be noted that the precious metals used in many catalytic converters can have significant resale value.

Much of the literature on I and M programmes has focused on the following debate in the United States between the (Federal) Environmental Protection Agency and the (California) Department of Consumer Affairs: whether a "centralized" or "decentralized" structure for an I and M programme is more effective. In a centralized structure, motorists bring their vehicles to relatively few, high-volume test centres, usually run on behalf of the public or regulatory authority by a private contractor. A de-centralized programme involves tests at private garages, which undergo a periodic certification process. A decentralized programme can involve lower start-up costs, greater convenience for the motorist, and reduced risk of carbon monoxide "hot spots" from a large volume of idling cars. However, the disadvantages of a decentralized system are significant. Having the same establishment both carry out the tests and undertake repairs can create an incentive for fraud, which seems to be borne out by empirical evidence (Glazer and others 1993). In addition, decentralized facilities cannot generate the throughput and economies of scale needed to purchase the most sophisticated testing equipment–advanced exhaust analysers and chassis dynamometers. Consequently, decentralized structures generally cannot subject cars to the standardized testing procedures based on those used to certify new car emissions in the first place.

Accelerated retirement (scrappage) incentives

A second strategy often suggested to address emissions from in-use vehicles is voluntary accelerated retirement, or "scrappage" schemes, which target the most polluting vehicles, in an effort to take them out of regular use. The logic of the approach stems from the evidence that a small minority of vehicles is responsible for a substantial portion of vehicle emissions. In the United States, for example, studies have found that 20 per cent of vehicles emit roughly 80 per cent of vehicle emissions. For these "gross emitters," removing them from service may be cheaper than trying to repair them.

Moving from this simple observation to successful scrappage programmes, however, has proved to be complex. An effective accelerated retirement programme needs to avoid certain pitfalls:

(a) It should not create an inappropriate market demand for older vehicles that would cause a flood of those vehicles to the programme target area;

(b) It should target only those vehicles actually being used;

(c) It should not pay to scrap vehicles that would have been scrapped even without the programme.

Creating effective programmes that avoid these pitfalls has proved elusive. The risk of inappropriate demand creation is particularly troublesome, because if increased demand causes a rise in vehicle prices, owners may be discouraged from replacing their vehicles. In addition, an unwanted effect of such demand creation could be a flow of vehicles from rural to urban areas. In guidelines published in 1993, the EPA recommended a number of requirements to be included in programme design to ensure against this, including: (a) that vehicles should be registered in the area where the programme is being implemented for a certain amount of time (two years); (b) that they be able to be driven to the scrappage site; and (c) that the owner present a fairly recent I/M certificate, if such programmes exist in the target area. Even with such restrictions in place, there remains a risk that the market created by former owners of newly scrapped vehicles might still lead to an influx of older, high-emitting vehicles to urban areas.

In the United States, vehicle scrappage pilot programmes have had mixed results in terms of cost-effectiveness for reducing HC and CO emissions. Cost per ton of pollutant emissions avoided in several pilot programmes in different States throughout the 1990s have ranged from about US$ 1,000 per ton in California, to about US$ 8,300 per ton in Illinois (combined HC and CO). The lower end of this range implies some degree of cost-effectiveness, but the upper end suggests that other measures, such as vehicle repair and upgrading emissions control systems, may be more cost-effective. Consequently, American experience so far is inconclusive.

In Europe, as well, a number of car scrappage programmes were implemented throughout the 1990s, with mixed success. Denmark initiated an 18-month scheme in January 1994. Owners were given about US$ 1,000 for cars over 10 years old. Within the first six months, slightly more than 6 per cent of the fleet (about 100,000 cars) were traded in, but about 19 per cent of these owners subsequently repurchased a vehicle that was older than 10 years old, compared with only about 11 per cent who subsequently purchased new vehicles.

France also initiated a scrappage scheme similar to Denmark's, at about the same time, but followed this up with a second, more generous scheme. This second scheme, implemented from October 1995 to September 1996, offered about US$ 1,300 for cars over eight years old. These two schemes were estimated to have netted about 700,000 scrapped vehicles. Ireland initiated a scrappage scheme in 1995, under which payment for the scrapped vehicle was linked to reimbursement for registration taxes of a new car. In this way, the programme ensured that old cars were replaced with new ones; unfortunately, it also provided little incentive to reduce car ownership. None the less, the scheme succeeded in scrapping about 5 per cent of the fleet, the majority of which were between 10 and 12 years old. Norway, Italy, and Spain have also had experience with car sharing schemes (Beg 1999).

Perhaps the most successful design of a car scrappage scheme has been in British Columbia. A voluntary and still ongoing programme initiated there in 1996 involved variable amounts of compensation. Depending on the action taken by the vehicle owner, he or she could opt for 750 Canadian dollars (Can$) for a new car or Can$ 500 for a used car, or receive a free transit pass for a year (at a value of roughly Can$ 1,400). Table A.9 shows the cost-effectiveness of these different compensation schemes, as well as a blended cost-effectiveness for all the compensations, for a number of pollutants, in 1998 Canadian dollars. About 52 per cent of programme participants in the Vancouver metro area opted for a transit pass, suggesting the importance of tying vehicle scrappage to alternative transport options.[8] The tie-in to public transport also helps to alleviate the problem of revolving-door demand for inexpensive, high-emitting vehicles. It should be noted that each 1,000 vehicles removed also reduced CO_2 emissions by about 4,300 tons, at an average cost of Can$ 130 per ton. Had this been evaluated on its own, scrappage would not have been considered cost-effective as a CO_2 measure. By explicitly tying the scrappage scheme to a public transport option, the programme has created ancillary benefits for global emissions, even though it was intended as a local pollution control measure.

[8] Scrappage schemes may also be linked to car-sharing schemes.

Table A.9. Cost-effectiveness of different incentives in the Vancouver scrappage scheme

(Canadian dollars)

Pollutant	New car	Used car	Transit pass	Programme average
HC	4,574	3,581	5,247	4,798
CO	704	563	786	729
NO_x	16.543	16,640	19,835	18,255
HC + NO_x	3,579	2,947	4,146	3,796
HC + NO + CO/7	2,073	1,686	2,364	2,177

Source: OECD/UNEP, *Older Gasoline Vehicles in Developing Countries and Economies in Transition: Their Importance and the Policy Options for Addressing Them* (Paris, 1999).

These North American and West European experiences need to be understood in context; because of the relatively advanced state of emissions control, the marginal cost of emissions reduction per ton tends to be higher than it would likely be for similar scrappage schemes in developing countries. Poorer countries tend to have significant numbers of completely uncontrolled vehicles operating in regular use. The cost-effectiveness of removing these vehicles through well-designed accelerated retirement programmes are probably significantly better than in developed countries and relatively better than maintenance or retrofit options (compared with developed countries), because of the technical difficulties of improving uncontrolled gasoline vehicles in a cost-effective manner. These relative differences, however, do not imply that car scrappage schemes are necessarily more advantageous than maintenance or retrofit options; such a conclusion can only be made by examining local circumstances, taking into account the risk of creating an attraction pole in urban areas for high-emitting cars.

Perhaps the most extensive experiment with car scrappage in a developing country or economy in transition was the programme set up in Budapest in the middle 1990s to replace two-stroke Trabants and Wartburgs–highly polluting products of cold-war-era production from the former German Democratic Republic. The programme offered four- or six-year transit passes, depending on the car turned in, or coupons towards the purchase of a SEAT Marbella, an Opel Corsa, a Suzuki Swift, a Volkswagen Polo, or a Renault. As of mid-1995, about 2000 Trabants and Wartburgs had been taken off the streets of Budapest, less than 2 per cent of those in operation.

Annex VI

FUEL SPECIFICATION AND QUALITY

A number of aspects of fuel specification and quality can influence the overall levels of emissions, and quality and specification problems are prevalent in many regions of the developing world. In developing a fuel specification policy, none of these aspects should be considered in isolation, because the response of refiners to changes in requirements for any one specification will inevitably affect the others.

Lead

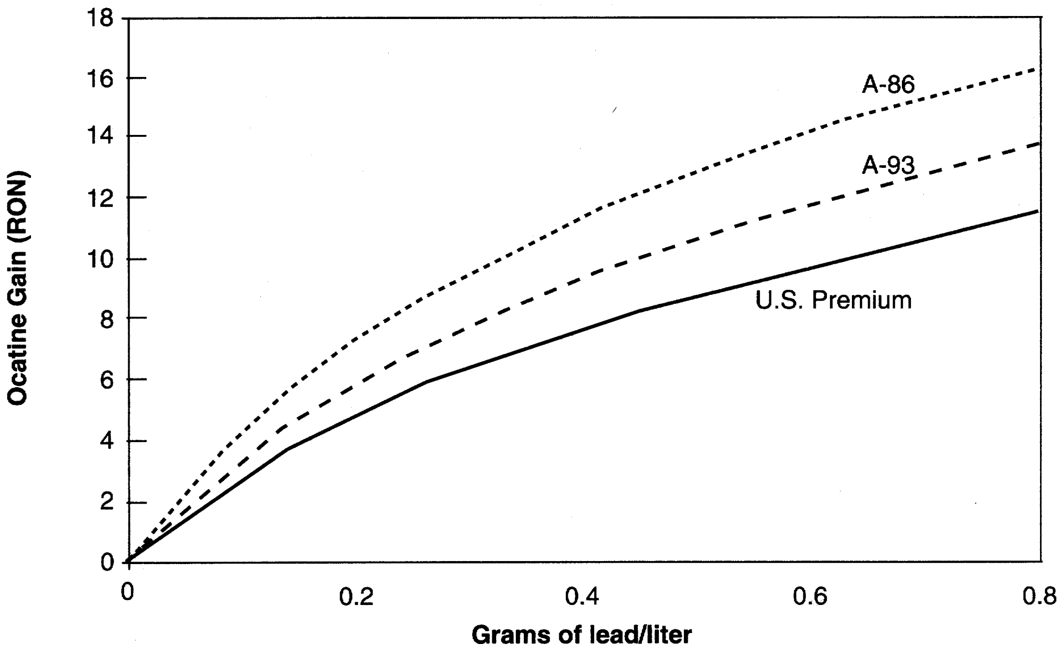
Tetra-ethyl lead is added to gasoline to raise octane ratings of otherwise low-octane fuels cheaply. Octane is an indicator of how easily the fuel combusts; higher octane fuels are more resistant to premature combustion (knocking). Catalytic reforming of naphtha can yield gasoline feedstocks of higher octane value than unreformed naphtha, but overall yield is reduced substantially. Refiners, therefore, have historically found the use of lead a more economic choice, although the health cost to society is over 10 times that of the cost to refiners. In addition to increasing health costs, lead can irreversibly poison platinum catalysts used in exhaust aftertreatment of fuel to reduce CO, VOC and NO_x emissions, rendering these devices ineffective. Lead is also associated with increased operating costs of even uncatalysed motor vehicles, and some studies suggest that savings from these operating costs alone economically justify the reduction in lead content (EPA 1999; Walsh and Shah 1997).

Technically, removing lead from gasoline is straightforward. A number of options exist to boost gasoline octane in the absence of lead: use of alternative additives (such as ethers), changes in naphtha reforming output at refineries, or use of different crude oil inputs. Which technical measures are adopted will depend on characteristics of fuel refining or fuel supply in a particular country or region, the specification of other public policy goals with respect to fuel content and air quality, and costs. Procedural methods to weigh these various considerations are well established (see, for example, EPA 1999). In many respects, addressing the problem of lead in gasoline is one of the most straightforward and easy to solve environmental challenges facing the transport sector.

In countries where catalytic technology use is extremely limited or non-existent, and an intransigent petroleum refining industry is reluctant to switch to unleaded fuel production, an effective interim strategy may be to limit the amount of lead used in gasoline, rather than eliminate it entirely (Walsh and Shah 1997). The impact of lead on octane rating is not linear; as figure XII shows, the initial 25 per cent of tetra-ethyl lead addition is responsible for 50 per cent of the octane enhancement for a 93 octane fuel. Reducing this excess portion of lead additive would yield benefits far in excess of costs.

One of the more important aspects of any lead strategy is addressing some of the common myths surrounding unleaded fuel. One of these is that older, uncatalysed cars are not able to use unleaded fuel, because of valve seat recession in engine cylinders. Another is that gasoline without lead necessarily produces higher levels of benzene emissions than leaded gasoline. While both are potential problems if left unaddressed, relatively simple technical measures can address both of them at minimal cost (Lovei 1996).

Figure A.XII. Octane enhancements versus lead concentration for some typical gasolines



Source: ECMT, *Traffic Congestion in Europe*, European Conference of Ministers of Transport, Report of the 110th Round Table, 12-13 March 1998 (Paris, OECD, 1999).

Note: Ocatine should read Octane.

Sulphur

The sulphur content of fuel is another important area of concern for fuel refining and specification. Like lead, sulphur in fuels is both a source of pollutants (sulphur dioxide and sulphate particulates) and a poisoner of catalytic devices that normally reduce other pollutants. For conventional two- and three-way catalytic converters, however, the effects of sulphur are temporary (unlike those of lead); once low-sulphur fuel is used in the vehicle, the catalytic system recovers. Whether such recovery occurs with more state-of-the-art catalytic technologies, such as de-NO_x systems or continuously regenerating particulate filters, is unclear at present. Where sulphur is present in fuels in significant amounts, catalytic devices can actually exacerbate sulphate particulate emissions by causing the oxidation of SO_2 to SO_3^+, which reacts with hydrogen to produce sulphuric acid and other sulphates.

Sulphur is present in varying quantities in different crude petroleum stocks. It tends to remain concentrated in heavier products of the distillation process–for example, heavy oil, diesel and gasoline-blended predominantly from reformed (rather than straight run) naphthas. Refining processes can remove sulphur from fuel, but doing so significantly raises production costs, because the capital investment needed can be enormous. Such investment may be economic only for high-capacity facilities. For non-refining countries, low-sulphur diesel is available on international markets. However, as a result of emissions regulations enacted in many countries–primarily in the industrialized world–the demand for low-sulphur fuels is growing faster than the supply. Consequently, low-sulphur fuels remain relatively costly, and enforcement may be problematic.

Because of these costs, a policy of low-sulphur diesel may be relatively expensive per gram of pollutant avoided compared with other interventions. Conventional wisdom suggests it should be considered (in conjunction with the exhaust aftertreatment technologies it enables) only after other, lower cost abatement measures have been implemented, as is the case in Europe and North America. Nevertheless, reducing sulphur content in diesel (and gasoline) has the advantage that the impact on particulate emissions reduction is immediate (for sulphates) as well as long-term (for carbonaceous particulates, if aftertreatment technology is adopted as a result), and that its cost increment would be variable, rather than fixed, for the motorist.

Technically, the simplest option for producing low-sulphur fuels is to use a low-sulphur crude stock. Even so, even the lowest sulphur crudes start with a minimum sulphur content of 1,000 ppm (Faiz and others 1996). Diesel from Middle Eastern crude, for example, has about 15,000 ppm sulphur prior to treatment (CONCAWE 2000). For gasoline, most of the sulphur makes its way into fuel via fluid catalytic cracking (FCC), so desulphurization technology focuses on this step. Because FCC boosts high-octane olefin output, the petroleum industry argues that desulphurization would require additional energy consumption in refining in order to maintain octane parity, and that the CO_2 emissions associated with this increased consumption would counteract any energy-efficiency improvements from reduced catalytic regeneration frequency (CONCAWE 2000).

The equipment for desulphurization processes, as noted, can be prohibitively expensive for all but the highest volume refineries. Most of these are located in industrialized countries, but high volume, low-sulphur refineries are operational in Mexico and India. For most developing countries, however, access to low-sulphur diesel will come through imports. The costs of reducing sulphur from gasoline in the United States to acceptable levels to use lean-NO_x catalytic technology was estimated to be between 1.2 and 1.3 cents per litre. Reduction of sulphur in diesel in an Asian refinery to 200 ppm was estimated to increase costs between 1.6 and 1.9 cents per litre. Reduction of sulphur in diesel to acceptable levels for advanced exhaust aftertreatment is likely to cost significantly more (Faiz and others 1996). It should be noted that actual costs are very dependent on throughput.

Fuel volatility

Evaporative emissions are responsible for a significant amount of non-methane hydrocarbon emissions in hot climates. A recent inventory in Buenos Aires found that evaporative emissions accounted for about 44 per cent of total hydrocarbon emissions; of these, about 70 per cent came from vehicle “hot-soak”, with the remaining 30 per cent coming from service stations, tank trucks and bulk terminals (Weaver 2001b). The tendency of gasoline to evaporate is measured by Reid vapour pressure (RVP), which is correlated with the paraffin and aromatic content of gasoline. Studies suggest that a 33 per cent increase in RVP can roughly double the average evaporative emissions from a fuel (Faiz and others 1996). Where evaporative emissions are not reflected in fuel specifications, refiners often increase light paraffin content, particularly butane, in order to ensure adequate starting of vehicle engines in colder climates. Consequently, fuel specifications need to be tailored to local climate; adoption of inappropriate standards from another climate can lead to substantial and needless NMHC emissions.

In addition to lowering paraffin and aromatic content from gasoline during warm, summer months through appropriate fuel specifications and enforcement, other less technically sophisticated methods for reducing evaporative emissions can also be adopted. Mandating exhaust gas recapture equipment at refuelling stations can be quite effective in reducing evaporative emissions, as can simply providing shade for parked vehicles, particularly in hot, sunny climates.

Oxygen content and octane rating

The ability of a gasoline to avoid combustion from compression prior to the spark-ignition in the engine (knocking) is measured by its octane rating, a scale derived from the proportion of octane in an octane/n-heptane comparator mix that produces the same level of knocking as the gasoline blend being tested. The higher the compression ratio of an engine, the higher the octane rating of gasoline it must use. High-octane fuels are crucial for high performance or high efficiency vehicles, but all vehicles require at least minimal octane fuels. Countries with relatively large numbers of cars from the mid-1990s and later model years from Europe generally need higher octane gasolines. While very low octane fuels (below 85 RON) are generally not produced for international trade, smaller, independent refineries in highly protected markets in the developing world still produce low-octane (frequently leaded) fuels for domestic consumption, often inexpensively from straight-run naphtha. Efforts to remove lead from these fuels need to work to raise octane levels of production.

Technical options to enhance octane characteristics without lead include:

- Use of crude feedstocks with lower concentrations of paraffins, and higher concentration of aromatics and naphthenes;
- Use of higher octane naphthas in gasoline blends, produced, perhaps, from catalytic reforming of naphtha;[9]
- Fluid catalytic cracking (FCC) to boost olefin-rich blendstocks;
- Use of oxygenate additives, such as ethers or alcohols.

