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Implementer's Guide To Phasing Out Lead In Gasoline

Disclaimer

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Foreword

Lead in the environment is an important hazard to human health. Epidemiological and clinical studies conducted over the last two decades have demonstrated significant links between lead concentrations in the body and a variety of ills. These include impaired mental development, reduced intelligence, and behavioral disorders in children; and high blood pressure, cardiovascular disease, and cancer in adults. These effects have been found at levels of lead exposure that were previously considered safe.

Human exposure to environmental lead occurs through many pathways, including exposure to lead-based paints; lead dissolved in water from lead pipes, brass fittings, and solder joints; and lead in food from improperly glazed pottery and soldered cans. However, the single most important source of human exposure to lead is lead aerosol formed by the combustion of lead antiknock additives in gasoline. The elimination of these additives is the most important single step toward reducing lead exposure and the resulting damage to public health.

Because of progress in refining technology, lead additives are no longer required to achieve gasoline octane specifications. The United States has successfully eliminated lead from its own gasoline, and the U.S. Government supports phasing out the use of lead in gasoline worldwide. Among the most important obstacles to promptly phasing out lead in gasoline in many countries is the uncertainty felt by many policy makers regarding the technical alternatives to lead, the costs and benefits of reducing or eliminating lead use, and the potential impacts on the refining sector and on the vehicle fleet. In many cases, political decisions to eliminate lead have already been taken, but the implementation of these decisions is impeded by uncertainty as to how best to carry them out.

This Guide is intended to support the worldwide phaseout of lead in gasoline by providing a checklist and guidance for government officials tasked with developing and implementing a lead phaseout policy, and by assembling the data and resources these officials need to carry out their task.

Acronyms

ASTM	American Society for Testing and Materials
BTX	benzene-toluene-xylene
CH_4	methane
CO	carbon monoxide
DIPE	di-isopropyl ether
EPA	United States Environmental Protection Agency
ETBE	ethyl tertiary butyl ether
FCC	fluid catalytic cracker
g	gram
GC-OFID	gas chromatography, using an oxygenate flame ionization detector
HC	hydrocarbon
HCl	hydrochloric acid
Hg	mercury
HNO3	nitric acid
H_2S	hydrogen sulfide
IQ	intelligence quotient
km	kilometer
kPa	kilopascals
l	liter
LPG	liquefied petroleum gas
MIBK	methyl isobutyl ketone
µg	microgram
MMT	methylcyclopentadienyl manganese tricarbonyl
Mn	manganese
MON	motor octane number
MTBE	methyl tertiary-butyl ether
NGO	non-government organization
NMHC	non-methane hydrocarbon
NO_x	oxides of nitrogen
Pb	lead
PM2.5	fine particulate matter
PONA	paraffin, olefin, naphthene, and aromatic
ppb	parts per billion
ppm	parts per million
PSI	pounds per square inch

RON	research octane number
RVP	Reid vapor pressure
SO_2	sulfur dioxide
TAME	tertiary amyl methyl ether
TEL	tetraethyl lead
UNECE	United Nations Economic Commission for Europe
U.S. EPA	United States Environmental Protection Agency
VOC	volatile organic compound
VOSL	value of a statistical life saved
WTP	willingness to pay

IMPLEMENTER'S GUIDE TO PHASING OUT LEAD IN GASOLINE

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USAID

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1. OVERVIEW

This Guide is written for officials who are responsible for implementing the phaseout of lead additives in gasoline. It assumes that their governments have already made the decision to eliminate the use of lead additives, but have not yet determined how and when to accomplish this.

The activities described in this Guide are not necessarily sequential; they may be best applied simultaneously so that the output of each step is evaluated as a whole, and not solely as an input to the next step along a critical path. For example, although involving key stakeholders is presented as the last activity in the development of a lead phaseout strategy, it should not be conducted separately at the end of the process. In fact, stakeholders need to be involved at the outset if the phaseout plan is to be successful.

> This chapter provides a summary and checklist of the issues and actions to consider in developing and implementing a lead phaseout policy. It also gives two examples of successful lead phaseout programs.

1.1 Why Phase Out Lead In Gasoline?

Using lead additives to increase the octane rating of gasoline enabled the development of modern high-compression gasoline engines. But these additives have also produced dangerously high levels of lead aerosol (fine particles suspended in air) pollution in cities worldwide. Lead is a dangerous air pollutant, contributing to high blood pressure, cancer and heart disease in adults, and to reduced intelligence, behavioral disorders and impaired development in children. Health risk assessments in cities around the world where leaded gasoline is common have shown that lead aerosol is one of the most important causes of health damage due to air pollution. Lead in gasoline also increases vehicle maintenance costs and reduces the life of automobile engines.

With modern refining technology, lead additives are no longer needed to meet gasoline octane specifications. High gasoline octane ratings can be achieved without lead, at an incremental cost to the refiner of about US $0.005 to $0.02 per liter. These costs are less than the resulting savings in vehicle maintenance costs, and far less than the health benefits of reducing lead pollution. Thus, there is a clear economic case for phasing out lead additives as quickly as possible, and a strong movement toward doing so worldwide.

1.2 Myths And Misconceptions About Lead Phaseout

Efforts to phase out lead in gasoline have been impeded by a number of myths and misconceptions that have concerned both government officials and the public. In some cases, these myths have been fostered or promoted by organizations with vested interests in continuing leaded gasoline sales. Three very common misconceptions are:

Myth 1: Older engines require leaded gasoline, and will suffer damage if it is not available. This was a widespread concern in the United States during the 1970s and 1980s. Although laboratory tests have demonstrated that unleaded gasoline can damage valve seats in extreme cases, it affects only a negligible percentage of vehicles in actual use on the road. Where such damage occurs, it can be repaired and further damage can be prevented by replacing the seats with hardened inserts. The use of unleaded gasoline reduces corrosion and extends the lives of valves, spark plugs, engines, and exhaust systems. Unleaded gasoline use reduces maintenance costs overall, as the savings from reduced corrosion are far more than the costs of the occasional cases of valve seat damage with unleaded fuel.

Myth 2: Vehicles using unleaded gasoline must be equipped with catalytic converters. It is true that vehicles with catalytic converters *require* unleaded gasoline to prevent lead deposits from poisoning the catalyst and blocking exhaust flow through the converter. However, it is also true that vehicles without converters can successfully use unleaded gasoline. Thus, reducing or eliminating the lead content of gasoline will reduce lead emissions from both new and existing vehicles. Exhaust hydrocarbon emissions are likely to decrease as well, due to the effect of reducing lead deposits in the combustion chamber.

Myth 3: Emissions of toxic hydrocarbons such as benzene could increase greatly from unleaded gasoline use. The changes in gasoline composition needed to meet octane specifications without lead may change the emissions of other pollutants. For instance, the use of alcohols or ethers as high-octane blendstocks tends to reduce hydrocarbon and carbon monoxide emissions, but may raise aldehyde emissions. Increasing the fraction of benzene or other aromatic hydrocarbons in the fuel – if permitted – may lead to higher emissions of these compounds. However, increased benzene emissions can be prevented by using such technologies as alkylation and isomerization to increase fuel octane levels instead of catalytic reforming, or by specialized processes that extract or chemically eliminate benzene. In any event, the effects of increased benzene emissions on public health would be minor compared to the benefits of reducing lead aerosol exposure.

1.3 How To Use This Guide

The remainder of this chapter contains a checklist and summary of the issues and actions to consider in developing and implementing a lead phaseout policy. The involvement of key stakeholders is presented last among these actions, but its importance cannot be overstated. Because it is critical to a lead phaseout strategy's success, it should be emphasized throughout the process.

Implementers should first review the checklist, and then read the corresponding summaries in Section 1.4. Detailed information on each of the topic areas addressed in the checklist is presented in Chapters 2 through 11.

1.4 Summary Of Issues And Actions To Consider In Phasing Out Lead In Gasoline

There are ten main issues and actions to consider in developing and implementing a lead phaseout policy. Each of these topics is addressed in the subsections that follow.

Checklist For Phasing Out Lead In Gasoline

Identify technical options for reducing or eliminating lead additives (Chapter 2)

- ❑ Characterize present gasoline supply
- ❑ Assess the domestic refining industry
- ❑ Identify alternative sources of gasoline octane value
- ❑ Evaluate gasoline supply scenarios
- ❑ Assess the impacts on gasoline distribution and marketing systems
- ❑ Assess the costs of alternative strategies to the fuel supply sector

Assess lead phaseout impacts on the vehicle fleet (Chapter 3)

- ❑ Assess maintenance benefits of unleaded gasoline
- ❑ Assess potential for valve seat damage
- ❑ Assess potential valve seat protection strategies
- ❑ Evaluate net costs and savings for the vehicle fleet

Assess lead phaseout effects on vehicle emissions and air quality (Chapter 4)

- ❑ Assess gasoline composition effects on emissions and air quality
- ❑ Assess need for policies affecting gasoline composition
- ❑ Consider vehicle emission control policy

Assess the health benefits of lead phaseout (Chapter 5)

- ❑ Estimate the air quality impacts of lead and lead alternatives
- ❑ Conduct risk assessment for lead and lead alternatives
- ❑ Assess the public health benefits of phasing out lead
- ❑ Conduct economic valuation of public health benefits

Conduct a cost-benefit analysis (Chapter 6)

- ❑ Identify alternative phaseout strategies
- ❑ Assess net costs to public and public health benefits of each strategy
- ❑ Select preferred phaseout strategy

Choose policy instruments (Chapter 7)

- ❑ Identify legal authority
- ❑ Assess available policy instruments
- ❑ Evaluate "fit" between strategy and instruments
- ❑ Select "best" combination of instruments

Monitor compliance (Chapter 8)

- ❑ Identify monitoring needs
- ❑ Identify legal authority/requirements for monitoring gasoline composition
- ❑ Identify institutional and physical requirements for monitoring
- ❑ Identify responsibilities for monitoring and enforcement
- ❑ Plan gasoline monitoring and enforcement program
- ❑ Implement gasoline monitoring and enforcement program
- ❑ Identify and prosecute violators
- ❑ Follow up to ensure that monitoring and enforcement are effective

Conduct followup evaluation and reporting (Chapter 9)

- ❑ Monitor trends in ambient lead and other air pollutants
- ❑ Monitor trends in human exposure to lead
- ❑ Evaluate the effectiveness of the phaseout program
- ❑ Identify the cause of any problems found
- ❑ Communicate results to the public, politicians, and legal authorities

Conduct public education (Chapter 10)

- ❑ Define public education goals
- ❑ Develop public education strategy
- ❑ Identify potential communication media
- ❑ Assign responsibilities for communication and public education
- ❑ Follow up to assess effectiveness of the communication program
- ❑ Begin public education activities

Ensure public consultation and involvement (Chapter 11)

- ❑ Identify stakeholders
- ❑ Identify strategy for stakeholder involvement
- ❑ Communicate risk assessment and benefit estimates
- ❑ Communicate/consult on alternative phaseout strategies

1.4.1 Identifying Technical Options For Reducing Or Eliminating Lead Additives

Lead additives typically improve the octane rating of gasoline by about 6 to 12 octane numbers, depending on the amount of lead added and the octane response of the base fuel. To reduce or eliminate the use of these additives, it is necessary to find other ways to attain gasoline octane specifications.

Some Options For Making Up Octane Shortfall When Lead Is Reduced Or Eliminated

Near-term options. These include blending gasoline with such high-octane components as blending gasoline with methyl tertiary-butyl ether (MTBE), ethanol, alkylate, or mixtures of aromatic compounds. Some countries have also used the manganese-based octane enhancer MMT (however, please see EPA's cautions about MMT in Section 2.6).

Longer-term options. Here, the most economical approach is usually to add new refinery process units to convert the low-octane straight-chain paraffins in crude oil to higher-octane hydrocarbon types such as branched-chain paraffins, naphthenes, and aromatic compounds.

Gasoline supply. The first step in identifying options for making up the octane shortfall is to characterize the existing gasoline supply. This includes the volume of gasoline consumed and its projected growth, and the sources of supply. It is also necessary to identify the octane value; the paraffin, olefin, naphthene, and aromatic (PONA) content; and the lead content of gasoline from each source. Alternative sources of gasoline supply should also be identified.

Refining industry. The second step is to assess the capabilities of the domestic refining industry, if one exists. This would include its installed capacity, process units, octane production capability, the overall condition and economics of each refinery, and its technical and financial capabilities to invest in the construction of new process units. This assessment should be carried out in consultation with the industry involved, and may require the assistance of specialist consultants.

Octane value sources. After characterizing gasoline supplies and the local refining industry, implementers are now ready to quantify the shortfall in the "octane pool" that would result from reducing or eliminating lead. Once this is done, they should identify additional sources of octane value available to make up this shortfall, as well as the costs and investment needed per "octane-barrel" for each source. The minimum time required to provide additional octane from each source should also be identified.

Supply scenarios. Once potential octane sources are identified, various combinations of sources can be assembled to make up the octane shortfall under different lead phaseout schedules.

Impact assessment. Different lead phaseout strategies may mean different requirements and costs for transporting and distributing gasoline blendstocks and finished gasoline. Changes in the volume of imported gasoline and blendstocks may affect port and pipeline capacities, and possibly require additional investment to overcome bottlenecks. Similarly, changes in the number of gasoline grades, or in the sales volume of different grades may affect distribution and marketing costs.

Cost assessment. The circumstances of a country will determine which specific lead phaseout schedules and strategies are to be assessed. For each scenario assessed, the implementer should characterize the costs, investment requirements, and the reduction in lead emissions over time. To ensure that all of the options are considered, the scenarios evaluated should include at least the two extreme cases:

- A very quick phaseout in six months or less, with the octane shortfall made up by imported blendstocks.
- A very slow phaseout over three to five years, in which lead concentrations would gradually be reduced as new refinery process units come on line.

1.4.2 Assessing Lead Phaseout Impacts On The Vehicle Fleet

Maintenance benefits assessment. To assess the maintenance benefits of unleaded gasoline, the implementer should quantify how often such maintenance as spark plug changes, oil changes, valve repairs, valve seat repairs, and exhaust system replacements must take place and their costs. The change in these maintenance requirements can then be estimated using the information in Chapter 3.

Valve seat assessment. The implementer should also assess the potential for some engines to suffer valve seat damage from using unleaded gasoline and the costs of potential valve seat protection strategies if these are indicated.

Cost/savings evaluation. Here, the implementer should calculate and evaluate the resulting net benefits or costs to the vehicle fleet as functions of time for each of the lead phaseout scenarios considered, in order to compare them with the other costs and benefits.

1.4.3 Assessing Lead Phaseout Effects On Vehicle Emissions And Air Quality

Gasoline composition effects assessment. Phasing out lead will entail changes in gasoline composition, and these changes will affect the emissions of lead and other pollutants from gasoline vehicles. For instance, raising the aromatic hydrocarbon content of gasoline may increase emissions of benzene and other aromatics in exhaust and evaporative emissions. Changes in gasoline composition may also affect the photochemical reactivity of volatile organic compound (VOC) emissions, and thus affect the formation of ground-level ozone (photochemical smog). In a number of cases, public concerns over these secondary effects have delayed lead phaseout programs.

It is thus important to assess and quantify the potential secondary effects of lead phaseout on emissions and air quality. The assessment should be included as part of the phaseout plan, and – where necessary – measures should be taken to mitigate any adverse impacts. Such measures might include setting limits on or taxing the benzene, aromatic, and/or olefin content of fuels, and limiting vapor pressure to minimize evaporative emissions (see Chapter 4).

Policy assessment. Lead phaseout also provides an opportunity to assess the need for policies affecting gasoline composition. This would include a more general review of emission control policies for vehicles and fuels, such as the adoption of catalytic converters and/or evaporative emission controls, and limits on gasoline sulfur content. To the extent that such policies will mean changes in either the composition or the market shares of different fuels, they will affect investment plans in the refining and fuel distribution sectors. To avoid waste and confusion, it is best that they be adopted as an integrated package with the lead phaseout policy, rather than in piecemeal fashion.

1.4.4 Assessing The Health Benefits Of Lead Phaseout

Lead exposure risk and health benefits assessments. To assess the health benefits of reducing or eliminating lead emissions, the implementer should ideally know how the distribution of lead concentrations in ambient air and in human blood will change in response to changes in gasoline lead concentrations. Given this information, dose-response relationships derived from epidemiological data can be used to estimate the change in the incidence of high blood pressure, impacts on children's health, cardiovascular illness, and other health outcomes due to a given lead phaseout scenario. Detailed data and calculation examples are given in Chapter 5.

Economic valuation. In comparing the health benefits with the costs of reducing lead in gasoline, it is often useful to express the health benefits in monetary terms. The value to society of preventing a case of lead-related illness or premature death can be estimated based on treatment costs, lost productivity, and people's willingness to pay to reduce the risk of premature death and other adverse consequences. If the decision has already been made to phase out lead, the best use of cost-benefit analysis is to compare and evaluate the costs and benefits of different options for phaseout. Chapter 5 describes some of the bases for developing such estimates.

1.4.5 Conducting A Cost-Benefit Analysis

Selecting a strategy should take into account the costs and benefits of the different alternatives, and such considerations as technical and political feasibility, the legal basis for the strategy, equity among different social sectors, and acceptability to political decision makers and to the public.

Strategy identification, assessment, and selection. First, the implementer should identify a number of alternative phaseout strategies. Then, the strategies should be assessed to determine which of them are technically feasible, legally viable, equitable, and acceptable to decision makers and the public. From these, he or she should select the one with the greatest net benefits. The evaluation and selection processes are discussed in more detail in Chapter 6.

1.4.6 Choosing Policy Instruments

One goal of this Guide is to provide tools to help the implementer carry out the appropriate lead phaseout strategy for his or her country. Any one of these tools may be useful to a particular country, but not all of them will be useful to all countries.

The potential policy instruments for implementing a lead phaseout strategy include regulatory "command-and-control" measures and market-based incentives. Examples of *command-and-control measures* include limiting the maximum lead content of gasoline and prohibiting imports of lead additives. Examples of *market-based incentives* might include a tax on lead additive imports, or on the lead content of gasoline sold. Where legally feasible, market-based measures are generally preferable, as their flexibility reduces the chance that a regulatory mistake would disrupt the gasoline market, and may allow a faster phaseout overall.

Legal authority and instruments. In choosing policy instruments, the implementer should first identify the legal authority or authorities available as a basis for such instruments, and then assess the types of instruments legally permissible under that authority. For example, governments often have the authority to limit or prohibit toxic substance emissions, but may require new legislation in order to change tax rates on fuel.

Strategy fit and instruments selection. The implementer should also assess the compatibility between the strategy chosen and the instruments available to implement it. He or she should then select the best combination of instruments, considering their effectiveness, costs and benefits, timing, flexibility, and political acceptance.

1.4.7 Monitoring Compliance

Sampling and checks to confirm that the gasoline sold complies with the lead limits and quality specifications in effect are integral parts of the lead phaseout strategy. To guard against adulteration or smuggling, gasoline samples should be collected for analysis at retail service stations, as well as at the refinery and/or the port of importation. Chapter 8 gives details on the sampling and analytical procedures for lead, gasoline octane, and gasoline properties and composition.

Needs identification. In developing this portion of the lead phaseout strategy, the implementer should identify the monitoring requirements. These would include the number of samples and the types of locations to be sampled to ensure adequate coverage.

Authority and responsibilities identification. The implementer should identify the legal authority that will monitor fuel composition, including any ongoing monitoring efforts.

Physical and institutional monitoring requirements identification. The implementer should then identify the equipment and personnel required for the monitoring program, the institutional responsibilities of these personnel, and the sources of financing for any new equipment or personnel needed.

Enforcement program planning and implementation, and prosecuting violators. Based on the information developed, the implementer should work with the organizations responsible for enforcement to prepare a detailed plan for the enforcement program and obtain any necessary authorizations or approvals. The agency responsible should then implement the plan, which should include provisions for identifying and prosecuting individuals who are violating the lead phasedown requirements.

Followup. Once the program is underway, the implementer should follow up to confirm that monitoring is being done according to the plan.

1.4.8 Conducting Followup Evaluation And Reporting

Followup monitoring and evaluation are needed to ensure that the lead phaseout program achieves its goals, and to demonstrate to decision makers and the public that these goals have been achieved.

Trends monitoring. In addition to monitoring changes in the lead content of gasoline, implementers should assess the changes in concentrations of lead and other pollutants in ambient air and changes in the distribution of blood lead concentrations among the exposed population, particularly children. Chapter 9 gives more information on monitoring and measurement techniques.

Program effectiveness and communications. In most cases, the followup evaluation will demonstrate that lead concentrations in air and in human blood have declined significantly. This information should be communicated to decision makers and the public in order to maintain their support for the phaseout program. Should the monitoring show that lead concentrations in either the air or the exposed population have not declined as expected, it may indicate that other sources of lead exist and need to be identified.

1.4.9 Conducting Public Education

Goals definition. An effective public education program will help assure public support for the lead phaseout policy. The program goals ("the message") should include:

- Making the public aware of the health and developmental problems caused by exposure to lead, and the importance of gasoline additives as the main source of lead in the environment.
- Counteracting myths by providing accurate information about the ability of older vehicles to use unleaded gasoline and the maintenance benefits of reducing or eliminating lead.
- Providing for effective dissemination and consultation about the overall lead phaseout strategy.

Strategy, media, and responsibilities identification. Specific strategies should be designed to meet the program's goals and be targeted to specific audiences. The implementer should also identify appropriate communication media and assign responsibilities for communication and public education to the appropriate organization.

Program followup. During and after the public education process, followup studies should be conducted. These should assess the effort's effectiveness and determine whether further public education efforts are required.

1.4.10 Ensuring Public Consultation And Involvement

The type and amount of public consultation and involvement needed in developing a lead phaseout strategy will vary depending on a country's institutional arrangements and practices. As a general rule, active consultation with the businesses and organizations affected by the lead phaseout is important in reducing opposition and guarding against unforeseen consequences. Consultation with public health and environmental organizations, and with concerned members of the public will generally help gain their support of the lead phaseout program.

Stakeholder identification. Effective public consultation should begin by identifying the stakeholders: the individuals and organizations whose interests will be affected. These include oil refiners and importers, retail service station owners and operators, vehicle owners and their representatives, public health officials and the medical profession, parents, educators, and environmental organizations.

Strategy identification and communications. Implementers should define a strategy for communicating with stakeholders, and for involving them in the decisions on the lead phaseout through such means as public workshops. This strategy should be closely linked to the public education strategy discussed in Section 1.4.9, to ensure that a consistent and effective message is communicated. Equally important, implementers should pay careful attention to the questions and objections that surface during the public consultation process. In some cases, these may only indicate a need for more effective public education, but they will often identify real problems that must be addressed in the program's design. During meetings with stakeholders, implementers should communicate the results of risk assessments, benefit estimates and alternative phaseout strategies.

1.5 Examples of Successful Lead Phaseouts

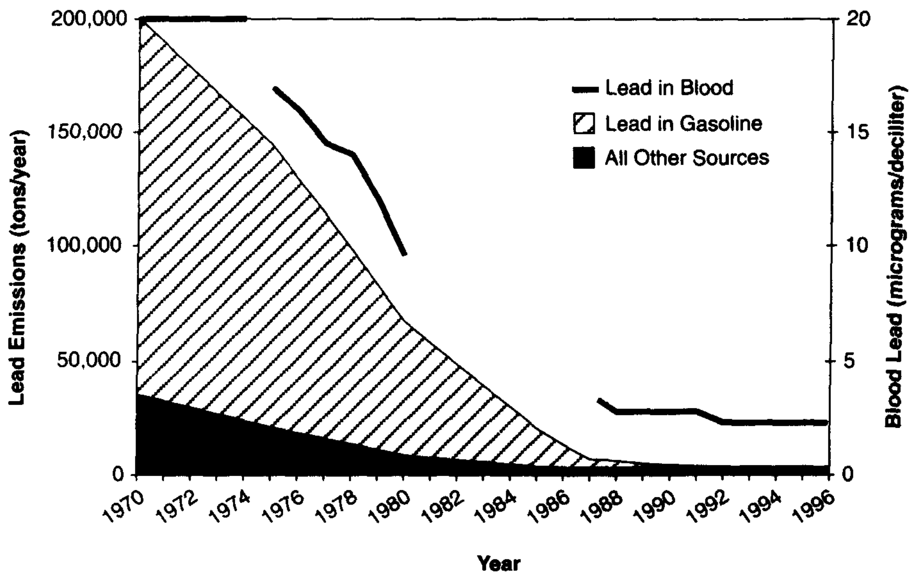
1.5.1 United States

In the 1970s, average lead concentrations measured in U.S. cities often far exceeded EPA's average air quality standard of 1.5 $\mu g/m^3$ (today, it is recognized that even this standard does not adequately protect human health). The mandatory sale of unleaded gasoline was introduced in 1974 in order to meet the needs of cars equipped with catalytic converters. At that time, leaded gasoline contained an average of 2.4 grams of lead per gallon (0.63 g/liter), and average blood lead concentrations among children in major cities were around 20 µg/dl (twice the level now considered to warrant medical action).

Through a phased program, the allowable lead concentration in leaded gasoline was reduced to 1.1 gram per gallon (0.29 g/l) by 1982. This program also introduced the trading of lead rights between refineries, so that a refinery that was able to produce gasoline containing less than 1.1 gram per gallon could sell the excess "lead rights" to another refinery that needed them. In 1984, a major cost-benefit evaluation (Schultz et al., 1985) concluded that the benefits of further reducing lead use in gasoline greatly outweighed the costs, and that allowable lead concentrations should be reduced to a minimum as quickly as possible. The allowable lead concentration was reduced to 0.5 gram per gallon in July 1985 and to 0.1 gram per gallon (0.026 g/l) on January 1, 1986. The allowable concentration was retained at this level until sales of leaded gasoline were finally banned in 1995.

During the same period, emissions of lead from other sources were also reduced, as was the use of lead solder in cans. Steps were also taken to reduce human exposure to lead in drinking water. Figure 1 shows the resulting changes in nationwide lead emissions and in average blood lead content as measured in nationwide health studies. Lead emissions to the atmosphere have been virtually eliminated in the United States, and average blood lead concentrations have been reduced more than 85 percent, to 2.3 µg/dl. Today, the main sources of human exposure to lead in the United States are the legacy of past use: lead paint and water pipes in old buildings, and lead-contaminated soil near roadways and industrial sites.

