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Cleaner Transportation Fuels for Air Quality Management

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Deteriorating air quality is a growing concern in urban centers in developing countries. Urban air pollution imposes significant economic and human costs. In fast-growing developing countries, economic costs of air pollution are estimated to be a significant percentage of GDP. Moreover, the costs are borne disproportionately by the poor. Vehicle emissions are a major contributor to urban air pollution. Improving the quality of transportation fuels is an important step in mitigating vehicle emissions. This paper addresses both the technical and policy issues related to the introduction of cleaner transportation fuels.

On the technical side, critical steps include the elimination of lead in gasoline and reductions in the sulfur contents and end vaporization points of diesel. Key policy issues that need to be addressed in petroleum sector reform include dealing with price distortions and sector subsidies, barriers to international trade of petroleum products, and government regulations that hinder competition.

Deteriorating urban air quality causes significant economic losses in many developing countries. In some of the more industrialized developing countries, whose cities are now cloaked in smog, the cost of local air pollution has been estimated at between 0.5% and 2.5% of GDP. In China, perhaps the most dire case, the cost has been estimated at 5% in 1995 and, assuming today's trends continue, is predicted to reach 13% of GDP in 2020[1].

Because people migrate from rural to urban areas as countries undergo economic development, the population exposed to urban air pollution is steadily increasing, raising economic costs in turn. In South Asia between 1990 and 1995, for example, the growth rate of cities with more than one million inhabitants was two to three times population growth[2]. Furthermore, experience shows that the poor bear a disproportionate share of the costs of pollution.

One of the major contributors to urban air pollution is vehicular emissions. Demand for transportation fuels grew rapidly in developing countries in the decades from 1970 onwards. In some countries growth was at double digit rates (during the 80s and 90s, it grew at 14 per cent per annum in Korea, and at over 6 per cent in both India and China). Most energy outlooks postulate that transportation fuel growth in developing countries will remain strong. Mitigating vehicular emissions will therefore play an increasingly important role in mitigating urban air pollution.

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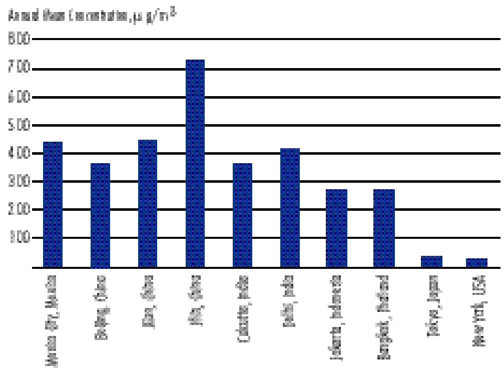
A number of options exist for reducing vehicular emissions. The options include establishing emission standards, enforcing vehicle inspection and maintenance programs, catalytic converters and other emission control devices, traffic management, and motor fuel reformulation, i.e., improving the quality of transportation fuels. Fuel quality and vehicle technology options go hand in hand, because exhaust control technology relies on cleaner fuels, and investments made to make transportation fuels cleaner generally achieve much less impact in improving air quality if vehicle maintenance is neglected. This Energy Issues paper focuses on the role of fuel quality in urban air quality management.

Figure 1. Air Pollution in Selected Cities: Total Suspended Particulates



Health Impacts

Two pollutants that merit special attention in developing countries are lead and respirable particulates.

Lead

The combustion of leaded gasoline is a significant source of lead exposure. A broad range of governments and institutions, including the World Bank, have called for worldwide elimination of lead in gasoline on account of the documented adverse effect of lead on public health, particularly the intellectual development of children. Gasoline lead removal has been consistently correlated with reductions in the level of lead in the blood of exposed populations. Exposure to lead leads to diminished IQ which results in lower productivity. Direct costs, such as for health care and remedial education for children, are also incurred. There is evidence that more lead is absorbed when dietary calcium intake is low or if there is iron deficiency. The amount of lead absorbed by the body increases significantly when the stomach is empty. The rate of absorption is also higher for children than adults. In short, poor, malnourished children are more susceptible to lead poisoning than others. The benefits to society of eliminating lead from gasoline exceed the cost (which is typically in the neighborhood of 1–2 U.S. cents per liter) by an order of magnitude.

Particulates

Particulates smaller than several microns have been shown to affect mortality and morbidity of the exposed population. In many developing countries, particulate levels are extremely high. Figure 1 compares the levels of total suspended particulates (TSP) in 10 cities. Although the percentage of fine particulates in TSP varies from city to city and hence the data in Figure 1 cannot be linked directly to fine particulate pollution, it is clear that cities in developing countries are substantially more at risk than those in rich countries.