The last alternative has an added benefit of increasing the oxygen content of the gasoline, which helps to reduce CO and hydrocarbon emissions by ensuring more complete combustion. Brazil, for example, effectively eliminated the use of lead as an additive through the widespread adoption of ethanol as a gasoline additive (gasohol). In the United States and Mexico, methyl tertiary butyl ether (MTBE) has been used as an additive to gasoline, initially as an octane-enhancing replacement for lead, and later in greater quantities to increase oxygen content of the fuel. While these additives are preferable to lead, both have subsequently proved somewhat problematic because of increased emissions of aldehydes (particularly acetaldehyde) and 1,3 butadiene, both significant toxics. In addition, concern has been growing about MTBE contamination of groundwater in the United States.

Benzene and aromatic content

Benzene is one of the more toxic substances in gasoline, and emitted from motor vehicle tailpipes. It is also associated with emissions of 1,3 butadiene (Walsh and Shah 1997). Catalytic cracking techniques which have become commonplace in refineries to boost yield of naphthas, kerosene and gas oils have the unfortunate side effect of increasing benzene and other aromatic content. In diesel vehicles, polycyclic aromatic hydrocarbon (PAH) content is strongly correlated

[9] Some high octane products may increase emissions of certain air toxics, such as 1,3 butadiene, or the reactivity of VOCs in the atmosphere (increasing risk of ozone formation). These issues need to be taken into account in strategy development.

with SOF formation. A number of jurisdictions, consequently, have moved to limit PAH content in diesel fuels (Faiz and others 1996).

Lubricant additive to gasoline in two-stroke engines

Small gasoline engines, using cheaper, two-stroke rather than four-stroke mechanical design, are in widespread use in the transport sectors of certain developing countries, particularly in South and East Asia, parts of the Middle East, and urban areas. These engines have much poorer pollution emission characteristics than the equivalent-sized four-stroke engines. Two-stroke engines are lubricated by the addition of lubricant to gasoline. Since a relatively large portion of the air-fuel mixture of two-stroke engines remains uncombusted after the full cycle, much of the lubricant additive is also released uncombusted, as white smoke.

Only a 2 per cent mixture is needed to provide adequate lubricating capability, but, because of poor information and technical understanding, widespread misconceptions persist in many South Asian cities that more lubricant is better. As a result, a number of jurisdictions have mandated the sale of pre-mixed “kits” of gasoline/lubricant mixture. New Delhi, for example, implemented a programme in 1996 to sell pre-mixed fuels; in 1997, roughly 30 per cent of all retail outlets supplied pre-mixtures (Government of India 1997). A World Bank assessment estimated that such a policy, if fully implemented, would reduce particulate emissions from two-stoke three-wheelers by 30 per cent (Xie and others 1988).

Fuel adulteration and cross-border smuggling

Adulteration of fuels or cross-border smuggling of cheaper, lower-grade fuels can be a significant problem in countries and regions where there are either significant geographic variations in prices or significant differences in the quality of fuel availability. In certain parts of the world, it is not uncommon to mix kerosene into gasoline or diesel fuels, because of the relative difference in costs. Kerosene has excellent combustion characteristics in compression-ignition engines, but in spark-ignition engines, can produce crusty carbon coatings along different parts of the engine, which increase hydrocarbon and particulate emissions, as well as degrade engine performance. As a jet fuel, and abundantly available all-purpose fuel for cooking and heating, kerosene is generally untaxed. All else equal, therefore, increases in taxation rates on gasoline and diesel would thus probably lead to increases in the incidence of fuel adulteration. Black market sales of cheaper fuels constitute a potentially serious problem when the emissions control technology in extensive use relies on a supply of good-quality, unleaded or low-sulphur fuel.

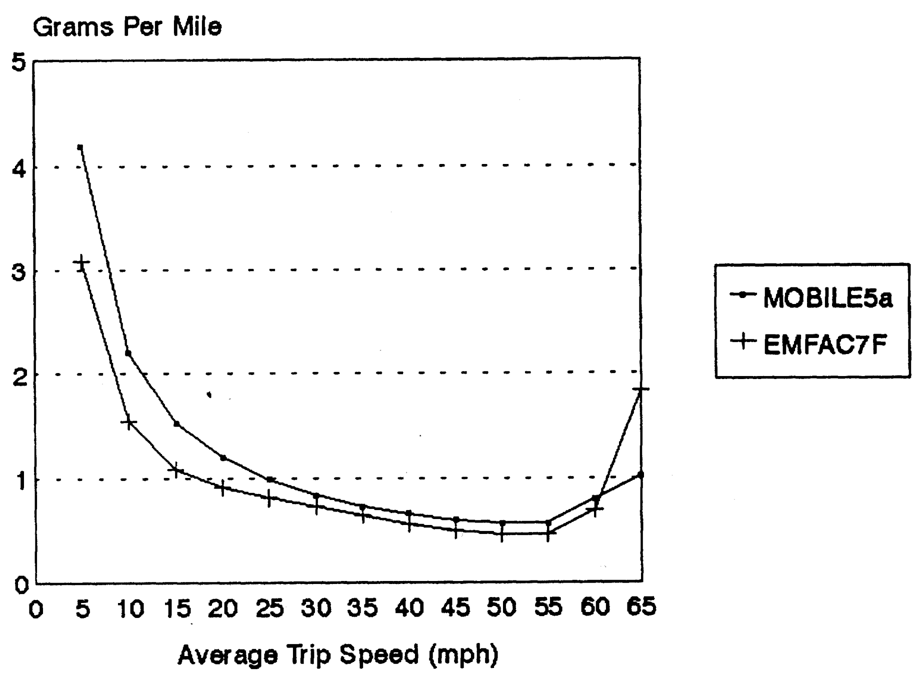
Annex VII

NETWORK EFFECTS: SPEED, FLOW, AND INDUCED TRAVEL

Influence of speed, flow and congestion on emissions rates from vehicles

The behaviour of traffic on a road system can have important effects on specific energy consumption and pollutant emissions of vehicles. There are two such effects. Average speeds influence both aggregate pollutant emissions from any individual vehicle and the total amount of energy consumed for a given vehicle trip. The figures below show some of these relationships for selected pollutants and energy consumption, averaged across vehicles representing the American automobile fleet. For urban settings, where the effects of pollution are the most concentrated, these graphs suggest that the specific emissions of VOCs (and also of CO and No_x, not shown) can be collectively minimized at speeds between 25 and 45 miles per hour (40 to 75 kilometres [km] per hour), and that fuel economy is equally maximized around this range. Urban traffic congestion that reduces speeds below this level will therefore cause vehicles to emit more grams of pollutants and burn more fuel per kilometre than they otherwise would at such a level.

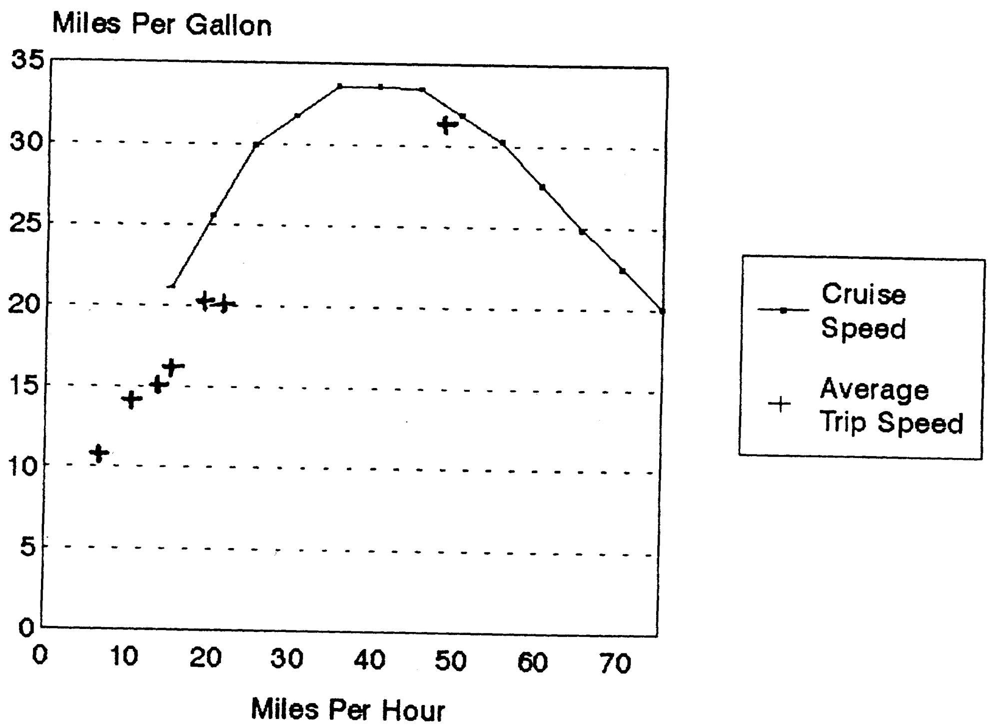
Figure A.XIII. Speed correction factor for VOC emissions from light-duty vehicles



Source: Transportation Research Board, *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use,* Special Report 245, National Research Council (Washington, DC, National Academy Press, 1995).

A second, perhaps more important effect, is the impact on overall emissions of frequent and violent accelerations, the kind associated with both aggressive urban driving and highly congested traffic conditions. Different average speeds on paper can be associated with very different observed stops, starts and accelerations in practice. Figures A.XV and A.XVI show emissions of CO and VOCs during the same trip, made by two drivers: a "normal" driver and an "aggressive" driver.

Figure A.XIV. Speed correction factor for fuel efficiency from light-duty vehicles



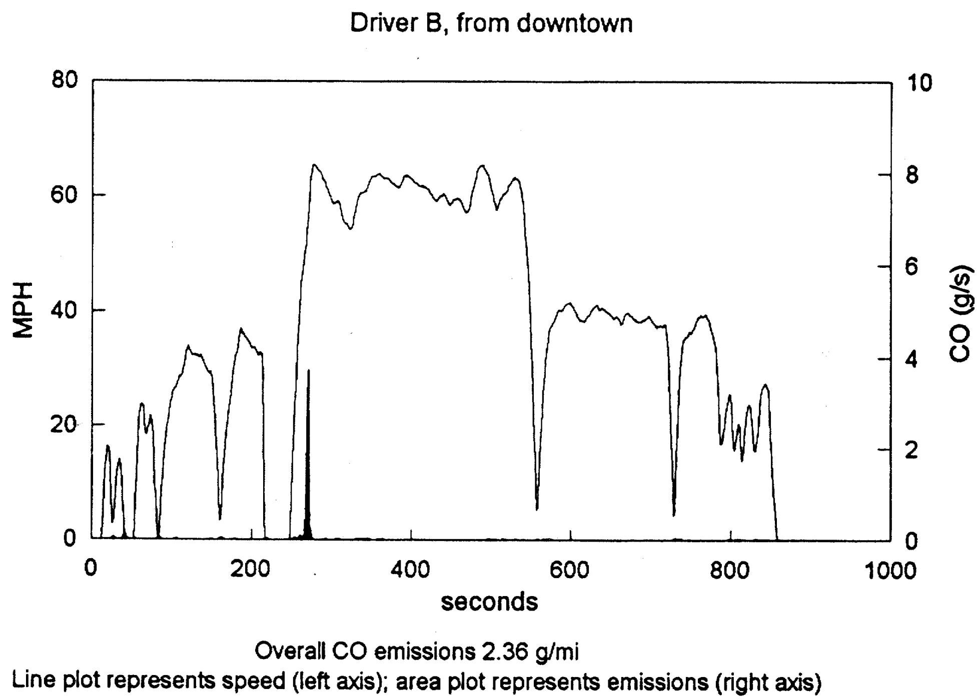
Source: S.C. Davis, *Transportation and Energy Data Book* (Oak Ridge [Tennessee], Oak Ridge National Laboratory, 1994).

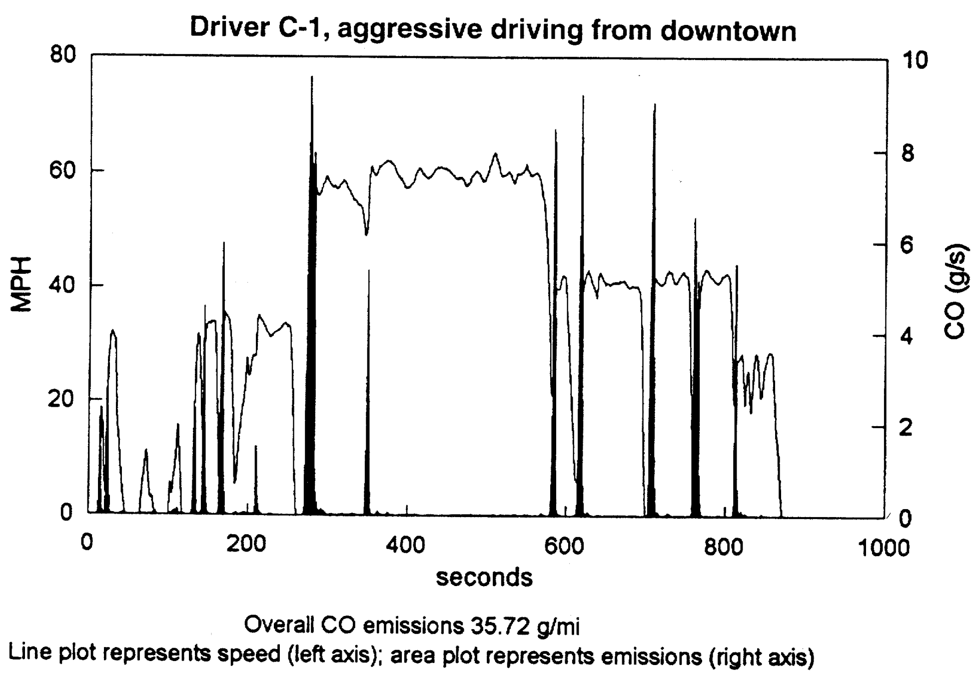
The aggressive driver emits over 14 and 15 times as much CO and VOCs respectively per kilometre as the normal driver, even though, as the figures show, cruising speeds after acceleration are similar. These considerations suggest that the emissions of individual vehicles can be reduced or minimized by using traffic management techniques that both ensure the smooth flow of traffic (by minimizing stops and starts) and maintain an average speed of traffic between 40 and 75 kilometres per hour.

Induced demand

One of the most intuitively obvious ways to improve the flow along a link in a transport network is to increase the effective capacity of that link. For this reason, capacity improvements are often touted as having air quality and congestion relief benefits. Heuristic, engineering relationships (see chap. IV, sect. B of this study) are often used as the justification. Capacity improvements to improve flow may involve physical additions to infrastructure, such as expanding or widening roadways, but they may also involve traffic management, better signal timing, or other enhancements in order to increase the performance of existing roadways. Whether physical or managerial in nature, any increase in roadway capacity will be associated with a certain amount of induced demand, defined as an increase in vehicular travel that occurs as a result of any increase in the capacity of the transportation system, that is, that would not have otherwise occurred in the absence of the capacity increase (Noland and Cowart 2000; Lee and others 1999; DeCorla-Souza and Cohen 1999). For this reason, the actual improvement to air quality and energy efficiency resulting from a change in capacity is significantly more complex than the above heuristic relationships would suggest.

Figure A.XV. Time-speed emissions traces for carbon monoxide for an "average"driver and an aggressive driver in an 11-km trip from downtown

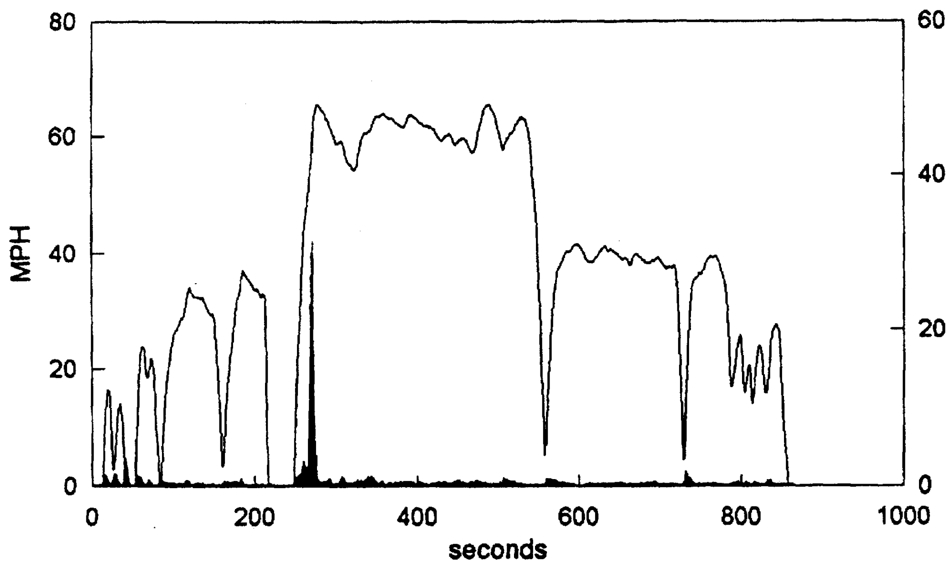




Source: Transportation Research Board, *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*, Special Report 245, National Research Council (Washington, National Academy Press, 1995).

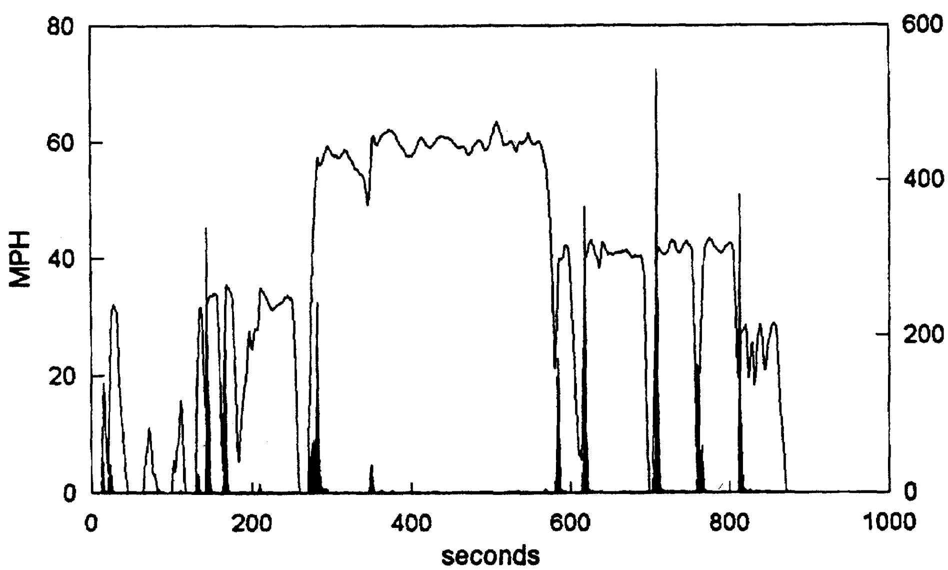
Figure A. XVI. Time-speed emissions traces for volatile organic compounds for an "average" driver and aggressive driver in an 11-km trip from downtown

Driver B, from downtown, drive no. 07206.prn



Overall VOC emissions 0.06 g/mi
Line plot represents speed (left axis); area plot represents emissions (right axis)

Driver C-1, aggressive driving from downtown, drive no. 072012.prn



Overall VOC emissions 0.85 g/mi
Line plot represents speed (left axis); area plot represents emissions (right axis)

Source: Transportation Research Board, *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*, Special Report 245, National Research Council (Washington, DC, National Academy Press, 1995).