Figure 1: Lead Emissions And Average Blood Lead Content In The United States, 1970-1995

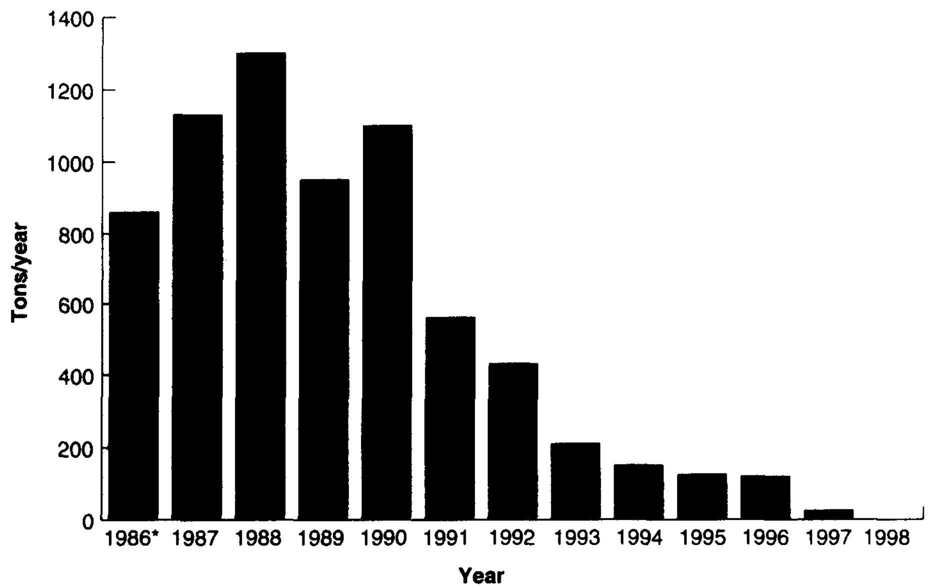


1.5.2 Mexico City[1]

Measured lead concentrations in Mexico City's air have fallen more than 98 percent in the last 10 years, despite increasing gasoline consumption. This has been a result of gradual reductions in the lead content of leaded gasoline, as well as the introduction and increasing use of unleaded gasoline. The reduction in lead content began in 1986, when a new specification of 0.5-1.0 ml of tetraethyl lead (TEL)/gallon was established, replacing the previous limit of 3.5 ml TEL/gal (1 ml TEL contains approximately 1 gram of lead). The standard was then successively reduced to 0.3 to 0.54 ml in 1991, 0.2-0.3 ml in 1992, and 0.2-0.1 ml/gallon in 1994. As a result of these increasingly stringent standards, lead emissions from gasoline decreased until they were practically eliminated, as shown in Figure 2.

[1] This description was provided by Eng. Sergio Sánchez, former director of environmental planning for the Government of the Federal District of Mexico City.

Figure 2: Use Of Lead In Gasoline In The Valley Of Mexico, 1988-1998



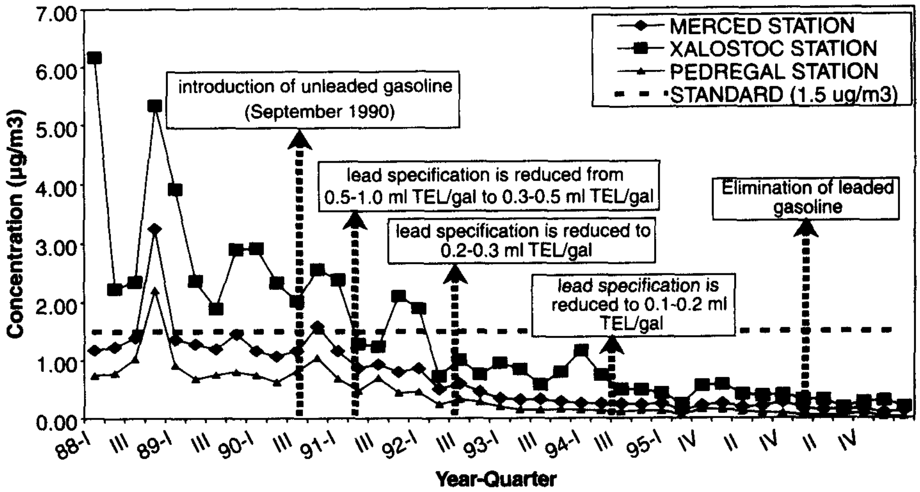
Unleaded gasoline was introduced in Mexico in September 1990 in order to accommodate the new vehicle emission standards adopted nationwide in 1991. These required the introduction of catalytic converters in new vehicles. Unleaded gasoline sales in the Valley of Mexico increased as the catalyst-equipped vehicle fleet grew – especially after a change in tax structure in 1992, which brought the prices of leaded and unleaded gasoline closer together. In 1995, the Mexican government announced its commitment to phase out leaded gasoline by the year 2000. This goal was achieved by the end of 1997. Since then, only unleaded gasoline has been distributed in Mexico.

Reducing the lead content in leaded gasoline and the introduction of unleaded gasoline have been part of a comprehensive gasoline reformulation process intended to improve air quality by reducing toxic and ozone-forming components. This reformulation process required a series of refinery improvement projects, including continuous catalytic reforming plants, isomerization plants, and plants for the production of methyl tertiary butyl ether (MTBE) and tertiary amyl methyl ether, as well as the addition of alkylation plants.

Figure 3 illustrates the evolution of airborne lead concentrations, from 1988 to 1998, for three representative stations of the Air Quality Monitoring Network.[2] In the late 1980s, lead levels peaked to more than 6 µg/m^3, and exceeded the 1.5 µg/m^3 three-month average standard throughout Mexico City. With the reductions in fuel lead content, atmospheric lead concentrations gradually decreased to very low levels throughout the urban area. The corresponding trend in average blood lead concentrations is shown in Figure 4. These concentrations have decreased dramatically, from about 16 µ/dl in 1988 to about 6 µ/dl today.

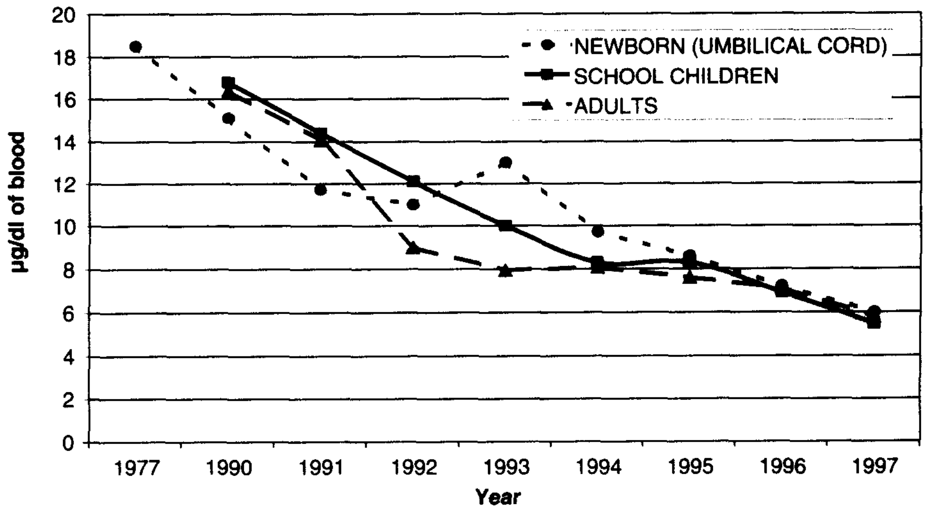
[2] The Xalostoc station is located in an industrial area that is north and upwind of the urban area. Merced station is located downtown, in the middle of an active commercial area. The Pedregal station is sited downwind in a residential area.

Figure 3: Airborne Lead Concentrations In The Valley Of Mexico, 1988-1998



Source: Mexico City Air Quality Monitoring Network.

Figure 4: Average Blood Lead Content In Mexico City, 1977-1997



Source: Mexican Institute of Public Health and American British Cowdray Hospital.

The effects of lead on health and the impact of atmospheric lead levels have been extensively studied in Mexico (Pardon and Martinez, 1998). Some investigations made in the 1980s demonstrated impacts on weight at birth, IQ reduction and neurological and metabolic disorders related to lead. A cost/benefit estimation of the reduction in airborne lead levels and health was made in 1993 (GIEP, 1993). According to that analysis, the total cost of lead content reduction and the use of unleaded gasoline was estimated at $717 million.[3] The benefits for health and vehicle maintenance improvement were calculated at around $1,740 million.[4] Therefore, the net benefit was estimated at $1,022 million.

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[3] Cost estimates included technology changes at refineries, consumer costs for using unleaded gasoline, and costs for introducing catalytic converters in new cars.

[4] Benefit estimates considered medical treatment costs, special education costs, prevention of death from heart disease, reductions in lost work and school days, etc.

OVERVIEW

Lead from gasoline has been eliminated as a threat to health in the Valley of Mexico. However, other sources of lead exposure remain serious, such as lead from leaded pottery and paints.

2. IDENTIFYING TECHNICAL OPTIONS FOR REDUCING OR ELIMINATING LEAD ADDITIVES

Lead is added to gasoline to improve knock resistance, as measured by the gasoline's octane rating. Lead additives can be reduced or eliminated by employing other means to attain gasoline octane specifications. A number of options are available to achieve increased octane levels without lead. These options can be broadly categorized as:

- Purchasing high-octane gasoline components and blending them into low-octane fuel.
- Upgrading and adding refinery equipment to produce higher-octane gasoline components.
- Using octane-enhancing additives based on substances other than lead.

Lead additives typically improve the octane rating by about 6 to 12 octane numbers, depending on the amount of lead added and the octane response of the base fuel. The technical options for making up the octane shortfall due to reducing or eliminating lead include:

- *Near term:* These include blending gasoline with oxygenates such as ethanol and methyl tertiary-butyl ether (MTBE), blending with high-octane hydrocarbon components such as alkylate and benzene-toluene-xylene (BTX) blends, and using the manganese-based octane-enhancer MMT.
- *Longer term:* The most economical way to increase octane is usually to add new refinery process units to convert low-octane hydrocarbons such as straight-chain paraffins into higher-octane hydrocarbon types such as branched-chain paraffins, naphthenes, and aromatic compounds.

> This chapter helps implementers to evaluate the physical and chemical options available for reducing or eliminating lead additives in gasoline, while maintaining octane levels. It discusses:
>
> - Octane ratings worldwide.
> - The blending octane values attained with a number of gasoline components.
> - The relationship between lead concentrations and octane levels.
> - The octane producing capabilities of various refinery types.
> - The sources, volumes and prices of the oxygenates blended in gasoline and their impacts.
> - The properties and performance of the anti-knock additive MMT.
> - Considerations in developing a lead phaseout strategy.

The Steps In Identifying Technical Options

1. Characterize the current gasoline supply

To identify the options for making up the octane shortfall by reducing or eliminating lead, one should first characterize the existing gasoline supply. This includes the volume of gasoline consumed and its projected growth, and sources of supply. It is also necessary to identify the octane value; the paraffin, olefin, naphthene, and aromatic (PONA) content; and the lead content of gasoline from each source. Alternative sources of gasoline supply should also be identified and characterized where possible.

2. Assess the domestic refining industry

If there is a domestic refining industry, its capabilities should be assessed. These include the installed capacity, process units already in place, octane production capability, the overall condition and economics of each refinery, and its technical and financial capabilities to invest in the construction of new process units. This assessment should be carried out in consultation with the industry involved, and may require the assistance of specialist consultants.

3. Identify alternative sources of gasoline octane value

Having characterized gasoline supplies and the local refining industry, implementers can now quantify the shortfall in the "octane pool" that would result from reducing or eliminating lead. Once this is done, they should identify the sources of additional octane value available to make up this shortfall, as well as the costs and investment requirements per "octane-barrel" for each source. The minimum time required to provide additional octane from each source should also be identified. Different combinations of sources can then be assembled to make up the octane shortfall under different lead phaseout schedules.

4. Evaluate gasoline supply scenarios

Once potential octane sources are identified, various combinations of sources can be assembled to make up the octane shortfall under different lead phaseout schedules.

5. Assess the impacts on gasoline distribution and marketing systems

The requirements and costs for transporting and distributing gasoline blendstocks and finished gasoline may vary under different lead phaseout strategies. Changes in the volume of imported gasoline and blendstocks may affect port and pipeline capacities, and possibly require additional investment to overcome bottlenecks. Similarly, changes in the number or sales volume of different gasoline grades may affect distribution and marketing costs.

6. Assess the costs of alternative strategies to the fuel supply sector

The specific lead phaseout schedules and strategies to be assessed will depend on each country's circumstances. For each scenario, the implementer should characterize the costs, investment requirements, and the reduction in lead emissions over time. To ensure that the full range of options is considered, the scenarios evaluated should include at least the two extreme cases: a very quick phaseout in six months or less, with the octane shortfall made up by imported blendstocks; and a very slow phaseout in three to five years, in which lead concentrations would gradually be reduced as new refinery process units come on line.

2.1 Knock And Octane Rating

Definitions. The octane number of a fuel is a measure of its resistance to detonation and "knocking" in a spark-ignition engine. Knock reduces engine power output, and severe or prolonged knock will likely result in damage to the pistons and/or overheating of the engine. The tendency for a fuel to knock increases with increasing engine compression ratio. Higher-octane fuels are more resistant to knocking, and can thus be used in engines with higher compression ratios. This is desirable, as higher compression ratios result in better thermodynamic efficiency and power output. Engines designed for use with high-octane fuels can thus produce more power and have lower fuel consumption than engines designed for lower-octane fuels. For a given engine design, however, there is no advantage in using a higher-octane fuel than what the engine requires.

Engines designed for use with high-octane fuels can produce more power and consume less fuel than engines designed for lower-octane fuels.

Measuring Octane Number

The octane number is measured by two standard tests — the research and motor octane tests. The results of these tests are expressed as either the research octane number (RON) or the motor octane number (MON) of the fuel. Both tests involve comparing the antiknock performance of the fuel to that of a mixture of iso-octane and n-heptane, with the "octane number" being defined as the percentage of iso-octane in the octane/heptane mixture that gives the same antiknock performance as the fuel under test. For fuels with octane numbers above 100, mixtures of iso-octane and tetra-ethyl lead are used to extend the octane scale to 130.

The research and motor tests differ in detail: the research test reflects primarily low-speed, relatively mild driving, while the motor test reflects high-speed, high-severity driving. Most fuels have a higher RON than MON. In the United States and parts of Latin America, gasoline antiknock ratings are expressed as the average of RON and MON, denoted by (R+M)/2. Elsewhere, the RON is typically the value quoted, but specifications limit the minimum MON value as well.

Why people buy high-octane gasoline. In many countries, gasoline vendors have sought to associate high octane ratings with "quality" in the public mind, allowing them to charge much higher margins for "premium" gasoline, thus increasing their profits. The public may buy this "premium" gasoline in the belief that they will reduce their vehicle's maintenance costs or improve its reliability. Except for a few vehicles that *require* higher-octane gasoline (generally high-performance and luxury models), the extra money spent on higher-octane grades provides little or no benefit, while the extra lead and/or aromatic compounds that may be used to achieve the higher octane rating contribute to environmental degradation.

Except for a few vehicles that require higher-octane gasoline, the extra money spent on higher-octane grades provides little or no benefit.

Specifications for gasoline octane rating and lead content among some of the main automobile-producing countries and regions. As Table 1 shows, the two main unleaded gasoline grades are an unleaded "regular" grade with typical RON and

MON values of 91 and 82 (corresponding to the U.S. (R+M)/2 specification of 87); and an unleaded "premium" grade with typical RON and MON values of 95 and 85, respectively. Most cars produced or sold in North America since 1975 have been designed to use unleaded regular fuel, while most cars produced or sold in Europe in the last decade have been designed to use unleaded premium.

Table 1: World Specifications For Gasoline Octane Rating And Lead Content

	Octane Rating			Max. Lead*
Country/Grade	RON	(R+M)/2	MON	(g Pb/lt)
United States				
Regular		87	82	0.0
Mid-grade		89		0.0
Premium		91-95		0.0
European Union				
Unleaded super	98		87-88	0.0
Unleaded premium	95		85	0.0
Leaded premium	96-99		86-87	0.15
Japan				
Premium	96			0.0
Regular	89			0.0
South Korea				
Unleaded	91		83	0.0
Thailand				
Premium	95		84	0.0
Regular	87		76	0.0
Proposed Latin America/ Caribbean Harmonized Standard				
Regular	91		82	0.0
Premium	95		85	0.0

* Most countries allow a tolerance of up to 0.013 grams of lead per liter to account for possible cross-contamination by leaded gasoline. Actual lead concentrations are normally well below this level, and often below detection limits.

Sources: Owen and Coley (1995), ESMAP (1998).

2.2 Hydrocarbon Classifications And Octane Values

The octane rating of a given gasoline blend is determined by:

- The hydrocarbon composition of the fuel.
- The content of high-octane non-hydrocarbon blendstocks such as ethers and alcohols.
- The amount of antiknock additives used, if any.

Because of non-linearities and interactions between different gasoline components, the effect of adding a given component to a given gasoline blend may not be strictly proportional to the octane value of the pure component. For this reason, refiners have defined "blending" octane values for different compounds that reflect their effects when blended into typical gasolines.

Blending octane values. Table 2 gives blending octane values for a number of typical gasoline components. As this table shows, straight-chain "normal" paraffinic hydrocarbons have low octane values, while branched-chain isoparaffins, olefins, naphthenes, and aromatic hydrocarbons have higher octane values. Oxygenated compounds such as alcohols and ethers also have very high blending octane values.

"Straight run" gasoline distilled from typical crude oils has a high percentage of normal paraffins, and thus tends to have relatively low octane value. Typical RON values for straight-run gasoline are in the range of 60 to 75. A major focus of modern refining technology is to improve the octane value of the hydrocarbons that are eventually blended into gasoline by converting them from normal paraffins to higher-octane aromatics, naphthenes, olefins, and isoparaffins.

Refiners have defined "blending" octane values for different compounds that reflect their effects when blended into typical gasolines.

Table 2: Blending Octane Values Of Some Typical Hydrocarbons And Gasoline Components

	RON	MON
Normal Paraffins		
n-Hexane	19	22
n-Heptane	0	0
n-Octane	-19	-15
Isoparaffins		
2,3-Dimethylhexane	71	76
2,2,4-Trimethylpentane (iso-octane)	100	100
Olefins (Alkenes)		
1-Butene	144	126
1-Pentene	119	109
Aromatics		
Benzene	99	91
Methylbenzene (toluene)	124	112
1,2-Dimethylbenzene (o-xylene)	120	103
1,4-Dimethylbenzene (p-xylene)	146	127
Naphthenes (Cycloalkanes)		
Cyclopentane	141	141
Cyclohexane	110	97
Oxygenates		
Methanol	127-136	99-104
Ethanol	120-135	100-106
Tertiary butanol	104-110	90-98
Methanol/TBA (50/50)	115-123	96-104
Methyl tertiary butyl ether (MTBE)	115-123	98-105
Tertiary amyl methyl ether (TAME)	111-116	98-103
Ethyl tertiary butyl ether (ETBE)	110-119	95-104

Source: Owen and Coley (1995).

2.3 Properties Of Tetraethyl Lead

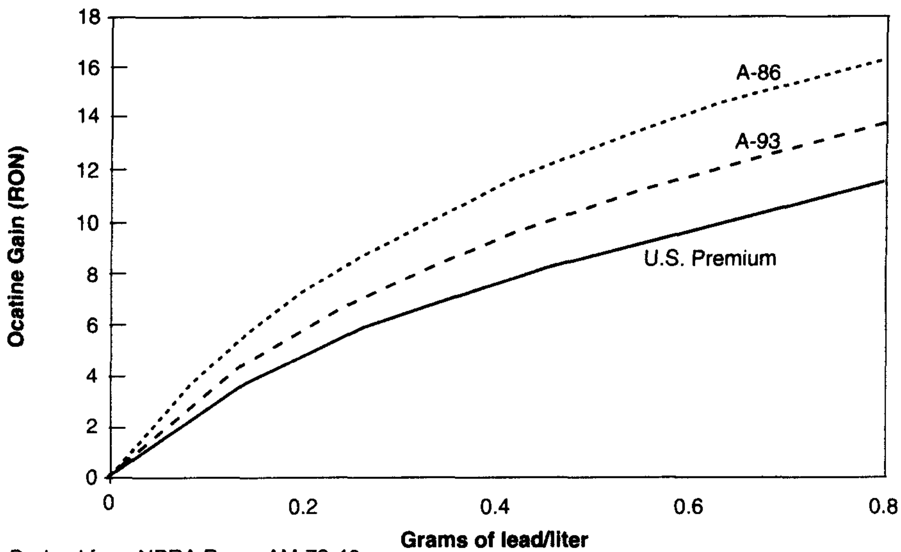
With the development of advanced refining technologies, it is now possible to achieve high octane ratings without the use of lead.

Tetraethyl lead (TEL) has been used to reduce the knocking tendencies of gasoline since 1922. Before advanced refining technology was developed, the antiknock properties TEL imparted to gasoline enabled the development of efficient, high-compression gasoline engines. By adding approximately 0.8 to 1.0 gram of lead per liter to straight-run gasoline, the octane rating can be raised to around 85 RON. The first higher-octane gasolines were produced in this way, and many of the smaller and older refineries in developing countries are still configured in this manner.

With the development of advanced refining technologies, it is now possible to achieve high octane ratings without the use of lead. Where permitted by law, however, lead additives are still the cheapest means of producing high-octane gasoline.

The relationship between lead concentration and octane increase. As Figure 5 shows, the octane boost due to lead typically varies both with the lead content and with the octane value of the base fuel. The octane increase resulting from a given amount of lead is greater for low-octane regular gasoline than for higher-octane premium fuel. This increase also varies with the amount of lead already in the fuel. The first 0.1 g/liter of lead additive gives the largest octane boost, with subsequent increases in lead concentration giving progressively smaller returns. *This non-linear relationship between lead addition and octane increase has very important implications for a lead phaseout strategy.*

Figure 5: Octane Enhancement Vs. Lead Concentration For Some Typical Gasolines



Derived from NPRA Paper AM-79-46.

Source: Abt (1996).

If refinery octane capacity is limited, the quickest and most economical way to reduce lead emissions will generally be to reduce the lead content of existing leaded gasoline grades as much as possible, rather than to encourage refiners and vehicle owners to switch from leaded to unleaded fuel. The non-linear relationship between lead and octane means that less lead is required to produce two liters of low-lead gasoline than to produce one liter of high-lead gasoline and one liter of unleaded with the same octane value.

TEL additive package. In order to prevent excessive buildup of lead deposits in the engine, TEL is normally sold and blended into gasoline in combination with a mixture of ethylene dibromide and ethylene dichloride; this mixture is known as "motor mix." The bromine and chlorine atoms combine with lead in the combustion chamber to form lead bromide and chloride, limiting the buildup of lead oxide on the combustion chamber walls.

TEL is extremely toxic and (unlike inorganic lead compounds) is readily absorbed through the skin, making it dangerous to handle. Both ethylene dibromide and ethylene dichloride have been identified as possible carcinogens, as has inorganic lead.

When refinery octane capacity is limited, the quickest and most economical way to reduce lead emissions is to reduce the lead content of existing leaded gasoline grades as much as possible, rather than to encourage a switch from leaded to unleaded fuel.

2.4 Petroleum Refining And Gasoline Supply

Gasoline is produced by refining crude oil as a co-product with other oil products such as liquefied petroleum gas (LPG), kerosene, jet fuel, diesel fuel, fuel oils, lubricating oils, and feedstocks for the petrochemical industry. Gasoline and diesel fuels comprise a large percentage (between 30 and 70 percent) of the products from most refineries. Because of increasing demand for gasoline and diesel fuels compared to other products, and increasingly stringent environmental requirements for gasoline and diesel quality, the refining industry has had to undergo an important transition in technology and product slate.

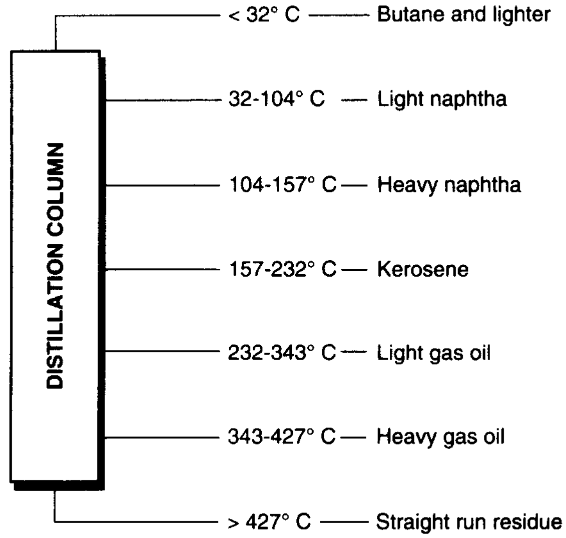
Crude oil contains a wide range of hydrocarbons, organometallics and other compounds containing sulfur, nitrogen, etc. It varies in chemical composition, from oil field to oil field, and also with time within a given oil field. The hydrocarbons (HCs) in crude oil are as simple as CH_4 (methane) or as complex as $C_{85}H_{60}$, with each of these compounds having its own boiling temperature. A refinery will distill crude oil into various fractions and, depending on the desired final products, will further process and blend those fractions. With gasoline making up only a fraction of the constituent hydrocarbons in crude oil, a refinery must either sell the remainder as marketable products or convert the larger molecules into smaller gasoline molecules.

2.4.1 Different Refinery Types And Capabilities

Petroleum refineries vary greatly in size and complexity, depending on the level and sophistication of the physical and chemical processes they perform. One commonly used classification divides refineries into three groups: topping refineries (the simplest), hydroskimming refineries, and "complex" refineries.

Topping refinery. The initial processing step in all petroleum refineries is the separation of crude oil by distillation into a variety of process streams with different boiling ranges (Figure 6). In a topping refinery, these "straight run" process streams receive minimal further processing (e.g., to remove impurities such as sulfur) before being blended into final products. Topping refineries do not include process units designed to increase the octane of the "straight-run" gasoline they produce, and must therefore rely on the use of lead additives or other blending components such as oxygenates in order to meet octane specifications.

Figure 6: Distillation Of Crude Oil

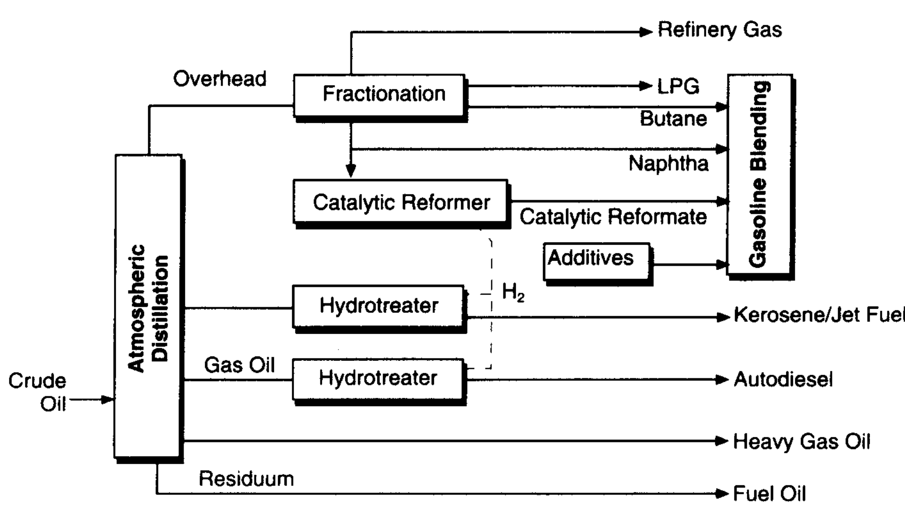


Although many older refineries were originally built as topping refineries, most of these have since been upgraded to hydroskimming or complex types. The few remaining topping refineries are mostly small units serving isolated markets in developing countries.