There are many sources of particulate emissions from the combustion of fossil fuels: vehicles, domestic heating, power generation, small and large industries, and solid waste burning. Among vehicles, diesel- and two-stroke gasoline-engines (used in two- and three-wheelers)[3] are the dominant source of particulates. What makes transport pollution a serious concern is that particulates

Integrated Approach to Urban Air Quality Management

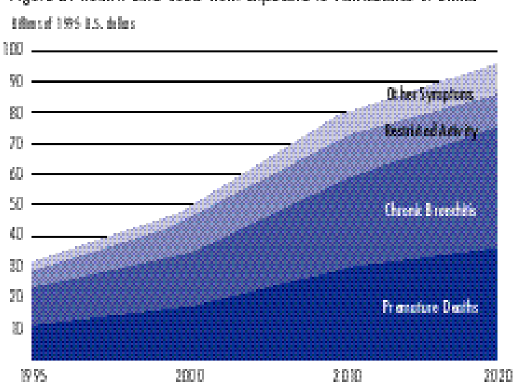
In tackling air pollution, it is important to make an accurate estimate of the inventory of emissions from all major sources, and estimate their relative impacts on air quality in order to evaluate cost-effectiveness of various mitigation options. Vehicles are not necessarily the most serious source of pollution, nor fuel reformulation the most cost-effective measure. It is important to take into account both mobile and stationary sources, and not focus on one to the exclusion of the other. In the case of carbon monoxide, vehicles almost always account for the bulk of the emissions. With respect to other pollutants, each situation needs to be assessed separately. Utility boilers may contribute significantly to the emissions of oxides of nitrogen. Lead in gasoline often accounts for the majority of airborne lead in cities, although other sources such as smelters need to be examined. In a number of large cities in developing countries with rapid growth in transportation, however, mobile sources contribute significantly to air pollution, and motor fuel reformulation, if well designed, is cost-effective.

emitted from vehicles are predominantly submicron in size, making them especially damaging to public health. The World Health Organization (WHO) estimates that total excess mortality due to particulates worldwide could amount to 460,000 premature deaths each year.[4] An illustration of the impact of exposure to particulates on public health in China is provided in Figure 2.

Other pollutants

As fossil fuel consumption grows, the levels of pollutants other than lead and particulates begin to exceed the WHO air quality guidelines. These other pollutants include sulfur dioxide (SO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), and a secondary air pollutant, ozone, which is formed by photochemical reaction of NO_x and hydrocarbons. Vehicular emissions contribute to all these pollutants. SO_2 and NO_x, aside from contributing to acid rain, undergo secondary reactions to form fine particulates. CO inhibits the capacity of blood to carry oxygen to organs and tissues, and at high levels impairs vision, manual dexterity and learning ability. Ozone is responsible for photochemical smog and has been associated with transient effects on the human respiratory system, including asthma attacks. The airborne levels of these pollutants are alarmingly high in cities such as Mexico City and Santiago.

Figure 2. Health Care Costs from Exposure to Particulates in China



Source: Clear Water, Blue Skies: China's Environment in the New Century, World Bank, 1997.

Elimination of Lead in Gasoline

Eliminating lead from gasoline requires changes in gasoline composition. Historically, lead has been added to gasoline as an octane booster to ensure smooth combustion. A crucial issue in lead elimination is selecting alternative octane sources in a way that minimizes their adverse effects on air quality. Developing countries that are now phasing lead out of gasoline have the advantage of learning from the experience of countries that have already eliminated lead. The lessons learned are summarized in Table 1. Table 2 lists a number of gasoline blending components that are used in place of lead to boost octane. The table details their physical properties that impact air quality and that should be taken into account when reformulating gasoline.

Benzene and total aromatics tend to increase as lead is phased out. Benzene is a carcinogen which is found in gasoline as well as being formed as a byproduct of combustion of aromatics. Various studies have indicated the cost-effectiveness of controlling benzene itself rather than total aromatics. Controlling gasoline volatility to minimize evaporative emissions is another cost-effective measure, because gasoline fractions that evaporate could contain photochemically reactive hydrocarbons (ozone precursors) as well as toxins such as benzene. Controlling total aromatics, which are benzene and ozone precursors, is also an important consideration, although to a lesser extent as explained in Table 1. In addition, in order to take advantage of the growing number of catalyst-equipped cars, sulfur reduction should be seriously considered. Sulfur acts as a temporary poison for the catalyst, and decreasing sulfur has a large impact on reducing exhaust emissions.