Mechanism behind induced travel. All else equal, the effect of a capacity increase in a stretch of roadway is to reduce the amount of time needed to travel along the link, assuming the link was operating under congested conditions before the improvement. Since time is a cost having monetary value (people are willing to pay money to save time), any reduction in time amounts to a reduction in the cost of travel. Basic economics suggests that a reduction in costs is associated with an increase in demand, and this increase is the amount of demand "induced" by the capacity change. Quantifying this effect has been a challenge for researchers, however, because controlled experiments to determine how much traffic is baseline and how much induced are not possible. (DeCorla-Souza and Cohen 1999). In addition, there is significant theoretical discussion and disagreement about the distinction between short-run and long-run induced demand (Lee and others 1999).

In both the short and long run, induced travel reflects changes in consumer and business decisions. Over the short run, a change in roadway capacity may cause travellers to change their departure times (resulting in no direct VKT increase, but there may be ripple effects as capacity is released at different times of the day), their routes, their travel mode, their destinations, and the number of trips they make in a day (trip generation). Over the long run, however, additional changes resulting from roadway capacity increases may also occur, including increases in household car ownership or driver licensing rates, changes in residential location (shift of time-savings benefit into real estate values), employee changes in work locations, employer changes in business location, changes in land-development location and patterns, and changes in aggregate amount of economic activity in a region. All of these changes can be reflected in increased vehicle kilometres travelled–that is, increases that would not have occurred in the absence of the capacity expansion.

A common assumption is that induced travel necessarily implies increased economic activity, a clear benefit for the region. While this assumption may be true for predominantly rural areas whose accessibility may be greatly enhanced through transport capacity enhancement, the above enumeration of potential changes in travel behaviour for residents of urbanized areas suggests that net increases in economic activity may be only a small component of overall induced demand. Rather, much of the change in activity may simply be the result of a transfer of resources–in the form of time-savings–from society at large, to motorists. In this sense, induced travel may be a reflection of a hidden subsidy for car users.

Measuring induced travel. Recent research has begun to suggest that the effects of induced travel demand may be quite strong. In the United States-based literature, induced travel is often reported as either an elasticity (for VMT) with respect to either lane-miles or travel-time savings, or as the proportion of observed overall VMT growth which is attributable to capacity expansion (as opposed to socio-demographic or economic factors driving VMT growth).

Studies in the United States suggest that long-run lane-mile elasticities for vehicle miles travelled (VMT) are on the order of .8 to 1.1, controlling for population, income, fuel cost, and other variables such as density (Noland and Lem 2000).[10] Short-run elasticities tend to be somewhat lower (between .3 and .6 according to Noland and Lem 2000). Significantly for developing countries, this research is also suggesting that lane-mile elasticity is sensitive to the base amount of transport network–the fewer the lane-kilometres per resident in the base case, the more the induced effect of capacity expansion observed (Noland and Cowart 2000). In the United States, it is estimated that, on average, about 15 per cent of annual increases in VMT is attributed to an induced demand effect from capacity expansion, although considerable variation

[10] It should be noted that the finding that lane-mile elasticities might be greater than 1 has been the subject of a fair amount of debate and even consternation among induced-travel experts.

is observed between metropolitan areas (Noland and Cowart 2000). This figure is likely to be higher in developing countries because of lower baseline levels. In the United Kingdom, an important study there suggested not only that new capacity increases induced new demand, but also that, in certain instances, eliminating capacity might help reduce demand (SACTRA 1994). A range of data from various studies on induced travel are presented in tables A.10, A.11 and A.12. Table A.10 shows various estimates of vehicular travel (VMT or VKT) elasticities with respect to travel time. Table A.11 shows the same elasticities with respect to road capacity (lane miles or lane kilometres). Table A.12 shows various estimates of the proportion of the share of vehicular travel attributable to induced, as opposed to natural, demand.

Table A.10. Various estimates of vehicular travel elasticities with respect to travel time

Author(s)	Study area	Elasticities
Domencich (1968)	Boston	-0.82/-1.02 (work/shopping)
Chan and Ou (1978)	Louisville	-0.4 (work)
SACTRA (1994) for UK DOT	European Synthesis	-0.5 to –1.0
Dowling (1995)	Synthesis	0.0 to -1.0
NRC/TRB (1995)	Based upon Dowling (1995)	0.0 to –1.0
Goodwin (1996)	Synthesis	-0.28 to –0.57
USDOT (1999) report to Congress	United States modeling	-0.8 to 1.0 (generalized user cost)
Lee (1999)	Based upon Hansen et al (1993)	-1.05

Table A.11. Various estimates of vehicular travel elasticities with respect to lane capacity

Author(s)	Study area	Short run	Long run
Goodwin (1996)	United Kingdom synthesis		1.00
Hansen and Huang (1997)	California counties	0.28-0.75	0.62
Hansen and Huang (1997)	California metro areas	0.43-0.91	0.94
Noland (2001)	50 States	0.23-0.51	0.71-1.22
Noland and Cowart (2000)	70 Metropolitan areas	0.28	0.81-1.02
Fulton and others (2000)	Mid-Atlantic countries	0.13-0.43	0.47-0.81

Table A.12. Various estimates of the share of vehicular travel attributable to induced demand

Source	Study area	Percentage share VMT from induced travel
Heanue (1998)	Milwaukee, 1962-1992	6-22
USDOT (calculated from unpublished data)	National forecasts to 2015	8-11
USDOT (calculated from unpublished data)	Urban areas forecast to 2015	10-14
Noland (2001)	Average State forecast to 2010	20-28
Noland and Cowart (2000)	Average metro forecasts to 2010	15-45

Accounting for induced travel. Transportation planners and travel forecasters acknowledge that induced travel is a real phenomenon, and that forecasting efforts in the past have not adequately accounted for it. There is, however, a fair amount of disagreement on the degree to which existing travel demand forecasting methodologies actually do take induced travel into account. Some of the behavioural change factors enumerated above are adequately captured by standard travel demand forecasting techniques, while others are not. For example, Michael

Replogle, in an annex published together with a special report of the Transportation Research Board (TRB 1995), argues that current knowledge is too rudimentary to be able to determine if a given capacity expansion will result in a net improvement or deterioration, with respect to air quality.

While it may not be possible to characterize or quantify accurately the extent of induced demand from a given capacity change with the current state of knowledge, a number of short-term improvements to travel demand forecasting techniques can help to ensure more accurate accounting of this phenomenon. First, in the economic assessment of a given project or programme that is expected to increase the functional capacity of an urban transportation system, analysts might include as a standard part of their evaluation methodology an assessment of critical inducement loads–that is, back calculate the implied rate of induced demand (as measured by elasticity) at which a given project would be rendered uneconomical (for example, where the economic rate of return–including air quality benefits–drops below 12 per cent). Analysts can then make judgements as to whether such an elasticity is possible, likely, or inevitable, and assess the project accordingly. Secondly, analysts could apply sensitivity tests to various parts of four-step transportation models to approximate different aspects of induced travel behaviour, and similarly make judgements about project risk. In the long run, increased data and information from around the world will help to refine the methodologies and calibrations of techniques to predict actual levels of induced travel.

Balancing speed and flow considerations with induced travel

Improving flow and maintaining speeds within the optimal range in a transportation network may to help reduce energy consumption and pollutant emissions of individual vehicles using the system, but if the flow and speed improvements increase effective capacity, they may also induce additional vehicle travel that might not have occurred had the intervention not been undertaken. The actual effects of traffic flow interventions on air quality and energy use, therefore, must be examined on a case-by-case basis.[11] A clear pitfall in air quality analysis would be to use an air quality model–such as the EPA MOBILE6 model–to assess the impact of a policy or investment decision that increases the effective capacity of the road network, without taking into account appropriate vehicle travel data from a well-calibrated travel demand forecasting system that accounts for induced travel as much as possible.[12]

[11] This was the final recommendation of a Transportation Research Board panel convened to look into the question (TRB 1995).

[12] One frequently cited shortcoming of travel demand forecasting methods is that they often do not adequately account for land-use changes resulting from changes in transportation capacity. Consequently, even models that do account fairly well for induced travel effects may still be missing these land-use “knock-on” effects (Hunt 2001).

Annex VIII

ECONOMIC ANALYSIS IN URBAN AIR QUALITY MANAGEMENT

The art and science of urban air quality management is well established, if still in need of refinement, and expertise in cities in developing countries as well as in the developed world is growing. The World Bank has developed an Air Quality Management System that has been used extensively in Asia, under the auspices of the URBAIR programme, in Latin America, under the Clean Air Initiative and other Bank-sponsored efforts, and in Teheran. This process is data-intensive, as it requires several years for the collection and evaluation of information, but it can be of significant help in better directing scarce resources to those measures that will yield the greatest results. The present annex provides an overview of the process, highlighting strengths and weaknesses.

The formal system of analysis involves a number of evaluation "modules", including:

(a) An emissions module, to determine sources of pollutants (emissions inventory);

(b) A dispersion module, to determine photochemical reactions and ambient concentrations;

(c) An exposure module, to determine population exposure risks;

(d) A damage assessment module, including dose-response relationships (which may be supplemented to include non-human-health costs);

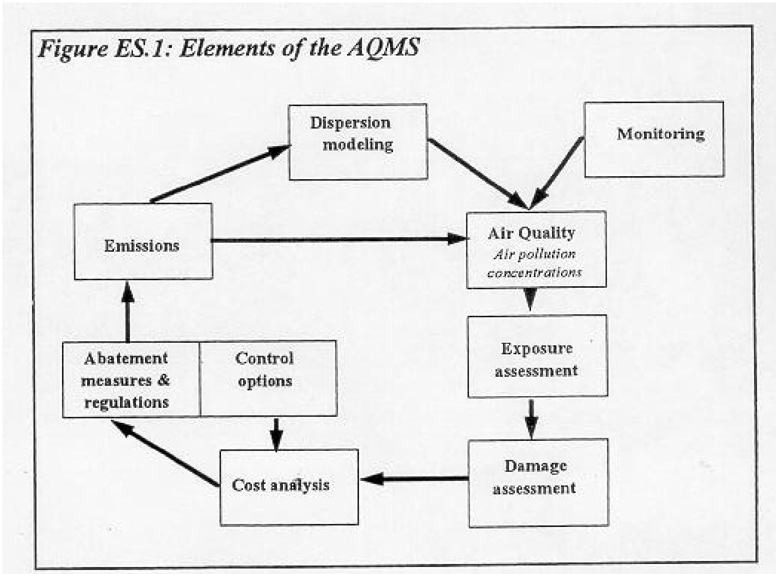
(e) A cost-ranking analysis module, to evaluate least-cost damage abatement measures.

Under ideal conditions, these evaluation modules are carried out against a background of rigorous ambient air quality monitoring in the urban airshed. The emissions inventory and dispersion module associate economic activity in various sectors with measured ambient air quality, to apportion the source of pollutants to different sectors. The inventory of emissions applies measured emissions factors to observed sectoral activity, to determine the sectoral emissions, which the dispersion module models atmospheric, local climactic, and topological features that determine how pollution disperses from sources to measured ambient concentrations. The exposure and damage assessment modules should quantify the health and other costs of pollution exposure, and the cost-ranking module evaluates potential interventions. For the transport sector, interventions most often analysed include:

- Introduction of unleaded gasoline;
- Implementation or improvement of inspection and maintenance programmes;
- Addressing excessively polluting vehicles through scrappage or retrofitting programmes;
- Improving diesel fuel quality;
- Fuel switching to LPG or CNG;
- Adoption of vehicle standards;
- Where appropriate, improving quality and quantity of lubricating oil for two-stroke engines.

These modules are shown in relation to each other in figure A.XVII.

Figure A.XVII. Elements of air quality management system



Source: World Bank, *Urban Air Quality Management Strategy in Asia: Guidebook*, edited by J.J. Shah, T. Nagpal, and C.J. Brandon (Washington, DC, 1997).

In practice, the AQMS has a number of limitations that need to be understood in order to ensure that it is properly used.

Cost-effectiveness versus cost-benefit

The formal system described above includes modules to assess exposure and damage assessment (health costs). In practice, however, evaluation is often carried out without these modules, meaning that detailed assessments of costs and benefits of different measures are not possible. Rather, the evaluation often conducts a cost-effectiveness evaluation, which ranks the costs of reducing physical volumes of pollutants, but does not provide any inherent means to prioritize among these volumes.

Not including such damage assessment in economic evaluation can be politically risky, since important political decisions and determination of the allocation of resources—specifically, with regard to what level of investment is justified—are left undecided. In Europe, the costly first Auto-Oil Programme collapsed around this point; once abatement measures were ranked and marginal cost curves established, different constituents (the automobile and petroleum industries, the European Commission and members of the European Parliament) could not agree on appropriate levels of abatement, and the analysis did not provide them with a means to move beyond the log jam. A more rigorous inclusion of abatement benefits in the analysis programme might have allowed these political and value decisions to be more openly discussed and negotiated (Nevin and Barrett 1999). An important, and often overlooked, role of rigorous economic analysis, therefore, can be to provide a structured forum in which values and political interests would be discussed and negotiated, but this role can only be carried out if cost-benefit, rather than cost-effectiveness, criteria are used.

Technical bias

The focus on quantitative assessments of specific interventions has led in practice to a predominance of technical rather than behavioural or systemic solutions–such as traffic management, travel demand restraint, or public transport enhancement–as the subject of analysis. In most cases, these types of interventions do find their way back into the set of final recommendations, but there is little quantitative support for these actions; they therefore do not have the same weight among policy makers as the more technical interventions, even though, over the long run, systemic or behavioural measures may be more effective.

Static evaluation methodology

With regard to the above criticism, the evaluation methodology of the air quality management system is not dynamic; it involves a static view of traffic with little demand-side or systemic evaluation to assess how pollution is likely to change over time. In particular, it ignores the effects of planned infrastructure on overall levels of activity. For Manila, Mumbai, and Jakarta, for example, all the assessments of the URBAIR programme recommended that short- to medium-term measures should be implemented to improve the capacity of the existing road network and to improve/eliminate bottlenecks. In a static analysis, such recommendations may make sense; in a closed system, eliminating bottlenecks reduces stop and go traffic, thereby reducing emissions from high-load conditions. In a dynamic framework, however, such recommendations are ill-conceived, absent better analysis.

Annex IX

FUEL PRICING FOR ENVIRONMENTAL PURPOSES

Fuel taxes as generalized proxy for Pigouvian tax

Pigouvian taxes tax an offensive or deleterious outcome of a market transaction, for which neither the buyer nor the seller bears the cost (a negative externality). Classical economics suggest that a tax on a pollutant equal to the marginal damage it causes would cause the market to correct the problem automatically. Formally, fuel taxes levied for this purpose are an imperfect example of a Pigouvian tax, because the input–fuel–is taxed, rather than the damaging output–emissions. Nevertheless, because of the relative administrative simplicity of the tax, and the strong correlation between content of the input and observed pollution, especially for greenhouse gases, it is an attractive implementation measure (Eskeland and Devarajan 1996). As an input tax, fuel taxes can be combined with regulatory measures to mimic the market responses that would be expected were a true Pigouvian tax to be assessed (Eskeland and Devarajan 1996).

Until very recently, fuel taxes were not used as a policy instrument explicitly to change behaviour; rather, they were used for revenue raising, in three contexts. In the United States, they have been the primary mechanism of financing for road infrastructure development and subsequent maintenance. Consequently, they have been hypothecated within the sector, and taken off budget. In Europe, Japan, and many developing countries, fuel taxes are a primary means of raising general revenue. The share of funds "returned" to the transport sector varies from budget to budget, and is generally unrelated to the revenue raised from the sector. In some developing countries, fuel taxes are used to finance road maintenance funds (Heggie and Vickers 1998) in which supplemental revenue raised via a fuel tax is allocated to a road fund maintained off-budget, for the purpose of maintenance of facilities.

Explicit use of fuel taxes in a Pigouvian sense—that is, to change behaviour—is recent, with experience limited, for the most part, to Western Europe. Between 1995 and 2000, the United Kingdom imposed regular fuel tax increases at a rate of 5 per cent (6 per cent for diesel) per year over the rate of inflation. Not surprisingly, the measure was unpopular with motorists, and became increasingly so after large increases in world petroleum prices in late 1999. The programme, which was intended to "sunset" in 2003, was abruptly cut off in 2000. In addition to the United Kingdom, eight countries have instituted some kind of CO_2 tax or increased fuel taxes in response to environmental pressures, although in some cases, gasoline and other transport-related taxes are either exempted or receive special treatment (ECMT 1997). It is difficult to know the extent to which these new environmental taxes have affected behaviour thus far, but countries with high fuel taxes tend to have fleets with higher fuel efficiency (World Energy Council 1998).

Types of fuel taxes

Different types of fuel taxes can be mixed and matched to target different types of pollution; doing so, however, requires a rather sophisticated mechanism for setting, implementing and monitoring the taxes. In order for Pigouvian taxes to work, it is crucial for the structure of the taxes to be transparent and well understood by consumers. Otherwise, it will be difficult for consumers to understand what changes in their behaviour they need to make in order to reduce their costs, and the intended price signal will be muddled.

Energy tax. A tax on energy content of fuel is primarily intended as an incentive for transport fuel consumers to reduce aggregate amounts of fuel used, either by choosing more fuel-efficient vehicles, or by reducing the amount of motor vehicle use they undertake. The advantage of an energy tax is that it is easy to administer—the energy content of fuels is well known—and that it constitutes a rough proxy for damage caused by local and global pollutants. The disadvantage is that, as a proxy, its relationship to local pollutants is only a rough one.