Hydroskimming refinery. A hydroskimming refinery is similar to a topping refinery, except that it includes one or more catalytic reformer units. As discussed in Section 2.4.2, the catalytic reformers convert some of the low-octane paraffinic components in "straight run" gasoline into higher-octane aromatics and naphthenes. This operation produces excess hydrogen, which is often used for hydrotreating the jet and diesel fuel streams to remove sulfur and improve combustion quality. Otherwise, it may be burned as fuel. Figure 7 shows a simplified process diagram for a typical hydroskimming refinery.

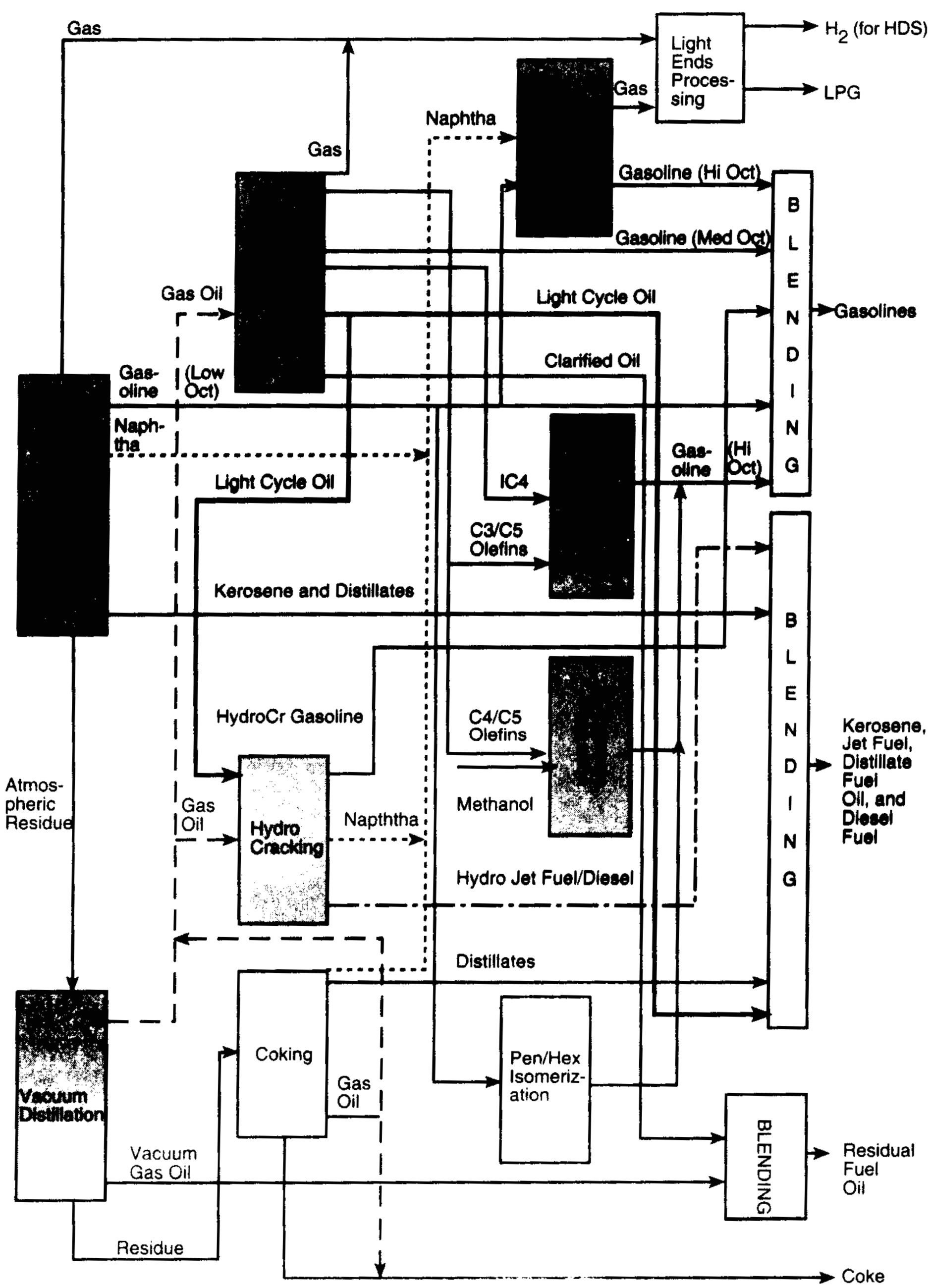
Topping and hydroskimming refineries have little flexibility to change the proportion of crude oil input that goes to different products. The relative amounts of gasoline, jet fuel, diesel, and fuel oil produced are determined primarily by the hydrocarbon composition of the crude oil. A crude oil with a high percentage of light hydrocarbons will make it possible to produce more gasoline and diesel fuel, while a heavier crude oil will result in greater production of heavy fuel oil. In the last two decades, the demand for (and hence the value of) "white" products such as gasoline and diesel fuel has increased more than that for "black" products such as fuel oil. As electrical generation increasingly shifts from oil-fired steam turbines to natural gas-fired combined-cycle plants, this trend is likely to continue.

Figure 7: Simplified Process Diagram For A Hydroskimming Refinery



Complex or "conversion" refineries. These refineries are distinguished from topping and hydroskimming refineries by possessing one or more process units intended to convert low-value residual products into higher-value products such as gasoline and diesel fuel. The most common conversion unit is a fluid catalytic cracker (FCC). This process unit heats the heavy gas oils produced by vacuum distillation of the residual oil in the presence of a catalyst, causing the large hydrocarbon molecules present in these oils to "crack" into smaller molecules. The resulting product is high in naphthenes, aromatics, and olefins, and thus has a relatively high octane value. This process also produces a significant amount of light olefins (propene and butenes). These can be used in subsequent process units to produce high-octane species such as alkylate and ethers. Figure 8 shows a process diagram for a typical deep conversion refinery.

Figure 8: Process Diagram Of A Deep Conversion Refinery



Source: Abt (1996).

Hydrocracking, a related process, is carried out in the presence of excess hydrogen, and thus tends to produce less in the way of unsaturated aromatics and olefins. This process is becoming increasingly popular, however, because it produces very high-grade, low-sulfur diesel and jet fuels. The gasoline-range product produced by the hydrocracker is often further processed by catalytic reforming to increase its octane rating.

The residuum left after the vacuum distillation of crude oil is a heavy, tarry substance that must be heated in order to be pumped, and which contains much of the sulfur and metallic contaminants found in the crude oil. This residual oil can be used as fuel in power plants and marine vessels. As environmental concerns have shifted fuel demand for electric generation from oil to low-sulfur natural gas for power generation, however, an increasing number of refineries have adopted "*deep conversion*" techniques such as thermal cracking or coking to crack this residual material as well.

2.4.2 Principal Process Streams Used In Gasoline

In a modern refinery, a number of process streams are blended together to form the gasoline "pool." Table 3 lists some of these, along with the corresponding octane numbers. In the simplest case, a topping refinery, the gasoline pool comprises light naphtha, heavy naphtha, and enough butane to bring the vapor pressure of the resulting product up to specification. In a hydroskimming refinery, the heavy naphtha is sent to the catalytic reformer, producing reformate to be blended into the gasoline pool. Within some limits, the octane value of the reformate can be varied by increasing or decreasing the severity of reforming. More severe reforming gives a higher octane rating, but a lower gasoline yield. Table 4 shows typical feed and product composition for a catalytic reformer. Catalyst manufacturers are continually working to improve the efficiency and octane yields of catalytic reformers.

Table 3: Typical Octane Values For Some Process Streams Used In Gasoline Blending

Blending Component	RON	MON
Butane	93	92
Straight-run light naphtha	66	62
Straight-run heavy naphtha	62	59
Catalytic reformate	94-100	84-88
Alkylate	97	96
Pen-hex isomerate	84-89	81-87
Cat cracked gasoline	92	77
Coker gasoline	85	77
Light hydrocrackate	75	74
Heavy hydrocrackate	79	76

Sources: Leffler (1984), Meyers (1996).

Table 4: Typical Feed and Product Composition for a Catalytic Reformer

	% Volume	
Hydrocarbon Type	**Feed**	**Product**
Paraffins	50	35
Olefins	0	0
Naphthenes	40	10
Aromatics	10	55

Source: Leffler (1984).

Light straight-run naphtha includes a large percentage of n-pentane and n-hexane, compounds with very low octane values. The octane value of this stream can be raised considerably by processing it in a pentane-hexane isomerization unit to convert these straight-chain paraffins to their branched-chain equivalents. The resulting isomerate can vary from 84 to 89 RON, depending on the process configuration.

Gasoline-range hydrocarbons from catalytic or thermal cracking (coking) are rich in aromatics, naphthenes, and olefins, and thus have relatively high RON values. The gasoline-range products of hydrocracking are much lower in aromatics and olefins, and thus have lower RON, but good MON, values.

Catalytic cracking and deep conversion processes also produce significant quantities of light olefins such as butenes and propene. In a process called alkylation, these compounds are reacted with isobutane to form isoparaffins containing seven or eight carbon atoms. The resulting alkylate has an extremely high RON and MON, making it very valuable in meeting octane specifications. Isobutene and isoamylene can also be reacted with methanol in an etherification unit to form MTBE and TAME (tertiary amyl methyl ether), respectively.

Unlike olefins and aromatic compounds, the isoparaffins in alkylate and isomerate are not considered highly toxic or carcinogenic, and have low reactivity in the formation of photochemical smog. Thus, these compounds are especially desirable for producing cleaner-burning "reformulated" gasoline.

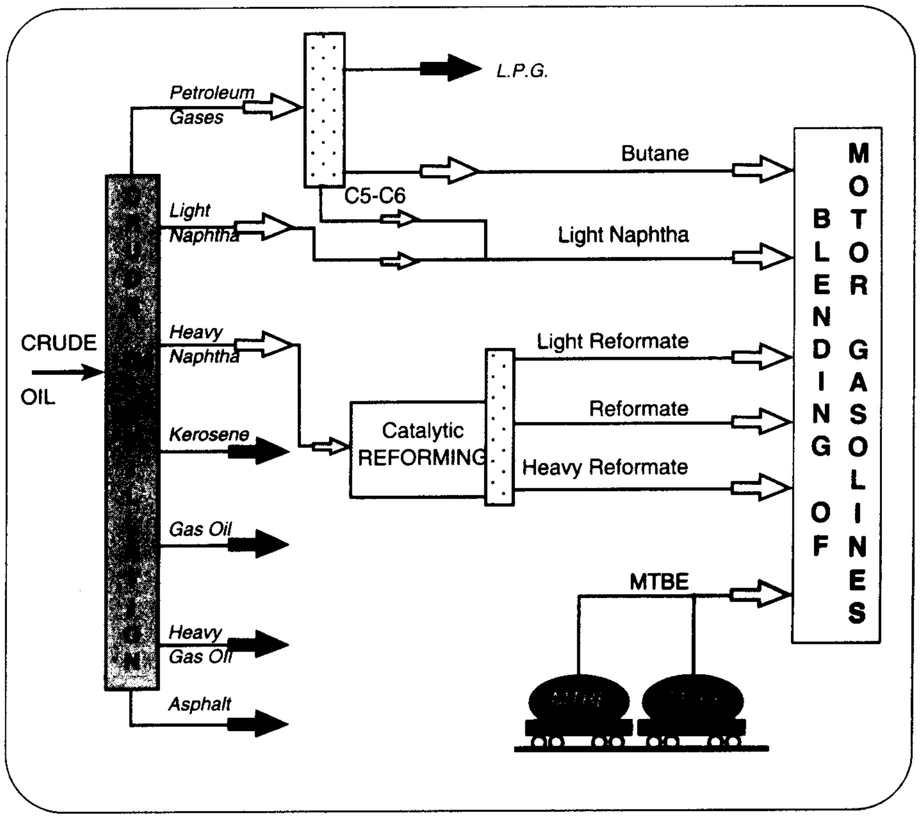
2.4.3 Examples Of Refinery Upgrades To Produce Unleaded Gasoline

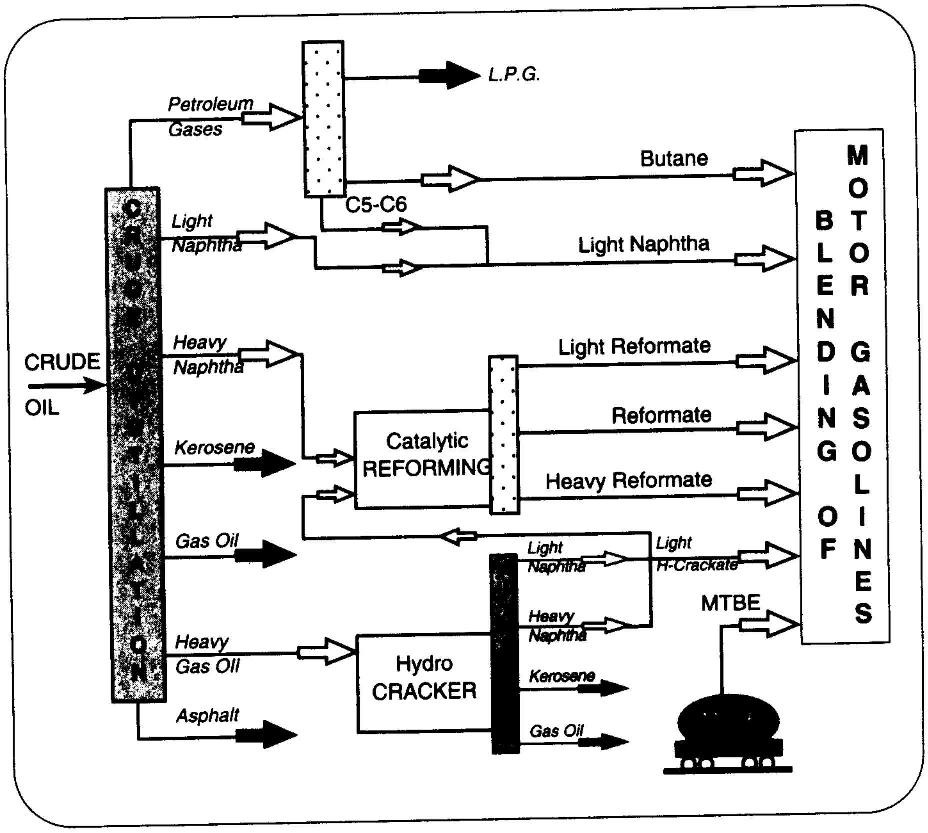
The worldwide demand for petroleum products has shifted strongly toward unleaded gasoline and low-sulfur, high-cetane diesel fuel, and away from "black" products such as heavy fuel oil. In response, many refineries are installing additional process units to upgrade the clear octane rating of gasoline in order to do without lead, and to convert an increasing fraction of low-value residual oil into high-value products such as gasoline and diesel.

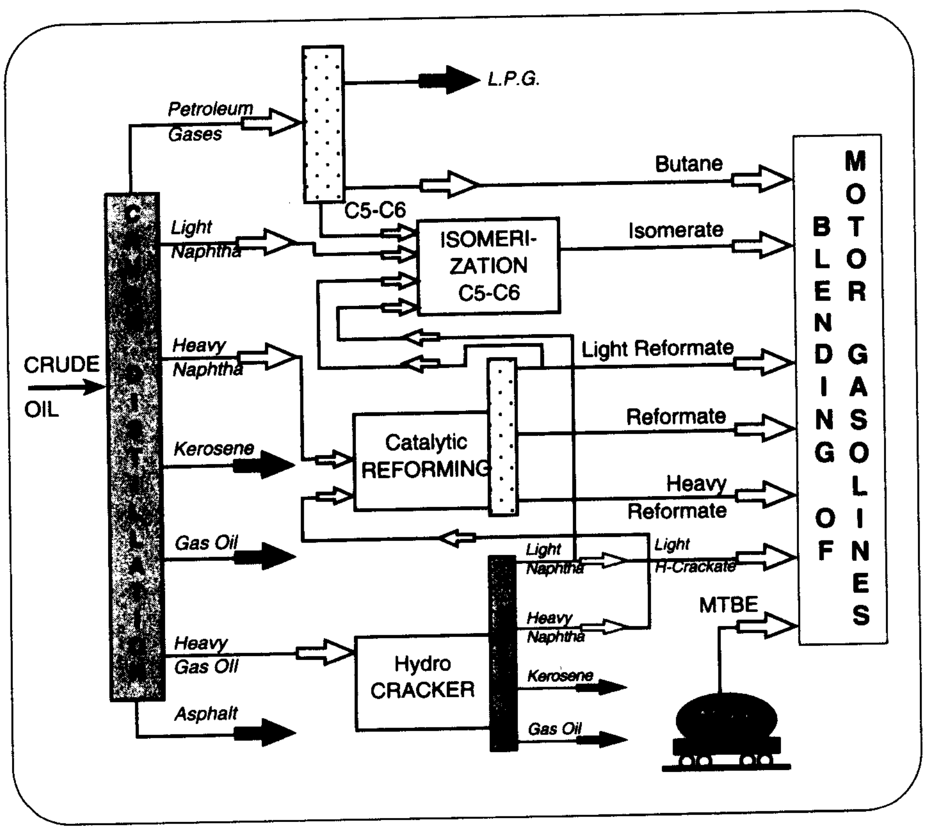
Many refineries are installing additional process units to upgrade the clear octane rating of gasoline in order to do without lead.

Slovak Republic. The upgrade of the Slovnaft refinery in the Slovak Republic over the last decade (Lovei, 1997) is a typical example of the upgrading process. Originally configured as a hydroskimming refinery, the Slovnaft refinery was upgraded in several stages. The first stage was to increase the severity of catalytic reforming, making possible a reduction in gasoline lead content from 0.7 to 0.4 grams per liter. Blending MTBE and adjusting the distillation process made it possible to reduce lead further, to 0.25 gram per gallon. In the second stage, a hydrocracker was added to convert part of the crude residue to gasoline and diesel fuel stocks. Reforming the hydrocracked gasoline stream made it possible to reduce the lead content of 96 RON fuel to 0.15 g/gallon, and at the same time to introduce unleaded gasoline at 95 RON. In the third stage, an isomerization unit was added as well, making it possible to eliminate lead completely. Figure 9 shows how the Slovnaft refinery evolved during this period.

Figure 9: Evolution Of The Slovnaft Refinery, Slovak Republic







Source: Lovei (1997).

Russia. Many Russian refineries are being updated to be able to produce unleaded gasoline, both to meet Russian lead phasedown targets and for export. The Perm refinery, opened in 1958 and located in the North Urals region, provides an example. This refinery is one of the largest in Russia, with a crude oil capacity of 300,000 barrels per day. The first step implemented was to replace the catalyst in the largest of the four existing catalytic reformers with an improved catalyst provided by UOP. This and related operational changes increased the octane value of the reformate from 91 to 99.5, while nearly doubling the cycle time between catalyst regenerations. Two other catalytic reformers were subsequently shifted to use the new catalyst type (Shuverov et al., 1997). At the same time, the crude distillation units were revamped, and a vacuum distillation unit was installed to recover additional heavy gas oil from the residue from the crude distillation units.

The next steps at the Perm refinery will include a hydrocracking unit to break down the heavy gas oil into lighter products in the gasoline and diesel fuel ranges, revamp the existing catalytic cracking unit, make further upgrades to the catalytic reformers, and install a di-isopropyl ether plant. The cost of these changes is estimated at US $340 million (Rudin, 1998). A later set of upgrades is planned to include another hydrocracker for the vacuum distillation residue and an alkylation unit to increase gasoline octane capacity. These and related changes are expect to cost $290 million.

Another Russian refinery going through the upgrading process is Sibneft's Omsk refinery in Siberia. This refinery is increasing octane capacity by constructing a sulfuric acid alkylation unit with 8,600 barrels per day capacity, and a semiregenerative catalytic reforming unit capable of processing 25,000 barrels per day. The project is estimated to cost $55 million, and will be completed in 2000.

Persian Gulf. Many refineries in the Persian Gulf are also being upgraded to meet market demands for unleaded gasoline and lower fuel oil production. A good example is the Sitra refinery in Bahrain. The refinery plans to cut fuel oil production by more that half, from 26-27 percent of total product output to 10-12 percent, while increasing gasoline production by the same amount. The proposed upgrade includes replacing four atmospheric distillation units with a single 15,000 barrel per day unit, a 7,500 barrel per day LPG recovery unit, an 18,000 barrel per day catalytic reformer, a 750 barrel per day MTBE unit, and a 4,600 barrel per day alkylation unit. The project is expected to cost about $600 million.

2.5 Oxygenates As Gasoline Blending Components

Several oxygenated compounds are commonly used as high-octane blending components for gasoline. They include methyl tertiary butyl ether (MTBE), tertiary amyl methyl ether (TAME), di-isopropyl ether (DIPE), and ethanol (ethyl or grain alcohol). Of these, MTBE and ethanol account for by far the largest shares. MTBE is typically blended with gasoline at levels up to 15 percent by volume, while ethanol is blended up to 10 percent by volume in the United States. Brazil has successfully blended 22 percent ethanol in gasoline for many years, thus completely eliminating the use of lead additives while requiring little in the way of refinery process equipment to increase gasoline octane.

Brazil has successfully blended 22 percent ethanol in gasoline for many years, thus completely eliminating the use of lead additives while requiring little in the way of refinery process equipment to increase gasoline octane.

In the past, methanol (methyl or wood alcohol) was also blended with gasoline to some extent, combined with tertiary butyl alcohol as a cosolvent. Such use is no longer common, however, due to economic considerations.

In addition to increasing octane, the blending of gasoline with oxygen-containing compounds such as ethanol and the ethers helps to reduce carbon monoxide and hydrocarbon emissions from vehicles using the fuel. This effect is greatest for vehicles without emission control systems, and relatively small for modern vehicles equipped with closed-loop control of the air-fuel ratio. To take advantage of this effect, U.S. specifications for reformulated gasoline require at least 2 percent oxygen by weight, and 2.7 percent in winter months, when CO emissions tend to be highest.

As Table 2 shows, the blending RON of MTBE is about 115 to 123. Thus, blending 15 percent MTBE into gasoline having a base RON of 87 will result in a blend with RON in the range of 91 to 92: an increase of four to five octane numbers, or the equivalent of 0.1 to 0.15 g/liter of lead. Similarly, the blending octane value for ethanol is 120 to 135, so that a 10 percent blend of ethanol with 87 RON gasoline will give a RON of 90 to 92 for the blend.

At current prices, MTBE is considerably cheaper than ethanol. Most of the reformulated gasoline sold in the United States thus contains MTBE, except where state tax subsidies encourage ethanol blending. MTBE is also very widely blended into gasoline in Mexico, Egypt, Thailand, Argentina, and other countries. MTBE use has recently become controversial in the United States, however, due to concerns over ground and surface water contamination.

Although MTBE is considerably cheaper than ethanol at current prices, its use has become controversial due to concerns over ground and surface water contamination.

2.5.1 Sources, Supply Volumes, And Prices

MTBE is produced by reacting isobutene (2 methyl propene) and methanol in the presence of a catalyst. The isobutene may be obtained from a refinery, but more commonly is produced in a stand-alone plant by the dehydrogenation of isobutane extracted from natural gas. Methanol, the other feedstock, is usually produced by the partial oxidation of methane from natural gas. Methanol can also be reacted with isoamylene (2 methyl butene) to produce TAME, and ethanol can be reacted with isobutene to produce ETBE using the same process unit, thus providing some flexibility in feedstock selection (Meyers, 1996).

Due to the worldwide phaseout of leaded gasoline and the increasing demand for clean-burning "reformulated" gasoline, demand and production capacity for MTBE and other ethers have been growing rapidly over the last two decades. In 1997, there were 172 MTBE plants in operation worldwide, with a total production capacity of 502,000 barrels per day (80,000 m^3/day), and 20 TAME plants with a combined capacity of 46,000 barrels per day (7,300 m^3/day) (Saunders, 1997). Another 76 oxygenate plants were planned or under construction at that time. If all of these plants were completed, they would add another 337,000 barrels per day to world MTBE capacity by 2000, significantly exceeding the projected demand of 582,000 barrels per day.

Market prices for MTBE and methanol have historically been highly volatile, due to a combination of low short-term elasticity of supply and unpredictable fluctuations in demand. For example, September 1998 MTBE prices of US $215 to $230 per metric ton were 25 percent less than those prevailing one year earlier, and more than 40 percent below the peak prices of over $355 per ton reached in 1992 and 1994. The price of methanol on the world market has fluctuated even more dramatically, from around US $0.25/gallon in the early 1980s to $0.60-0.70 in the late 1980s, to as much as $1.80 in 1994, and then to $0.30 per gallon in summer 1998. The lower prices reflect the effects of a glut, while the higher values reflect shortages.

Ethanol is produced primarily by the fermentation of starch from grains or sugar from sugar cane. As a result, the production of ethanol for fuel is in direct competition with food production in most countries. The resulting high price of ethanol (ranging from $1.00 to $1.60 per gallon in the United States in the last few years) has effectively ruled out its use in motor fuel except where (as in Brazil and the United States) it is heavily subsidized. New developments in the fermentation of cellulosic biomass offer some potential for lower-cost production of ethanol in the future, but this technology has not yet been demonstrated in a full-scale plant.

2.5.2 Impact On Vehicles

Corrosion and materials compatibility. Blends of MTBE and other ethers in gasoline have been used successfully for many years in several countries, including the United States. No problems with materials compatibility or corrosion have been identified in either the vehicle or fuel distribution system. There have been some reports of corrosion problems with alcohol blends (Owen and Coley, 1995). However, analyses of the available data by EPA (1985) indicate that alcohol mixtures did not result in corrosion or damage to fuel system elastomers when the base gasolines were blended properly and typical corrosion inhibitors were used. In practice, the widespread addition of ethanol to gasoline has not created significant problems in the United States or Brazil.

Leaner air-fuel mixtures. Unless the fuel system is adjusted to compensate for the oxygen content, the use of oxygenate/gasoline blends results in a somewhat leaner mixture than would result from an all-hydrocarbon fuel. This is the major source of the emission reductions experienced with the use of oxygenates, and usually presents no performance problems. If a vehicle were adjusted with the air-fuel ratio already near the lean limit, however, the additional enleanment due to the oxygenate could cause performance problems.

Fuel and energy consumption. Because oxygenated gasolines contain less energy per unit volume than gasolines without oxygen, the volumetric fuel consumption (liters per 100 km) may increase by a few percent using oxygenated fuel. Specific energy consumption usually improves slightly, however, due to the overall leaner mixture.

The leaner air-fuel mixture produced by the addition of oxygenates to gasoline helps reduce CO and HC emissions, while NO_x emissions may increase slightly.

2.5.3 Impact On Pollutant Emissions

Carbon monoxide and hydrocarbons. Assuming no change in the settings of the fuel metering system, the addition of oxygenates to gasoline will result in a leaner air-fuel mixture, thus helping to reduce exhaust CO and HC emissions. This approach has been made mandatory in a number of localities suffering from high wintertime CO emissions. (CO emissions are highest at low temperatures, with low traffic speeds, and at high altitude.)

Oxides of nitrogen. Recently a test program that studied the impact of ethanol and MTBE on NO_x emissions attracted considerable attention when it stated that, although HC and CO emissions are reduced by the use of oxygenates, NO_x emissions may increase slightly by the leaner operation (see the Auto/Oil Air Quality Improvement Research Program, AQIRP, 1992). EPA studied this issue carefully and reached a different conclusion from the AQIRP study. In developing the Agency's own highly complex model, EPA concluded that NO_x emissions are not significantly affected by the addition of oxygen to the fuel. These data were based on more than 4,000 individual vehicle tests of 1990 technology vehicles and on many test programs.