Some misconceptions about the elimination of lead in gasoline persist in developing countries. One is that only cars equipped with catalytic converters can use unleaded gasoline. All gasoline vehicles, whether or not they are equipped with catalysts, can be fueled with unleaded gasoline. A vehicle performance concern in the use of unleaded gasoline is soft engine exhaust valve-seats in old vehicles. In the absence of lead which acts as a lubricant, cars with soft valve-seats have been shown, under extreme test conditions, to suffer from valve-seat recession, leading to loss of compression and requiring major repairs to the engine. In practice, however, valve-seat recession has seldom been a problem in most countries that have eliminated lead. In Latin America and the Caribbean, where lead phase-out has progressed rapidly, none of the countries have observed any marked increase in valve-seat problems.

While cars without catalytic converters can run on both leaded and unleaded gasoline, cars equipped with catalysts must use unleaded gasoline because lead deactivates catalysts permanently. Efficiently operated catalytic converters can reduce exhaust CO and hydrocarbon emissions by as much as 95%, and NO_x by over 75%. For these pollutants, catalytic converters are by far the most effective means of reducing gasoline-vehicle exhaust emissions. The availability of unleaded gasoline throughout the country is a pre-requisite for the introduction of catalytic converters.

Most countries take a number of years for lead phase-out but countries such as El Salvador achieved it in less than a year. Such a swift transition has a number of advantages. Little investment in new distribution infrastructure is needed because a dual distribution system does not have to be set up to segregate leaded and unleaded gasoline. Minimizing the transition period when both leaded and unleaded gasoline is marketed also minimizes the chances of cross-contamination and misfueling (when catalyst equipped cars are fueled with leaded gasoline).

The relative tax treatment of leaded and unleaded gasoline is another important issue. A number of European countries have successfully adopted the policy of reducing tax on unleaded gasoline so as to make the consumer price of unleaded gasoline lower than that of leaded gasoline, thereby accelerating the transition. The incidence of misfueling is also reduced when unleaded gasoline receives preferential tax treatment.

Diesel Reformulation

Diesel combustion gives rise to high levels of small particulates and NO_x. In order to reduce particulate emissions from diesel engines, standard engine overhaul and maintenance coupled with diesel reformulation has a significant impact. Some diesel parameters that affect vehicular emissions can be controlled by the choice of crude oil or by refining operations.

- Sulfur content. Reducing sulfur lowers sulfur oxide emissions as well as particulate levels. Sulfur reduction also opens up the possibility of using exhaust control technology such as catalytic converters. While the United States and the European Union have moved to an upper limit of 0.05 mass percent sulfur in diesel, a number of developing countries still have a legally permissible sulfur level of 1 mass percent or even higher. Diesel sulfur levels can be reduced either by selecting a low sulfur crude oil (which has a premium cost) or by use of desulfurization units in the refinery (which can require significant capital investment).
- End boiling point. Many developing countries have relatively high T90 (temperature at which 90% of diesel evaporates) so as to maximize the yield of diesel, exacerbating the problem of air pollution from particulates. Heavy diesel "ends" are not completely combusted in engines and thus contribute to fine particulate emissions.
- Cetane number. Particulate and NO_x emission levels generally decrease with increasing cetane number, although some studies have found no statistically significant effect on particulate emissions.
- Diesel density. Lowering density enables the fuel-air mixture to become leaner, since diesel engines inject a constant volume of fuel into a fixed amount of air; leaner mixtures in turn lower particulate emissions.

Petroleum Sector Reform

Price Distortions

In many developing countries, the prices of petroleum products are administered by the government. Government price policies have led to price distortions, including subsidies either to the downstream petroleum sector (refineries and distributors) or to final consumers. These price distortions in turn make it more difficult to develop downstream petroleum sector projects such as a refinery modernization (to satisfy new environmental regulations) that earn an acceptable financial return. In one developing country, the subsidies provided by the government to the downstream petroleum sector in 1997 were estimated to exceed $200 million, amounting to more than 10% of the government budget.

A frequently encountered price distortion is when there exists a large differential between the price of gasoline on one hand and of diesel and kerosene on the other. The prices of diesel and kerosene are set low by fiscal means to benefit farmers, commercial transport, industrial users of diesel and domestic users of kerosene. The costs of these indirect subsidies are often recovered by loading them onto the gasoline price. The low price of diesel encourages its overconsumption, while the low price of kerosene leads to adulteration of gasoline with kerosene (resulting in much higher emission levels). In India where the price of diesel is less than half of that of gasoline, for example, the consumption of diesel exceeds that of gasoline several-fold. The effects of overconsumption of diesel are extensive, ranging from direct health impacts to depletion of underground water (owing to excessive use of diesel-powered water pumps). The effects on public health can be addressed by switching from diesel to cleaner fuels but there is no economic incentive as long as the diesel price remains artificially low. Governments have been reluctant to increase the price of diesel, because the price increase adversely impacts not only direct diesel consumers but those who indirectly benefit from lower cost of diesel.