Specific Pigouvian levies on fuel content. A generalized fuel tax as reviewed above constitutes an easy-to-administer proxy for a Pigouvian tax on environmental externalities (Eskeland and Devarajan 1996). Alternatively, specific attributes of the fuel, associated empirically with emissions of particular species of pollutants, could be taxed directly. A Pigouvian tax is particularly suited to the problem of lead, since lead is added for economic, not technical, reasons. Such a tax need not be equal to the actual amount of damage caused per weight of lead present in fuel; even a modest tax could serve as a strong incentive to reduce lead use by refiners (EPA 1999). Other attributes of fuels—such as sulphur, oxygen content or octane rating—might also be taxed (or negatively taxed) in order to create demand incentives for changes in fuel content.

Fuel-specific differential tax rates. Fuel taxation has been used extensively in many countries as a means of favouring one technology over another, for example, diesel over gasoline. Many countries maintain an artificial price distinction between diesel and gasoline much greater than international prices would warrant, as shown in table A.13 below. In some cases, these price distinctions are made in order to favour diesel vehicles over gasoline; in most countries, however, they are maintained primarily as a general subsidy to agriculture and other industries dependent on diesel fuel.

Whatever the intention of the policy, economic theory suggests, and empirical evidence shows, that switching to diesel would be accompanied by an increase in vehicle use, all else equal (the so-called "rebound" effect of fuel economy savings) (Hivert 1996). The reason is that diesel vehicles enjoy an inherent fuel economy advantage over gasoline vehicles. That fuel economy advantage means that at a certain anticipated annual mileage, the additional ownership and maintenance costs of diesel vehicles are offset by a reduction in operational costs. The effect of diesel price incentives is to lower that barrier for prospective buyers. Their costs to travel a given amount are therefore lower than they would otherwise be, creating an income effect, some of which translates into greater vehicle use.

Adjusting the relative costs of gasoline and diesel involve a review of the mechanisms for implementing intended subsidies for certain industries and agriculture. For example, targeted subsidies, through vouchers issued to certain industrial and agricultural users of diesel fuel entitling them to rebates on diesel purchases, might be more effective than artificial price controls. Targeted subsidies may also help to limit overall demand for diesel fuel, helping to restrain underlying prices better than price controls, resulting in a more efficient and, ultimately, less costly means of delivering subsidies to target populations.

Carbon taxes. Carbon taxes are a particular Pigouvian levy on a pollutant species—carbon dioxide—which has the long-term effect of influencing both the desirability of particular fuels (diesel versus gasoline and alternative versus conventional) and the aggregate amount demanded (vehicle energy-intensity and the amount of vehicular activity). Unlike energy taxes, carbon taxes can influence the fuel choice based on carbon content, as well as energy efficiency (Schipper and others 2000) and, unlike specific levies on other types of fuel content, such as sulphur or aromatics, carbon taxes more directly influence aggregate amounts of fuel consumed.

Table A.13. Comparative prices of gasoline and diesel in countries of the former Soviet Union and Central and Eastern Europe, with reference to prices in select OECD countries

Country	Gasoline (US$ per litre)	Diesel	Diesel/gasoline ratio
Albania	0.90	0.40	0.44
Armenia	0.34	0.28	0.82
Azerbaijan	0.37	0.21	0.57
Belarus	0.35	0.18	0.51
Bulgaria	0.50	0.32	0.64
Croatia	0.77	0.64	0.83
Czech Republic (1997)	0.76	0.67	0.88
Estonia	0.45	0.39	0.87
Hungary	0.85	0.69	0.81
Kazakhstan	0.29	0.15	0.52
Kyrgyzstan	0.45	0.20	0.44
Latvia	0.56	0.35	0.63
Lithuania	0.49	0.38	0.78
Former Yugoslav Republic of Macedonia (1997)	0.86	0.49	0.57
Poland	0.57	0.44	0.77
Romania (1997)	0.45	0.32	0.71
Russian Federation	0.34	0.22	0.65
Slovakia (1997)	0.67	0.62	0.93
Slovenia (1997)	0.53	0.50	0.94
Tajikistan	0.41	0.38	0.93
Turkmenistan	0.10	0.07	0.70
Ukraine	0.48	0.24	0.50
Uzbekistan	0.63	0.33	0.52
France	1.18	0.82	0.69
Germany	1.20	0.82	0.68
United Kingdom	0.97	0.91	0.94
United States	0.38	0.37	0.97

Source: European Bank for Reconstruction and Development, *Transport Operations Policy* (London, n.d.), http://www.ebrd.org/english/opera/sector/top_fin.pdf.

Note: Prices refer to 1996 unless otherwise stated; premium unleaded gasoline, where available.

Estimates of the value of carbon emissions taxes vary significantly, from as low as US$ 14 per ton to as high as US$ 265 (Prototype Carbon Fund 2000). The reasons for such variation have to do with the assessment methodology, assumptions about the expected costs of climate change and discount rates, and the anticipated time when carbon emissions actually occur (a ton of carbon emitted in 2010 is considered to do more marginal damage than one emitted in 1990, for example.) The World Bank's rapid assessment methodology recommends using US$ 20 per ton of carbon abated, but figures in this range generally do not reflect an equity adjustment for the marginal value of a dollar, and are probably therefore somewhat biased against damage in poorer countries (Tol 1999). Tol (1999) estimates marginal values of carbon abatement at between US$ 26 and US$ 60 per ton (depending on discount rate) if equity adjustments are made. This range is closer to those that were discussed in the European Union immediately following the Kyoto Protocol.

Political and economic implications of fuel taxes

Fuel taxes to encourage or discourage behaviour are difficult to implement because they are politically unpopular and because of concern about the overall impact on the economy. They are politically unpopular not because most people oppose them or the goals they are trying to attain, but rather because those whose behaviour they are intended to modify have strong motivation to take political action to prevent that modification, while those who benefit from such modification (the public at large) receive too diffuse a benefit to engage in active efforts to influence the policy (Olson 1965). Concern about the economic effects of the tax relate to possible depressive effects on the economy, increased unemployment, and reduction in economic output resulting from the ripple effects from reduction in demand for cars, and possibly reduced economic exchange from reduced car use. These effects need to be weighed against increased availability of funds for expenditure by the entity (government) collecting the funds. It is likely that such effects would be a relatively short-term adjustment, but how much of an adjustment a political economy can tolerate depends on local conditions. Long-run economic efficiency, and consequently productivity, is likely to be significantly increased, but the uncertainty about the transition period and the rarity of such policy in practice suggests that the implied discount rates for such long-run efficiency are minuscule. A number of offsetting policies, however, have been proposed with regard to the specific uses of the revenues raised and a reduction on tax rates of capital investments (Office of Technology Assessment 1994).

Annex X

MENU OF TACTICAL OPTIONS

The present annex is intended to provide a more detailed description of specific measures that might be considered under the tactical framework outlined in chapter IV of this study. As fuel pricing and I and M programmes have been reviewed extensively elsewhere, they are not included here, but both can be integral components of a tactical approach to reducing emissions. All the measures are summarized in table A.14.

Variabilizing costs

Variable costs, other than the cost of fuel, are the most perceptible costs to the individual trip maker of the cost of a trip, and therefore the easiest to equate with the value of a particular trip for the trip maker. For this reason, policies to variabilize costs—that is, transfer the overall life-cycle burden of car-based mobility from vehicle ownership to use—constitute one of the most effective means of addressing excessive vehicle use. This section reviews four such measures for variabilization: parking policy; road pricing; variable-priced insurance and financing payments; and car-sharing.

Parking policy

Of the measures considered for variabilization of costs, parking policy has the most chance for short-term success; it is already familiar to motorists, good practice is well grounded in experience, it is clear-cut to implement, and it is an intervention using the legal authority that most municipalities already possess, even if they do not have the institutional capacity. In addition, implementation of effective parking policy should be self-financing in a relatively short period, or amount to a revenue earner for the municipality.

The basis for using parking policy to influence vehicle use stems from the observation that, for those who own vehicles, ease and cost of parking at the destination is often the strongest determinant of whether a car will be used for a particular trip or trip chain (Cervero 1994). In many developed countries–and in a growing number of out-of-town employment centres in developing countries as well–employer provision of free parking provides a strong incentive to drive to work. Similarly, poor pricing or poor enforcement of on-street parking, particularly in the central business district (CBD)—as is the case in many cities in developing countries—can have a similar effect (see, for example, World Bank 2000). Poor management of on-street parking can also greatly hinder traffic flow.

For cities with no existing on-street parking management, implementation of such a programme can be one of the most cost-effective measures to discourage excessive use of private vehicles, while enhancing smoothness of flow on urban streets. On-street parking management programmes usually favour short-term parking (under one-hour), using fees and meters to discourage parking for long periods, or all day. All-day parkers must find off-street space to avoid a hefty fine—a service for which they usually need to pay a fee, thereby increasing their marginal costs—or find some other means to come to the central business district. In situations in which employers provide free parking for employees, techniques such as employer cash-out of parking benefits might also be used to help variabilize costs (see chapt. IV, sect. C, for a more detailed review of measures to influence mode choices).

Table A.14. Transport emission reduction measures: tactical targets and strategies supported

Menu of measures	Tactic	Group targeted	Primary strategy supported	Level of government for implementation	Examples
Fuel pricing policy	Variable cost pricing	Fuel users	Behavioural	National	Fuel tax, energy tax, CO_2 tax
Parking policy	Variable cost pricing	Motor vehicle users	Behavioural	Local	On-street parking management to favour short-term parking in intense-use zones; zoning provisions for parking minima in trip-production zones; zoning provisions for parking maxima in trip-attraction zones; taxing parking benefits as ordinary income; parking "cash-out" for employer-provided parking
Road pricing	Variable cost pricing	Motor vehicle users	Behavioural	Provincial or national	Area (cordon) pricing; distance (odometer) charges; electronic road pricing
Variable insurance and financing	Variable cost pricing	Motor vehicle users	Behavioural	National	Pay-at-the-pump insurance; odometer-based insurance
Car sharing	Variable cost pricing	Motor vehicle users	Behavioural	Local	Station-cars; car-sharing organization
Public transport fare/service integration	Influencing mode choice	Travellers	Behavioural	Local or provincial	System transfers; "Smart" card technology; feeder/trunk structure
Public transport enhancement	Influencing mode choice	Travellers	Behavioural	All	Dedicated busways; increasing frequencies; increasing geographic coverage
Targeted subsidies for public transport	Influencing mode choice	Travellers	Behavioural	Any	Vouchers for public transport users; employer-provided subsidies; related discounts or privileges for PT users
Work schedule and location policies	Influencing travel choice	Travellers	Behavioural	Any	Work-at-home programmes; staggered work schedules; flexible working hours
Traffic management and flow control	Changing traffic conditions	Motor vehicle operators	Systemic	Local or provincial	Traffic "calming" to reduce aggressive driving; time-of-day traffic patterns to smooth flow; congestion pricing (pricing roads by time-of-day and location); dedicated busways
Adjustment to vehicle acquisition and registration costs	Influencing fleet demand / turnover	Vehicle purchasers	Technical	National	Emissions or efficiency criteria for vehicle registration fees or purchase taxes; "feebates"; tax credits
Full lifecycle costing	Influencing fleet demand / turnover; improving in-fleet maintenance	Fleet managers	Technical	Any	Lifecycle costing to account for stream of maintenance expenditures during purchase decisions
Price restraints or quotas on vehicle ownership	Influencing fleet demand / turnover	Vehicle purchasers	Technical	Any	Ownership "entitlement" auctions; high purchase fees
Adoption of vehicle emissions standards	Influencing fleet supply	Vehicle suppliers	Technical	National	Sales-based standards implementation; import-based standards implementation; certification and compliance for implementation burden on after-market
Inspection and maintenance programmes	Improving in-fleet maintenance	Vehicle owners / fleet managers	Technical	Local or provincial	
Mobile enforcement to support inspection and maintenance programmes	Improving in-fleet maintenance	Vehicle owners / fleet managers	Technical	Local or provincial	Random roadside testing; roadside testing of visually emitting vehicles; remote sensing

Menu of measures	Tactic	Group targeted	Primary strategy supported	Level of government for implementation	Examples
Training and education for drivers and fleet managers	Improving in-fleet maintenance	Drivers / fleet managers	Technical	Any	
Explicit policy to determine what infrastructure is allowed to go where	Influencing the built environment	Planners / developers	Behavioural	All	Smart growth; analysis of alternative scenarios of infrastructure investment
Improve functioning and transparency of land-markets	Influencing the built environment	Planners / developers	Behavioural	National	Cost recovery of infrastructure capital through development fees or in-kind requirements; betterment charges to recoup ordinance-created value; better institutions for land-markets, including cadastral services, land titling/deed recording, and impartial adjudication of disputes; development of private sector institutions
Full cost accounting of infrastructure supply and maintenance	Influencing the built environment	Planners / developers	Behavioural	Local or provincial	Full cost analysis of infrastructure investment, including stream of maintenance payments
Influence household location choices	Influencing location choices	Households	Behavioural	Any	Tax incentives; location efficient mortgages (LEM); corrections to distortions in housing finance system; location decisions of public services and institutions
Influence firm location choices	Influencing location choices	Firms	Behavioural	Any	“Reverse” zoning (for example, Dutch ABC policy); tax incentives with "Location Efficiency Zones"; location choices of public services and institutions
Educate the public on transportation, air quality, and lifestyle choices	Influencing public attitudes	General public	Behavioural	All	Public awareness campaigns, children's education

In practice, off-street parking policy is often set by zoning and land-use policy, rather than as a specific transport demand or emission control measure. Here, the goal has historically been to avoid overloading surrounding streets with excess demand for parking created by vehicle trips "generated" by a new building, by ensuring that the building itself incorporates on-site parking. Zoning codes, therefore, often specify parking minima. For land uses that are trip-attractors, however, not only can such a policy encourage excess vehicle usage, but it can also make walking and using public transport less attractive. For example, if people are obliged to walk from their bus stop on through a sea of parking spaces in order to enter a building, this will discourage the use of public transport. In North America and Western Europe, however, a growing number of jurisdictions are adopting parking maximums, that is, limiting the amount of parking that can be provided in a location, under the assumption that parking induces vehicle trips.

Road pricing

Parking policy helps to variabilize costs by placing a charge on vehicle use; road pricing similarly variabilizes costs by charging for distance driven. Conceptually, the simplest form of road pricing is an odometer tax, charging per kilometre driven. An odometer tax, however, does not adjust for where and when vehicles travel; instead it averages incremental vehicle costs over time and space. Road or facility specific charges are possible through tolls or, in urban areas, increasingly through advanced technology.

In practice, road pricing has been implemented in few places, and rarely as a pure demand management measure to shift cost structure. In Norway, the central portions of Oslo and Trondheim have been "cordoned" off for about 20 years, so that motorists entering the central city must pay a toll, which today is collected electronically from "smart" cards. These cordons, however, were implemented initially not as demand restraints, but rather as a revenue-raising measure to finance the completion of the respective urban roadway networks. Singapore has developed a rather comprehensive scheme of road pricing, in which smart cards mounted in an in-vehicle unit automatically deduct a price when the vehicle crosses an electronic cordon. This electronic road-pricing (ERP) scheme is better described as a generalized road charge than a congestion-pricing scheme *per se*, because charges are not adjusted to stochastic changes in traffic volumes, although they are periodically reviewed to adjust for traffic congestion trends. A number of cities in the United Kingdom, including Cambridge and London, are also actively considering implementing road-pricing schemes in order to encourage greater use of public transport.

Variable-priced insurance

Another proposed method of cost variabilization is to transform recurring costs—that is, those that are traditionally time-dependent (paid periodically)—into variable costs—that is, those that are use-dependent. The most frequently discussed of these transformation methods, and also the most commercially viable in the near term, is variable-priced insurance. Variabilizing insurance costs by transforming them from a pay-as-you-own to a pay-as-you-drive basis has intuitive logic, since risk of accidents, damage to the car, and damage to people and other property increases the more the car is driven. The most frequently discussed form that variable-priced insurance might take is either a distance-based (odometer) periodic insurance premium, or pay-at-the-fuel-pump insurance. The latter form, however, is incompatible with traditional, fault-based systems of insurance.

Car-sharing

The most extreme form of cost variabilization for motor vehicle use is car-sharing. Car-sharing is an organizational structure for pooled vehicle ownership allowing members access to a range of vehicles for short-term use. Members pay only for the time they use the car, and for distance driven.[13] All costs related to the vehicle, including acquisition, financing, maintenance, cleaning and even fuel, are covered by the car-sharing organization itself. In the short run, car-sharing may serve to delay decisions to motorize—that is, to acquire a car for households that have marginal need for one, but would otherwise need to acquire one in the absence of a car-sharing programme. In the longer run, some households may begin to "shed" cars as their vehicles begin to age and break down, or as they approach a critical lifestyle choice, such as marriage, divorce, the birth of a child, or a change of job.

The anticipated air quality benefits of car-sharing stem partially from cost-variabilization—because travellers are confronted with a total set of costs for each and every trip, they may choose to make a number of trips by public transport or by walking—and partially from the potential for better and more appropriate vehicle loading. Car-sharing participants choose the particular vehicle for each and every trip (rather than trying to select one vehicle that can meet the needs of a stream of trips); they can therefore select the most appropriate-sized vehicle for the needs of an individual trip or chain of trips.

To date, car-sharing has been implemented only in certain cities in Europe and North America, as well as Singapore. These experiences are too new to assess the long-term impact, but the short-term effects have been assessed. These assessments show that, as intuition suggests, previously non-motorized households increase their total amount of annual vehicle kilometres travelled by car, and previously motorized households reduce their annual vehicle kilometres. In European car-sharing programmes, these changes have resulted in a net loss in total vehicle kilometres travelled of between 50 and 75 per cent (Zegras and Gakenheimer 1999).

The applicability of car-sharing to developing country contexts is unclear. On the one hand, car-sharing seems to be a promising potential strategy to help stem the rapid growth of vehicle ownership in cities in developing countries. Combined with a well- conceived strategy of two-wheeler adoption or public transport development, car-sharing might be able to play a role in retarding or otherwise offsetting the motorization that would have occurred for a given income level.

On the other hand, a number of factors suggest that car-sharing may not be entirely feasible in cities in developing countries. First, wage rates in many developing country contexts may be sufficiently low that price structures that meet costs may not be competitive with basic taxi service. This is particularly true where taxi fleets consist largely of very old, poorly maintained vehicles. Secondly, decisions to motorize in many developing countries may be made more with a view to facilitating the productivity of small enterprises linked to households, rather than to expanding household mobility *per se*. It is not clear whether car-sharing would be a viable option in these cases.