Moreover, the use of oxygenates in a real-world refining situation typically results in significant decreases in olefins and sulfur as well as aromatics, due to both simple dilution and to octane considerations. This, EPA found, results in significant NO_x decreases, especially in vehicles with catalysts.

Research results. The Auto/Oil Air Quality Improvement Research Program (AQIRP) study in the United States tested the effects of adding 10 percent ethanol (3.5 wt. percent oxygen) and 15 percent MTBE (2.7 wt. percent oxygen) to industry average gasoline. For late-model gasoline vehicles with three-way catalysts, the ethanol addition results showed a net decrease in non-methane hydrocarbon (NMHC) and CO emissions of 5.9 percent and 13.4 percent, respectively, and a net increase in NO_X emissions of 5.1 percent. The MTBE addition results showed net decreases in NMHC and CO of 7.0 percent and 9.3 percent, respectively, and a net increase in NO_X emissions of 3.6 percent (Hochhauser and others, 1991). In tests performed in Mexico City, the addition of 5 percent MTBE to leaded gasoline was found to produce a 14.7 percent reduction in CO and an 11.6 percent reduction in HC emissions from non-catalyst gasoline vehicles.

Tests in Mexico City found that adding 5 percent MTBE to leaded gasoline produces reductions in CO and HC emissions from non-catalyst gasoline vehicles.

Mandating the use of oxygenates to reduce emissions. The State of Colorado (USA) initiated a program to mandate the addition of oxygenates (such as ethanol and MTBE) to gasoline in the Denver metropolitan area during winter months when high ambient CO tends to occur. The mandatory oxygen requirement for the winter of 1988 (January to March) was 1.5 percent by weight, equivalent to about 8 percent MTBE. For the following years, the minimum oxygen content required was 2 percent by weight, equivalent to 11 percent MTBE. These oxygen requirements were estimated to reduce CO exhaust emissions by 24-34 percent in vehicles already fitted with three-way catalyst systems. The success of this program led the U.S. Congress to mandate the use of oxygenated fuels (minimum 2.7 percent oxygen by weight) in areas with serious winter-time CO problems.

The U.S. Congress has mandated the use of oxygenated fuels in areas with serious winter-time carbon monoxide problems.

Evaporative emissions. Although exhaust HC emissions tend to be lower with oxygenate blended fuels, the use of alcohols as blending agents may increase evaporative emissions considerably. Because of their non-ideal behavior in solution, blends of ethanol or methanol with gasoline have higher vapor pressure than either component alone.

However, although mass HC emissions may increase from a higher Reid vapor pressure (RVP) caused by the use of ethanol, data indicate that the ozone-causing reactivity of the resulting emissions is less, thus resulting in no real ozone degradation.

Effects of oxygenates. The presence of oxygenates in the fuel changes the hydrocarbon composition of the exhaust and evaporative emissions. For gasoline containing 11 percent MTBE, exhaust MTBE emissions account for about 2.5 percent of total exhaust VOC emissions, and 8 to 10 percent of total evaporative emissions (California EPA, 1998). Formaldehyde emissions also tend to increase with MTBE, while emissions of benzene and 1,3 butadiene are reduced significantly. The use of ethanol in gasoline increases ethanol and acetaldehyde emissions, while also reducing emissions of benzene and 1,3 butadiene.

2.5.4 Impact On Soil, Groundwater, And Surface Waters

Unlike most hydrocarbons, both alcohols and ethers dissolve readily in water. Thus, where spilled gasoline comes in contact with water, the oxygenate can be expected to migrate from the gasoline into the water. This presents little problem in the case of the alcohols, as these have been shown to biodegrade fairly rapidly. In the case of MTBE and other ethers, however, this degradation appears to be slower, if it occurs at all.

Soil. Gasoline containing oxygenates is no more hazardous than ordinary gasoline when spilled on or leaked into soil. Indeed, because these oxygenates tend to replace more hazardous compounds such as benzene or TEL, spills of oxygenated gasoline will generally be less hazardous. In addition, alcohols in soil tend to biodegrade rapidly.

Groundwater. In a number of cases, leaking underground tanks containing MTBE-gasoline blends have resulted in the contamination of groundwater with MTBE. Although the level of health risk posed by this contamination appears to be small, the taste and odor of MTBE can be detected in water at concentrations as low as 50 parts per billion (ppb). The current EPA Drinking Water Advisory level for MTBE is 20 to 40 ppb, based on the taste and odor thresholds, and a 10,000-fold safety factor below the lowest observed adverse effect level in animals (California EPA, 1998).

Surface waters. MTBE contamination of surface waters has also been detected on occasion as a result of fuel spills into the water body. The use of two-stroke gasoline engines in outboard motors and personal watercraft has also contributed to contamination in some cases. These engines emit as much as 50 percent of the total fuel they consume in their exhaust, which is injected into the water. So far, the levels of surface water contamination due to this source have all been found to be well below the EPA advisory levels (California EPA, 1998). However, concerns about the potential for widespread contamination of drinking water sources with MTBE have led to calls for the use of MTBE in gasoline to be banned in California.

2.5.5 Health Risks Associated with MTBE

Chronic inhalation studies in animals suggest that MTBE may be weakly carcinogenic, with an estimated unit risk of 7.5×10^{-8} for mouse liver tumors and 1.7×10^{-7} for rat kidney tumors. For comparison, unit risk values for benzene and 1,3 butadiene – two other toxic air contaminants associated with gasoline – are 8.3×10^{-6} and 2.8×10^{-4}, respectively.

An analysis by the California Air Resources Board found that overall toxic risk from using reformulated gasoline containing MTBE was reduced by more than 40 percent compared to that to be expected from industry-average gasoline without MTBE (California EPA, 1998).

In California, concerns about the potential for widespread contamination of drinking water sources with MTBE has led to calls to ban the use of MTBE in gasoline.

2.6 MMT Properties And Performance

The only non-lead antiknock additive now offered commercially is methylcyclopentadienyl manganese tricarbonyl (MMT). Its manufacturer recommends the use of MMT concentrations up to 0.0165 grams of Mn (manganese) per liter in gasoline intended for non-catalyst vehicles, and half this concentration in gasoline intended for catalyst cars. At the 0.0165 gram per liter concentration, it adds about 1.9 octane numbers to gasoline. In the United States, MMT concentrations are limited to 0.00825 gram per liter to protect emission control systems.

The use of MMT as an octane-enhancing additive in gasoline is controversial, due to concerns over its possible effects on automotive emission control systems, and over the toxicity of the resulting manganese emissions. During the 1980s, when lead concentrations in U.S. gasoline were severely limited, MMT was used extensively to improve the octane rating of leaded gasoline. MMT was also used extensively in both leaded and unleaded gasolines in Canada.

MMT was not permitted in unleaded gasoline sold in the United States until 1996, when EPA lost a lawsuit filed by the manufacturer, Ethyl Corporation, after rejecting the company's application to approve MMT for unleaded gasoline use. EPA's disapproval was due to uncertainty over the potential toxic effects of manganese emissions. In its 1994 rejection of Ethyl's petition to approve MMT, EPA concluded that "*Although it is not possible based on the present information to conclude whether specific adverse health effects will be associated with manganese...[exposures resulting from the use of MMT]...neither is it possible to conclude that adverse health effects will not be associated with such exposures.*"[5] Auto manufacturers had also opposed the approval of MMT, arguing that it could impair the effectiveness of vehicle emission control systems. EPA concluded in its evaluation, however, that this was not the case.

With the U.S. court decision, and another decision in Canada overturning a ban on interprovincial trade in MMT, it can legally be used in unleaded gasoline in both the United States and Canada. EPA's administrator has stated, however, that a definitive risk evaluation is not possible until more data are collected, and that use of MMT in unleaded gasoline in the United States ought to be delayed until such data are collected (Browner, 1996). In determining the advisability of MMT use, or the use of any fuel or fuel additive, in any particular country or

[5] 59 FR 42260, August 17, 1994.

The time required to phase out lead in gasoline has ranged from a few months (e.g., Egypt) to more than 15 years (the United States).

regional setting, an assessment of health risk ought to be taken into consideration.

2.7 Lead Phaseout Strategies

Slow vs. fast phaseout. Different countries have taken different approaches to phasing out lead in gasoline, and have pursued very different schedules. The time required to phase out lead has varied from periods of more than 15 years in the United States to a few months in Egypt. In general, a slower phaseout schedule will reduce the costs of the lead phaseout to the refining industry, and give more time for any old cars that might suffer valve seat damage to retire from the fleet. However, it also means that more people are exposed to high lead concentrations for a longer time, and thus suffer from the adverse effects of lead on their health (and in the case of children, their mental development). In addition, vehicle maintenance costs tend to be higher with leaded than with unleaded gasoline, so that continuing the production of leaded fuel will mean higher maintenance costs.

Considering a range of scenarios. Because the costs and benefits of rapid vs. slow lead phaseout will vary from one country to another, implementers should consider a range of phaseout scenarios, including very rapid and less rapid reductions. In the short term, the feasible reduction in lead use is likely to be limited by the refining capacity available. It may take three to five years to design, finance, and upgrade or build the refinery process units required to produce high-octane unleaded blending components. In the meantime, some of the octane shortfall may be recovered by importing oxygenates such as MTBE, high-octane hydrocarbon blendstocks, or unleaded gasoline.

EPA recommends that lead phaseout be accomplished as quickly as possible. There are two main reasons for this. First, lead poisoning is one of the most important preventable diseases associated with urbanization. Although lead in gasoline represents only 2.2 percent of total global lead use, it remains by far the single-largest source of lead exposure in urban areas. Approximately 90 percent of all lead emissions into the atmosphere are due to the use of leaded gasoline. Second and most important, some of the health effects associated with lead poisoning, such as lowered IQ in children, cannot be reversed no matter how high the future investment.

The approach recommended here is first to reduce the lead content of leaded gasoline as quickly as possible, and then to eliminate leaded gasoline as quickly as possible thereafter.

Managing the transition to unleaded gasoline. Although it is sometimes possible to eliminate leaded gasoline overnight, more commonly some transition period is required. Two approaches have been taken to managing this transition. One approach has been to encourage refiners and vehicle owners to switch from leaded to unleaded fuel, without changing the lead content of leaded fuel. This approach has been typical of Western Europe. The second approach, followed in the United States and Mexico, has been to reduce the lead content of the leaded gasoline as quickly as possible, while providing enough completely unleaded gasoline to meet the needs of vehicles equipped with catalytic converters. This second approach (reducing the lead content of leaded fuel instead of shifting from leaded to completely unleaded fuel) has several advantages, and is recommended in most cases.

- *Lower total lead emissions.* As discussed in Section 2.2, the octane-improving effects of lead are not a linear function of lead concentration. The first 0.1 g/

liter of lead additive gives the largest octane boost, with subsequent increases in lead concentration giving progressively smaller returns.

- *Refining costs.* Reducing the lead content in leaded gasoline reduces the difference in refining costs between leaded and unleaded gasolines. This, in turn, makes it easier to adopt a policy taxing gasoline so as to set the pump price of unleaded gasoline lower than that of leaded gasoline. This policy is considered important to minimizing the chances of misfueling catalyst-equipped cars with leaded gasoline.
- *Improved public perception.* Another advantage of this approach is in the area of public relations. This is because no changes are required in consumer behavior, and the change in lead concentration is not visible at the gasoline pump. Since only a tiny amount of lead is required to prevent valve seat recession even in extreme cases, a change in lead concentration even to very low levels is unlikely to worry the public. For example, EPA's decision to limit lead to 0.1 g/gal (0.03 g/l) in 1986 reduced ambient lead concentrations by 90 percent, but was little noticed by the gasoline-buying public.

Of course, all countries should move to eliminate leaded gasoline entirely, and as quickly possible. This is most readily accomplished by leaving the change from leaded to unleaded for the end of the phase-out process, when there has been more opportunity to educate the public and when the elimination of most of the *economic* benefits from the use of lead will have reduced the motivation for vested interests to spread misinformation.

An example of near- and longer-term lead phaseout. Table 5 shows a simplified example of how octane requirements could be met while phasing out the use of lead additives. The example assumes that the existing gasoline market comprises equal shares of 85 RON leaded regular and 93 RON leaded premium gasoline, produced in a mix of topping and hydroskimming refineries. As the "existing situation" column shows, the regular gasoline is blended from a combination of straight-run naphtha and butane, with a "clear" RON (before the addition of lead) of 73.2. Adding 0.7 grams of lead per liter raises the octane rating by 12 numbers, to slightly more than 85 RON. The leaded premium gasoline is blended from a combination of straight-run gasoline, reformate, and butane, with a clear RON of 83.6. Adding 0.7 grams of lead per liter raises the RON by 10 numbers, to 93.6. The difference of two octane numbers between the octane boost from lead in the premium gasoline, compared to that produced by the same amount of lead in the lower-octane regular gasoline, is due to the reduced lead susceptibility of aromatics and naphthenes in the reformate.

This very simplified example shows the potential to reduce lead emissions substantially, even before new refinery process units can be brought on line.

The second, near-term column shows how the total lead in gasoline might be reduced within a relatively short period. In this example, the base regular gasoline is blended from the same components as before, but with the addition of 9 percent by volume of imported high-octane (97 RON) hydrocarbon components. These could be either alkylate or aromatics, or a combination of both (although alkylate would be preferred in order to minimize benzene emissions), and increase the octane value of the clear gasoline by 2.3 numbers. The resulting clear gasoline is then blended with 15 percent MTBE (contributing 7.1 octane numbers). The remaining shortfall of 2.5 octane numbers is made up by blending 0.1 gram of lead per liter, taking advantage of the non-linear relationship between lead and octane boost.

Table 6: Costs Of Phasing Out Lead In Gasoline — Hypothetical Case

	1998 Prices	Contribution of Gasoline Cost: Existing	Near Term	Long Term
Regular Gasoline 85 RON				
Gasoline 73 RON $/liter	$0.066	$0.066	$0.056	
Gasoline 85 RON $/liter	$0.090			$0.090
MTBE $/liter	$0.183		$0.027	
TEL $/gram Pb	$0.021	$0.015	$0.002	
High octane imports $/liter	$0.138		$0.011	
Total Cost		$0.080	$0.096	$0.090
Increase US$/liter			$0.015	$0.009
Premium Gasoline 93 RON				
Gasoline 84 RON $/liter	$0.088	$0.088		
Gasoline 87 RON $/liter	$0.094		$0.080	
Gasoline 93 RON $/liter	$0.106			$0.106
MTBE $/liter	$0.183		$0.027	
TEL $/gram Pb	$0.021	$0.015		
High octane imports $/liter	$0.138		$0.007	
Total Cost		$0.102	$0.114	$0.106
Increase US$/liter			$0.012	$0.003

3. ASSESSING LEAD PHASEOUT IMPACTS ON THE VEHICLE FLEET

Using lead additives in gasoline has many effects on a vehicle's engine, in addition to its effects on fuel octane level. Most of these effects are undesirable, including the corrosion of exhaust valve materials, the contamination of engine oil with corrosive acids, the fouling of spark plugs, and the corrosion of exhaust systems.

Gasoline lead does have one desirable effect, however: it serves as a lubricant between exhaust valves and their seats, helping to prevent excessive wear. In the absence of lead, older-technology engines can suffer from the rapid wear of the exhaust valve seats when operated at high speed for long periods of time. This phenomenon, known as *valve seat recession*, has been the subject of considerable misinformation and public concern, which in turn poses a serious obstacle to eliminating leaded gasoline in many countries. However, detailed studies and extensive practical experience in a number of countries show that the potential problems due to valve seat recession have been highly exaggerated and that use of low-lead or unleaded gasoline will result in longer engine life and lower maintenance costs overall.

Valve seat recession (where the exhaust valve seats of older engines that run without lead suffer rapid wear) is not as serious a problem as once thought. Low-lead or unleaded gasoline produces longer engine life and lower maintenance costs for these and other engine types.

> This chapter first describes the reasons underlying EPA's finding that the maintenance costs for vehicles using unleaded gasoline are less than those for vehicles using leaded gasoline.
>
> This conclusion has been supported by actual experience in countries using unleaded gasoline. In the United States, several studies covering thousands of vehicles found no maintenance problems that could be attributed to the effects of unleaded gasoline. Likewise, Brazil has not experienced such problems as valve seat recession, which have been commonly attributed to the use of unleaded gasoline.
>
> Last, the chapter shows how to calculate the maintenance cost savings resulting from the use of low-lead and unleaded gasoline. The results show that, for typical maintenance costs, using low-lead gasoline would result in savings of about US $550 over the life of a car; the total savings for unleaded fuel would be about $800.

The Steps In Assessing Lead Phaseout Impacts On The Vehicle Fleet

1. Assess maintenance benefits of unleaded gasoline

To assess the benefits of reducing or eliminating lead in gasoline for the vehicle fleet, implementers should quantify the frequency of occurrence and the costs of maintenance items such as spark plug changes, oil changes, valve repairs, valve seat repairs, and exhaust system replacements. The savings in maintenance costs due to lead phaseout can then be estimated using the information provided in Section 3.4.

2. Assess potential for valve seat damage

The implementer should also assess the potential for some engines to suffer valve seat damage.

3. Assess potential valve seat protection strategies

Next, implementers should assess the costs of potential valve seat protection strategies if these are indicated. (See Section 3.1.1 for some ways to protect valve seats.)

4. Evaluate net costs and savings for the vehicle fleet

The resulting net benefits or costs should then be calculated as functions of time for each of the lead phaseout strategies considered, in order to compare them with the other costs and benefits.

3.1 Lead's Role In The Engine

During the 1960s and 1970s, many technical papers discussed the effects of lead additives and unleaded fuels on engines. Weaver (1986) reviewed the literature through 1984, as well as a number of unpublished results of fleet experience using unleaded gasoline. The results of his review were cited in the EPA's 1985 cost-benefit study of lead phaseout, and provided the technical basis for its conclusion that the vehicle maintenance savings would outweigh the costs. The remainder of this section summarizes the results of that study.

3.1.1 Valve Seat Recession

The exhaust valves and valve seats of modern gasoline engines operate at high temperatures and under great mechanical stresses. When it closes, the valve strikes the seat with great force thousands of times per minute. Under high-speed and high-power output conditions, small "warts" of iron oxide may form on the valve. This results from segments of the valve seat welding to the valve upon impact, and then being torn loose when the valve opens. When these "warts" repeatedly strike against the valve seat, it causes deformation, cracking, and flaking of the seat, while the presence of hard iron oxide particles being scrubbed across the valve face causes abrasive wear. The resulting rapid wear of the valve seat can lead to a loss of compression and require major repairs to the engine in less than 10,000 km.

The presence of lead deposits on the valve seat appears to prevent the initial adhesion and welding that leads to valve seat recession. Only a small amount of lead is required to provide this protection: 0.02 grams per liter has been found to be effective in laboratory tests. A similar protective effect is obtained from deposits of other elements such as manganese (from MMT), phosphorus, zinc, and calcium (from engine oil). Valve seat recession can also be prevented by heat-treating the valve seat area to harden it, or by using valve seat inserts made of hard material. A hardness of approximately 30 on the Rockwell C scale is adequate to prevent valve seat recession.

Nearly all gasoline engines and replacement cylinder heads now produced in the world have hardened valve seats, and thus are not subject to valve seat recession. This applies generally to U.S. vehicles made after 1970, and European vehicles beginning in the early 1980s. Some older engines still in service may have soft valve seats, however, and could potentially experience valve seat recession.

Valve seat recession can occur in some older vehicles when they are subjected to prolonged high-speed operation, but the hardened valve seats manufactured after 1970 in the United States and the early 1980s in Europe protect against this problem.

Although valve seat recession can readily be produced in the engine laboratory, practical experience and a number of specific studies have shown that it is very uncommon in actual use. This is apparently because few gasoline vehicles (especially old ones) experience long periods of uninterrupted operation at high speeds and loads. There appears to be a threshold effect — a certain period of high-speed operation is required to wear through the deposit layer on the valve seat before recession can begin. Interrupting this period of high-speed operation with periods of lighter use may allow the deposit layer to re-form, prolonging engine life.

McArragher et al. (1993) reviewed a number of later studies and assessed the potential for valve seat recession due to lead phaseout in Europe. Like the EPA study, McArragher and his colleagues concluded that valve seat recession was likely only where vulnerable engines were subject to prolonged high-speed operation. They noted, however, that this was more likely in Europe, due to the smaller engines common there and the high speeds reached on autobahns and similar motorways. They also concluded that a minimum of 0.05 g/liter of lead would provide complete protection to the most vulnerable engines, even under the most extreme conditions. A potassium additive was found that gave complete valve seat protection at high concentrations and good protection at lower concentrations.

The McArragher team projected the fraction of surviving cars in Europe with soft seat valves potentially vulnerable to recession. This percentage was projected to drop from around 40 percent in 1990 to less than 20 percent by 1997. They pointed out as well that many of the "soft" seats were actually hard enough to be unlikely to suffer valve seat recession except under extreme conditions, so that the number of vehicles actually vulnerable to valve seat recession would be even less than what they projected.

In the minority of vehicles that experience valve seat recession, the problem can be corrected and kept from recurring. This is done either by replacing the cylinder head with a new one having hardened valve seats, or by machining out the valve seats in the old cylinder head and replacing them with hardened inserts. The cost of this operation is about US $500 in the United States, and is expected to be considerably less in most developing countries, which have lower labor costs.

In the minority of vehicles that experience valve seat recession, the problem can be corrected and kept from recurring.

3.1.2 Valve Corrosion And Guttering

Although lead deposits protect valve seats from accelerated wear, they can reduce the life of exhaust valves. At high temperatures, the lead oxide layer on the seat can attack the protective oxide layer on the valve, causing corrosion. This weakens the metal and can eventually cause "guttering" — the formation of a channel on the valve surface. Hot combustion gases escaping through this channel rapidly enlarge it, causing the valve to fail. A similar effect can occur when lead deposits build up too thickly on the valve seat. When these deposits flake, they can create a path for hot gases past the valve face.

Studies carried out for EPA found that using unleaded gasoline greatly reduces the number of valve-related repairs needed, more than offsetting any increase in repairs due to valve seat recession.

Measures to prevent lead deposit buildup were designed into engines intended for use with leaded gasoline. These include the use of valve rotators, greater spring loadings, and steeper valve seat angles. U.S. experience and a number of fleet studies have shown that the use of unleaded gasoline greatly reduces the number of valve-related repairs needed, more than offsetting any increase in repairs due to valve seat recession.

3.1.3 Oil Changes And Engine Life

Before unleaded gasoline was used, engine rusting was an important and widely studied problem. To prevent the excess buildup of lead deposits, leaded gasoline includes ethylene dichloride and ethylene dibromide to serve as "scavengers." The bromine and chlorine atoms introduced to the combustion chamber combine with the lead, forming compounds that are more easily removed. Unfortunately, chlorine and bromine also form corrosive hydrochloric and hydrobromic acids, respectively. Some of these acids get into the engine oil, where they will readily combine with any water that may be present to cause internal corrosion and rust.

To delay this phenomenon, engine oils contain special basic additives that react with the acids to neutralize them. Since the reaction consumes the additives, the oil must be changed at intervals to supply fresh additive. Reducing the lead content of the fuel reduces the corrosive burden on the lubricating oil, and allows oil change intervals to be extended.

Unleaded gasoline can extend engine life by reducing engine rust and the corrosive wear of piston rings and cylinder walls.

The lead scavengers used with leaded gasoline also contribute to corrosive wear inside the cylinder, especially wear of the piston rings. For example, taxi studies in the 1970s showed that corrosive wear of the piston rings and cylinder walls was 70 to 150 percent greater with leaded than unleaded fuel (Carey et al., 1978, Gergel and Sheahan, 1976). Switching to unleaded gasoline can thus be expected to extend engine life significantly.

3.1.4 Spark Plug Fouling And Replacement Frequency

Cars using leaded gasoline need spark plug replacements twice as often as those running on unleaded gasoline.

Lead deposits can foul spark plugs and contribute to chemical corrosion. The spark plugs used with leaded gasoline can suffer serious corrosion and require replacement generally within 20,000 km, while those used with unleaded fuel can go 40,000 km or more without replacement. As a result, the costs for spark plug replacement and servicing are much lower for vehicles using unleaded fuel. A study in Canada (Hickling Partners, 1981) concluded that spark plug maintenance costs would be reduced by about 49 percent with unleaded fuel.

3.1.5 Exhaust System Corrosion

Vehicle exhaust systems can corrode from both the inside and the outside. From the inside, the primary corrosion process is cold corrosion, which occurs when water condenses inside the exhaust system. Where leaded gasoline is used, this water is contaminated with hydrochloric and hydrobromic acids. Exhaust gas condensates in engines burning leaded gasoline typically have pH values in the range of 2.2 to 2.6, which is highly corrosive. The pH values of unleaded gasoline condensates are around 3.5 to 4.2.

Fleet tests comparing leaded and unleaded fuel show that vehicles using leaded gasoline require four to ten times as many replacements of exhaust system components. In warm climates, where road salt is not used, exhaust systems used with unleaded gasoline can be expected to last the life of the vehicle, while those used with leaded fuel require replacement about every 50,000 km.

Vehicles run on leaded gasoline need four to ten times as many replacements of exhaust system components as those running on unleaded gasoline.

3.2 U.S. Fleet Experience

As the preceding review has shown, the use of unleaded gasoline offers many advantages in terms of vehicle life and maintenance costs. However, these advantages are counterbalanced by a potential major disadvantage in engines not equipped with hardened valve seats: valve seat recession. For this reason, proposals to eliminate leaded gasoline have caused public concern.

The likelihood that valve seat recession will occur, and the consequences if it does occur, have often been exaggerated. The great body of in-use experience with unleaded gasoline, including its widespread use in vehicles without hardened valve seats, shows that the likelihood of valve seat damage due to unleaded fuel use is very small, while the overall savings in maintenance costs are generally substantial.

A number of controlled fleet studies were carried out in the 1960s to compare maintenance costs of vehicles running on leaded and unleaded gasoline. A study financed by Ethyl Corporation, a major lead additive supplier, showed that over a 5-year period, 4 out of 64 vehicles using unleaded gasoline required cylinder head replacement (1 vehicle required 2 replacements), compared to 1 out of 64 vehicles using leaded gasoline (Wintringham et al., 1972). However, the unleaded gasoline group required only 6 valve repairs, compared to 16 among the vehicles using leaded gasoline. Other studies conducted in the same time period showed that overall maintenance costs were lower with unleaded than leaded gasoline.

Engines in heavy-duty gasoline vehicles are more likely to undergo severe service than those in passenger cars, and thus might be expected to show an increased incidence of valve seat recession. This has not been the case, however. A major test conducted by the U.S. Army involved switching all of the vehicle fleets of three army posts to unleaded gasoline. This included some 7,600 vehicles (some dating from the 1940s), as well as many items of power equipment. The results of this test were definitively negative: *no* untoward maintenance problems were experienced that could be attributed to the effects of unleaded gasoline. The U.S. Army subsequently converted its entire establishment to unleaded gasoline without ill effects.