Trade Liberalization

High tariffs are frequently imposed on petroleum products to protect inefficient domestic refineries. Cleaner fuels available internationally are not competitive in the domestic market in these countries.

In addition, import licenses may be restricted to one or two parties in the domestic oil industry. Countries such as Bangladesh, Tanzania, Romania and Zambia are in this category. Trade liberalization would help deliver higher quality products at lower costs to consumers, although it could result in refinery closures in some cases. While some countries are concerned to safeguard against increased import dependence on oil products, they should assess how their energy security needs can be better satisfied or hedged by diverse supply options including liberalized international oil trade.

Taking lead phase-out as an example, countries with open borders can readily take advantage of unleaded gasoline prices which have often been less than that of leaded in regional petroleum product markets such as the Mediterranean and Caribbean. Some countries in Central America and the Caribbean that have an open petroleum product market and that rely on gasoline imports to a significant extent have been able to eliminate gasoline lead in less than a year.

Government Ownership and Regulation

Where the downstream petroleum sector is regulated in terms of its pricing, ownership and product trade, the government necessarily becomes involved in any change to fuel quality. Many refineries in developing countries are still owned by the government, and some are not economic. In the absence of reforms, refineries are unlikely to be able to recover the cost of capital investment needed to upgrade product slate and quality. Under these circumstances, the government may resist making changes in fuel quality, or if it does consider changes, will do so only with the protection of import restrictions or high tariffs. Downstream petroleum sector reform, i.e., transfer of ownership from the government to the private sector and liberalization of petroleum product trade, is therefore an integral part of improving fuel quality.

Energy Sector Management Assistance Programme (ESMAP)

The Energy Sector Management Assistance Programme (ESMAP) is a global technical assistance program jointly sponsored by the UNDP and the World Bank. ESMAP provides policy advice on sustainable energy development to governments of developing countries and of economies in transition. ESMAP centers its interventions around three priority areas:

- energy sector reform and restructuring
- increasing access to modern energy for unserved or underserved populations
- promoting environmentally sustainable energy practices.

ESMAP’s activities are executed by energy staff in the World Bank under the guidance of the ESMAP Manager.

The paper was prepared using the analysis carried out in the ongoing ESMAP project “Elimination of Lead in Gasoline in Latin America and the Caribbean”, where technical issues concerning gasoline lead removal—refinery modification, establishing new fuel specifications, assessing the impact of fuel composition on air quality—are being examined in the broader context of integrated urban air quality management. The project has provided a forum for dialogue among all the stakeholders, building a consensus lead elimination strategy in individual countries, as well as providing for information exchange.

This ESMPAP project is supported by the Canadian International Development Agency (CIDA).