Zegras and Gakenheimer (1999) have analysed the costs of a hypothetical car-sharing programme for Santiago, Chile. Based on assumptions of varying degrees of demand, car

[13] In some instances, members may pay an annual membership fee, which, at any rate, is significantly lower than the annual fixed costs they would likely otherwise pay for car ownership.

utilization, and vehicle-to-member ratios, they develop a matrix matching revenues with costs from a break-even paradigm. They then apply these costs to potential real-world trips in Santiago, and compare them with alternatives such as private car ownership, rentals and taxi trips. Based on their optimality assumptions, they estimate that car-sharing is economically competitive with the private car at 8,250 kilometres per year or lower. These numbers are somewhat lower than those found in Switzerland and Germany (Shaheen and others 1999). Zegras and Gakenheimer (1999) also compare car-sharing with taxi trips. For different trip durations, they estimate distance break-even points for car-sharing against taxi trips, as shown in table A.15.

Table A.15. Price comparison of car-sharing and taxis in Santiago
(in dollars)

Trip time (hours)	Distance (km)	Taxi	Car-share
1	4	2.40	2.37
2	7	4.50	4.46
3	10	6.60	6.55
4	13	8.70	8.64
5	16	10.80	10.73

These results do not in and of themselves demonstrate the viability of car-sharing in developing countries, but they do suggest the strength of the concept, even for emerging countries; they also indicate that car-sharing merits focused experimentation.

Influencing (day-to-day) trip choices

Any number of measures can indirectly influence travellers' choices, by influencing the context in which those choices are made. For example, policies that affect lifestyle and location choices of households and firms will indirectly influence traveller choices. This section, however, reviews only those measures intended to influence directly the choices travellers make—when, where and how they travel—on a day-to-day basis. The longer-term influences of these decisions—changes in city form and locations of activities—are reviewed below in this annex. Measures to influence the choices travellers make on a day-to-day basis are often grouped under the heading Travel Demand Management, and fall loosely into three categories: incentives to use alternative modes, incentives to change patterns of trip-making, and disincentives to use private cars.

Incentives to use public (collective) transportation

Convincing travellers to use public transport is important in markets where most riders are not "captive"—that is, where they have a choice about how to move around. In developed countries, "captive" public transport riders have traditionally been defined as those who do not own a car or have a driver's licence. In many developing countries, with the growth of informal sector transport operations, such a definition does not apply. Even relatively poor riders with no access to private transportation are not captives of the public transport system.

Well-designed incentives to encourage public transport use can be tricky. While they can involve a combination of enhancing public transport services, "paying" travellers to use alternative modes, or reducing public transport fares (for example, by restraining increases lower than inflation), actual effectiveness will depend on local circumstances. Where baseline fares are low to begin with, for example, demand for public transport services—even among the poor—tends to be more time- than price-elastic. In Cairo, for example, the growth in popularity of informal, micro-bus services at the expense of traditional public buses—despite the fact that the latter are nearly a third less expensive—shows that time sensitivity is an important element, even among the poor; among the poorest two quintiles, micro-bus mode shares are 10 per cent higher than those of conventional buses (Metge 2000). A reduction in fares would be less effective than an increase in service to attract new or retain existing riders. Adequate knowledge of travel behaviour and mode-choice behaviour—through revealed or stated preference methods—is therefore important to identify where public transport resources need to be invested to create effective ridership incentives.[14]

Fare integration

Instead of reducing fares, authorities may seek to integrate fares (and services), which often amounts to a de facto fare reduction. In fare and service integration, numerous operators and responsible agencies or companies provide services in a metropolitan area for a single fare, often coordinating schedules. Integration allows travellers to pay a single fare for a trip made on several public transport vehicles, regardless of the operator. It is effective in that it amounts to an actual enhancement of service, in addition to being a fare reduction, by allowing some users to take advantage of services they would not have been willing to pay for otherwise.

In developed countries, fare and service integration forms the core of an emerging concept known as mobility management (MM). MM focuses on facilitating multimodal trips in a "seamless" manner. Information technology and intelligent transportation systems (ITS) applications are used so that the traveller finds a multimodal trip almost as convenient as a car. In New York City, introduction of the MetroCard, an electronic swipe card that is usable on the subway, buses, and certain ferries, made free subway-to-bus and bus-to-subway transfers available that had not been available previously. Not only did ridership increase following introduction of the MetroCard but so did revenue for the New York City Transit Authority. As the cost of this technology comes down, applications should become more practicable in developing country contexts as well.

In many developing countries, however, institutional arrangements and cooperation among different agencies, operators, and regulators may be more of an impediment to effective fare integration than technology. A sense of competition between operators may limit their willingness to cooperate. In addition, poor data on ridership patterns inhibit the development of revenue-sharing schemes. Nevertheless, there have been numerous successes with fare integration in developing countries, predominantly in Latin America. Curitiba, Brazil, has accomplished effective fare integration without reliance on ITS technology, with a seamless bus transit system for which passengers pay a standardized fare for the whole system, even though it is actually run by nine different private companies. Mendoza, Argentina, and São Paulo, Brazil, have also integrated fares among a number of bus operators.

[14] Where fare restraint policies lead to resource constraints, maintenance tends to be forgone, breakdowns occur more frequently, and service frequency and reliability suffer. Average time spent travelling increases, generally at faster rates than prices have decreased, resulting in significantly reduced ridership and revenues.

Enhancing public transport service

Fare integration can be a relatively inexpensive means of producing a service enhancement effect, in some cases increasing both ridership and revenues with minimal expense. Other methods of enhancing service involve adding new public transport routes or increasing the frequency of service on existing routes. Advanced traffic management controls can help with both, if public transport services are to be run on streets in mixed traffic. Bus priority, both as a legal concept inscribed in the highway code and as a strategic choice in traffic management decisions, can also help, but only to the extent that enforcement mechanisms are functional.

Separating public transport from the rest of traffic might be a more effective way of increasing the relative speed, frequency and reliability of public transport. It is also an important signal to land markets that the accessibility created by public transport services is fairly permanent, which can help to encourage land development conducive to public transport use (Cervero 1994). Traditionally, this separation has been accomplished using heavy rail and, more recently, light rail in its own right-of-way. Dedicated busways are not new as a concept, but are considered with increasing frequency in both developed and developing countries, largely because of the prohibitive costs and relative inflexibility of rail investments. Busways are also advantageous because they make buses more competitive with private automobiles (or informal transport), while decreasing costs for operators.

Targeted subsidies for public transport users

Financial incentives are another means of encouraging public transport use. Vouchers could be used, either as an employment benefit, or as a means for compensating the poor. Indeed, vouchers, combined with a cost-recovery fare policy, are a more efficient means of delivering public transport services to the poor than simply restraining fare increases, since the public transport operators would have less of an incentive to cut service because of the perception that certain lines are non-remunerative. In urban areas of Western Europe, North America, and Japan, vouchers or subsidies for public transport use are an increasingly standard part of company compensation packages. Many companies offer these packages because of tax advantages offered by the government if they do.

Incentives to change trip-making patterns

How to travel is but one of the day-to-day decisions taken by travellers. When and where to travel are equally as important. Public policy can influence these decisions. For example, policy can encourage employers to use flexible work schedules for their employees: some developing countries in Asia, the Middle East, and North Africa maintain six-day work weeks for public sector employees, in which employees work only half days. Changing official working times in these countries might reduce the overall need to travel. Policy might also encourage employers to develop work-at-home programmes where the technology permits, or to develop neighbourhood “telecommute” or “telework” centres. These centres might be tied directly into vocational training and/or administrative centres, such as Curitiba’s well-known Citizen Streets.

Experience with policies to change trip-making patterns in industrialized countries has been mixed, but the impact has generally been marginal. On aggregate, it is unclear whether such policies have a behavioural effect of reducing the amount of travel by car, although they do seem to have some beneficial effect on car travel during congested periods. In developing countries, experience has been minimal.

Disincentives to private car use

Incentives to use public transport or change patterns of trip-making are most effective when coupled with disincentives to private automobile use. Measures to provide disincentives to private car use, while not popular, can be compatible with efforts to variabilize the costs of motor vehicle ownership and use. In California and other parts of the United States, where on-site parking has traditionally been provided at the workplace, many employers receive tax incentives to offer a parking "cash-out" to employees, whereby employees give up the use of the space in return for an annual cash payment. Taxing the market value of employer-provided parking as ordinary income might help to expand the demand for a parking cash-out option (Shoup and Breinholt 1997).[15] As noted above, the development and implementation of an effective on-street parking management programme can also provide an important disincentive to private car use for trips to the city centre or other business locations.

Controlling the flow of traffic

As noted in annex VII above, controlling the flow of traffic can affect air quality, but not always in predictable ways. Smoothing flow or increasing speeds of traffic along a link can induce more travel. A narrowly drawn policy goal can produce unintended consequences, but even identifying measures to accomplish a stated policy goal can be elusive in the area of traffic flow and congestion. A number of different types of measures can be applied to control the flow of traffic, but their success depends mainly on local conditions and how wisely they are devised.

A well-known example of a poorly designed policy is the "*Hoy no circula*" programme in Mexico City. Under this programme, vehicle access to central Mexico City is rationed by licence plate number, with permission alternating between odd and even plates on bad air days. The policy effectively encouraged relatively wealthier households to purchase a second car in order to circumvent the restriction. This led to a net increase in the car stock in Mexico City, and probably an increase in off-peak driving because of the increased availability. In addition, Mexico City became a net importer of second-hand cars from the countryside (Eskeland and Feyzioglu 1995). Finally, the policy was regressive, because it penalized only those households unable to purchase a second car, while generating no additional revenue to support or enhance their accessibility by other means.

Successful traffic flow policies are feasible, but may not be intuitively clear to the average motorist, and thus may be subject to strong opposition at first. Traffic calming or slowing, as well as congestion pricing, can all be effective mechanisms to improve flow, but the mechanisms need to be clearly explained. Traffic calming involves physical mechanisms to restrain the speed at which vehicles can travel along a link. These can reduce accident risk—reducing stochastic variability in congestion—as well as reduce the amount of stop and start traffic along the link. In addition, they can make a street more inviting to pedestrians and bicyclists. Traffic-calming measures can include narrowing rights of way, raising and installing more frequent crosswalks, shifting the through lane in the right-of-way, installing street trees, and altering the flow of traffic so that vehicles are forced to turn periodically.

---

[15] Currently, in the United States, parking of a value up to US$ 155 per month is not considered "remuneration" and is therefore untaxed. While the Clinton administration considered, but rejected, a proposal to change this tax exemption, it did agree to extend a similar tax exemption to public transport benefits paid by the employer, although the taxing threshold is significantly lower.

Congestion pricing is also a feasible means of smoothing traffic flow changes, as noted in chapter IV of this study. Congestion pricing involves charging each motorist the marginal cost of the amount of delay he or she imposes on other motorists during congested conditions. Numerous applied and theoretical schemes exist to implement these charges (see World Bank 2001 and Button 1982 for more details).

Influencing vehicle fleet demand and turnover

Public policy can influence fleet demand with regard to the kinds of vehicles preferred, the speed with which they are turned over, and the rate at which private motor vehicles penetrate the population. Policies that are most often discussed include changing the structure of vehicle acquisition and registration fees to favour more environmentally benign vehicles, changing the way fleet vehicles are procured and maintained for public and large private fleets and, for better or worse, pricing or quotas to restrain car ownership.

Tax incentives, "feebates" and other adjustments to vehicle registration costs

Most countries maintain fees to register vehicles, and these fees are often based on characteristics of the vehicle such as engine size and displacement or gross vehicle weight. The inclusion of emissions or energy-efficiency criteria in these registration fees has been proposed and studied extensively in a number of developed countries. These may be simple tax incentives, as proposed recently in the United States for purchasers of hybrid electric and other energy-efficient technology, or complex changes to the structure of acquisition taxes and registration fees to provide a strong incentive to purchase cleaner or more efficient vehicles. The "feebate" has been studied extensively for the United States, and proposed for a number of countries in the OECD, including Japan, and applied in a select number of cases. Feebates adjust registration fees from an average baseline, so that they impose a "fee" on high-emitting or energy-intensive vehicles, and provide a "rebate" to purchasers of low-emitting or energy efficient vehicles. Feebates may be particularly conducive to strategies favouring alternative fuels. Table A.16, from the OECD (1997), shows a number of different feebate schemes for various countries in the OECD.

A feebate scheme has also been proposed for Japan. Under this scheme, a "neutral" point is established for each class of car, as categorized according to engine displacement. Actual fees paid then would be a function of the fuel economy in relation to the "neutral" point, so that average fees collected for the car class would remain unchanged. This feebate structure is shown schematically in table A.17.

Variants of feebates have been applied in the Netherlands, Germany, the United Kingdom, Austria, and some Scandinavian countries. In Germany, feebates were used as a means to implement a strategy of catalytic converter adoption, alongside subsidies to convert uncatalysed cars and changes in fuel tax to disfavour leaded gasoline. A number of countries (including France, the United States and Canada) provide special tax discounts or exemptions for purchasers of particular types of vehicles, such as those using CNG or electronic vehicles. The author is unaware of any examples of feebates in developing countries.

Full life-cycle costing for fleet vehicles

Fleet vehicles, such as those owned by large companies (for own-account transportation), trucking concerns, governments, and public transport operators, are traditionally procured with an outlay from a capital budget, following price competition on an initial capital asset, which depreciates over a useful life (usually 12 to 15 years for an urban fleet vehicle). Funds for maintenance of the vehicle, which may be handled in-house or procured separately, are accounted for and allocated from a separate operating or maintenance budget. In extreme cases, the staff who procure vehicles may have no contact with those who maintain them.

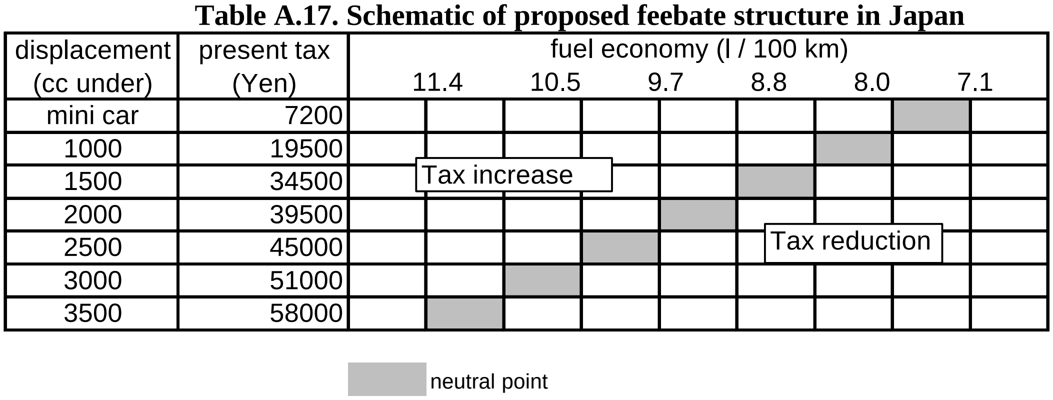
Table A.16. Feebate options evaluated in Europe and North America

Measure Definition	Definition in US$ per L/100 km	Location	Vehicle Group
Linear, $50 000 per gallon/mile(gpm)	Linear, $210 per L/100 km	United States	Cars and Light Trucks (separate zero-points)
Linear, $100 000 per gpm	Linear, $420 per L/100 km	United States	Cars and Light Trucks (separate zero-points)
Linear, $50 000 per gpm, one zero point	Linear, $210 per L/100 km	United States	Cars and Light Trucks (one zero-point)
Linear, $70 per mpg	Non-linear with respect to energy intensity, $210 per L/100 km at average fuel economy	United States	Cars and Light Trucks (separate zero-points)
Non-linear, average $100 000 per gpm, highest at midrange	Average $420 per L/100 km	United States	Cars and Light Trucks (separate zero-points)
Size-based, $3.75 million per gpm per ft 3 of interior volume for cars. Linear, $50 000 per gpm for trucks.	Cars: $450 per L/100 km per cubic meter of interior volume. Trucks: Linear, $210 per L/100 km	United States	Cars and Light Trucks (separate scale)
Revenue neutral tax 68 Ecu/(g/km CO2)	$2000 per L/100 km	Denmark, France, Germany, Italy, Spain, United Kingdom	Cars
Net tax 52 Ecu/(g/km CO2) with zero-point 20g/CO2 better than current average	$1500 per L/100 km; 1040 Ecu net tax.	Denmark, France, Germany, Italy, Spain, United Kingdom	Cars
300-500 Ecu per litre per 100 km (rate is chosen to achieve a fuel economy target equivalent to CO2 emissions of 179g/km and depends on fuel)	$375-625 per L/100 km	European Union	Cars

Source: Organisation for Economic Cooperation and Development, *CO_2 Emissions from Road Vehicles*, by L. Michaelis, annex I, Expert Group Meeting on the United Nations Framework Convention on Climate Change, Working Paper No. 1 (OECD/GD[97]69) (Paris, OECD, 1997).

Note: Ecu = European currency unit, precursor of the euro which was introduced in 1999.

Table A.17. Schematic of proposed feebate structure in Japan



Source: K. Minato, *Automotive Technology and Regulations on Fuel Economy and Exhaust Emissions* (Japan Automobile Research Institute, 2000).

This dichotomy between acquisition and maintenance can have perverse effects on both maintenance schedules and/or replacement strategies. Neither vehicle procurers nor maintenance managers have any incentive to find the optimal combination of repairs and replacement that minimizes costs while meeting a standard of operational and environmental performance. Each pursues his or her mandate in isolation.

Changing the way fleet vehicles are procured, therefore, can be an important practical measure both to ensure adequate fleet turnover as well as in-fleet maintenance. Own-maintain leasing arrangements, for example, combine ownership and maintenance functions in one entity, and separate it from the operator. Under these arrangements, a fleet operator, like a public transport agency, leases a set of vehicles from a supplier for a set period of time (for example, 10 years). The supplier undertakes a performance contract under the lease to guarantee that the vehicle remains functional to an agreed level of performance. In other words, the operator leases a vehicle service from the supplier, who has a built-in incentive to find the right combination of vehicle maintenance and replacement so as to minimize costs while contractually meeting his service obligations. In effect, this structure forces the operator to take into account the stream of maintenance payments expected over the life of the vehicle, as well as the amortized purchase price, providing a more realistic assessment of its expected costs. Since environmental performance, such as emissions, can be included, this structure of procurement might facilitate better maintenance of the in-use fleet.