Analyses of 42 months of maintenance data for heavy-duty gasoline trucks used by the U.S. Postal Service (during which the trucks averaged 280,000 kilometers of service) showed that 4.2 percent of the trucks suffered valve failures and 1.2 percent suffered valve seat failures during that period (Weaver et al., 1986). The valve seat failure rate was comparable to that expected when using leaded gasoline, while the valve failure rate was significantly lower. Experience in numerous public utility truck fleets during the 1970s also showed no increase in valve- or valve seat-related problems with the use of unleaded fuel.

3.3 Worldwide In-Use Experience

In recent years, the use of leaded gasoline has been eliminated in a number of developing countries, including Brazil, Colombia, Egypt, Thailand, Guatemala, Costa Rica, and Argentina. Increased seat valve problems have not been observed in any of these countries.

The case of Brazil is especially important, given the size of its vehicle fleet. With the inclusion of 22 percent ethanol by volume in gasoline as part of the Proalcool program, lead additives were no longer needed, and Brazil began eliminating gasoline lead in 1979. It completed its lead phase-out in 1991 (Faiz et al., 1996). Despite the presence of large numbers of vehicles with soft valve seats, no significant or widespread problems have been experienced with valve seat recession.

3.4 Monetizing Maintenance Costs And Savings

An evaluation of the costs and benefits of phasing out lead in gasoline should include an estimate of the maintenance savings to vehicle owners. Table 7 shows a hypothetical example of such a calculation. The assumptions used in this example are outlined below.

Spark plug life. Here, the assumptions were that:

- The vehicle's useful life is 200,000 kilometers.
- The average interval between spark plug changes with leaded gasoline is 15,000 kilometers (if available, actual data on the average spark plug change interval in the area under consideration should be substituted instead).
- The average spark plug change interval will be doubled with unleaded gasoline, and extended by two-thirds using low-lead fuel (0.1 gram of lead per liter).

The lifetime costs are then the cost of a single spark plug change (estimated at US $20), multiplied by the number of spark plug change intervals over the vehicle's life, minus one (since the vehicle comes equipped with one set of plugs).

Engine overhauls. The number of engine overhauls required during the vehicle's lifetime was estimated at 1.0 with leaded gasoline, and 0.8 with low-lead or unleaded fuel. This is based on the much lower rates of piston ring wear, rusting, and corrosion with low- and zero-lead fuel.

Exhaust system replacements. The numbers of exhaust system replacements and valve repairs are based on the data of Wintringham et al., extrapolated to the full engine life. The number of exhaust system replacements with low-lead gasoline is assumed to be similar to that with high-lead fuel, as the critical factor is considered to be the presence of acids formed by the lead scavengers in the exhaust pipe, and not the amount of the acid present.

Cylinder head replacements. The number of cylinder head replacements is also based on the data of Wintringham et al., and reflects a pessimistic assumption that 20 percent of the vehicle fleet will suffer valve seat recession at some point during their useful lives when using unleaded gasoline. This is considerably higher than the observed rate of occurrence of this problem in the countries that have already phased out leaded gasoline.

Net maintenance savings. Adding up the total maintenance costs and savings in this hypothetical case suggests that the use of low-lead gasoline would result in savings of about US $557 over the life of a car, equivalent to about $0.033 per liter of gasoline used. For unleaded fuel, total savings would be $783, or about $0.047 per liter. These costs can be compared directly to the additional costs of producing the low-lead and unleaded fuels in a cost-benefit evaluation.

Table 7: Hypothetical Maintenance Cost Savings With Low-Lead And Unleaded Gasoline

	Gasoline Type		
Maintenance Item	**High Lead**	**Low Lead**	**Unleaded**
Vehicle life (km)	200,000	200,000	200,000
Spark Plugs			
Change interval	15,000	25,000	30,000
Change cost	$20	$20	$20
Lifetime cost	$247	$140	$113
Oil Change			
Change interval	4,000	6,000	8,000
Change cost	$12	$12	$12
Lifetime cost	$588	$388	$288
Engine Overhaul			
Total overhauls	1.0	0.8	0.8
Overhaul cost	$500	$500	$500
Lifetime cost	$500	$400	$400
Exhaust System Replacement			
Total replacements	3	3	1
Replacement cost	$80	$80	$80
Lifetime cost	$240	$240	$80
Valve Repairs			
Total number	0.5	0.2	0.2
Cost/repair	$500	$500	$500
Lifetime cost	$250	$100	$100
Cylinder Head Replacements			
Total number	0.1	0.1	0.3
Cost/repair	$300	$300	$300
Lifetime cost	$30	$30	$90
Total lifetime cost	$1,855	$1,298	$1,071
Saving compared to leaded		$557	$783
Total fuel used (l)	16,667	16,667	16,667
Saving per liter		$0.033	$0.047

4. ASSESSING LEAD PHASEOUT EFFECTS ON VEHICLE EMISSIONS AND AIR QUALITY

The changes in gasoline composition resulting from phasing out lead will affect the emissions of lead and other pollutants from gasoline-powered vehicles.

Phasing out lead will entail changes in gasoline composition, and these changes will affect the emissions of lead and other pollutants from gasoline-powered vehicles. For instance, increasing the aromatic hydrocarbon content of gasoline may increase emissions of benzene and other aromatics in exhaust and evaporative emissions. Changes in gasoline composition may also affect the photochemical reactivity of volatile organic compound (VOC) emissions, and thus affect the formation of ground-level ozone (photochemical smog).

In a number of cases, public concerns over these secondary effects have delayed lead phaseout programs. It is thus important that the potential secondary effects of lead phaseout be assessed and quantified as part of the phaseout plan, and that – where necessary – measures be taken to mitigate any adverse impacts. Such measures might include setting limits on or taxing the benzene, aromatic, and/or olefin content of fuels, and limiting vapor pressure to minimize evaporative emissions.

Lead phaseout also provides an opportunity for a more general review of emission control policies related to vehicles and fuels, such as the adoption of catalytic converters and/or evaporative emission controls, and limits on gasoline sulfur content. To the extent that such policies require changes in either the composition or the market shares of different fuels, they will affect investment plans in the refining and fuel distribution sectors. To avoid waste and confusion, it is best that they be adopted as an integrated package with the lead phaseout policy, rather than one at a time.

> This chapter first examines the effects of vehicle emission control technology on CO, HC, and NO_x emissions. It then discusses the emission standards in effect in North America and Europe, which implementers should consider incorporating in their own countries' lead phaseout strategies.
>
> Next, the studies examining the differences in emissions between leaded and unleaded gasoline in vehicles without catalytic converters are examined. The chapter concludes with a discussion of the rationale for considering the inclusion of regulations that reduce sulfur, fuel volatility, olefins, aromatics and benzene when establishing a lead phaseout program.

4.1 Emission Control Technologies For Gasoline Vehicles

In addition to lead emissions from leaded gasoline, gasoline engines in cars, light-duty trucks, and motorcycles are responsible for more than 90 percent of the carbon monoxide (CO) emissions and substantial fractions of the emissions of unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) in most large cities. Carbon monoxide is a poisonous gas, and exposure to it may increase the risk of heart attack in persons with existing cardiovascular disease. HC emissions include cancer-causing organic chemicals such as benzene and 1,3 butadiene. HC

The Steps In Assessing Lead Phaseout Effects On Vehicle Emissions And Air Quality

1. **Assess gasoline composition effects on emissions and air quality**

Implementers should assess and quantify the potential secondary effects of lead phaseout on emissions and air quality.

2. **Assess the need for policies affecting gasoline composition**

Where necessary, implementers should specify measures to mitigate any adverse impacts resulting from changes in gasoline composition. Such measures might include setting limits on or taxing the benzene, aromatic, and/or olefin content of fuels, and limiting vapor pressure to minimize evaporative emissions.

3. **Consider vehicle emission control policy**

Implementers should conduct a general review of emission control policies for vehicles and fuels, such as the adoption of catalytic converters and/or evaporative emission controls, and limits on gasoline sulfur content.

and NO_x also react in the presence of sunlight to form ozone and other photochemical oxidants, the main ingredients in photochemical smog. Ozone is an irritant gas with effects that include increased risk of asthma attacks, respiratory illness, and death. Most large cities worldwide exhibit unhealthy levels of carbon monoxide, ozone, or both.

Modern technologies can reduce CO, HC, and NO_x emissions from new gasoline vehicles by more than 90 percent compared to those of vehicles without emission controls.

With modern emission control technology, emissions of CO, HC, and NO_x from new gasoline vehicles can be reduced by more than 90 percent compared to the levels typical for vehicles without emission controls. The emission control system used to achieve this reduction has three main components: a three-way catalytic converter, an electronic fuel injection system, and an electronic engine control system incorporating a lambda sensor (air-fuel ratio sensor) for feedback control of the air-fuel ratio.

Both catalytic converters and lambda sensors depend on catalytic reactions, and both require the use of unleaded gasoline. Otherwise, lead compounds in the exhaust will rapidly coat the active surface of the catalyst, blocking contact between the catalyst and the exhaust gas. This was the original reason for mandating the sale of unleaded gasoline in the United States in 1975, and subsequently in other countries. At that time, the health dangers of lead aerosol contamination were not as well understood as they are today.

The benefits of phasing out lead in gasoline do not depend on whether catalyst-forcing emission standards are adopted or not. The decision to phase out lead in gasoline should not be delayed while this question is debated.

The decision to phase out lead in gasoline is fully justifiable on health grounds, whether or not a government also chooses to adopt emission standards for HC, CO and NO_x emissions that require the use of catalytic converters. Once the decision is taken to phase out lead, however, it removes a major roadblock to adopting such standards. The decision on whether to adopt strict emission limits for HC, CO, and NO_x can then be considered on its own merits, taking into account both the costs and the benefits of such controls. Proper evaluation of the costs, benefits, and feasible schedule for implementing vehicle emission controls can be time consuming. It is important to emphasize, therefore, that the benefits of phasing out lead in gasoline do not depend on whether catalyst-forcing emission standards are adopted or not, and the decision to phase out lead in gasoline should not be delayed while this question is debated.

4.2 Systems Of Emission Standards

If a nation or other jurisdiction does decide to require gasoline vehicles to meet emission standards, it will have to face the question of what emission standards to adopt. It is very costly and time consuming for vehicle manufacturers to develop unique emission control systems. Therefore, considerations of economies of scale, the lead-time required, the cost to vehicle manufacturers to develop unique emission control systems, and the cost to governments of establishing and enforcing unique standards all argue for adopting one of the sets of international emission standards and test procedures already in wide use.

The main international systems of vehicle emission standards and test procedures are those of North America and Europe. North American emission standards and test procedures were originally adopted by the United States, which was the first country to set emission standards for vehicles. Under the North American Free Trade Agreement, these standards have also been adopted by Canada and Mexico. Other countries and jurisdictions that have adopted U.S. standards and/or test procedures include Argentina, Brazil, Chile, Taiwan, Hong Kong, Australia, the Republic of Korea, and Singapore (for motorcycles only). The standards and test procedures established by the United Nations Economic Commission for Europe are used in the European Union, a number of former Eastern bloc countries, and some Asian nations. Japan has also established a set of emission standards and testing procedures that have been adopted by some East Asian countries as supplementary standards.

Economies of scale, the costs to governments and vehicle manufacturers, and other factors argue for adopting a set of international emission standards and test procedures, rather than developing standards and test procedures that are unique to one country.

U.S. and European emission standards and test procedures are described by Faiz et al. (1996) in a publication by the World Bank. Updated information as of mid-1998 was included in another report prepared under contract to the U.S. Agency for International Development (Chan and Weaver, 1998). Generally, gasoline passenger cars and light-duty trucks in Europe and North America use very similar technologies, and are certified to similar emission levels. Vehicles meeting each set of standards (and sometimes both) are readily available on the world market.

With this in mind, countries may wish to maximize their access to international automotive markets by allowing vehicles to comply with either North American or European emission standards. Thus, vehicles could be allowed if they were certified either to the current European emission standards for passenger cars and light-commercial vehicles (contained in EU directive number 96/69/EC) or to U.S. Tier 1 emission standards as defined in the U.S. Code of Federal Regulations (40 CFR 86, Part B). The cost of meeting either of these sets of emission standards is estimated to be on the order of US $1,000 per vehicle compared to a vehicle without emission controls. This cost would be partly offset by an improvement in fuel economy of approximately 10 percent due to the use of electronic fuel injection with electronic management of air-fuel ratio and spark timing.

The incremental cost of meeting international emission standards can be partly offset by improvements in fuel economy from electronic fuel injection with electronic management.

Incorporating emission control technologies and new-vehicle emission standards into vehicle production is a necessary, but not a sufficient, condition for achieving low emissions. Measures are also required to ensure the durability and reliability of emission controls throughout the vehicle's lifetime. Low vehicle emissions at the time of production do little good if low emissions are not maintained in service. To ensure that vehicle emission control systems are durable and reliable, countries such as the United States have programs to test vehicles in service, and recall those that do not meet emission standards. Vehicle emission warranty requirements have also been adopted to protect consumers. It is recommended that countries seek the advice of specialists in this field to aid them in designing effective and cost-effective emission control programs. The International Activities Branch of the U.S. EPA's Office of Mobile Sources, located in Ann Arbor, Michigan, USA, may be able to offer advice in this area.

4.3 Effect Of Leaded Vs. Unleaded Gasoline

A number of studies examined the differences in emissions between leaded and unleaded gasoline in vehicles without catalytic converters. Existing studies were summarized by the Coordinating Research Council (1970) and by Weaver (1986). The Council's summary found that stabilized HC emissions were reduced by 5 to 17 percent using unleaded gasoline compared to leaded fuel in consumer-type driving tests, and by an even larger fraction in accelerated mileage accumulation schedules.

Studies have found that using unleaded gasoline reduces hydrocarbon emissions by 5 to 17 percent over leaded fuel.

Weaver (1986) describes the reason for these differences. With leaded gasoline, lead deposits in the combustion chamber develop over time. These take longer to develop with low-lead gasoline, but eventually build up to the same level. The unburned fuel-air mixture trapped in this deposit layer does not burn, and later contributes to HC emissions when it is swept into the exhaust along with the burned charge. With unleaded fuel, deposits consist of carbon rather than lead, and are much more variable. A period of high-load operation can reduce deposit levels considerably, and overall deposit levels are lower, on average. These lower deposit levels result in lower hydrocarbon emissions.

The presence of tetra-ethyl lead acts as a combustion inhibitor, and this may also contribute to increasing hydrocarbon emissions. For example, in studies by the Instituto Mexicano del Petroleo (1994), the average of 28 vehicles tested in back-to-back tests on leaded, low-lead, and unleaded gasoline showed lower HC emissions as gasoline lead content was reduced (Table 8). Benzene and 1,3 butadiene emissions using low-lead and unleaded fuel were less than with leaded gasoline, despite slightly higher benzene and aromatic content in the unleaded fuel. Tests by CSIRO in Australia (Duffy et al., 1998) also showed that emissions of benzene and 1,3 butadiene were reduced using unleaded gasoline (Table 9).

In actual consumer use, the difference in HC emissions between vehicles using leaded and unleaded fuel is likely to be much greater than in these controlled studies. This is due to the effect of lead on spark plug replacement requirements. All of the controlled studies included routine maintenance, which would have included timely spark plug changes. In the real world, however, spark plug replacement is often delayed until misfire develops. Since spark plugs require changing at much shorter intervals when leaded gasoline is used, vehicles using leaded gasoline are more likely to be operating with one or more cylinders misfiring due to fouled plugs. The increase in HC emissions due to misfire is very large compared to the typical emissions from properly functioning vehicles.

Table 8: Comparison Of Pollutant Emissions Using Leaded, Low-Lead, And Unleaded Gasoline In Vehicles Without Catalytic Converters

	Baseline	Ref. Nova	Nova A
RON	81.7	81.1	81.5
MON		77.2	77.3
Composition			
Paraffins	57.3%	56.4%	54.4%
Olefins	10.0%	7.9%	8.8%
Naphthenes	10.2%	11.4%	11.4%
Aromatics	18.1%	17.3%	18.4%
Benzene	1.4%	1.3%	1.3%
MTBE	5.0%	7.0%	7.0%
TEL g/l	0.37	0.19	0.0
Emissions (g/km)			
CO	31.7	30.4	30.0
HC	2.95	2.9	2.8
NOx	1.50	1.53	1.52
Toxic Air Contaminants (mg/km)			
1,3 Butadiene	87.56	85.45	81.50
Benzene	82.61	76.4	79.7
Formaldehyde	78.72	85.1	83.0

Source: Instituto Mexicano de Petroleo (1994).

Table 9: Toxic Air Contaminant Emissions Using Leaded And Unleaded Gasoline

	Leaded	Unleaded
RON	91.3	96
Composition		
Paraffins + naphthenes	43.7%	45.0%
Olefins	5.2%	6.8%
Aromatics	42.8%	40.5%
Benzene	5.7%	5.0%
TEL g/l	0.37	0.0
Toxic Air Contaminants (mg/km)		
1,3 Butadiene	15.5	14.00
Benzene	146.6	122.8

4.4 Effect Of Gasoline Properties And Composition on Emissions

In establishing programs to phase out lead in gasoline, implementers may also want to consider the desirability of other regulations on gasoline composition and properties. The potential reduction in HC and CO emissions due to the inclusion of oxygenated compounds such as MTBE and ethanol was discussed in Section 2.5. Other gasoline properties that may be of interest for pollution reduction purposes include its sulfur content, the content of benzene and other aromatic hydrocarbons, olefin content, and volatility, as measured by Reid vapor pressure.

When establishing lead phaseout programs, implementers should consider developing other regulations on gasoline composition and properties.

4.4.1 Sulfur

Sulfur in gasoline is undesirable for several reasons. The most important of these is that, in vehicles with catalytic converters, sulfur binds to the precious metal catalyst under rich conditions, temporarily poisoning it. Although this poisoning is reversible, the efficiency of the catalyst is reduced while operating on high-sulfur fuel. A 1981 study by General Motors (Furey and Monroe, 1981) showed emissions reductions of 16.2 percent for HC, 13.0 percent for CO, and 13.9 percent for NO_x with aged catalysts in going from fuel containing 0.09 percent sulfur to 0.01 percent. An even larger percentage reduction was seen in vehicles with relatively new catalysts.

Similar results have been reported from modern fuel-injected vehicles with three-way catalysts, tested as part of the Auto/Oil Cooperative Study in the United States (1992). This study showed that reducing fuel sulfur content can contribute directly to reductions in mass emissions (HC, CO, and NO_x), toxic emissions (benzene, 1,3-butadiene, formaldehyde, and acetaldehyde), and potential ozone formation. The Auto/Oil sulfur reduction study used test fuels with nominal fuel sulfur levels of 50, 150, 250, 350, and 450 ppm in 10 late-model vehicles. Reductions in HC, NMHC, CO, and NO_x were 18, 17, 19, and 8 percent, respectively, when fuel sulfur level was dropped from 450 ppm to 50 ppm. Reducing the fuel sulfur level also reduced benzene emissions by 21 percent and acetaldehyde emissions by 35 percent. Formaldehyde emissions were *increased* by 45 percent, while 1,3-butadiene changes were insignificant.

In addition to its effects on catalyst efficiency, sulfur in gasoline contributes directly to SO_2, sulfate, and H_2S emissions, and indirectly to the formation of sulfate particles in the atmosphere. These particles are a significant contributor to ambient concentrations of fine particulate matter (PM2.5), which has recently been shown to have strong links to human health and mortality. Under lean conditions, fuel sulfur forms particulate sulfates and sulfuric acid in catalytic converters. Under rich conditions, hydrogen sulfide is formed by the reduction of SO_2 and sulfates stored on the catalyst substrate. The strong offensive odor of H_2S in the exhaust contributes to a public perception that catalysts "don't work," and may lead to increased tampering with emission controls.

4.4.2 Volatility

Fuel volatility, as measured by Reid vapor pressure (RVP), has a marked effect on evaporative emissions from gasoline vehicles, both with and without evaporative emission controls. In tests performed on European vehicles without evaporative emission controls, it was found that increasing the fuel RVP from 62 to 82 kilopascals (kPa) roughly doubled evaporative emissions (McArragher et al., 1988). The percentage effect is even greater in controlled vehicles. In going from 62 to 81 kPa RVP fuel, average diurnal emissions in vehicles with evaporative controls increased by more than 5 times, and average hot-soak emissions by 25-100 percent (U.S. EPA, 1987). The large increase in diurnal emissions from controlled vehicles is due to saturation of the charcoal canister, which allows subsequent vapors to escape to the air. Vehicle refueling emissions are also strongly affected by fuel volatility. In a comparative test on the same vehicles (Braddock, 1988), fuel with 79 kPa RVP produced 30 percent greater refueling emissions than gasoline with 64 kPa RVP (1.45 vs. 1.89 g/litre dispensed).

In response to data such as these, EPA has established nationwide summertime RVP limits for gasoline. These limits are 7.8 pounds per square inch (PSI) (4 kPa) in warm-climate areas and 9.0 PSI (62 kPa) in cooler regions. Still lower RVP levels will be required in "reformulated" gasoline sold in areas with serious air pollution problems.

An important advantage of gasoline volatility controls is that they can affect emissions from vehicles already produced and in use, and from the gasoline distribution system. Unlike new-vehicle emissions standards, it is not necessary to wait for the fleet to turn over before they take effect. The emissions benefits and cost-effectiveness of lower volatility are greatest where few of the vehicles in use are equipped with evaporative controls. Even where evaporative controls are in common use, as in the United States, the control of volatility may still be beneficial to prevent in-use volatility levels from exceeding those for which the controls were designed.

An important advantage of gasoline volatility controls is that they can affect emissions from vehicles that are already in use and from the gasoline distribution system.

In its analysis of the RVP regulation, EPA (1987) estimated that the long-term refining costs of meeting a 62 kPa RVP limit throughout the United States would be approximately US $0.0038 per liter, assuming crude oil at $20 per barrel. These costs were largely offset by credits for improved fuel economy and reduced fuel loss through evaporation, so that the net cost to the consumer was estimated at only $0.0012 per liter.

Gasoline volatility reductions are limited by the need to maintain adequate fuel volatility for good vaporization under cold conditions. Otherwise, engines will be difficult to start. Volatility reductions below about 58 kPa have been shown to impair cold starting and driveability, and increase exhaust VOC emissions somewhat, especially at lower temperatures. For this reason, volatility limits are normally restricted to the warm months, in which evaporative emissions are most significant. The range of ambient temperatures encountered must also be considered in setting gasoline volatility limits.

4.4.3 Olefins

Olefins, or alkenes, are a class of hydrocarbons that have one or more double bonds in their carbon structure. Examples include ethylene, propylene, butene, and 1,3 butadiene – a powerful carcinogen. Olefins in gasoline are usually created by the refining process of cracking naphthas or other petroleum fractions at high temperatures. Olefins are also created by partial combustion of paraffinic hydrocarbons in the engine. Compared to paraffins, olefins have extremely high ozone reactivity. Because of their higher carbon content, they also have a slightly higher flame temperature than paraffins, and thus NO_x emissions may be increased somewhat. It has been shown (Duffy et al., 1998) that the evaporation of 1,3 butadiene in gasoline contributes to ambient levels of this toxic air contaminant.

The Auto/Oil study in the United States examined the impacts of reducing olefins in gasoline from 20 percent to 5 percent by volume (Hochhauser and others, 1991). The results show that while there tends to be a slight reduction in NO_x emissions from both current and older catalyst-equipped vehicles, VOC emissions tend to rise in both vehicle classes. This was ascribed to the fact that a reduction in olefin content implies an increase in the paraffins. The olefins react much more readily in a catalytic converter than do paraffins. Increasing the paraffin content of the fuel therefore tends to reduce the overall VOC efficiency of the catalytic converter. The result of this change is higher paraffinic VOC emissions (which have substantially reduced reactivity in comparison to olefinic VOC emissions) and an associated reduction in vehicle exhaust reactivity.

4.4.4 Aromatics And Benzene

Aromatic hydrocarbons are hydrocarbons that contain one or more benzene rings in their molecular structure. In order to meet octane specifications, unleaded gasoline normally contains about 30-50 percent aromatic hydrocarbons. Aromatics, because of their high carbon content, have slightly higher flame temperatures than paraffins, and are therefore thought to contribute to higher engine-out NO_x emissions. Aromatics in the engine exhaust also raise the reactivity of the exhaust VOC because of the high reactivity of the alkyl aromatic species such as xylenes and alkyl benzenes. Reducing the content of aromatic hydrocarbons in gasoline has been shown to reduce NO_x emissions, exhaust reactivity, and benzene emissions.

An EPA study of toxic air contaminant emissions from mobile sources (EPA, 1993) gives a regression equation relating the fraction of benzene in the exhaust hydrocarbons to the benzene and aromatic content of the fuel. For vehicles without catalytic converters, this fraction is given as

$$\text{Benzene as \% of total HC} = 0.86\,(\text{vol \% benzene}) + 0.12 \times (\text{vol \% aromatics}) - 1.16$$

It is recommended that appropriate limits on the benzene and aromatic content of gasoline be adopted at the same time as the lead phasedown program.

Evaporative and exhaust emissions of benzene are of significant public concern because benzene is a probable (albeit fairly weak) human carcinogen. In a number of cases, exaggerated concerns of supposed increases in benzene emissions due to lead phaseout have been allowed to delay lead phaseout programs. As Chapter 5 will demonstrate, the risks of even a very large increase in vehicular benzene emissions would be much less than the risks from lead. Even the relatively small risks due to benzene may be worth mitigating, however, if only to reduce public anxiety and potential delays in the lead phaseout program. Implementers may thus wish to consider establishing limits on both the benzene and total aromatic concentrations in gasoline.

As discussed in Chapter 2, increasing the aromatic content of gasoline by catalytic reforming is one of the most important octane-enhancing processes in the refinery. With advance planning, however, the increase in aromatic content due to lead phaseout can be minimized by emphasizing other octane-enhancing processes such as isomerization, alkylation, and blending of ethers. In addition, the benzene content of the aromatic fraction can be reduced considerably by using special reformer catalysts tailored to produce other aromatics, and by processes that either remove the benzene for sale as a petrochemical or chemically destroy it by converting it to non-toxic compounds such as cyclohexane. In order to minimize the cost impact on refiners, it is important that these considerations be taken into account at the time the refinery is upgraded to increase its octane capacity. Thus, it is recommended that appropriate limits on the benzene and aromatic content of gasoline be adopted at the same time as the lead phasedown program.

5. ASSESSING THE HEALTH BENEFITS OF LEAD PHASEOUT

Reducing or eliminating lead aerosol emissions through the use of unleaded gasoline can be expected to decrease lead concentrations in ambient air, dust, and other media. This, in turn, will lessen human exposure to lead and the resulting adverse health effects.

> This chapter presents data and a methodology for estimating the reduction in the average lead concentrations in human blood to be expected as a result of reducing or eliminating lead in gasoline.
>
> Given this information, dose-response relationships derived from epidemiological data can be used to estimate the change in the incidence of high blood pressure, cardiovascular illness, and other health outcomes due to a given lead phaseout scenario. Examples of these calculations are also presented in this chapter. Finally, this chapter presents an approach for calculating the monetary value attributable to these benefits.