Table 1. Key Gasoline Parameters for control and Their Impact on Air Quality

Component	Comments
Lead	Lead removal is the first step in gasoline reformulation. Combustion of leaded gasoline could result in high levels of PM_{10} emissions, due to lead particulates and a greater amount of incompletely burned hydrocarbons in the exhaust in the absence of catalytic converters. The standard maximally permissible level of lead in unleaded gasoline is 13 mg lead/liter, but even 5 mg/liter has been demonstrated to poison catalytic converters. Residual lead in gasoline arises mainly from lead contamination of the distribution system. It should be stressed that cars without catalytic converters can run on unleaded gasoline.
Sulfur	The amount of sulfur in gasoline should be below 500 parts per million by weight (wt ppm) to enable efficient operation of catalytic converters. Some developing countries have gasoline sulfur limits as high as 2,000 wt ppm. For cars not equipped with catalytic converters, sulfur has no effect on emission levels except that of oxides of sulfur, some of which in turn form particulate matter via further oxidation to SO_4. For all vehicle types, reducing sulfur reduces PM_{10} emissions. The cost of sulfur reduction follows a non-linear relationship with costs increasingly significantly if sulfur is to be reduced to 50–150 wt ppm. Auto-manufacturers recommend sulfur specifications of 100 wt ppm or lower.
RVP (Reid vapor pressure)	Reducing RVP is often the most cost-effective way of controlling volatile organic compound (VOC) emissions, including light olefins and airborne toxins such as benzene. This requires lowering the level of butanes, and possibly C_5 hydrocarbons. Ethanol has a high blending RVP, thereby further limiting the amount of light hydrocarbons that can be added to gasoline. In large parts of Europe and North America, the summer RVP is limited to 7–8 pounds per square inch (psi). Many developing countries with a warm climate still have RVP limits of around 10–11. In such cases, RVP reductions should be seriously considered, particularly if ground-level ozone is a problem.
Benzene	Benzene reduction is generally more cost-effective than total aromatics control for tackling toxic emissions. Aromatics dealkylate during combustion to form benzene, but the amount of benzene in the exhaust gas from aromatics is an order of magnitude smaller than that from benzene itself. Oxygenates reduce toxic emissions by diluting gasoline, thereby reducing the total amount of aromatics including benzene. Sulfur reduction decreases toxic emissions for catalyst-equipped cars by increasing hydrocarbon conversion over the noble metals.
Parameters affecting ozone	Ozone is not emitted directly by vehicles but is a product of photochemical reactions between atmospheric hydroxyls, NO_x and VOCs. Photochemically reactive VOCs include olefins, diolefins, aldehydes, and aromatics with two or more alkyl branches. Ozone abatement is complicated by non-linear interactions among ozone precursors; the relative effectiveness of VOC and NO_x controls for reducing ozone depends on the ambient VOC/NO_x ratios. Limits have been proposed for olefins and aromatics in gasoline. It is the light olefins that are of concern because of their high volatility. The majority of olefins in gasoline come from light catalytic cracker naphtha; they can be controlled by reducing RVP. In the case of aromatics, the US Auto/Oil Air Quality Improvement Research Program found that reducing aromatics from 45 percent to 20 percent had no effect on peak ozone. For cars not equipped with catalytic converters, available data are sparse. The European Programme on Emissions, Fuels and Engine Technologies found that increasing aromatics from 20 percent to 51 percent had no effect on engine-out emissions of hydrocarbons. There are earlier unpublished data which showed that engine-out hydrocarbon emissions increased by about 45 percent as the aromatics content was increased from 25 to 50 percent. Without catalytic converters, increasing aromatics increases NO_x emissions.

Table 2. Gasoline Blending Components with High Octane

Component	RON	Comment
normal butane	93	By far the cheapest source of octane, but has high volatility. Refiners typically add as much butane as possible until the maximally permissible RVP is reached.
isomerate	82-90	Isomerization converts straight chain pentane and hexane, both of which are low in octane, to higher octane isomers. It is an inexpensive process, and the product has nearly the same values of RON and MON. C_5 paraffins have relatively high volatility.
fluid catalytic cracker (FCC) naphtha	90-93	FCC units increase the yield of gasoline while providing octane at the same time. Light olefins in FCC have high volatility, are ozone precursors,and contribute to the formation of 1,3-butadiene, a carcinogen with greater potency than benzene. At high concentrtions, olefins are one of the major sources of NO_x emissions. The heavy end of FCC naphtha tends to be high in sulfur and aromatics.
reformate	90-103	Contains benzene which is carcinogenic, and xylenes and higher molecular weight aromatics which are ozone precursors. Reducing the amount of reformate in gasoline affects the overall profitability of the refinery. The reformer is the least expensive source of hydrogen; the hydrogen thus produced in turn is used in hydrodesulfurization for sulfur reduction.
alkylate	90-97	Contains little olefins, no sulfur, virtually no aromatics, and burns cleanly. Alkylate has high RON and MON. Alkylation increases the gasoline yield, but is a relatively costly option and requires specific feedstocks, including olefins from FCC units.
MTBE (oxygenate)	118	High RON and MON. The presence of oxygen enables more complete combustion of fuel, resulting in lower CO and VOC emissions. The use of oxygenates to lower CO levels is particularly effective with older cars. Newer cars have sensors that automatically adjust the ratio of oxygen to fuel, so that they benefit less from oxygenated gasoline in respect of CO emissions.

RON: research octane number, a measure of resistance to knocking under city driving conditions
MON: motor octane number, a measure of resistance to knocking under highway driving conditions
MTBE: methyl tertiary butyl ehter

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1 Clear Water, Blue Skies: China's Environment in the 21st Century. East Asia and Pacific Region, World Bank. 1997.

2 World Development Indicators, 1997.

3 Gasoline is typically mixed directly with lubricating oil for use in two-stroke engines which are widely in use in Asia. Aside from the once-through nature of lubricant use, excessive concentration and poor quality of lubricating oil contributes to high particulate emissions.

4 Dietrich Schwela, World Congress on Air Pollution in Developing Countries, San José, Costa Rica, 21-26 October 1996. Proceedings Volume II, 94-113.