Restraining vehicle ownership through pricing/quotas

Trying to limit vehicle ownership through either taxation or mandates is a potential minefield of unintended consequences due to poor conception, poor implementation, or both. If poorly conceived and implemented, such a policy might discourage vehicle turnover, encourage excess vehicle use, or foster development of a black market. Nevertheless, in some instances, notably in Singapore, wise and well-targeted measures have proved effective. Since 1990, Singapore has auctioned "entitlements" to own a car, which are valid for 10 years. The price for any given round of entitlement auctioning, which is rationed according to the amount of road space constructed on the island, is set at the lowest of the accepted bids.[16] Motorization rates in Singapore remain very low—about 125 cars per 1,000 persons—despite a per capita GDP of over US$ 26,000.[17]

Setting and enforcing standards for vehicle emissions and fuel economy

Existing standards

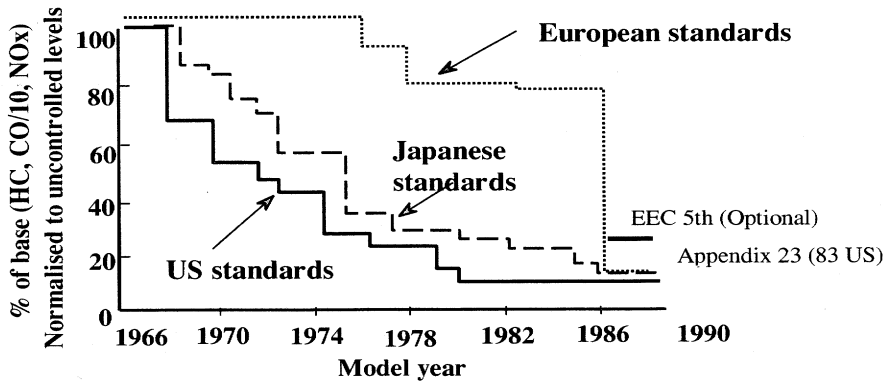
Because of the rich and varied experience in developing and implementing standards in the United States, Europe and Japan, developing countries need not develop completely new vehicle emissions standards; most developing countries with standards choose to adapt them from either the United States or Europe (or, in many cases, both). Standards are generally established for different types or classes of vehicles (for example, cars, light-duty trucks, medium-duty trucks, and heavy-duty trucks), with limits specified in grams of a pollutant emitted per unit vehicle distance travelled, or per unit of engine power output in the case of medium- and heavy-duty trucks. For cars and light-duty vehicles, diesel and gasoline emissions standards are usually

[16] Bids are accepted, according to amount, until all available entitlements have been allocated.

[17] See Statistics Singapore (http://www.singstat.gov.sg/FACT/SIF/sif.html).

specified separately. European regulation through the 1980s also distinguished between engine sizes, in an effort to support ongoing energy efficiency incentives. Comparative European, United States and Japanese standards are shown in figure A.XVIII.

Figure A.XVIII. Car emission standards in Japan, the European Union and the United States, 1990-2000



Source: Cited in M. Nevin and M. Barrett, *Global Vehicle Emissions: Commercial Opportunities from Emissions Regulations* (London, Financial Times Automotive, 1999).

Factors in selecting standards

A number of factors need to be considered in choosing a set of standards. First, and most important, is the question of whether the standards are intended to lead (or force) technological change (technology-forcing), or whether they simply are intended to ensure that the best available technology is used (technology-following) (Faiz and others 1996). Historically, European standards, initially through the Economic Commision for Europe and then the European Union directives, have been technology-following, while standards set in California, and to some degree the United States as a whole, have been technology-forcing. Whether forcing or following, technical standards should be developed and phased-in so as to allow the most cost-effective solutions to be implemented first (Eskeland and Derevejan 1996). Secondly, product cycle and development time have a crucial impact on the responsiveness of car suppliers; all else equal, the more lead time, the more willingly they would accept any given set of standards. Even for countries with little domestic production of vehicles, manufacturers and importers may still require significant lead-time to make adjustments to their regional or international distribution strategies.

Thirdly, an effective testing and certification programme needs to be in place in order to give teeth to the enforcement of standards. Testing and certification procedures in the United States and European Union are complicated, and constantly undergoing refinement. In both regions, prototype vehicles provided by manufacturers wishing to sell cars within the jurisdiction are tested in a standardized setting (such as the Federal Test Procedure). The results are then assigned to the entire class of vehicle, and these emissions "ratings" are then used to determine compliance to the implementation standards as reviewed below. The European Union requires only that new vehicles undergo certification testing; by contrast, the United States mandates ongoing in-use surveillance of vehicles through random sampling and threat of vehicle recalls. Recently, the EPA proposed a substantial modification of the system of compliance, by relaxing certification test requirements for new vehicles in return for more after-market surveillance of vehicle emissions, and greater company liability for these results (through the proposed Compliance Assurance Program (CAP 2000).

Fourthly, vehicle emissions standards must recognize the actual and potential availability of fuel of sufficient quality to enable those standards to be met. In practice, this means that vehicle standards must be set in concert with realistic fuel standards and specifications. For example, NMHC and CO levels might be set so as to force the adoption of catalytic converters; without the availability of lead-free fuel, however, such standards may be unattainable. Some vehicle emissions standards may also be able to be met in large part by changing fuel composition (for example, oxygenation of fuels to reduce hydrocarbon emissions). Creative emissions permitting and trading solutions might permit the vehicle manufacturers, in concert with fuel refiners via a market mechanism, to select the least expensive means of meeting these standards.

Fifthly, an important lesson learned from industrialized country experience is that how vehicles are classified or "binned" can be as important as the standards set for each bin themselves. In the United States, Japan, and Western Europe, regulation of light-duty vehicles has tended to either be more lax or several years behind that of cars. In Japan, car-buying behaviour shifted away from the standard, small-family vehicle, to medium- and light-duty vehicles (supplemented with a "mini" car for the household's second driver) throughout the 1990s. While these shifts in part reflect changes in consumer tastes and technological improvements that make medium- and light-duty vehicles in Japan more practicable (and affordable), the differences in applicable emissions standards have affected the relative costs of the vehicles, depressing the income threshold at which consumers would have jumped categories in the absence of these differential standards. In the United States, too, sales of sports utility vehicles (SUVs), regulated as light trucks rather than as cars, were particularly strong throughout the 1990s, so that light trucks as a class, which constituted about 20 per cent of new vehicle sales in the 1970s, currently account for nearly 50 per cent of new car sales.[18] As in Japan, it is likely that the differently applied regulations change the relative costs of the two classes of vehicles for consumers looking for certain attributes, such as power, performance, or size. It is also likely that the threshold criteria for shifts to SUVs have been shifted as a result of changes in costs. Thus, the binning of vehicles into different categories and the phasing-in of standards for them need to be harmonized in order to avoid inappropriate market signals.

Sixthly, because industry is likely to argue that standards will impose enormous compliance costs (costs borne ultimately by the consumer), standards should be adopted only with rigorous and thorough economic evaluation of different scenarios of standard-setting, and in comparison with other possible measures (Lovei and Kojima 2000). Industry acceptance will be much more likely, however, if the standards proposed help companies to build regional strategies. Thus, to the extent that standards can be harmonized regionally, so that individual countries' standards are not incompatible with others, the more industry will support them.

Implementation of standards

The implementation of standards can be complex, because any number of combinations of compliance criteria can be adopted. In addition, if there are multiple jurisdictions (for example, a metropolitan area with substantially worse ambient air problems than the rest of the country), different compliance standards might be made applicable to different areas. In general, standards can be implemented through command-and-control measures, market-based incentives

[18] The United States has moved recently to tighten emissions regulations for sport utility vehicles, but these vehicles remain exempt from fuel economy standards under CAFE (corporate average fuel efficiency).

(MBIs), or some mixture of the two. Command-and-control measures impose fines on firms or manufacturers not in compliance with a given standard. They are administratively straight-forward, but can impose significant costs on smaller firms with less ability to transfer resources internally. For this reason, some jurisdictions actually exempt small manufacturers from compliance with regulations for a period of time. Alternatively, standards may be enforced through MBIs, usually understood as a system of tradable permits under a cap-and-trade regime. Under these schemes, firms that exceed the standards or performance criteria can sell credits to firms that do not, producing a net (industry-wide) effect at the level of the original performance criteria. While much has been written on MBIs, worldwide, nearly all standards are enforced via traditional regulatory means.

Whether command-and-control or MBI, emissions standards are implemented on sales standards based on fleet minima, averages, or both. Minima require a certain proportion of the fleet sold by any single commercial entity to match a given standard or set of standards. Examples include implementation of the tier I standards in the United States, or the Euro II standards in Europe. Differentiated standards across fleets according to certification bins, increasingly becoming the norm in the United States, were originally intended to be implemented in California according to fleet minimum requirements as well (the so-called "LEV [low emission vehicle] mandates" of the early 1990s).

Fleet averaging schemes are more complex, but more flexible, in that manufacturers need to ensure only that the *average* performance of new vehicles sold in a country or other geographic unit meets a given standard. The manufacturer, therefore, has some room to manoeuvre in determining how to meet such standards. CAFE standards in the United States, and the European Union's voluntary agreement with ACEA, JAMA (Japanese Automobile Manufacturers Association), and KAMA (Korean Automobile Manufacturers Association) have been set in this manner. Implementation of the new low-emission vehicle standards (LEV and NLEV) in the United States, however, involves a hybrid of fleet minima and averaging criteria.[19]

For developing countries, several adaptations to sales-based criteria might make sense. First, an MBI approach might help eliminate some of the regulatory complexity associated with sales-based criteria, and thus make them easier to implement by resource-constrained regulatory agencies. Secondly, because of the market importance of second-hand cars, even among those that are entering the developing country market for the first time, sales-based criteria that focus only on newly manufactured cars may be too limiting. Fleet minima or averaging standards may need to be applied to vehicle importers, rather than to manufacturers *per se*. Effective certification and compliance as well as inspection and maintenance would, of course, be necessary for enforcement.

Other import-based measures might also be considered as alternative, if less comprehensive, means of implementing standards or otherwise influencing vehicle supply. These might include an outright ban on importation of vehicles not meeting standards (or those of an excessive age) or using tariff incentives and disincentives to affect the price according to emission characteristics. An important factor in the cost-effectiveness of any such programme is the screening method used. One approach—similar to the sales-based approach reviewed above—is to screen only representative vehicles of particular models and model years, and to set

[19] At certification, vehicles are assigned to an emissions bin (transitional-, low-, ultra-low-, and zero-emissions vehicle). Fleet averages must conform to the appropriate non-methane organic gases (NMOG) standard (Federal or California, depending on the programme), but manufacturers are free to choose the blend of different bin classes they try to sell in order to conform to the fleet average standard.

proportional or averaging standards based on those results. A second approach would be to use manufacturers' estimates of the deterioration rates of emissions. Both of these rely on I and M programmes and market forces to ensure that every vehicle is in compliance. A third approach would be to reduce the burden of certification testing for the importer, but to require him or her to demonstrate, through follow-up tests of on-road vehicles, compliance with import standards. Poland adopted a variant of this approach in 1995 in response to a large influx of used vehicles from Western Europe. Used vehicles were not subject to type approval, but were required to undergo a pre-registration inspection as part of a broader I and M programme. Vehicles could be registered only if they met particular standards for idle CO, NMHC, and air-fuel equivalence ratio (ë) for gasoline-fuelled cars, and smoke level for diesel. While not explicitly an import-based measure, the policy amounted to a de facto control of used vehicles (OECD/UNEP 1999).

The stringency of any import restrictions needs to be weighed against the quality of the vehicle fleet already in a country. All else equal, encouraging turnover of the vehicle fleet is desirable, and stringent restrictions on imports may discourage vehicle retirement. Eight-year-old vehicles may not be ideal, but if restricting their importation effectively means keeping more 15-year-old vehicles on the road longer, the restriction may not make sense. Import-based measures, therefore, need to be constructed carefully with regard to the actual emissions characteristics of the on-road fleet. This, in turn, implies the need for information about existing fleet characteristics.

Improving maintenance of in-use vehicles

The core of any policy to ensure adequate maintenance and upkeep of the existing vehicle stock is the inspection and maintenance programme. Because it is so integral to any air quality policy in the transport sector, it is reviewed separately in annex V to this study. The present section focuses on additional policies that governments may adopt to help ensure adequate maintenance of in-use fleets. These include mobile enforcement, and training for drivers and fleet managers. In addition, full life-cycle costing during vehicle procurement, as noted above, can also be effective in ensuring better maintenance practices for larger fleets.

Mobile enforcement

Mobile enforcement of tailpipe emissions can be implemented either as an interim strategy in setting up an I and M programme, or as a supplemental enforcement mechanism to an established I and M programme. Both applications involve some form of roadside testing, in which vehicle exhaust is rapidly analysed for carbon monoxide, hydrocarbons, and opacity (black smoke)—an indicator of particulate matter present in exhaust. How vehicles are identified for such tests can vary. In some instances, such as mobile enforcement programmes in Brazil, trained police in specially equipped vehicles can pull over vehicles that appear (visually) to have excessive emissions (such as black smoke from the tailpipe), and then test those emissions. Roadside testing stations have also been established, and either visually offensive vehicles or a random sample are pulled over and tested. In many instances, results from these tests may not have the force of law, because the test cycle is not standardized. However, they can provide an indication that the vehicle is not up to code, and can be used as a means for determining which vehicles need to undergo a more thorough I and M test.

Remote sensing of tailpipe emissions, in particular CO and HCs, is another, less intrusive, means of mobile enforcement. The technology is still being developed and improved, and has not been implemented in widespread application as yet. The technology uses infrared light to analyse the exhaust gases of a vehicle as it passes the checkpoint. Its licence plate is photographed, so the owners can be contacted in the event of failure. These owners would then need to have their vehicles properly tested at an I and M testing station. Because remote sensing technology cannot determine whether a vehicle engine is under heavy load at any particular instance, it is susceptible to a high "false positive" rate, potentially undermining the credibility of the mobile enforcement system. Technical development and refinement of remote sensing systems, however, may be undermined by the proliferation of on-board diagnostics, which has been mandatory for new vehicles in the United States since 1996.

Training and education for drivers and managers

Training programmes for drivers and fleet managers can help to improve on-road energy efficiency of trucks and buses, improve maintenance practices, and cut costs for operators. Programmes to help drivers to learn about aerodynamic loading, proper maintenance of tyre pressure, protecting their vehicles from adulterated or lower grade fuels, and better driving patterns can substantially improve vehicle performance and cut down on risk of accidents. For many developing countries, driver and fleet manager training might be the most cost-effective and rapid means of effecting fuel efficiency improvements and reducing emissions from the heavy-vehicle sector.

Brazil has undertaken two such programmes, under the auspices of the National Programme for Rationalization of the Use of Petroleum (CONPET), which are oriented specifically towards efficiency improvements. The Siga Bem programme, targeted at individual driver/owners, involves training programmes and voluntary vehicle testing at about 100 filling stations of Petrobras, the Brazilian national petroleum company. Drivers can receive training on vehicle aerodynamics, economic driving behaviour, avoiding fuel contamination, daily and periodic maintenance, and keeping track of fuel consumption. A second programme, ECONOMIZAR, offers similar training to fleet managers, such as bus dispatchers, through the National Transportation Confederation. While quantitative assessments of these programmes have not been carried out, demand for expansion of these programmes has been strong, suggesting that they create significant economic benefit to recipients in the form of fuel and other operating cost reductions (Touma 2000)..

Influencing urban development

This section reviews three particular policy strategies for influencing the supply side of urban development: the location of infrastructure; traditional land-use planning and regulation; and cost-recovery in infrastructure provision.

Location and amount of infrastructure provision

One of the most straightforward ways that public policy can influence the built-environment is through the choice of public infrastructure provision: what infrastructure will be provided where. Even in institutional environments where the enforcement of regulations—traffic as well as land use—is highly uncertain, provision of infrastructure, in terms of roadways, electricity, sewerage and water services, is a highly influential sculptor of built form, because it influences underlying land values. In a classic urban system, land consumers trade off accessibility (for example, to the city centre) with costs of rent (Alonso 1964), and other features, such as space or amenities. Since transport infrastructure can significantly influence accessibility, it is an important determinant of land values and, consequently, the kinds of land uses and building forms that are viable in different locations. This influence is particularly important in new or fast growing parts of metropolitan regions.

In many cities in developing countries and transition economies, transport infrastructure is proposed, and occasionally provided, in response to perceived transport needs (for example, a given part of a city is perceived to be too congested, or a particular facility is too isolated). Assessments of the proposed infrastructure solution too often narrowly consider the goals of a given project without adequate consideration of the kinds of land-value and land-use changes such infrastructure would bring about. In other words, in carrying out transport planning in order to respond to particular perceived needs, policy makers and authorities often fail to understand the powerful influence that transport infrastructure has on the built environment—that which is not yet even planned—for decades.

Some examples of infrastructure planning as an instrument of urban and land-use planning do exist, however. In Singapore, policy makers have limited the amount of investment in transport infrastructure as part of a deliberate public policy, seeking a target of about 12 per cent of the land area to be devoted to road transport (Willoughby 2000b). In Curitiba, Brazil, planners used the development of bus corridors as a focus for commercial land uses, while using the overall structure to strengthen the position of the city centre.

In many countries, decisions about different types of urban infrastructure investment are made by different levels of government. While infrastructure decisions may be made at the local as well as national levels of government, higher levels of government can provide a policy framework for coherent infrastructure investment. The "smart growth" movement in the United States is based upon the development of supportive policy frameworks at higher levels of government. The State of Maryland's smart growth policy requires counties and cities to designate growth and non-growth areas according to strict criteria. Subsequently, State agencies are prohibited from helping to finance infrastructure investments, or themselves from making infrastructure investments, in areas not previously designated. Localities are not prevented from making their own investments wherever they wish—if they were, the sense of encroachment on local prerogative might have led to a political struggle. The State, however, provides a strong incentive for localities to respect their own designated areas of growth, through the power of the purse.

Land-use planning and regulation

Traditional land-use regulation is another useful tool to influence the built environment in a manner that might favour more sustainable forms of transportation. This includes a range of instruments, including "structure" or general plans, local plans, and zoning codes. The effectiveness of these land-use regulatory instruments in developing countries, however, has been mixed. In many instances, enforcement mechanisms are weak; in others, regulations have been too ambitious for income levels of target populations to be able to afford (Dowall 1995). Both lead to widespread disregard of formal codes. In addition, if regulatory codes are too stringent relative to the actual use-value of property in the absence of regulations (affected largely by transportation and other public investments), local policy makers will be under significant, long-term pressure to change them, pressure to which they may eventually yield. In most political environments, therefore, land-use regulation cannot compensate for poor infrastructure investment decisions over the long run.