In comparing the costs of reducing lead in gasoline with the resulting health benefits, it is often useful to express the health benefits in monetary terms. The value to society of preventing a case of lead-related illness or premature death can be estimated based on treatment costs, lost productivity, and people's willingness to pay to reduce the risk of such consequences as premature death. This chapter presents the bases for developing such estimates.

The Steps In Assessing The Health Benefits Of Lead Phaseout

1. Estimate the air quality impact of lead and lead alternatives
To assess the health benefits of reducing or eliminating lead emissions, the implementer should estimate how the distribution of lead concentrations in ambient air and in human blood will change in response to changes in gasoline lead concentrations. To relieve public concerns about these issues, the implementer should also estimate the effect of the resulting changes in gasoline composition on emissions of toxic air contaminants such as benzene and 1,3 butadiene.

2. Conduct a risk assessment for lead and lead alternatives
Given the estimated change in lead concentrations, coefficients derived from epidemiological studies of health outcomes as functions of blood lead concentration can be used to estimate the change in the risks of hypertension, impacts on children's health, cardiovascular illness, neurodevelopmental problems, and premature death due to a given reduction in lead emissions. Similarly, published factors on unit risk can be used to estimate the potential change in cancer incidence due to changes in toxic air contaminant emissions.

3. Assess the public health benefits of phasing out lead
The change in individual risk is multiplied by the population affected to give the total public health impacts of a given lead phaseout scenario.

4. Conduct an economic valuation of public health benefits
In comparing the health benefits with the costs of reducing lead in gasoline, it is often useful to express the health benefits in monetary terms. The value to society of preventing a case of lead-related illness or premature death can be estimated based on treatment costs, lost productivity, and people's willingness to pay to reduce the risk of premature death and other adverse consequences.

5.1 Emissions Vs. Ambient Concentrations

Ambient lead concentrations resulting from lead emissions in a given area such as a city are proportional to the quantity of leaded gasoline consumed in that area. The resulting ambient lead concentrations will depend on the:

- Quantity of leaded gasoline consumed.
- Proximity of the particular monitoring site to heavy concentrations of road traffic.
- Local meteorological conditions, which will determine the rate and extent of dispersion of the lead aerosol.

Table 10 compares the estimated lead emissions for seven of the world's megacities with their average lead concentrations. As this figure shows, the ratio of average lead concentrations to emissions is remarkably constant, averaging about 0.002 $\mu g/m^3$ per ton of lead emitted in the urban area per year. Surprisingly, this ratio does not appear to be much affected by variations in the size of the urban area, possibly because (except for London) heavy traffic concentrations and lead monitoring sites may tend to be concentrated in a much smaller region.

Table 10: Lead Emissions Vs. Ambient Concentration For A Selection Of World Megacities

City	Date	Lead Emissions (tons/year)	Avg. Lead Conc. ($\mu g/m^3$)	Ratio
Mexico City	1988	1400	2.8	0.0020
	1993	210	0.6	0.0029
Bangkok	1990	598	1.245	0.0021
	1992	182	0.44	0.0024
	1993	160	0.33	0.0021
	1994	110	0.185	0.0017
	1995	75	0.16	0.0021
	1996	25	0.08	0.0032
Delhi		600	0.52	0.0009
Cairo		1200	2.5	0.0021
London		525	0.3	0.0006
Manila	1992	689	1.45	0.0021
Jakarta		520	1.1	0.0021

Sources: Wangwongwatana (1998), WHO (1992), Romieu (1995).

If a large industrial source of lead is not located in the area being monitored, it is likely that over 90 percent of lead aerosol in the atmosphere is coming from leaded gasoline combustion.

In the absence of a significant industrial source such as a primary or secondary lead smelter or a steel mill, more than 90 percent of the ambient lead aerosol measured is likely to be attributable to leaded gasoline combustion. Reducing the total mass of lead used in gasoline will likely produce a nearly proportional reduction in lead aerosol concentrations in the atmosphere.

To estimate the change in ambient lead concentration that would result from reducing or eliminating lead in gasoline, it is best to rely on local monitoring data, if available. If measurements of ambient lead concentration are not available, then the data shown in Table 10 can be used to develop a first approximation. Multiplying the lead content of gasoline (in grams per liter) by annual leaded gasoline consumption in an urban area (in millions of liters) will give the annual lead emissions in tons. Multiplying this value by 0.002 μg/m^3-ton will give an order-of-magnitude estimate of the lead aerosol concentration caused by leaded gasoline use.

5.2 Ambient Concentration Vs. Blood Lead Concentration

A number of studies and reviews have examined the relationship between changes in the lead concentration in ambient air and the resulting change in average blood lead concentrations in children and adults. These include studies by the World Health Organization (WHO, 1995), the U.S. Environmental Protection Agency (1986), and the California Office of Environmental Health Hazard Assessment (OEHHA) (Ostro et al., 1997). These reviews generally concur in finding that this relationship is non-linear; it has a relatively high slope at low ambient lead levels, and a decreasing slope as the lead concentration increases.

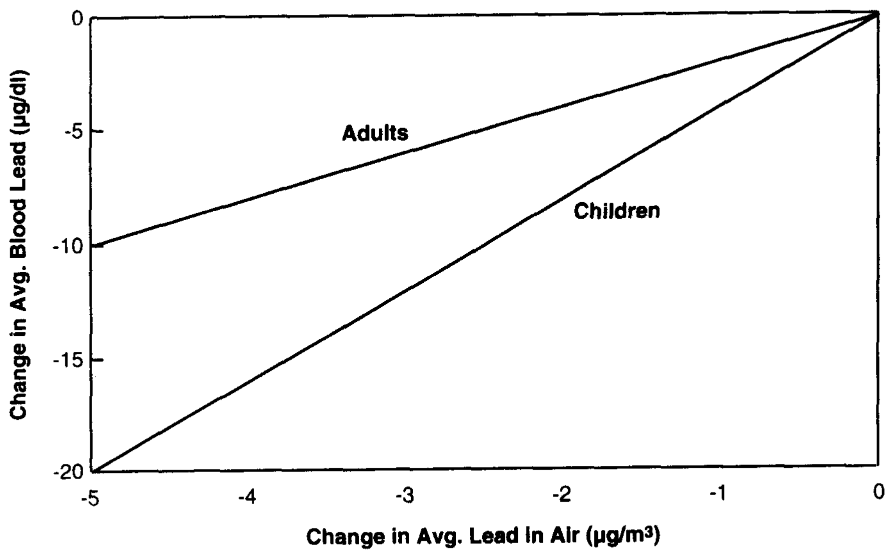
Most of the available data linking blood lead concentrations to lead concentrations in ambient air are based on studies in developed nations with temperate climates (such as the United States, United Kingdom, the Netherlands, and Australia) and where ambient lead concentrations were between 0.5 and 10 μg/m^3. The lead concentration in most urban atmospheres lies toward the lower end of this range. Although individual studies have shown a wide range of relationships, the WHO, EPA, and OEHHA reviews concur that – for the range of lead concentrations typical of non-occupational exposures — the relationship of blood lead to lead in ambient air can be approximated as a linear function. For adults, the slope of this function is approximately 2 μg/dl of lead in blood per μg/m^3 of lead in ambient air. For children, the slope lies between 3 and 5 μg/dl of lead in blood per μg/m^3 of lead in ambient air, with a best estimate value of approximately 4. Thus, a reduction in average ambient lead concentration of 1.0 μg/m^3 can be expected to produce a reduction in the average blood lead concentration of 2 μg/dl for adults and 4 μg/dl for children. The half-life of lead in blood is about 36 days (WHO, 1995), so that average blood lead concentrations can be expected to respond to changes in ambient lead levels within two months.

Lead can be absorbed by the body directly through inhalation or indirectly through lead aerosol settling on floors, cooking utensils, and other surfaces.

The blood lead/air lead relationships shown in Figure 10 account both for lead absorbed directly (as a result of inhalation) and indirectly (as a result of lead aerosol settling on floors and other surfaces, cooking and eating utensils, etc.). Based on direct inhalation alone, the blood lead to air lead ratio would be around 1.6 for adults and 2.0 for children. Young children are subject to much greater indirect exposure than adults because of their tendency to play on the floor, and to put their hands and other things in their mouths. Boys also tend to exhibit higher blood lead concentrations than girls, possibly because they spend more time playing outside.

Implementers should bear in mind that the average blood lead concentration in a given population is a function not only of the lead concentration in ambient air, but also of total lead exposure through other media such as food, water, and dust or chips from lead paint. Where lead exposure through other media is high, the incremental lead absorption due to lead in the air is likely to be less. Conversely, where people are less exposed to lead through other media, their blood lead concentrations may be more sensitive to lead concentrations in the air.

Figure 10: Expected Change In Average Blood Lead Concentration Due To A Change In Lead Concentration In Ambient Air



These blood lead/air lead relationships are based on population studies conducted mostly in developed nations with relatively cold climates, in which people tend to spend most of their time indoors, where there is relatively little interchange between indoor and outdoor air, where children are unlikely to spend much time on or near busy streets, and where anemia and malnutrition are uncommon. Each of these factors would tend to reduce the slope of the blood lead/air lead relationship. It is therefore very likely that the factors given here substantially underestimate the slope of the blood lead/air lead relationship in many developing countries, where people are likely to spend more time outdoors on busy streets, and where there is more interchange between indoor and outdoor air.

It is also important to note that these blood lead/air lead relationships reflect only the short-term effects of reducing ambient lead concentrations, and not the reduction in the long-term accumulation of lead in soil and croplands due to reducing overall lead emissions. Again, this means that these calculations will tend to understate the long-term benefit of reducing lead emissions, as they do not account for the long-term reduction in lead concentrations, and thus lead from food and soil due to reducing lead emissions to the air.

5.3 Estimating The Reduction In Blood Lead Due To Lead Phaseout

To estimate the reduction in blood lead concentrations from phasing out lead in gasoline, one must first calculate total lead emissions, and then relate these to ambient air monitoring data. Gasoline lead emissions (in tons) are equal to the product of leaded gasoline consumption (in millions of liters) and the lead concentration in leaded gasoline (in grams per liter).

Table 11 shows a hypothetical example. Leaded gasoline sales are 1000 million liters per year, with a lead concentration of 0.7 grams per liter, resulting in lead emissions of 700 tons per year. The ambient lead concentration is 1.4 µg/m^3. Reducing the lead content to 0.15 gram per liter would reduce annual lead emissions by 550 tons, and would be expected to reduce the average ambient

When people have high exposure to other sources of lead (for example, indirect exposure or exposure through food or lead paint), their absorption of lead in the air is likely to be less. And when they are less exposed through other media, their blood lead concentrations may be more sensitive to lead in the air.

Most of the studies done on the blood lead/air lead relationship were conducted in developed countries, where people tend to spend less time outdoors. For this and other reasons, the blood lead/air lead relationship's slope may be higher in developing nations.

These studies also do not account for the long-term effects of reducing lead in soils, and may thus understate the long-term benefits of reducing lead.

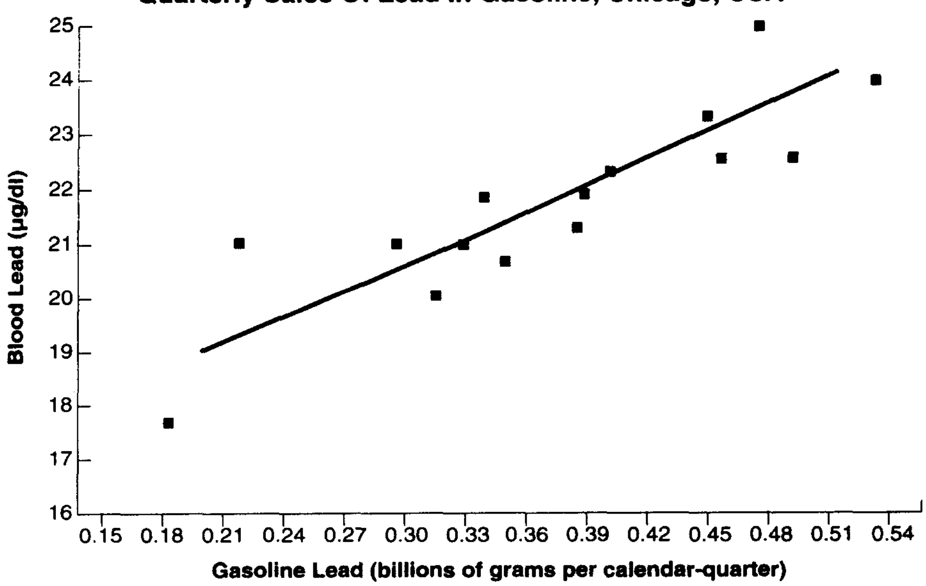
lead concentration proportionally (assuming that there are no other significant sources of lead aerosol emissions). The resulting reduction in lead concentration would be 1.1 µg/m^3.

As shown in Section 5.2, the slope of the short-term relationship between blood lead and lead in air is approximately 2 for adults and 4 for children. Thus, the expected short-term change in average blood lead concentrations for adults is two times the change in ambient concentration, or 2.2 µg/dl. For children, similarly, it is 4.4 µg/dl.

Table 11: Reduction In Blood Lead Concentrations Due To Reducing Lead In Gasoline: A Hypothetical Example

	Values	Units
Leaded gasoline sales	1,000	million liters per year
Lead concentration in gasoline	0.7	grams per liter
Annual lead emissions	700	tons Pb per year
Avg. lead concentration in air	1.4	grams per cubic meter
Effect of reducing lead to 0.15 g/liter		
Annual lead emissions	-550	tons Pb per year
Change in lead concentration in air	-1.1	grams per cubic meter
Change in blood lead: adults	-2.2	microgram per deciliter
Change in blood lead: children	-4.4	micrograms per deciliter

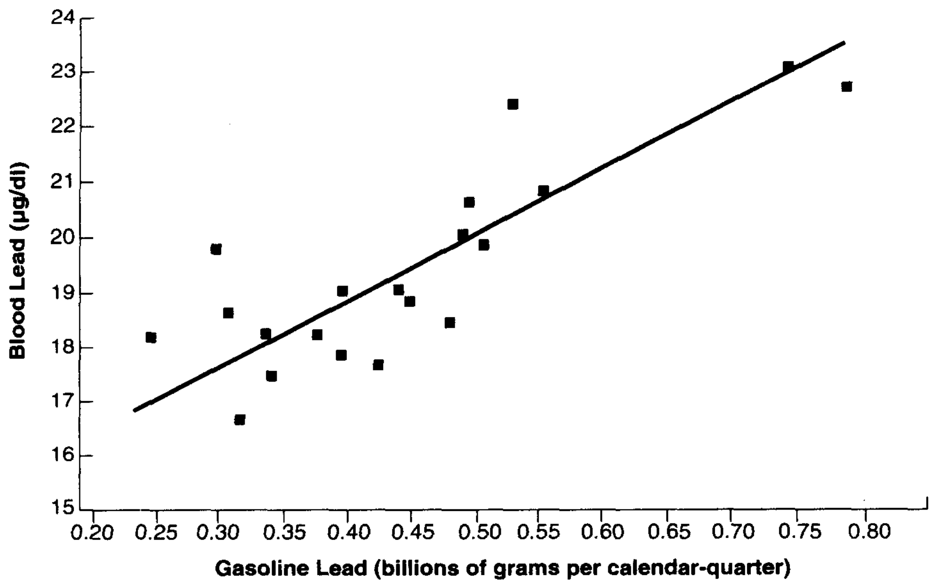
Figure 11: Blood Lead Concentration In Children Vs. Quarterly Sales Of Lead In Gasoline, Chicago, USA



Source: Schwartz et al. (1985).

In a number of U.S. cities, average blood lead concentrations have been related directly to changes in total consumption of lead in gasoline. In Chicago (Figure 11), a reduction of 300 tons per quarter in gasoline lead (1200 tons per year) resulted in a reduction of 5 µg/dl in the average blood lead concentration of children in a lead screening program. In New York City (Figure 12), a reduction of 550 tons per quarter gave an average reduction of 7 µg/m^3 in children's blood lead concentration.

Figure 12: Blood Lead Concentration In Children Vs. Quarterly Sales Of Lead In Gasoline, New York City, USA



Source: Schwartz et al. (1985).

5.4 Assessing The Health Benefits Of Lead Phaseout

Numerous studies have documented the effects of lead on human health. Major reviews of these studies have been carried out by the U.S. EPA (1986), World Health Organization (1995), and the California Office of Health Hazard Assessment (Ostro et al., 1997). The main adverse health effects associated with lead exposure in children are neurodevelopmental damage, resulting in lowered intelligence, increased incidence of behavioral problems, increased risk of learning disabilities, increased risk of hearing loss, and increased risk of failure in school. In adults, lead exposure is linked to increased blood pressure, leading to increases in the incidence of hypertension, cardiovascular illness, stroke, and premature death. Lead and the lead scavengers ethylene dichloride and ethylene dibromide are also considered possible human carcinogens, but the risk of cancer from emissions associated with lead in gasoline is much less than the risk of cardiovascular mortality due to hypertension.

The main effects of lead in children are neurodevelopmental damage, and in adults increased blood pressure.

5.4.1 Lead And Neurodevelopmental Effects In Children

All of the recent reviews of lead and its health effects agree in concluding that children with blood lead concentrations exceeding the "level of concern" of about 10 µg/dl can suffer impairments in the development of their central nervous system and other organs, impairments in cognitive function, and increased risk of behavioral problems. The impairment in cognitive function is most readily measured by comparing results on standardized intelligence tests. Performance on these tests has been shown to be a good predictor of later achievement in school, and to be correlated with lifetime earnings (Schwartz et al., 1985).

Schwartz (1994a) conducted an extensive meta-analysis of the studies linking lead in blood with children's IQ. He concluded that there is a highly significant association between blood lead levels and IQ in children, and that this association was robust to changes in model formulation, study type, and potential

Other things being equal, a child with 20 µg/dl of lead in his or her blood will score about 2.6 points lower in IQ than one with 10 µg/dl. To put this in perspective, U.S. children today average less than 5 µg/dl of blood lead, compared to around 15-20 µg/dl in the United States in the early 1970s or in many developing countries today. This is equivalent to around 4 IQ points – a significant difference.

Data suggest that the damaging effects of lead on IQ extend to blood lead levels as low as 1μg/deciliter.

In addition to its health effects, lead in the blood can affect children's lifetime earnings.

confounding factors. For an increase in blood lead concentration from 10 to 20 μg/deciliter, the meta-analysis predicted a decrease in mean IQ of 2.57 +/- 0.41 points, or 0.256 IQ points per μg/dl.

Schwartz also found that the results do not support the potential existence of a blood lead "threshold" below which no significant harm occurs. To the contrary, the data suggest that the damaging effects of lead on IQ extend to blood lead levels as low as 1 μg/deciliter, and that the slope of the lead/IQ curve may even be higher at low levels of lead exposure. If correct, this would imply that there is *no* acceptable level of lead exposure, and that every effort should be made to reduce even low levels of ambient lead.

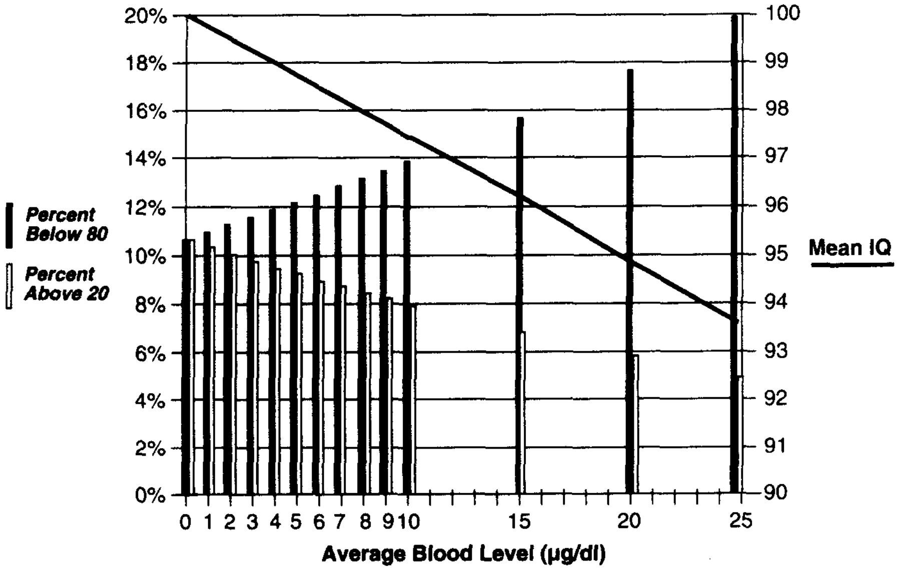
Accepting Schwartz's analysis, a 1 μg/dl change in the mean blood lead concentration of preschool children would be expected to shift the mean IQ of the same children by 0.256 points. It is not clear to what extent this effect is reversible: that is, whether it is possible to improve the mental performance of children exposed to high blood lead concentrations during the critical early childhood years by reducing their lead exposure later in life. There is some reason to believe that a significant part of the damage is permanent: that is, that children exposed to high blood lead concentrations from birth to age six years are unlikely to recover their full mental function, even if this exposure is subsequently reduced.

While the effect of blood lead on IQ is too small to be measurable in any individual child, the implications for the population of children as a whole may be significant. In particular, a shift in the mean of the intelligence distribution may have a disproportionately large impact on the numbers of children classified as learning-disabled (with IQs less than 80) or gifted (with IQs exceeding 120).

Schwartz (1994a) also estimated the effects of lead exposure on schooling and lifetime earnings of children in the United States. For people of near-normal intelligence, the effect of IQ on earnings was estimated at approximately a 0.5 percent change in lifetime earnings per one point change in IQ. However, lead exposure in children also reduces the chance of successfully completing school, which tends to reduce both wages and the probability of employment. Taking these effects into account, the present value of the total loss in earnings per μg/dl of lead in blood was calculated at approximately 0.6 percent of the total expected value of lifetime earnings.

The change in the number of learning-disabled and gifted children due to a lead-induced shift in mean IQ can also be calculated. Ostro (1997) indicates that IQ is normally distributed, with a mean of 100 and a standard deviation of 16. Figure 13 shows the projected effects of changes in blood lead concentration on mean IQ, and on the percentage of learning-disabled and gifted children, based on this distribution function.

Figure 13: Effect Of Changing Average Blood Lead Level On Percentage Of Learning-Disabled And Gifted Children



5.4.2 Lead And Blood Pressure In Adults

Numerous studies (Schwartz et al., 1985; EPA, 1990; WHO, 1995; Ostro et al., 1997) have shown a correlation between blood lead concentrations in adults (especially males aged 40 to 59) and blood pressure. The general relationship is that a doubling of blood lead concentration (e.g., from 5 to 10 µg/dl, or from 10 to 20) is associated with an increase in diastolic blood pressure of 1.9 mm of mercury (Hg). This directly increases the probability of hypertension (defined as diastolic blood pressure exceeding 90 mm Hg), and indirectly increases the chance of stroke, heart attack, and premature death. Since both the relations between lead and blood pressure and those between blood pressure and the different health outcomes are nonlinear, calculating the change in the incidence of each outcome is complicated. Ostro et al. (1997) give the following equation for hypertension:

$$\Delta H = (1 + \exp(-(-2.74 + b(\ln PbB1))))^{-1} - (1 + \exp(-(-2.74 + b(\ln PbB2))))^{-1} \qquad (1)$$

where

ΔH is the change in the probability of hypertension due to lead phaseout
PbB1 is the present mean blood lead concentration
PbB2 is the mean blood lead concentration expected after lead phaseout
b is a regression coefficient, equal to 0.79 +/- 0.48 (95% confidence interval).

The change in blood pressure due to a change in blood lead concentration is given by Ostro et al. (1997) as:

$$\Delta DBP = 2.74\,(\ln PbB1 - \ln PbB2) \qquad (2)$$

where

ΔDBP is the change in diastolic blood pressure due to lead phaseout
PbB1 and PbB2 are the lead concentrations in the blood before and after lead phaseout.

The probability that a middle-aged man will die during the next 12 years is affected by his diastolic blood pressure. For white males in the United States, aged 40 to 59, this probability is given by Ostro et al. (1997) as:

$$\Delta M = (1 + \exp(-(-5.32 + b(DBP1)))^{-1} - (1 + \exp(-(-5.32 + b(DBP1)))^{-1} \quad (3)$$

where

ΔM is change in the probability of death (from all causes) during the next 12 years

DBP1 = diastolic blood pressure associated with present lead exposure

DBP2 = diastolic blood pressure after lead phaseout, equal to DBP2 + ΔDBP

b = regression coefficient, equal to 0.035 +/- 0.14.

The effects of increased lead blood levels are about twice as great in men as women.

For women aged 40 to 59, they estimate that the effect will be half that for men.

Table 12 shows how this calculation would be done for the hypothetical case outlined in Table 11. The average blood lead concentration among adults in this case is assumed to be 10 µg/dl, and the mean diastolic blood pressure is assumed to be 85 mm Hg (a more accurate calculation would consider the actual distribution of blood pressure levels among the population). The phaseout of leaded gasoline would reduce the mean blood lead concentration by about 2.2 µg/dl. The resulting change in blood pressure is then calculated from Equation 2. Equation 3 is then used to calculate the probability that a man aged 40 to 59 will die within the next 12 years, based on this blood pressure level. Finally, the total change in annual mortality is calculated by dividing this value by 12. For women, the change is assumed to be half as much (Ostro et al., 1997).

Table 12: Calculating The Reduction In Mortality Due To A Hypothetical Reduction In Blood Lead Concentration

Current Blood Lead Level (ug/dl)	10.0
Current Mean Blood Pressure (mmHg)	85.0
Proj. 12 Year Mortality	8.75%
New Blood Lead Level (ug/dl)	7.8
New Mean Blood Pressure (mmHg)	84.3
Proj. 12 Year Mortality	8.56%
Avoided Deaths/Million Persons/Year	
Males 40-59	157
Females 40-59	78

5.4.3 Lead And Cancer

A number of the compounds associated with leaded gasoline and its emissions are classed as known or potential carcinogens. These include lead itself, the lead scavengers ethylene dibromide and ethylene dichloride, and such combustion products as 1,3 butadiene, benzene, formaldehyde, and acetaldehyde.

Table 13 lists these compounds, along with the estimated carcinogenic potency of each. Although benzene and formaldehyde have received more attention, 1,3 butadiene is actually much more important in terms of cancer risk, accounting for two-thirds of the estimated cancer cases due to toxic air contaminants from gasoline vehicles in the United States (U.S. EPA, 1993).

Overall, the cancer risk due to motor vehicle emissions is low relative to the risk of non-cancer health effects. For the United States, the total number of cancer cases due to gasoline-related mobile source emissions, based on upper-bound limits on carcinogenic potency, was calculated at 459 per year, with 1,3 butadiene accounting for 304 of these. For non-catalyst vehicles, the relative importance of 1,3 butadiene is even greater.

Overall, the cancer risk due to toxic contaminants from gasoline motor vehicle emissions is low relative to the risk of non-cancer health effects. 1,3 butadiene accounts for two-thirds of the estimated cancer cases caused by these emissions in the United States.

The arguments of lead additive suppliers, among others, have created public concern over a purported increase in cancer risk due to increased benzene emissions with unleaded gasoline. These arguments are invalid for several reasons.