Cost recovery in infrastructure provision

Infrastructure adds value to surrounding property; decisions about where to locate infrastructure facilities thus have a significant impact on the distribution of land values in a sub-region of a metropolitan area. Public investment in transport and other infrastructure can amount to a transfer of resources from public to private hands if no mechanism is in place to recoup, at least somewhat, the cost of the investment. These transfers can be distortionary, in that they encourage land development in locations and build-out patterns that contribute to excessive vehicle use.

Recovering these costs, therefore, can help reduce such distortions. Two such recovery mechanisms are development fees and in-kind requirements. Development fees are fees charged to developers for the relative burden the proposed development is anticipated to place on existing or planned infrastructure. In-kind requirements are conditions placed on the issuance of a building permit, requiring the developer himself to make infrastructure investments in relation to a given development. These in-kind investments usually refer to secondary, or, in some cases, primary infrastructure. Tertiary, or on-site, infrastructure is usually considered to be the responsibility of the developer anyway.

Development fees and in-kind requirements are highly imperfect mechanisms. They may not sufficiently internalize the cumulative (collective) burdens on infrastructure caused by development. For example, the effects on traffic in a particular analysis zone caused by a single development may be easily quantifiable, and an appropriate impact fee or in-kind requirement assessed. However, the cumulative effects of many developments may be significantly greater than the sum of the individual effects, and these cumulative effects would remain unpriced. Some distortions may remain, therefore, even with infrastructure cost-recovery mechanisms in place, which could contribute to excessive vehicle use.

The risk of uninternalized cumulative effects distorting the transport/land-use system is heightened if the use of development fees and in-kind requirements is substituted for sound planning and infrastructure development decisions, rather than used as a mechanism to help finance these. In some jurisdictions making extensive use of these mechanisms, fees and in-kind requirements are understood as "mitigation" measures: developers may proactively use offers of in-kind services or payment of impact fees as mechanisms to ensure the approval of individual projects, even though such projects may not make sense in the larger framework of a longer-term structural plan. (See Gorham 1998 for more detail on land-use control mechanisms.)

Function of and transparency in land markets

Tightly interwoven with the ability of transport infrastructure to influence the built environment and the ability of government to assess appropriate cost-recovery mechanisms is the question of transparency in land-market transactions (Dowall 1995). These aspects of the land market have been identified as serious problems in the context of facilitating housing and property markets (World Bank 1995), but it should be recognized that poor functioning of land markets often has potentially very damaging, long-lasting effects on the provision of transport infrastructure and on air quality. Around the world, local corruption frequently centres around land transactions, the value of which is strongly influenced by the provision of transport infrastructure. Landowners and speculators have strong financial interest in influencing the location of different types of transport facilities; similarly, officials charged with making transport decisions can be strongly tempted to make unethical investments in affected land markets. This corruption is facilitated by lack of transparency in the land markets.

Transparency in land markets is ensured by a number of institutions, both public and private, which help ensure the smooth functioning of transactions. The functions served by public institutions include cadastral services (surveying and official designation of property boundaries), land titling and deed recording/registration, and impartial adjudication of disputes.

Functions served by the private sector include title insurance, appraisal, and market brokerage, facilitation, and clearing services.

Full-cost accounting of infrastructure supply and maintenance

An emerging technique for the assessment of land-development patterns is full-cost accounting of infrastructure supply and maintenance, particularly for hypothetical alternative patterns or location of development. The origins of this technique are contained in a famous study carried out in the United States in the 1970s. "The Costs of Sprawl" by Anthony Downs (RERC 1974) described techniques to apply a full-cost accounting framework. The United States Federal Highway Administration, in conjunction with an update of the costs-of-sprawl study, has begun to investigate these techniques (FHWA 1998). The framework uses unit costs associated with particular patterns of development, mixes of building types by residential and non-residential sectors, projections of land consumption, projected water and sewer consumption, and projected transport costs, projected out over 25 years, to compare the net present value of different forms of land development patterns. The framework was developed for the United States, but could easily be adopted for application in rapidly growing metropolitan regions in developing countries. A refinement of the framework would be to account for additional infrastructure needed because of air quality degradation (for example, additional hospital beds needed to meet projected demand).

Influencing location choices

Location-efficient mortgages

In many housing finance systems, banks and other mortgage lenders are constrained by rules established by institutions governing the secondary mortgage market. In the United States and elsewhere, these rules have traditionally been applied equally and universally, without regard to urban context. Thus, the underwriting criteria for a mortgage in a central city are the same as those for one in a suburban location, even though the distribution of household expenditures may be quite different. Specifically, households in locations where automobility is a necessity may have additional transportation expenditures greater than those in dense, mixed-use neighbourhoods with proximity to public transport. The Institute for Location Efficiency argues that household expenditures on transport, however, are lower in "location-efficient" suburbs than in traditional suburban locations. This savings is available to pay down the mortgage, but conventional rules do not recognize it. Consequently, a two-year experiment is under way in selected cities in the United States (Chicago, Seattle and San Francisco) to offer a special location efficient mortgage (LEM) for purchasers of houses in the city centres close to public transport, sponsored by the largest purchaser of mortgages on the secondary market.

For developing countries, the LEM is an intriguing concept in instances where the mortgage finance system is relatively well developed, household expenditures can be quantified and localized with reasonable accuracy, and decentralization is a problem affecting predominantly the formal sector. It is too early, however, to gauge how effective it will be in the context of the United States; it is possible that if it generates too much demand for public transport accessible locations, increasing housing prices may wipe out any gain created by the programme.

Reverse zoning

Conventional (supply-side) zoning as a land-use control is parcel-specific: it regulates the kinds of uses that can locate on any particular parcel. Demand-side zoning would reverse this relationship, regulating the kinds of parcels that can host different types of uses. In other words, the regulation is tied to the activity, not (or not exclusively) the land. A form of this type of regulation has been applied, with limited success, in the Netherlands. Under a policy known as ABC, businesses and development parcels are assigned into one of three categories (A, B or C), depending, in the former case, on the type of business and aspects of its operation and, in the latter, the location of the parcel relative to regional transportation infrastructure. Activities that do not require substantial car- or truck-based access as part of their core business ("A" activities) can only locate on parcels that are easily accessible by public transport ("A" parcels).

Extensions and elaborations of reverse zoning schemes are also envisionable. For example, a system of market-based incentives built on the reverse-zoning concept might be feasible. Companies locating in a "location-efficient" site might receive marketable emission credits. Similarly, location fees or corporate taxes could be adjusted to reflect the marginal costs imposed by a location choice for an "A" firm on the rest of society.

Location choices in provision of public services

Location-efficient mortgages and reverse zoning try to influence, respectively, where households and firms locate. The public sector, however, also makes decisions about where to provide services and locate facilities, from the national or federal down to the very local levels. An important measure, therefore, is self-monitoring of location choices by public entities.

In Curitiba, Brazil, the authorities have developed an innovative method for focusing public sector location choices in a manner that supports public transport use and the overall need for travel reduction. The "Citizen Street" is an enclosed structure, generally designed along a central axis, like a mall, except with a civic, rather than commercial focus. Federal, State, and city agencies that regularly need to interact with citizens are located there, providing a one-stop destination for conducting official business, including getting permits, applying for housing, registering for public schools, making tax payments, applying for a driver's licence, making inquiries with public utilities, visiting the municipal library or post office, and even filing a claim in small claims court. They also contain some (small-scale) commercial facilities, community meeting rooms (for example, for civic associations) and neighbourhood recreation centres.

Because Citizen Streets are decentralized (seven of them are planned around Curitiba) and are integrated into Curitiba's well-known bus system, they effectively allow government services to be decentralized from the city centre, yet be recentralized in outlying areas in order to minimize the need to travel and allow public transport to be used.

REFERENCES

ACEA (European Automobile Manufacturers Association), Alliance of Automobile Manufacturers, Engine Manufacturers Association (EMA), and Japan Automobile Manufacturers Association (JAMA). 2000. *World-Wide Fuel Charter.* Brussels, European Automobile Manufacturers Association.

Alonso, W. 1964. *Location and Land Use: Toward a General Theory of Land Rent.* Cambridge (Massachusetts), Harvard University Press.

Argonne National Laboratory. 1999. *Transportation Fuel-cycle Model.* ANL/ESD-39, vols. 1 and 2. Argonne (Illinois).

Ang, B.W. 1996. Urban transportation management and energy savings: the case of Singapore. In *International Journal of Vehicle Design,* vol. 17, No. 1 (1996).

Aschauer, D.A. 1989. Is public expenditure productive? In *Journal of Monetary Economics* 23: 177-200.

———. 1990. *Public Investment and Private Sector Growth: the Economic Benefits of Reducing America's "Third Deficit".* Washington, DC, Economic Policy Institute.

———. 1991. *Transportation Spending and Economic Growth: the Effects of Transit and Highway Expenditures*. Washington, DC, American Public Transit Association.

Bagley, S.T., K.J. Baumgard, L.D. Gratz, J.J. Johnson, and D.G. Leddy. 1996. Effects of fuel modification and emission control devices on heavy-duty diesel engine emissions. *Research Report 76.* Cambridge, MA: Health Effects Institute.

Baldassare, M., S. Ryan, and C. Katz. 1998. Suburban attitudes toward policies aimed at reducing solo driving. *Transportation* 25 (1) (February).

Banaszak, S., U. Chakravorty, and P. Leung. 1999. Demand for ground transportation fuel and pricing policy in Asian tigers: a comparative study of Korea and Taiwan. *Energy Journal* 20(2): 145-165.

Barro, R., and X. Sala-i-Martin. 1995. *Economic Growth*. New York: McGraw-Hill.

Beg, N. 1999. Scrappage programs. Annex to *Thailand: Motorcycle Fleet Upgrade: Reducing Local and Global Emissions in Bangkok.*

Bell, M.E., T.J. McGuire, J.B. Crihfield, D.R. Dalenberg, R.W. Eberts, T. Garcia-Mila and J.Z. Man. 1997. *Macroeconomic Analysis of the Linkages between Transportation Investments and Economic Performance*. Washington, DC: Transportation Research Board and National Research Council.

Boarnet, M.G.. 1995. *Highways and Economic Productivity: Interpreting Recent Evidence*. UCTC Working Paper, No. 291. Berkeley, University of California Transportation Center.

Bose, R.K. 1998. Automotive energy use and emissions control: a simulation model to analyse transport strategies for Indian metropolises. *Energy Policy* 26(13) (November): 1001-1016.

Button, K.J.. 1982. *Transport Economics*. London, Heinemann.

Calabrese, E.J., and E.M. Kenyon. 1991. *Air Toxics and Risk Assessment*. Toxicology and Environmental Health Series. Chelsea (Michigan), Lewis Publishers.

Cervero, R. 1994. *Transit-supportive Development in the United States: Experiences and Prospects*. Institute of Urban and Regional Development, University of California at Berkeley.

Chan, Y., and F.L. Ou. 1978. Tabulating demand elasticities for urban travel forecasting. In *Transportation Research Record 673*, TRB, pp. 40-46. Washington, DC, National Research Council.

Cohen, H.S. 1995. Review of empirical studies of induced traffic. In *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use.* Transportation Research Board Special Report 245, pp. 295-309. Washington, DC, National Research Council.

CONCAWE (European oil industry organization for environment, health and safety). 2000. *EU Commission "Call for Evidence" on Ultra-low-sulphur (ULS) Fuels: CONCAWE Response*. Brussels, CONCAWE, 31 July.

Daescu, D. 1997. *A Generalized Reaction Mechanism for Photochemical Smog.* University of Iowa: http://www.math.uiowa.edu/~ddaescu/task3.html.

Dargay, J., and D. Gately. 1997. The demand for transportation fuels: imperfect price-reversibility? *Transportation Research Part B, Methodological* 31 B(1) February.

———. 1999. Income's effect on car and vehicle ownership, worldwide: 1960-2015. *Transportation Research Part A, Policy and Practice*. 33 A(2) February.

Davis, S.C. 1994. *Transportation and Energy Data Book.* Oak Ridge (Tennessee), Oak Ridge National Laboratory.

DeCorla-Souza, P., and H. Cohen. 1999. Estimating induced travel for evaluation of metropolitan highway expansion. *Transportation* 26(3) (August).

Delucchi, M.A. 1997. The annualized social cost of motor-vehicle use in the U.S., 1990-1991: summary of theory, data, methods and results. Institute of Transportation Studies, University of California at Davis.

Delucchi, M.A., D.L. Greene, and M. Quanlu. 1994. Motor-vehicle fuel economy: the forgotten hydrocarbon control strategy? *Transportation Research Part A, Policy and Practice* 28(A) (May).

Domencich, T.A., G. Kraft, and J.P. Vallette. 1968. Estimation of urban passenger travel behavior: an economic demand model. In *Highway Research Record 238*, HRF, pp. 64-78. Washington, DC, National Research Council.

Dowall, D.E. 1995. *The Land Market Assessment, a New Tool for Urban Management.* Washington, DC, World Bank.

———. 1998. *Making Urban Land Markets Work: Issues and Policy Options.* Working Paper 702. Berkeley, Institute of Urban and Regional Development, University of California.

Dowling, R. 1995. Effects of increased highway capacity: results of household travel behavior survey. In *Transportation Research Record*, No. 1493, July.

Dunn, J.A. 1998. *Driving Forces: the Automobile, its Enemies and the Politics of Mobility.* Washington, DC, Brookings Institution Press.

Earthwatch, Global Environment Monitoring System. 1992. *Urban Air Pollution in Megacities of the World.* Published on behalf of the World Health Organization and the United Nations

ECMT (European Conference of Ministers of Transport). 1997. *CO_2 emissions from Transport*. Organisation for Economic Cooperation and Development, 1997.

———. 1998. *Efficient Transport for Europe; Policies for Internalization of External Costs.* Paris, OECD/ECMT. Environment Programme by Blackwell Reference, Oxford (United Kingdom).

———. 1999. European Conference of Ministers of Transport. *Traffic Congestion in Europe.* Report of the 110th Round Table, 12-13 March 1998. Paris, OECD.

———. 2000. *Strategic Environmental Assessment for Transport.* Paris, OECD.

Environmental Protection Agency. 1999. Determination of NO_x and HC basic emission rates, OBD (on-board diagnostics) and I and M effects for tier I and later LDVs (light-duty vehicles) and LDTs (light-duty trucks)(http://www.epa.gov/otaq/m6-iud.htm).

———. 2000. EPA Health Effects Notebook for Hazardous Air Pollutants-Draft. EPA-452/D-95-00, PB95-503579, December 1994. Leads and compounds. Fact sheet at web site of the United States Environmental Protection Agency (available at: http://www.epa.gov/ttn/atw/hlthef/lead.html).

Eskeland, G., and E. Jimenez. 1991. Choosing policy instruments for pollution control: a review. *Policy, Research, and External Affairs Working Paper 624*. Country Economic Department. Washington, DC, World Bank.

Eskeland, G. 1994. A presumptive Pigouvian tax: complementing regulation to mimic an emission fee. *World Bank Economic Review* 8(3): 373-94.

Eskeland, G., and T. Feyzioglu. 1995. Rationing can backfire: the “day without a car” in Mexico City. *Policy Research Working Paper 1554*. Washington, DC, World Bank.

Eskeland, G., and S. Devarajan. 1996. Taxing bads by taxing goods: pollution control with presumptive charges. *Directions in Development.* Washington, DC, World Bank.

Eskeland, G., and J. Xie. 1998. *Acting Globally While Thinking Locally: Is the Global Environment Protected by Transport Emission Control Programs?* Development Research Group, Public Economics and Environment Department, Global Environment Unit. Washington, DC, World Bank.

Espey, M. 1997. Pollution control and energy conservation: complements or antagonists? A study of gasoline taxes and automobile fuel economy standards. *Energy Journal* 18(2). 23-38.

European Bank for Reconstruction and Development. *Transport Operations Policy.* London, n.d. (http://www.ebrd.org/english/opera/sector/top_fin.pdf).

European Environment Agency. 1999. *Are We Moving in the Right Direction? Term 2000*. Copenhagen, http://reports.eea.eu.int/ENVISSUENo12/en/page 025.html.

Ewing, R., M.B. DeAnna, and S.C. Li. 1996. Land use impacts on trip generation rates. In *Transportation Research Record,* No. 15 (July).

Faiz and others. 1990. *Automotive Air Pollution: Issues and Options for Developing Countries*. Policy, Research, and External Affairs Working Paper 492. Infrastructure and Urban Development Department. Washington, DC, World Bank.

Faiz, A., C.S. Weaver, and M.P. Walsh, with contributions by S. Gautam and L.M. Chan. 1996. *Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions.* Washington, DC, World Bank.

Federal Highway Administration (FHWA). 1998. *Social Costs of Alternative Land Development Scenarios (SCALDS).* Transportation and land-use planning tool, available at http://www.fhwa.dot.gov/scalds/scalds.html.

Flora, J. 1998. Keynote address at the Conference on Transportation in Developing Countries, Berkeley, California, 17-18 April.

Fulton, L.M., D.J. Meszler, R.B. Noland, and J.V. Thomas. 2000. A statistical analysis of induced travel effects in the US mid-Atlantic region. *Journal of Transportation and Statistics,* 3(1): 1-14.

Fundación de Investigaciones Económicas Latinoamericanas. 1995. *Financiamiento del Sector Transporte de la Región Metropolitana de Buenos Aires.* Buenos Aires, FIEL.

Glazer, A., D. Klein, and C. Lave. 1993. Clean for a day: troubles with California's smog check. *Working Paper 163*. University of California Transportation Center. Berkeley.

Goodwin, P.B. 1996. Empirical evidence on induced traffic, a review and synthesis. *Transportation*, 23: 35-54.

Gordon P., and H. Richardson. Are Compact Cities a Desirable Goal? In *Journal of the American Planning Association*. 63(1): 95-106

Gorham, R. 1998. *Land-Use Planning and Sustainable Urban Travel: Overcoming Barriers to Effective Coordination*. Paris: European Conference of Ministers of Transport.

———. Forthcoming 2002. Car dependence as a social problem. *In* Black, W.R. and P. Nijkamp (eds.), *Social Change and Sustainable Transport*. Bloomington (Indiana), Indiana University Press.

Government of India. 1997. *White Paper on Pollution in Delhi with an Action Plan.* New Delhi, Ministry of Environment and Forests.

Gramlich, E. 1994. Infrastructure investment: a review essay. In *Journal of Economic Literature*. XXXII: 1176-1196, September.

Greene, D.L. 1992. Vehicle use and fuel economy: how big is the "rebound" effect? *The Energy Journal* 13(1).

Greene, D.L., J.R. Kahn, and R.C. Gibson. 1999. Fuel economy rebound effect for U.S. household vehicles. *The Energy Journal* 20(3).

GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit). 2001. *Urban Transport Strategy Review: Experiences from Germany and Zurich*, by F. Schley. Edited by M. Breithaupt and S. Opitz. GmbH Division 44, Environmental Management, Water, Energy, Transport. Eschborn (Germany).

Hansen, M., and Y. Huang. 1997. Road supply and traffic in California urban areas. *Transportation Research* A, 31: 205-218.

Heanue, K. 1998. *Highway Capacity and Induced Travel: Issues, Evidence and Implications*. Transportation Research Circular, No. 481. Transportation Research Board, National Research Council.

Heggie. I., and P. Vickers. 1998. *Commercial Management and Financing of Roads.* Washington, DC, World Bank Technical Paper, No. WTP 409.

Hivert, L. 1996. *Le comportement des nouveaux diesélistes.* Paris (Arceuil), Institut National de Recherche sur les Transports et leur Sécurité (INRETS), Report No. N.690-9501/03.

Holtz-Eakin, D. 1988. *Private Output, Government Capital, and the Infrastructure Crisis*. Discussion Paper No. 394. New York, Columbia University.

Humphrey Institute. 2000. *Congestion Pricing Pilot Programs: Overview and Status Report.* Value pricing homepage of the State and Local Policy Program of the Hubert H. Humphrey Institute of Public Affairs (http://www.hhh.umn.edu/centers/slp/conpric/ovstat.htm).

Hunt, J.D. 2001. Induced demand in transportation demand models. Paper presented at the conference *Working Together to Address Induced Demand*. Washington, DC, Eno Transportation Foundation.

Institute for Sustainable Development. 1997. *Information Package No. 2 on Alternative Transport Policy in Poland.* Warsaw, ISD.

International Energy Agency. 1998. *World Energy Outlook.* Paris, International Energy Agency/ Organisation for Economic Cooperation and Development.

———. 1999. *Automotive Fuels for the Future: the Search for Alternatives.* Paris.

International Lead Management Center. 2000. *Lead in Gasoline Phase-out Report Card.* www.ilmc.org.

Jacobs, A. 1993. Personal communication, during land-use studio. University of California, Berkeley.

Jacobson, Mark. 2001. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. In *Nature* 409, 8 February.

Jian Xie, C.J. Brandon, and J.J. Shah. *Fighting Urban Transport Air Pollution for Local and Global Good: the Case of Two-stroke Engine Three-wheelers in Dhaka*. Washington, DC, World Bank.

Jones, C.T. 1993. Another look at U.S. passenger vehicle use and the "rebound" effect from improved fuel efficiency. *The Energy Journal* 14(4).

Kean, A.J., R.A. Harley, D. Littlejohn, and G.R. Kendall. 2000. On-road measurement of ammonia and other motor vehicle exhaust emissions. In *Environmental Science & Technology*, vol. 34, No. 17, 1 September.

Khazzoom, J.D. 1980. Economic implications of mandated efficiency in standards for appliances, *The Energy Journal* 1(4).

Krewski, D., R.T. Burnett, M.S. Goldberg, K. Hoover, J. Siemiatycki, M. Abrahamowicz, and W.H. White. 2000. *Reanalysis of the Harvard Six Cities Study and American Cancer Society Study of Particulate Air Pollution and Mortality: a Special Report of the Institute's Particle Epidemiology Reanalysis Project.* Cambridge (Massachusetts), Health Effects Institute Report.

Künzli, N., R. Kaiser, S. Medina, M. Studnicka, O. Chanel, P. Filliger, M. Herry, F. Horak Jr., V. Puybonnieux-Texier, P. Quénel, J. Schneider, R. Seethaler, J.C. Vergnaud, and H. Sommer. 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment. *The Lancet*, vol. 356, No. 9232, 2 September.

LBNL (Lawrence Berkeley National Laboratory). 1998. Database of Transportation and Energy, Berkeley, California.

Lee, D.B., Jr. 1997. Uses and meanings of full social cost estimates. *In* Greene, D.L., D.W. Jones, and M.A. Delucchi, *The Full Costs and Benefits of Transportation.* Heidelberg, Springer.

———. 2000. Methods for evaluation of transportation projects in the USA. *Transport Policy* 7(1) (January).

Lee, D.B., L.A. Klein, and G. Camus. 1999. Induced traffic and induced demand. *Transportation Research Record* 1659.

Levine, J. 1999. Access to choice. *Access: Research at the University of California Transportation Center* 14 (spring).

Litman, T. 1999. *The Costs of Automobile Dependency and the Benefits of Balanced Transportation.* Victoria, Victoria Transport Policy Institute (www.vtpi.org).

Lovei, M. 1995. Financing pollution abatement: theory and practice. *Environment Department Paper 28*. Washington, DC, World Bank.

———. 1996. Phasing out lead from gasoline: worldwide experience and policy implications. *Environment Department Paper 40*. Washington, DC.

——— (ed.). 1997. Phasing out lead from gasoline in central and Eastern Europe: health issues, feasibility and policies. *Implementing the Environmental Action Programme for Central and Eastern Europe.* Washington, DC, World Bank.

Lovei, M. and M. Kojima. 2000. *Urban Air Quality Management: the Transport-Environment-Energy Nexus.* Washington, DC, World Bank.

Lund, J.R., and P.L. Mokhtarian. 1994. Telecommuting and residential location: theory and implications for commute travel in the monocentric metropolis. *Transportation Research Record* 1463.

Lvovsky, K., G. Hughes, D. Maddison, B. Ostro, and D. Pearce. 1999. Environmental Costs of Fossil Fuels: a Rapid Assessment Method with Application to Six Cities, draft. Washington, DC, World Bank.

Lvovsky, K., and others. 2000. Environmental costs of fossil fuels: a rapid assessment method with application to six cities. *Environment Department Paper 78*. Washington, DC, World Bank.

MacKenzie, J.J., R.C. Dower, and D.D.T. Chen. 1992. *The Going Rate: What it Really Costs to Drive.* Washington, DC, World Resources Institute.

Maddison, D., D. Pearce, O. Johansson, E. Calthrop, T. Litman, and E. Verhoef. 1996. *The True Costs of Road Transport*. Blueprint No. 5. London, Earthscan for CSERGE.

Mage, D., and M.P. Walsh. 1999. Case studies from cities around the world. *Urban Traffic Pollution.* Edited by D. Schwela and O. Zali. London, World Health Organization, E & FN Spon Publishers.

Metge, H. 2000. *Relationship between Urban Land Use Planning, Land Markets, Transport Provisions and the Welfare of the Poor: the Case of Cairo, Egypt.* Background paper in World Bank series on World Bank Strategy Review. Washington, DC, World Bank (available at: http://wbln0018.worldbank.org/transport/utsr.nsf).

Michaelis, L. 1995. The abatement of air pollution from motor vehicles: the role of alternative fuels. *Journal of Transport Economics and Policy* 29(1) (January).

Miller, P., and J. Moffet. 1993. *The Price of Mobility: Uncovering the Hidden Costs of Transportation.* New York, Natural Resources Defense Council.

Minato, K. 2000. *Automotive Technology and Regulations on Fuel Economy and Exhaust Emissions.* Japan Automobile Research Institute.

Mokhtarian, P.L. 1997. The transportation impacts of telecommuting: recent empirical findings. In P.R. Stopher and M. Lee-Gosselin (eds.), *Understanding Travel Behaviour in an Era of Change.* Oxford (United Kingdom), Pergamon Press.

National Research Council, Transportation Research Board (NRC/TRB). 1995. *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use.* Transportation Research Board Special Report 245. Washington, DC, National Research Council.

Nevin, M., and M. Barrett. 1999. *Global Vehicle Emissions: Commercial Opportunities from Emissions Regulation for Vehicle Manufacturers and Component Suppliers*. London, Financial Times Automotive.

Newman, P., and J. Kenworthy. 1989. *Cities and Automobile Dependence: a Sourcebook.* Brookfield (Vermont), Gower Technical.

———. 1999. *Sustainability and Cities: Overcoming Automobile Dependence.* Washington, DC, Island Press.

Noland, R.B. 2001. Relationships between highway capacity and induced vehicle travel. *Transportation Research* A, 35(1): 47-72.

Noland, R., and W. Cowart. 2000. Analysis of metropolitan highway capacity and the growth in vehicle miles of travel. *Transportation,* vol. 27, No. 4, 363-390.

Noland, R., and L.L. Lem. 2000. Induced travel: a review of recent literature and the implications for transportation and environmental policy. In *European Transport Conference*. Cambridge (United Kingdom).

Office of Technology Assessment, Congress of the United States. 1994. *Saving Energy in U.S. Transportation*. Washington, DC.

Olson, M. 1965. *The Logic of Collective Action: Public Goods and the Theory of Groups.* Cambridge, Harvard University Press.

Onursal, B., and S.P. Gautam. 1997. Vehicular air pollution: experiences from seven Latin American urban centres. *World Bank Technical Paper 373*. Washington, DC, World Bank.

Organisation for Economic Cooperation and Development. 1997. *CO_2 Emissions from Road Vehicles.* By L. Michaelis. Annex I, Expert Group Meeting on the United Nations Framework Convention on Climate Change, Working Paper No. 1, OECD/GD(97)69, Paris.

Organisation for Economic Cooperation and Development and United Nations Environment Programme. 1999. *Older Gasoline Vehicles in Developing Countries and Economies in Transition: Their Importance and the Policy Options for Addressing Them.* United Nations publication, ISBN: 92-807-1796-9.

Peake, S. 1997. Transport, energy and climate change. *Energy and Environment Policy Analysis Series.* Paris, International Energy Agency.

Peeples, C. 2000. Personal communication.

Pendakur, V.S. 1996. A tale of two cities: Bangkok and Mexico. *In* OECD, *Towards Clean Transport.* Paris, Organisation for Economic Cooperation and Development.

Plassard, F. 1998. French experience. In *Infrastructure-induced-mobility.* Paris, European Conference of Ministers of Transport, Round Table 105.

Prototype Carbon Fund. 2000. Price signals in the emerging carbon market. Circular of the Prototype Carbon Fund. Washington, DC, World Bank.

Pucher, J. 1995. Urban passenger transport in the United States and Europe: a comparative analysis of public policies. Part 1: travel behaviour, urban development and automobile use. *Transport Reviews* 15(2) (April-June).

Puller, S.L., and L.A. Greening. 1999. Household adjustment to gasoline price change: an analysis using nine years of US survey data. *Energy Economics* 21(1) (February).

Real Estate Research Corporation (RERC). 1974. *The Costs of Sprawl.* Washington, DC, Council on Environmental Quality.

Romieu, I. 1999. Epidemiological studies of health effects arising from motor vehicle air pollution. In *Urban Traffic Pollution*, edited by D. Schwela and O. Zali. London, World Health Organization, E. & FN Spon Publishers.

Rostow, W.W. 1971. *The Stages of Economic Growth.* Cambridge: Cambridge University Press.

Rudnai and others. 1990. A survey of blood lead levels in Budapest. *Egeszsegtudomany* 34.

SACTRA (Standing Advisory Committee on Trunk Road Assessment). 1994. *Trunk Roads and the Generation of Traffic.* United Kingdom Ministry of Environment, Transport, and the Regions. London, HMSO, 1994.

Schipper, L.J., M.J. Figueroa, and R. Gorham. 1995. *People on the Move: A Comparison of Travel Patterns in OECD Countries.* Berkeley (California), Institute of Urban and Regional Development, University of California. Sponsored by the United States Department of Transportation through a grant to IURD.

Schipper, L., C. Marie-Lilliu, and R. Gorham. 2000. *Flexing the link between Transport and Greenhouse Gas Emissions: a Path for the World Bank.* Washington, DC, World Bank, June.

Schwartz, J. 1994. Societal benefits of reducing lead exposure. *Environmental Research*.

Schwela, D., and O. Zali. 1999. Motor vehicles and air pollution. In *Urban Traffic Pollution*. Edited by D. Schwela and O. Zali. London, E. & F. Spon.

Servaas, M. 2000. *The Significance of non-Motorised Transport for Developing Countries: Strategies for Policy Development.* Washington, DC, World Bank. Background report for World Bank Urban Transport Strategy Review, December.

Shah, J.J., and T. Nagpal, eds. 1997. Urban air quality management strategy in Asia, Greater Mumbai report. *World Bank Technical Paper 381*. Washington, DC, World Bank.

Shah, J.J., T. Nagpal, and C.J. Brandon, eds. 1997. *Urban air quality management strategy in Asia: Guidebook*. Washington, DC, World Bank.

Shaheen, S., D. Sperling, and C. Wagner. 1999. Car-sharing and partnership management: an international perspective. Paper No. 99-0826 in *Transportation Research Record No. 1666: Transit Bus; Rural, Intercity and Paratransit; New Technology, Capacity, and Quality of Service; Public Transit.* Washington, DC, National Academy Press.

Sharma, A., and A. Roychowdhury. 1996. Slow murder: the deadly story of vehicular pollution in India. Study directed by A. Agarwal, *State of the Environment Series* 3, Centre for Science and Environment, New Delhi.

Shoup, D., and M.J. Breinholt. 1997. Employer-paid parking: a nationwide survey of employers' parking subsidy policies. In *The Full Costs and Benefits of Transportation: Contributions to Theory, Method and Measurement.* Edited by D.L. Greene, D.W. Jones, and M.A. Delucchi. New York, Springer Press.

Sperling, D. 1995. *Future Drive: Electric Vehicles and Sustainable Transportation*. Washington, DC, Island Press.

Sub-Saharan Africa Transport Program, World Bank (SSATP). 1999. *Transport en Afrique—Note Technique.* SSATP note 19.

Swait, J.D., and G.S. Eskeland. 1995. Travel mode substitution in São Paulo: estimates and implications for air pollution control. *Policy Research Working Paper* 1437. Public Economics Division, Policy Research Department, World Bank. Washington, DC.

Swedish National Road Consulting AB (SweRoad) and Asian Engineering Consultants Corporation. 1997. Consulting Services for Developing a Road Safety Master Plan and a Road Traffic Accident Information System for the Ministry of Transportation and Communications, Kingdom of Thailand.

Theakston, F., ed. 1992. Acute effects on health of smog episodes: report on a WHO meeting, Hertogenbosch, Netherlands, 30 October-2 November 1990. *WHO Regional Publication, Europe* 39. Copenhagen, WHO Regional Office for Europe.

Tol, R. 1999. The marginal costs of greenhouse gas emissions. *The Energy Journal* 20(1).

Touma, J.E. 2000. Personal communication. 29 September.

TRB (Transportation Research Board). 1995. *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*. Special report 245. National Research Council. Washington, DC, National Academy Press.

United Nations. 1993. *Earth Summit, Agenda 21, the United Nations Programme of Action from Rio*. United Nations publication, Sales No. E.93.I.11.

US DOT (United States Department of Transportation). 1999. *Status of the Nation's Highways, Bridges and Transit: Conditions and Performance, Report to Congress.*

———. Calculated from unpublished data, n.d. Personal communication from R. Crichton of DOT.

Van Wee, B., H.C. Moll, and J. Dirks. 2000. Environmental impact of scrapping old cars. *Transportation Research* 5D(2) (March).

Walsh, M. 1993. Highway vehicle activity trends and their implications for global warming: the United States in an international context. In *Transportation and Global Climate Change*. Edited by D. Greene and D. Santini,. Washington, American Council for an Energy Efficient Economy.

Walsh, M., and J.J. Shah. 1997. Clean fuels for Asia: technical options for moving toward unleaded gasoline and low-sulfur diesel. *World Bank Technical Paper 377*. Washington, DC, World Bank.

Wang, M.Q. 2001. *Development and Use of GREET 1.6 Fuel-cycle Model for Transportation Fuels and Vehicle Technologies.* Working Paper ANL/ESD/TM-163 of the Center for Transportation Research. Argonne (Illinois), Argonne National Laboratory.

Weaver, C.S. 1999. *Implementer's Guide to Phasing Out Lead in Gasoline*. United States Environmental Protection Agency, Office of International Activities. Washington, DC.

———. 2001a. Personal communication. 26 January.

———. 2001b. Personal communication, 2 February.

Weaver, C.S., and M.J. Balam. 1999. *Air Pollutant Weightings for Mexico City.* Technical Memorandum to World Bank, 21 September.

Weaver, C.S., and L.M. Chan. 1999. *Economic Analysis of Diesel Aftertreatment System Changes Made Possible by Reduction of Diesel Fuel Sulfur Content*. Report of Environmental Protection Agency.

Wijetilleke, L., and S. Karunaratne. 1995. Air quality management: considerations for developing countries. *World Bank Technical Paper 278*. Washington, DC, World Bank.

Willoughby, D. 2000a. *Managing Motorization.* TWU Working Paper No. 42. Washington, DC, World Bank.

———. 2000b. *Singapore's Experience in Managing Motorization and its Relevance to Other Countries.* TWU Working Paper No. 43. Washington, DC, World Bank.

Winkelman, S., T. Hargrave, and C. Vanderlan. 2000. *Transportation and Domestic Greenhouse Gas Emissions Trading.* Washington, DC, Center for Clean Air Policy.

World Bank. 1994. Draft staff appraisal report for Brazil: São Paulo Integrated Urban Transport Project. Washington, DC.

———. 1995. *Reforming Urban Land Policies and Institutions in Developing Countries,* by C. Farvacque-Vitkovic and P. McAuslan. Urban Management Program Series, No. 5. Washington, DC.

———. 2000. Cairo urban transport note. Middle East Private Sector Finance and Infrastructure Department. Washington, DC.

———. 2001. Experience in urban traffic management and demand management in developing countries. Background paper for Urban Transport Strategy Review. Washington, DC.

World Energy Council. 1998. *Energy Efficiency Policies and Indicators.*

World Health Organization and United Nations Environment Programme. 1992. *Urban Air Pollution in Megacities of the World.* Oxford (United Kingdom), Blackwell.

Xie, J., J.J. Shah, and C.J. Brandon. 1998. *Fighting Urban Transport Air Pollution for Local and Global Good: The Case of Two-Stroke Engine Three-Wheelers in Delhi.* Energy Sector Management Assistance Program working paper. Washington, DC, World Bank.

Zegras, C., D. Guruswamy, E. Miller, and A. Tomazinis. 1995. *Modeling Urban Transportation Emissions and Energy Use: Lessons for the Developing World*. Washington, DC, International Institute for Energy Conservation.

Zegras, C. 1998. The costs of transportation in Santiago de Chile: analysis and policy implications. *Transport Policy 5.*

Zegras, C. and R. Gakenheimer. 1999. Car sharing organizations in Latin America: examining prospects for Santiago. Massachusetts Institute of Technology, Cooperative Mobility Program, Working Paper 99-4-1, May 1999.