- Increasing benzene and other aromatic compounds is only one of several options for making up the difference in gasoline octane due to the elimination of lead (see Chapter 2).
- Benzene emissions from motor vehicles would be unlikely to increase even if unleaded gasoline contained more benzene and aromatics. This is because total hydrocarbon emissions tend to be lower with unleaded gasoline (see Chapter 8).
- Most important, overall cancer risk would be reduced due to the reduction in other carcinogenic compounds, especially 1,3 butadiene and lead.

There is also some evidence that MTBE, a gasoline additive often used as a substitute for lead, may be weakly carcinogenic, although a formal determination of its carcinogenicity has not been made. Relatively little MTBE survives the combustion process, however. In emission measurements on non-catalyst Mexican vehicles using fuel with 7 percent MTBE by volume, MTBE made up only about 2.7 percent of the exhaust hydrocarbons (IMP, 1994). Because blending MTBE reduces benzene and 1,3 butadiene emissions, it is estimated to create a net reduction in cancer risk (California EPA, 1998).

Table 13: Carcinogenic Compounds Associated With Gasoline Combustion

Compound	Unit Risk 95% U.B.	Cancer Class	Est. Cases in U.S.⁺	Typical Non-Catalyst Emissions*	
				mg/km	benzene eq.
1,3 Butadiene	2.80E-04	A	304	88	2,954
Benzene	8.30E-06	B2	70	83	83
Formaldehyde	1.35E-05	B1	44	79	128
Acetaldehyde	2.20E-06	B2	5.3	NA	NA
Inorganic lead	1.20E-05	B2		48	69
Ethylene dibromide	7.10E-05			NA	NA
Ethylene dichloride	2.20E-05			NA	NA

*Average of 19 non-catalyst vehicles in Mexico (IMP, 1994). Fuel was 1.4% benzene, 18% aromatics, and 10% olefins.
⁺ U.S. EPA (1993).

To calculate the potential change in cancer incidence due to gasoline composition changes resulting from lead phaseout, it is necessary to know the existing levels of exposure to gasoline-derived carcinogens. This can be estimated by air dispersion modeling or by directly measuring ambient concentrations. A procedure for making such measurements is given by EPA (1997).

Unless a major non-gasoline emission source is present, such as a chemical plant, gasoline combustion is the main contributor to lead, benzene, and 1,3 butadiene in the urban atmosphere (EPA, 1993). As a first approximation, therefore, one can estimate the effects of a change in gasoline composition by multiplying the measured or estimated ambient concentrations of benzene and 1,3 butadiene in the atmosphere by the percentage change in these emissions from gasoline vehicles. To the extent that other sources contribute to these pollutants, this will overestimate the impact of the change in gasoline composition.

Ambient benzene concentrations in urban areas of the United States range from about 4 to 7 μg/m^3, while 1,3 butadiene concentrations range from 0.12 to 0.56 μg/m^3. In Bangkok, a risk assessment by the U.S. Agency for International Development estimated ambient concentrations at 3-14 μg/m^3 for benzene and 2 μg/m^3 for 1,3 butadiene. In Australia, the average ratio of 1,3 butadiene to benzene concentrations in a traffic tunnel was 0.21. To illustrate the potential impacts of a change in gasoline composition, initial concentrations of 10 μg/m^3 for benzene, 2 μg/m^3 for 1,3 butadiene, and 1.4 μg/m^3 for lead were assumed. As an extreme example, it was assumed that the changes in gasoline formulation due to lead phaseout increase benzene emissions by 50 percent, while reducing 1,3 butadiene emissions by 7 percent and lead emissions by 100 percent. It was further assumed that MTBE concentrations increase from zero to 15 μg/m^3 as a result of the lead phaseout. The total population of this hypothetical city, 5 million persons, is assumed to be exposed to these changed concentrations.

Table 14 shows the resulting change in cancer risk. In this case, the small increase in cancer risk due to the higher benzene concentration is more than offset by the reductions in 1,3 butadiene and lead, resulting in a net reduction in the 95 percent upper-bound risk of cancer of 0.8 cancer cases per year out of 5 million persons exposed. Compared with the changes in lead-related non-cancer mortality calculated in Section 5.4, these impacts are negligible.

Table 14: Example Of Change In Cancer Risk Due To Lead Phaseout

	Unit Risk*	Concentration (μg/m^3)		Cancer Incidence (cases/year)$^+$	
Compound	95% Upper Bound	Before	After	Before	After
1,3 Butadiene	2.80E-04	2.0	1.86	40.0	37.2
Benzene	8.30E-06	10.0	15.00	5.9	8.9
Inorganic Lead	1.20E-05	1.4	0.00	1.2	0.0
MTBE	1.70E-07	0.0	15.00	0.0	0.2
Total				47.1	46.3

* 95% upper bound estimate of the risk of acquiring cancer due to exposure to 1 μg/m^3 concentration over a 70-year human lifetime

$^+$ Unit risk x concentration x 5,000,000 exposed population / 70 years

5.5 Economic Value Of Reducing Adverse Health Impacts

As outlined earlier, reducing lead emissions can be expected to result in quantifiable reductions in hypertension, stroke, heart attacks, and premature death in adults; an increase in the average intelligence and improvements in the learning performance of children born in the future; and a future reduction in the number of mentally handicapped children. In order to compare these benefits with the costs of phasing out lead in gasoline, it is useful to express these benefits in monetary terms. In other words, it is necessary to place an economic value on such intangibles as death and disability, or at least on the avoidance of these problems.

To quantify the benefits of phasing out lead in gasoline, it is necessary to place values on such things as death and disability, or on the avoidance of these problems.

A lower bound for the economic value to society of avoiding premature death, disability, or illness can be established by considering the directly measurable costs of medical treatment for illness and compensatory education to overcome learning disabilities, as well as the calculable costs of lost wages or reduced earning power. However, these directly calculable economic losses are only a small part of the entire picture, as they fail to account for the inherent value that people place on their lives and those of their loved ones, or for the harm suffered to people's enjoyment of life due to disease or disability.

A fundamental tenet of economics is that the value of anything is determined by what people will pay for it. Although money is certainly not an adequate measure of the grief and loss suffered by someone who is crippled or the family of someone who dies prematurely due to stroke or heart attack brought on by hypertension, or of a mentally handicapped child, it is possible to measure the amounts that people are willing to pay to reduce their risk of suffering such hazards (or, alternatively, the amounts that they are willing to accept as compensation for bearing an increased risk). By assessing this "willingness to pay" (WTP) to reduce risk, or the compensation demanded to accept an increased risk, it is possible to assess the value that people place on reducing their risks of death or illness.

In economics, the value of anything is determined by what people will pay for it. By assessing people's "willingness to pay" to reduce risk or what they are "willing to accept" as compensation for an increased risk, it is possible to assess the value that people place on reducing their risks of death or illness.

Most of the available WTP studies have focused on the value to be imputed to reducing the risk of premature death, as this is generally the dominant factor in the calculation of health benefits. Maddison et al. (1997), in a study for the World Bank, reviewed the literature on the WTP to reduce the risk of death, and have adapted the results to the conditions common in developing countries. In developed countries such as the United States, the imputed value of a statistical life saved (VOSL) has been estimated at around US $3.6 million. This should not be interpreted as the "value" of saving any one individual life – a quantity that involves both theoretical and moral problems. Instead, it should be interpreted as the value imputed to reducing the risk of premature death by a small increment for a large population – for example, the value of reducing by one chance in a million the risk experienced by one million persons. Maddison et al. suggest that this value should be reduced to $3.2 million for pollution-related deaths in the United States, because the people at greatest risk are generally older, with fewer years of life remaining than those dying as a result of traffic accidents or industrial hazards.

People's willingness to pay to reduce risks depends on their income – countries with higher incomes are generally willing to pay more. For this reason, VOSL estimates for developing nations tend to be lower than those for the United States. In their work for the World Bank, Maddison and coworkers derived VOSL values for cities representing a range of middle-income and lower-income countries. These included Santiago de Chile, Shanghai, Manila, and Mumbai. Other VOSL estimates have been developed by Conte Grand (1998) for Buenos Aires, and Shetty et al. (1994) for Bangkok.

Most of the calculable economic benefits due to lead phaseout result from the reduced risk of premature mortality for adults, and the improvement in educational performance and future productivity and earnings of children.

Most of the calculable economic benefits due to lead phaseout result from the reduced risk of premature mortality for adults, and the improvement in educational performance and future productivity and earnings of children. Schwartz (1994b) reviewed all of the main health effects of lead in an attempt to quantify the societal benefits of reducing lead emissions in the United States. With respect to the economic impacts of neurobehavioral problems in children, Schwartz calculated the combined effects of lower IQ, reduced probability of completing school, and reduced participation in the workforce due to a 1 µg/dl increase in blood lead concentration as a reduction of US $1300 (0.6 percent) in the net present value of lifetime earnings for a child turning 6 years of age.

One researcher found that the benefits of reducing blood level concentrations in U.S. children by 1 µg/dl would have a net present value of nearly $7 billion. For adults, this figure exceeds $10 billion.

Table 15 summarizes the results of Schwartz's calculations. As this table shows, Schwartz calculated the net present value of increased earnings due to reducing blood lead concentrations in U.S. children by 1 µg/dl to be more than US $5.0 billion per year. Total benefits to children were calculated at $6.9 billion, with reduced infant mortality accounting for more than $1.1 billion, and reductions in the costs of medical care and compensatory education accounting for $0.8 billion. For adults, Schwartz valued the total benefits at $10.6 billion, of which $9.9 billion is attributed to reduced mortality, $0.6 billion to medical cost savings, and $0.1 billion to lost wages due to illness. Thus, these two main effects account for more than 85 percent of the total benefit. In calculating these values, Schwartz used a VOSL estimate for the United States of $3.0 million for both infants and adults, which is toward the low end of the range of recent VOSL estimates.

Table 15: Estimated Benefits Of Reducing Blood Lead Concentrations In The United States By 1.0 µg/dl

Nationwide Benefits (millions of US$)			
Adults		**Children**	
Premature mortality	9,900	Medical costs	189
Medical costs		Compensatory education	481
Hypertension	399	Lifetime earnings	5,060
Heart attacks	141	Infant mortality	1,140
Strokes	39	Neonatal care	67
Lost wages		Total children	6,937
Hypertension	50		
Heart attacks	67		
Strokes	19		
Total adults	10,615	**Combined population**	**17,552**

Source: Schwartz (1994b).

6. CONDUCTING A COST-BENEFIT ANALYSIS

The selection of a lead phaseout strategy should take into account the costs and benefits of the different alternatives, and such considerations as technical and political feasibility, the legal basis for the strategy, equity among various social sectors, and acceptability to political decision makers and the public. Ideally, the strategy selected should be the one with the greatest net benefits among those strategies that are technically feasible, legally viable, equitable, and acceptable.

> This chapter first explains the purpose of a cost-benefit analysis and describes the main components of a lead phaseout cost-benefit analysis.
>
> Next, it discusses the specific lead phaseout strategies implementers should consider in their cost-benefit analyses, stressing the inclusion of a strategy where lead content is reduced as much and as quickly as possible.
>
> Last, this chapter shows how the benefits and costs of lead phaseout are calculated under two hypothetical strategies: a near-term strategy that seeks to reduce the lead content of gasoline as quickly as possible, and a longer-term strategy that delays lead phaseout until new refinery process units can be constructed.

The Steps In Selecting A Lead Phaseout Strategy

1. Identify alternative phaseout strategies

First, implementers should identify a number of alternative phaseout strategies that are technically feasible and legally viable.

2. Assess net costs to the public and the public health benefits of each strategy

In this step, implementers should seek to quantify, to the extent possible, the social costs and benefits cf each strategy.

3. Select preferred phaseout strategy

Last, implementers should assess the strategies to determine which of them are technically feasible, legally viable, equitable, and acceptable to decision makers and the public, and from them, select the strategy with the greatest net benefits.

6.1 Cost-Benefit Analysis And Strategy Selection

Cost-benefit analysis is a technique for comparing the costs and the benefits of alternative courses of action, considered from the viewpoint of the society as a whole. (For the purposes of cost-benefit analysis, "society" can be considered to comprise the entire human population affected positively or negatively by a given decision — for instance, the entire national population if a decision is of national importance.)

Cost-benefit analysis helps implementers to determine the course of action that will result in the greatest net benefits (total benefits minus costs) for the society affected by a decision. This is an important technique in environmental decision making, where the costs can be quite large and the benefits difficult to quantify.

The cost-benefit analysis performed to assess the proposed lead phaseout in the United States was instrumental in creating a strong consensus for action and in reversing policies that had weakened controls on leaded gasoline.

The purpose of cost-benefit analysis is to determine the course of action that will result in the greatest net benefits (that is, total benefits minus costs) for the society in question. While not infallible, a rigorous cost-benefit analysis can help government leaders and legislators to avoid costly errors and to make the best use of limited resources. Cost-benefit analysis is especially useful in setting priorities and making decisions in the environmental field. Such decisions often involve significant economic costs, while the benefits of improved health and well-being may be more difficult to quantify. While cost-benefit analysis cannot substitute for value judgments or moral decisions, it can often help to clarify such judgments and the stakes involved in such decisions.

By providing a clear quantification and comparison of the costs and benefits of a given decision, cost-benefit analysis can also help to resolve controversies, overcome opposition, and secure public and political support for policies that are clearly justifiable on cost-benefit grounds. For example, the rigorous cost-benefit analysis performed for the proposed phaseout of leaded gasoline in the United States (Schwartz et al., 1985) created a strong consensus for immediate action, and led to a sharp reversal in the existing policy, which had previously been to weaken controls on leaded gasoline. Such a consensus would have been very difficult to develop in the absence of the clear conclusions derived from the cost-benefit analysis.

6.2 Cost-Benefit Comparison Of Alternative Strategies

A cost-benefit analysis of alternative lead phaseout strategies should begin with a definition of the different strategies under consideration. The analyst should then seek to quantify, to the extent possible, the social costs and benefits of each strategy.

In evaluating social costs, cost-benefit analysts normally focus on the actual consumption of resources (labor, goods, and services) available to society, excluding from consideration the effect of *transfer payments.* These payments shift resources from one economic actor to another, but do not directly reduce the overall stock of goods and services available.

Social Costs Vs. Transfer Payments

The social cost of a liter of gasoline in the refinery or in the port is generally evaluated as equal to the amount that a country would have to pay to purchase it from abroad (in the case of importing nations) or would receive from selling it abroad instead of using it at home (in the case of exporters). In both cases, this amount is the international price of gasoline, adjusted for applicable transport costs.

The transportation, distribution, and retail marketing of gasoline also involve the consumption or exclusive utilization of social resources such as labor, transport, buildings, and land, resulting in real social costs that must be taken into account in the cost-benefit analysis, where applicable. In contrast, a government tax on gasoline does not result in the consumption of resources, but only transfers them from the consumer paying the tax to the government. It is thus a transfer payment, not a cost.

In the case of lead phaseout, the principal social cost will be the increase in the cost of producing gasoline of a specified octane quality, while the principal benefits will be the reductions in the adverse health effects due to lead exposure and the savings on automotive maintenance costs experienced by vehicle owners. Methods for estimating the change in refining costs due to lead phaseout were discussed in Section 2.7, while a method for quantifying the maintenance benefits was demonstrated in Section 3.4. Because both refining costs and maintenance benefits are expressed in monetary terms, their quantification is relatively straightforward, and does not depend on questions of values (however, because of the complexity of the refining sector, considerable effort may be required to arrive at an accurate estimate of refining cost changes).

In lead phaseout, the principal social cost will be the increase in the cost of producing gasoline of a specified octane quality. The principal benefits will be reductions in adverse health effects and savings on automotive maintenance costs.

Quantifying the health benefits of lead phaseout is more complicated, as these benefits are very much linked to human values. As outlined in Chapter 5, the main identifiable health benefits due to lead phaseout are the reductions in the incidence of hypertension, stroke, heart attack, and premature mortality due to lower blood lead concentrations in adults; in children, they include reductions in the loss of IQ points (and associated earning power) and decreased incidence of developmental disabilities. Of these, the changes in adult mortality and children's average IQ account for most of the benefits that can be quantified and expressed in monetary terms. In the interest of saving analytical time, the analyst may wish to confine his or her attention to these factors. While omitting other, smaller health benefits from consideration will tend to bias the overall estimate downwards, this is unlikely to affect the ultimate conclusions, as even very conservative estimates of the benefits of lead phaseout have generally exceeded the costs by a factor of 10 or more.

Even very conservative estimates have found that the benefits of lead phaseout generally exceed the costs by a factor of ten or more.

6.3 Potential Lead Phaseout Strategies

Potential strategies for lead phaseout were discussed in Section 2.7. In general, it is recommended that the cost-benefit analyst consider several different lead phaseout strategies involving different generic approaches to meeting the octane deficit due to removing lead. The additional refining costs involved in each strategy, as well as any incremental costs for fuel transportation, distribution, and marketing, should be taken into account. These should then be compared with the benefits of reduced automotive maintenance costs, reduced mortality in adults, and improved intelligence in children. If adequate analytical resources are available, other benefits can also be included. These include the savings in medical costs due to reduced incidence of hypertension, stroke, and heart disease; reductions in the cost of remedial education for children; and reductions in the cost of medical treatment for lead toxicity.

In their cost-benefit analyses, implementers should consider at least one strategy in which the lead content in existing leaded gasoline grades is reduced as much as possible and as quickly as possible.

The specific lead phaseout strategies to be considered in each case will depend on each country's situation: its gasoline consumption levels, gasoline sources (especially the degree of reliance on local refining), the equipment already installed at local refineries, pipeline and port capacity, and related issues. It is strongly recommended, however, that the set of lead phaseout strategies considered include at least one strategy in which the lead content of existing leaded gasoline grades is reduced as quickly as possible, and by as much as possible – using measures such as the blending of imported MTBE, alkylate or other high-octane blendstocks, revamping of catalytic reformers, and other steps as necessary to achieve the greatest possible lead reduction in the shortest time. Although this rapid phaseout approach will often result in higher gasoline production costs than a slower approach based on upgrading refinery processing equipment, *the benefits of earlier reduction in lead emissions usually outweigh the additional costs.*

6.4 Example Of Cost-Benefit Comparison

This section presents an example of a cost-benefit comparison for the hypothetical case and two hypothetical strategies developed in previous chapters.

Hypothetical case. Chapter 5 estimated the probable reductions in ambient lead levels and average blood lead concentrations due to a given reduction in total lead emissions in a hypothetical city.

Hypothetical strategies. Section 2.7 developed costs for two hypothetical lead phaseout strategies:

- *A near-term strategy* using MTBE and imported high-octane blending components, along with increased reformer severity and some upgrading of reformer catalyst, to reduce the lead content of regular gasoline to 0.1 g/liter while eliminating lead entirely from premium gasoline.
- *A longer-term strategy* to achieve higher octane levels by adding new refinery process units such as isomerization, alkylation, and catalytic reforming.

Below, these two hypothetical strategies are applied to this hypothetical case. Existing gasoline sales under the status quo are assumed to comprise 500 million liters of regular and 500 million liters of premium per year, with lead contents of 0.7 g/liter in each case.

In the first, or slow phaseout strategy, refiners begin planning and building new process units in Year 1, in order to be able to eliminate the need for lead additives beginning in Year 4. *In the second, quick phaseout strategy*, refiners also begin planning and building process units in Year 1 to eliminate all need for lead in Year 4. In the meantime, however, they carry out the near-term strategy outlined in Section 2.7 – blending MTBE and imported high-octane components into both regular and premium grades, thus reducing annual lead emissions in the hypothetical city from 700 tons to 50 tons. Table 16 shows the effect of each strategy on ambient lead concentrations and average blood lead levels among adults and children.

Table 16: Effect Of Lead Phaseout Strategies On Blood Lead Concentrations: Hypothetical Case

	Values	Units
Leaded gasoline sales	1,000	million liters per year
Lead concentration in gasoline	0.7	grams per liter
Annual lead emissions	700	tons Pb per year
Avg. lead concentration in air	1.4	grams per cubic meter
Effect of Low-Lead Regular with Unleaded Premium		
Annual lead emissions	-650	tons Pb per year
Avg. lead concentration in air	-1.3	grams per cubic meter
Avg. lead in blood: adults	-2.6	micrograms per deciliter
Avg. lead in blood: children	-5.2	micrograms per deciliter
Effect of Eliminating Lead		
Annual lead emissions	-700	tons Pb per year
Avg. lead concentration in air	-1.4	grams per cubic meter
Avg. lead in blood: adults	-2.8	micrograms per deciliter
Avg. lead in blood: children	-5.6	micrograms per deciliter

To complete the benefits assessment, it is necessary to estimate the effect of the change in blood lead concentrations among adults on the mortality rate, and thus to calculate the number of premature deaths avoided under each strategy.

Table 17 shows the results of this calculation. The reduction in mortality among adults aged 40 to 59 can then be multiplied by the number of people in that age cohort to calculate the change in the total number of deaths.

Calculating the benefits to adults. In order to express the benefit of this mortality reduction in monetary terms, the change in the number of deaths per year must be multiplied by an estimate of the value of a statistical life (VOSL). For this hypothetical case, it was assumed that the total size of the cohort aged 40 to 59 is 500,000 persons. For conservatism, a relatively low value for VOSL of US $200,000 was assumed. This is the value suggested for Shanghai, Manila, and Mumbai by Maddison et al. (1997). The benefits calculated in this way amount to about US $ 30 million per year, as shown in Table 18.

Table 17: Effect Of Changes In Adult Blood Lead Concentrations On Mortality: Hypothetical Case

	Low Lead	Zero Lead
Current blood lead level (µg/dl)	10.0	10.0
Current mean blood pressure (mmHg)	85.0	85.0
Proj. 12 year mortality	8.75%	8.75%
New blood lead level (µg/dl)	7.4	7.2
New mean blood pressure (mmHg)	84.2	84.1
Proj. 12 year mortality	8.52%	8.50%
Avoided deaths/million persons/year		
Males 40-59	190	207
Females 40-59	95	103

Table 18: Calculation Of Population-Wide Health Benefits: Hypothetical Case

	Low Lead	Zero Lead	Units
Change in lead emissions	-650	-700	tons per year
Change in adult blood lead	-2.6	-2.8	micrograms per deciliter
Adults 40-59 affected	500,000	500,000	persons
Change in mortality 40-59	142	155	deaths /year
Assumed value of statistical life	$200,000	$200,000	US$
Monetized adult benefit	$28	$31	million US$
Change in child blood lead	-5.2	-5.6	micrograms per deciliter
Change in avg. child IQ	1.33	1.43	IQ points
Change in avg. lifetime earnings	3.12%	3.36%	
Monetized benefit/child	$1,248	$1,344	US$
Children affected	100,000	100,000	persons
Total child IQ benefit	$125	$134	million US$
Total health benefits	**$153**	**$165**	**million US$**

Calculating the benefits to children. Table 18 also shows how to calculate the benefits of reduced blood lead in children. Here, the main effect is the increase in average IQ, and thus the increase in the present value of lifetime earnings. Schwartz (1994b) calculated this benefit as 0.6 percent of lifetime earnings per µg/dl of blood lead at age six. The net present value of lifetime earnings was assumed to be US $40,000 in this case: about one-sixth of the estimate developed by Schwartz for the United States. This is consistent with the assumption of a relatively low income level, as in Shanghai or Manila. The resulting change in lifetime earnings is somewhat more than 3 percent, for a total of around $1300 per six-year old child. Here, it was assumed that 100,000 children turn 6 years old each year, giving a net benefit in the neighborhood of $130 million. The benefits are slightly less for the low-lead strategy, and slightly more for the zero-lead strategy.

Results. Table 19 compares the overall costs and benefits of each strategy. To simplify the calculation, the costs of the refinery investment are assumed to be included in the cost of the fuel (from Table 6), and are not accounted for separately. As this table shows, the slow phaseout strategy results in no difference in fuel cost or lead emissions during the first three years, and thus no difference in the costs or benefits compared to the status quo. Once the lead phaseout takes effect in Year 4, however, the net benefits amount to US $206 million per year.

In this hypothetical case, the change in gasoline costs is very small compared to the health benefits, or even to the reduction in vehicle maintenance costs alone. Although the quick phaseout strategy results in higher near-term costs of gasoline production, the benefits of rapidly reducing lead emissions are more than 14 times greater than these costs, resulting in net benefits of US $180 million per year. The difference in the total net present value of benefits, compared to the slow phaseout scenario, is $447 million.

Table 19: Cost-Benefit Comparison Of Lead Phaseout Strategies: Hypothetical Case

	Yr. 1	Yr. 2	Yr. 3	Yr. 4	Yr. 5	5-yr. NPV
Status Quo						
Added gasoline costs (million US$)	0	0	0	0	0	$0
Vehicle maint. saving (million US$)	0	0	0	0	0	$0
Lead emissions (t/y)	700	700	700	700	700	
Health benefits (million US$)	0	0	0	0	0	$0
Slow Phaseout						
Added gasoline costs (million US$)	0	0	0	0	6.2	$8
Vehicle maint. saving (million US$)	0	0	0	0	47	$61
Lead emissions (t/y)	700	700	700	700	0	
Health benefits (million US$)	0	0	0	165	165	$216
Total benefits compared to status quo	0	0	0	206	206	$269
Quick Phaseout						
Added gasoline costs (million US$)	13.6	13.6	13.6	6.2	6.2	$42
Vehicle maint. saving (million US$)	40	40	40	47	47	$161
Lead emissions (t/y)	50	50	50	0	0	
Health benefits (million US$)	153	153	153	165	165	$597
Total benefits compared to status quo	180	180	180	206	206	$716
Total benefits compared to slow phaseout	180	180	180	0	0	$447

7. CHOOSING POLICY INSTRUMENTS

The policy instruments available for implementing a lead phaseout strategy depend on the legal system, the ownership structure of any existing refineries, and the policy and/or regulatory framework governing motor vehicle fuels and their distribution.

Examples of instruments. Some of the most important instruments available for lead phaseout include:

- ***Direct action.*** Governments can take direct action when they own or control the refinery, or when they purchase fuel for the country's own use. Examples of direct action might include directing a state-owned refinery to reduce its use of lead, or specifying low-lead or unleaded gasoline for government purchases.
- ***Regulatory "command and control" measures.*** Examples of these instruments include limiting the maximum lead content of gasoline, or prohibiting imports of lead additives and gasoline containing them.
- ***Market-based incentives.*** Examples of these instruments might include a tax on lead additive imports, on leaded gasoline, or (preferably) on the lead content of gasoline.
- ***Public information measures.*** These instruments, which are discussed in Chapters 10 and 11, include such actions as requiring gasoline lead content to be posted at the service station, publicizing the adverse health impacts of lead from gasoline, and making consumers aware of the savings in maintenance costs possible with low-lead or unleaded fuel.

Where legally feasible, market-based measures are generally preferable to command-and-control regulations. The decision to add lead to gasoline is an economic one on the part of the refiner – lead is the cheapest way of achieving the necessary octane level. By changing market conditions so that this is no longer true, refiners can be induced to reduce, and ultimately eliminate, lead use as quickly as possible. The flexibility of market-based incentives also helps to reduce the chances of a regulatory mistake – allowing too little time for the necessary changes (and thus disrupting the gasoline market) or allowing too much time, and thus allowing the health damages due to leaded gasoline to continue longer than necessary.

Where legally feasible, market-based measures are generally preferable to command-and-control regulations.

CHOOSING POLICY INSTRUMENTS

After discussing the issues that surround the ownership structure of a country's refining sector, this chapter compares two important policy instruments that can be used in a lead phaseout strategy:

- Command-and-control instruments, which involve the government mandating the actions of industries or individuals.
- Market-based incentives, which allow industries or individuals more flexibility in their decisions, but provide incentives and disincentives for particular decisions.

It then reviews the lessons learned from employing these policy instruments in the United States.

Ownership structure considerations. Where petroleum refining and distribution are carried out by the private sector, the main concerns are generally to define the quickest phaseout schedule achievable without disrupting the gasoline market, and to incorporate sufficient flexibility in the regulations to accommodate legitimate differences in the time periods required for different refineries to comply. The monitoring and enforcement of compliance with the schedule should also receive careful attention, and it may be necessary to overcome political opposition from refinery owners. Where petroleum refineries are owned by the government, these issues are generally less difficult, but the mobilization of adequate funds for refinery investments may present a significant problem.

The Steps In Choosing Policy Instruments

1. Identify legal authority
Implementers should first identify the legal authority or authorities available as a basis for policy instruments.

2. Assess available policy instruments
Next, they should assess the types of instruments that are legally permissible under the authority(ies) identified. For example, government agencies often have the authority to limit or prohibit the emission of toxic substances, but may require new legislation in order to change the tax rates on fuel.

3. Evaluate the "fit" between strategy and instruments
Implementers should then assess the compatibility between the strategy chosen and the instruments available. They should carefully review existing regulations and legislation to ensure that these do not present a barrier to the changes required. For example, gasoline quality regulations sometimes specify *minimum* as well as maximum lead content, or they may fix maximum limits on ethers or other components at lower levels than necessary.

4. Select "best" combination of instruments
Last, implementers should select the best combination of instruments, considering their effectiveness, costs and benefits, timing, flexibility, and political acceptance.

7.1 Command-And-Control Instruments

In most countries, government agencies already have been granted authority to set and enforce quality and composition standards for motor fuels. They will often have the authority to limit or prohibit the use of harmful additives such as TEL. The legal basis for such limitations might be found either in the demonstrable damage to human health due to lead emissions, or, alternatively, in the harmful effects of lead and lead scavengers on engines.

The transition from leaded to unleaded gasoline cannot occur overnight. Thus, command-and-control regulations must allow enough time for the refining industry to adjust to the phaseout requirements. The amount of time required will vary depending on the situation in each country, including the availability of excess domestic octane-producing capacity, the availability and cost of imported octane enhancers such as MTBE and high-octane gasoline blendstocks, and the capacity of ports and transportation systems to handle imports of these materials.

It is important that the amount of time allowed for industry to comply not be too short, as this may result in disruptions of the gasoline market, which in turn are likely to lead to a reversal of the lead phaseout decision on political grounds. On the other hand, the grace period allowed for compliance should not be longer than necessary, in order to minimize the adverse impacts on human health and the environment.

The example of Egypt shows that lead phaseout can proceed very quickly – within a few months – given favorable circumstances and adequate availability of high-octane blending components such as MTBE. The refining industry will generally argue for a longer grace period. Unless the agency involved has such expertise in-house, it is generally advisable to seek the advice of expert consultants in determining the length of any grace period allowed, and the maximum lead levels to be allowed in gasoline during the interim.

In most countries, government agencies already have been granted authority to set and enforce quality and composition standards for motor fuels.

Because it takes time to make the transition from leaded to unleaded gasoline, command-and-control regulations must allow enough time for the refining industry to adjust to the phaseout requirements.

lead used, which is readily monitored both at the port (for imports of TEL) and in the finished gasoline.

Ideally, the rate of tax on lead used in gasoline would be equal to the economic disbenefits imposed by its use. In practice, however, implementers must consider the negative effects on the market if a high tax is suddenly imposed.

Ideally, the rate of tax on lead used in gasoline would be equal to the economic disbenefits (costs) imposed by its use. For example, in the hypothetical case outlined in the preceding chapter, total lead emissions of 700 million grams per year resulted in health damages equivalent to US $165 million. This would justify a tax rate of $0.236 per gram of lead ($165 million/700 million grams). In practice, such a high tax rate would likely disrupt the gasoline market if it were imposed suddenly. Even a much lower tax rate, on the order of $0.10 per gram, would more than offset the saving in refining costs due to lead use, and would serve as a strong incentive to refiners to reduce their lead use as quickly as possible. At the same time, the funds mobilized by the tax could be used to set up an effective monitoring and enforcement program, to fund publicity campaigns, and for other purposes in connection with the phaseout of lead in gasoline. If necessary, some of the funds raised in this manner could be used to finance the needed investments in refinery process units.

The trading of "lead rights" may provide an alternative mechanism for introducing flexibility into the lead phaseout process.

Lead "rights trading." If a Pigouvian tax on lead is not feasible, the trading of "lead rights" may provide an alternative mechanism for introducing flexibility into the lead phaseout process. In this approach, regulators fix a limit on the average lead content of each refinery's gasoline production. If a refinery produces gasoline with a lower lead concentration than the maximum, it can sell to another refinery the right to produce gasoline containing a corresponding amount of lead in excess of the maximum. To guard against abuses, such trading requires careful safeguards and effective verification mechanisms. If properly implemented, however, lead rights trading can make it possible to achieve much faster reductions in lead use than would be possible if all gasoline producers had to meet the same lead limits without trading.

The lead rights trading approach was used by the EPA as part of its lead phaseout plan in the 1980s. The experience with lead rights trading in the United States is summarized in the next section.

7.3 Lessons From The U.S. Experience

In the United States, the allowable lead content in leaded gasoline was reduced to 1.1 gram per gallon by 1982 and to 0.1 gram per gallon in 1986. By 1995, sales of leaded gasoline were banned.

The U.S. experience in phasing out leaded gasoline is described by Nichols (undated). In the 1970s, average lead concentrations measured in U.S. cities often exceeded EPA's 3-month average air quality standard of 1.5 $\mu g/m^3$ (today, it is recognized that even this standard is insufficiently protective of human health). The mandatory sale of unleaded gasoline was introduced in 1974, in order to meet the needs of cars equipped with catalytic converters. At that time, leaded gasoline contained an average of 2.4 grams of lead per gallon (0.63 g/liter), and average blood lead concentrations among children in major cities were around 20 $\mu g/dl$.

Through a phased program, the allowable lead concentration in leaded gasoline was reduced to 1.1 gram per gallon (0.29 g/l) by 1982. This rule also introduced the trading of lead rights between refineries, so that a refinery that was able to produce gasoline containing less than 1.1 gram per gallon could sell the excess "lead rights" to another refinery that needed them. By 1984, about half of the refineries in the United States were participating in this market, with the larger, more complex refineries generally selling lead rights to smaller refineries that had less capability to produce high-octane gasoline through process changes (Nichols, undated).

In 1984, EPA carried out a major cost-benefit evaluation of further lead reductions (Schwartz et al, 1985). This study concluded that the benefits of further reducing lead use in gasoline greatly outweighed the costs, and that allowable lead concentrations should be reduced to a minimum as quickly as possible. A final rule was promulgated in March 1985, reducing the allowable lead concentration to 0.5 gram per gallon in July 1985 and to 0.1 gram per gallon (0.026 g/l) on January 1, 1996. The decision to reduce the allowable lead content to 0.1 gram per gallon instead of zero was due to widespread public concern (fomented by the lead industry) over the potential for damaging valve seat recession to occur in older engines. The allowable concentration was retained at this level until leaded gasoline sale was finally banned in 1995, pursuant to the 1990 revisions to the Clean Air Act.

An important feature of the 1985 regulation was the provision allowing refiners to "bank" unused lead rights for later sale or use. At the time the rule was promulgated, many refineries had the capacity to produce gasoline containing substantially less than 1.1 gram per gallon. By reducing their lead use in advance of the legal limit, they were able to store up lead rights for the future, when they would be more valuable. As discussed in Chapter 2, the nonlinear relationship between lead and octane means that the benefit of going from 0.1 to 0.2 grams of lead per gallon is much greater than the octane loss due to going from 1.1 to 1.0 gram per gallon. Thus, lead rights saved when the maximum limit was 1.1 g/gallon became much more valuable when it dropped to 0.1 gram/gallon.

EPA estimated that the trading and banking of lead rights would save between US $173 and $226 million between 1985 and 1988, or about 10 percent of the total cost of complying with the rule during that period (Nichols, undated). In fact, the actual use of lead banking was even greater than projected by EPA's analysis, and it seems likely that the overall costs were lower as a result. More importantly, the incorporation of lead trading and banking provisions made it feasible for small, simple refineries to comply with the phasedown rule by buying lead rights from larger refineries. Had this not been allowed, the prospect that some small refineries would be driven out of business would likely have resulted either in a delay in the phasedown, or a special exemption for small refineries that would have allowed them to continue to produce high-lead gasoline for some time.

The incorporation of lead trading and banking provisions in EPA's rule allowed small refineries to stay in business without delaying the phase-down or permitting them to continue to produce high-lead gasoline.

8. MONITORING COMPLIANCE

Sampling and checks, which confirm that the gasoline sold actually complies with the lead limits and quality specifications in effect, are an integral part of a lead phaseout strategy. A statistical sampling procedure should be set up that is adequate to ensure that any significant cheating or noncompliance is detected. To guard against adulteration or smuggling, gasoline samples should be collected for analysis at retail service stations as well as at the refinery and/or port of importation. As an additional check on lead additive use during the lead phaseout process, authorities may wish to establish special procedures for monitoring the importation and use of lead additives. Since only a few chemical companies produce these extremely hazardous compounds, monitoring lead additive shipments should not be difficult.

Sampling and checks on the importation and use of lead additives are used to detect cheating or non-compliance with a lead program, and to guard against the adulteration or smuggling of gasoline.

This chapter presents information on standard sampling and analytical procedures for lead, gasoline octane, and gasoline properties and composition, together with information on the laboratory equipment required and their costs.

The Steps in Monitoring Compliance

1. Identify monitoring needs

The monitoring requirements implementers should identify include the number of samples and the types of locations to be sampled to ensure adequate coverage. This will involve a tradeoff between enforcement costs and adequacy of control.

2. Identify legal authority/requirements for monitoring gasoline composition

Implementers should identify the legal authority that will monitor fuel composition, including any ongoing monitoring efforts.

3. Identify institutional and physical requirements for monitoring

In this step, implementers should identify the equipment and personnel required for the monitoring program and the sources of financing for any new equipment or personnel needed.

4. Identify responsibilities for monitoring and enforcement

Here, implementers should identify the institutional responsibilities of the personnel identified in Step 3.

5. Plan and implement gasoline monitoring and enforcement program

Based on the information developed, the implementer should work with the organizations responsible for enforcement to prepare a detailed plan for the enforcement program, obtain any necessary authorizations or approvals, and implement the program.

6. Identify and prosecute violators

The program should include provisions for identifying and prosecuting individuals who are violating the lead phasedown requirements.

7. Follow up to ensure program effectiveness

Once the program is underway, the implementer should follow up to confirm that monitoring is being done according to the plan.

8.1 Gasoline Sampling

The samples collected must be truly representative of the gasoline in question. A detailed description of the procedures for obtaining representative samples of gasoline for Reid vapor pressure measurements can be found in the U.S. Code of Federal Regulations (CFR 40, Part 80, Appendix D). The CFR can be accessed on the World Wide Web at www.access.gpo.gov. Gasoline samples obtained by these procedures can also be analyzed for other properties of interest.

Recently, EPA proposed to modify Appendix D to allow the use of sampling procedures developed by the American Society for Testing and Materials (ASTM). The main standard for gasoline sampling is ASTM D-4057-95 (Standard for Sampling Petroleum and Petroleum Products). The other ASTM standards involved include: D-4177-82 (Standard for Automatic Sampling), D-5842-95 (Standard Practice for Sampling and Handling of Fuels for Volatility Measurement), and D-5854-96 (Standard Practice for Mixing and Handling Liquid Samples of Petroleum and Petroleum Products).

8.1.1 Sampling Precautions

Numerous precautions are required to ensure that the character of the samples is representative. These depend upon the tank, carrier, container or line from which the sample is being obtained, the type and cleanliness of the sample container, and the sampling procedure that is to be used. A summary of the sampling procedures and their application is presented in Table 20. Each procedure is suitable for sampling a material under definite storage, transportation, or container conditions. The basic principle of each procedure is to obtain a sample in such manner and from such locations in the tank or other container that the sample will be truly representative of the gasoline.

Table 20: Summary Of Gasoline Sampling Procedures And Applicability

Type of Container	Procedure
Storage tanks, ship and barge tanks, tank cars, tank trucks	Bottle sampling
Storage tanks with taps	Tap sampling
Pipes and lines	Continuous line sampling
Retail outlet and wholesale purchaser-consumer facility storage tanks	Nozzle sampling

8.1.2 Sampling Terms

A description of terms shows the complexity involved in sampling:

- *Average sample* is one that consists of proportionate parts from all sections of the container.
- *All-levels sample* is one obtained by submerging a stoppered beaker or bottle to a point as near as possible to the draw-off level, then opening the sampler and raising it at a rate such that it is 70-85 percent full as it emerges from the liquid. An all-levels sample is not necessarily an average

sample because the tank volume may not be proportional to the depth and because the operator may not be able to raise the sampler at the variable rate required for proportionate filling. The rate of filling is proportional to the square root of the depth of immersion.

- *Running sample* is one obtained by lowering an unstoppered beaker or bottle from the top of the gasoline to the level of the bottom of the outlet connection or swing line, and returning it to the top of the gasoline at a uniform rate of speed such that the beaker or bottle is 70-85 percent full when withdrawn from the gasoline.
- *Spot sample* is one obtained at some specific location in the tank by means of a thief bottle or beaker.
- *Top sample* is a spot sample obtained 6 inches (150 mm) below the top surface of the liquid.
- *Upper sample* is a spot sample taken at the mid-point of the upper third of the tank contents.
- *Middle sample* is a spot sample obtained from the middle of the tank contents.
- *Lower sample* is a spot sample obtained at the level of the fixed tank outlet or the swing line outlet.
- *Clearance sample* is a spot sample taken 4 inches (100 mm) below the level of the tank outlet.
- *Bottom sample* is one obtained from the material on the bottom surface of the tank, container, or line at its lowest point.
- *Drain sample* is one obtained from the draw-off or discharge valve. Occasionally, a drain sample may be the same as a bottom sample, as in the case of a tank car.
- *Continuous sample* is one obtained from a pipeline in such a manner that it gives a representative average of a moving stream.
- *Mixed sample* is one obtained after mixing or vigorously stirring the contents of the original container, and then pouring out or drawing off the quantity desired.
- *Nozzle sample* is one obtained from a gasoline pump nozzle which dispenses gasoline from a storage tank at a retail outlet or a wholesale purchaser-consumer facility.

Other important aspects to be considered are sample containers (including cleaning procedure), sampling apparatus, time and place of sampling, handling, shipping, labeling, and testing procedures.

The directions for sampling cannot be made explicit enough to cover all cases. Extreme care and good judgment are necessary to ensure samples that represent the general character and average condition of the material. Clean hands are important. Clean gloves may be worn but only when absolutely necessary, such as in cold weather, when handling materials at high temperature, or for reasons of safety. Select wiping cloths so that lint is not introduced, contaminating samples.

8.2 Measuring Lead In Gasoline

EPA has approved three methods for measuring lead in gasoline. For details on any of these methods, consult The United States Code of Federal Regulations Title 40 Part 80, Appendix B. This document can be downloaded from the World Wide Web at: 1) http://www.legal.gsa.gov, or 2) http://www.epa.gov/docs/epacfr40/chapt-I.info/.

In using any of the three methods, care should be taken to collect and store samples in containers that will protect them from changes in the lead content of the gasoline such as from loss of volatile fractions of the gasoline by evaporation or leaching of the lead into the container or cap. Since metal cans are sometimes sealed with lead solder, it is preferable to collect samples in glass bottles. If samples have been refrigerated, they should be brought to room temperature (25° Celsius) prior to analysis.

Also, gasoline is extremely flammable and should be handled cautiously and with adequate ventilation. The vapors are harmful if inhaled, and a prolonged breathing of vapors should be avoided. Skin contact should be minimized.

8.2.1 Standard Method Test By Atomic Absorption Spectrometry

This method determines the total lead content of gasoline. The method compensates for variations in gasoline composition and is independent of lead alkyl type. The gasoline sample is diluted with methyl isobutyl ketone (MIBK) and the alkyl lead compounds are stabilized by reaction with iodine and a quarternary ammonium salt. The lead content of the sample is then determined by atomic absorption flame spectrometry at 2833 Å, using standards prepared from reagent-grade lead chloride. Using this treatment, all alkyl lead compounds give an identical response.

The equipment needed to perform this method includes an atomic absorption spectrometer, volumetric flasks, pipettes, and micropipettes. This method is now rarely used, since automatic equipment for lead determination is readily available.

8.2.2 Automated Method Test By Atomic Absorption Spectrometry

This method is very similar to the one above, and has largely replaced it in practice. The main difference is that an automated system is used to perform the diluting and the chemical reactions, and to feed the products to the atomic absorption spectrometer. This method requires an auto-analyzer system and an atomic absorption spectroscopy detector system

8.2.3 X-Ray Spectrometry

As with the other two methods, this determines the total lead content of gasoline. It is insensitive to variations in gasoline composition, and is independent of lead alkyl type.

A portion of the gasoline sample is placed in an appropriate holder and loaded into an X-ray spectrometer. The ratio of the net X-ray intensity of the lead L alpha radiation to the net intensity of the incoherently scattered tungsten

L alpha radiation is measured. The lead content is determined by reference to a linear calibration equation that relates the lead content to the measured ratio. The incoherently scattered tungsten radiation is used to compensate for variations in gasoline samples.

The primary apparatus needed for using this method is an X-ray spectrometer. It is recommended that the optical path in the spectrometer be helium instead of air. The use of air produces ozone, and could also pose flammability problems if a container with a sample of gasoline ruptures.

8.3 Octane Measurements

There are two ASTM methods for measuring the antiknock quality in gasoline: ASTM D 2699 (Test for Knock Characteristics of Motor Fuels by the Research Method), and ASTM D 2700 (Test for Knock Characteristics of Motor and Aviation-Type Fuels by the Motor Method). Both methods require the use of a special single-cylinder laboratory engine with a variable compression ratio, known as a CFR engine. The Research Method (which results in the RON) simulates driving under mild conditions, while the Motor Method (which results in the MON) simulates more severe conditions, as well as operation under load or at high speeds. Both methods relate the knocking characteristics of the test gasoline to that of two pure fuels: iso-octane (2,2,4 tri-methyl pentane) and n-heptane. These are defined to have octane numbers of 100 and zero, respectively.

The octane number of a gasoline is measured by determining the compression setting on the laboratory engine at which the knock begins to occur when operating on the test gasoline. This is then compared to the compression settings at which known mixtures of iso-octane and n-heptane begin to knock. The octane value is equal to the percentage of octane in the mixture. Thus, a gasoline blend that knocks at the same compression setting as a mixture of 80 percent iso-octane and 20 percent n-heptane would have an octane rating of 80.

8.4 Gasoline Composition

This section summarizes the measurement of the reformulated gasoline fuel parameters followed by EPA. The entire document is the United States Code of Federal Regulations (CFR) Title 40 Part 80, including appendixes A through G. This document is available through the World-Wide Web at the following addresses (other addresses are also available):

http://www.legal.gsa.gov, or
http://www.epa.gov/docs/epacfr40/chapt-I.info/

ASTM documents can be obtained through the American Society for Testing and Materials. ASTM can be contacted via the World-Wide Web at the following address: http://www.astm.org, or at their physical address: ASTM, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania USA 19428-2959.

8.4.1 Sulfur

Sulfur content is determined using ASTM standard method D–2622–92, entitled "Standard Test Method for Sulfur in Petroleum Products by X-Ray Spectrometry."

8.4.2 Olefins

Olefin content is determined using ASTM standard method D–1319–93, entitled "Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption." The gas chromatographic method described below for aromatics can also be used to determine olefin content.

8.4.3 Reid Vapor Pressure (RVP)

Reid vapor pressure is determined using the procedure described in the U.S. CFR Title 40 Part 80, Appendix E, Method 3 (Evacuated Chamber Method), in which a known volume of air-saturated fuel at 32-40° F (0-4.4° C) is introduced into an evacuated, thermostatically controlled test chamber, the internal volume of which is or becomes five times that of the total test specimen introduced into the test chamber. After the injection, the test specimen is allowed to reach thermal equilibrium at the test temperature, 100° F (37.8° C). The resulting pressure increase is measured with an absolute pressure measuring device whose volume is included in the total of the test chamber volume. The measured pressure is the sum of the partial pressures of the sample and the dissolved air. The total measured pressure is converted to Reid vapor pressure by use of a correlation equation.

8.4.4 Distillation

Distillation parameters are determined using ASTM standard method D–86–90, entitled "Standard Test Method for Distillation of Petroleum Products." EPA has determined, however, that the figures for repeatability and reproducibility given in degrees Fahrenheit in Table 9 in the ASTM method are incorrect, and are not to be used.

8.4.5 Benzene

Benzene content is determined using ASTM standard method D–3606–92, entitled "Standard Test Method for Determination of Benzene and Toluene in Finished Motor and Aviation Gasoline by Gas Chromatography"; except that instrument parameters must be adjusted to ensure complete resolution of the benzene, ethanol and methanol peaks because ethanol and methanol may cause interference with ASTM standard method D–3606–92, when present.

8.4.6 Aromatics

Aromatics content is determined by gas chromatography identifying and quantifying each aromatic compound as set forth in either of the two methods described in the U.S. CFR Title 40, Part 80.46. The equipment used is an atomic gas mass spectrometer detector.

The first method for determining aromatic content involves developing a three-component internal standard, where a curve is developed using calibration points for each level of a particular peak in the instrument's calibration table. The response of the compound in a sample is divided by the response of the internal standard to provide a response ratio for that compound in the sample. A corrected amount ratio for the unknown is calculated using the curve fit equation determined earlier. Finally, the amount of the aromatic compound is equal to the corrected amount ratio times the amount of the internal standard. The total aromatics in the sample is the sum of the amounts of the individual aromatic compounds in the sample.

The second method uses a percent normalized format to determine the concentration of the individual compounds. No internal standard is used in this method. The calculation of the aromatic compounds is done by developing calibration curves for each compound using the type fit and origin handling specified in the instrument's calibration table. The percent normalized amount of a compound is calculated using an equation, where the total aromatics is the sum of all the percent normalized aromatic amounts in the sample.

This method allows the quantification of non-aromatic compounds in the sample. Correct quantification can only be achieved, however, if the instrument's calibration table can identify the compounds that are responsible for at least 95 volume percent of the sample.

Last, there is an alternative test method (allowed by EPA prior to September 01, 1998): ASTM standard method D-1319-93, entitled "Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Absorption." This method, which is still used by EPA for determining olefin content, is considerably less expensive, but less accurate in identifying aromatic compounds.

8.4.7 Oxygen And Oxygenate Content Analysis

Oxygen and oxygenate content are determined by gas chromatography, using an oxygenate flame ionization detector (GC-OFID) as set out in U.S. CFR Title 40, Part 80.46. The equipment needed for performing this method includes: a gas chromatograph equipped with an oxygenate flame ionization detector, an autosampler (highly recommended), a non-polar capillary gas chromatograph column (J&W DB-1 or equivalent), an integrator to process the gas chromatograph signal, and a positive displacement pipet.

This method is a single-column, direct-injection gas chromatographic technique for quantifying the oxygenate content of gasoline, where a sample of gasoline is spiked to introduce an internal standard, mixed, and injected into a gas chromatograph (GC) equipped with an oxygenate flame ionization detector (OFID). After chromatographic resolution, the sample components enter a cracker reactor in which they are stoichiometrically converted to carbon monoxide (in the case of oxygenates), elemental carbon, and hydrogen. The carbon monoxide then enters a methanizer reactor for conversion to water and methane. Finally, the methane generated is determined by a flame ionization detector (FID).

Because gasoline is extremely flammable and its vapors are harmful if inhaled, it must be handled cautiously and only in areas with adequate ventilation.

Special care should be taken when collecting and handling gasoline samples. Samples must be collected and stored in containers which will protect them from changes in the oxygenated component contents of the gasoline, such as loss of volatile fractions of the gasoline by evaporation. If samples have been refrigerated, they must be brought to room temperature (25° dC) prior to analysis. Also, gasoline is extremely flammable and should be handled cautiously and with adequate ventilation. The vapors are harmful if inhaled and prolonged breathing of vapors should be avoided. Skin contact should be minimized.

8.5 Laboratory Equipment And Costs

Table 21 lists the laboratory equipment most commonly used in lead sampling and the average prices of the equipment.

Table 21: Prices For Analytical Equipment

Equipment	Cost ($US)
Lead	
Method 1 (manual)	
Atomic absorption spectrometer	N/A
Method 2 (automatic)	
Atomic absorption spectrometer system	$20,000
Method 3 (can measure sulfur too)	
X-ray spectrometer (helium optical path)	$110,000 - $200,000
Sulfur (can measure lead too)	
X-ray spectrometer	$80,000 - $200,000
Olefins	
Fluorescent indicator adsorption	$200
Reid Vapor Pressure	
Grabner	$15,000
Distillation	
Special distillation apparatus (manual)	$12,000
(automatic)	$15,000 - $20,000
Benzene and Oxygenates	
Gas chromatograph + OFID	$50,000
Aromatics	
Gas mass spectrometer	$80,000

9. CONDUCTING FOLLOW-UP EVALUATION AND REPORTING

Followup monitoring and evaluation are needed to ensure that the lead phaseout program achieves its goals, and to demonstrate to decision makers and the public that these goals have been achieved.

> This chapter reviews the procedures available for measuring lead concentrations in human blood and ambient air.

The Steps In Follow-Up Evaluation And Monitoring

1. Monitor trends in ambient lead and other air pollutants
In addition to monitoring changes in the lead content of gasoline, implementers should assess the changes in concentrations of lead and other pollutants in ambient air.

2. Monitor trends in human exposure to lead
Implementers should also assess the changes in the distribution of blood lead concentrations among the exposed population, particularly children, that result from the phaseout program.

3. Evaluate the effectiveness of the phaseout program
Implementers should measure the effectiveness of the program in terms of declines in lead concentrations in both air and human blood.

4. Identify the cause of any problems found
In most cases, the followup evaluation will demonstrate that lead concentrations in air and human blood have declined significantly. Should the monitoring show that lead concentrations in either the air or the exposed population have not declined as expected, it may indicate that other sources of lead exist and need to be identified.

5. Communicate results to the public, politicians, and legal authorities
The information on declining levels of lead concentrations in air and human blood should be communicated to decision makers and the public in order to maintain their support for the phaseout program.

9.1 Measuring Lead Concentrations In Blood

Measuring blood lead concentrations can help to track the reduction in average blood lead concentrations due to the phaseout of lead in gasoline. In addition, these tests can identify individuals – especially children – who are at risk of health damage due to abnormally high blood lead concentrations. Such concentrations may result either from excessive exposure to airborne lead, or exposure to other sources such as lead-based paint, improperly glazed pottery, or lead water pipes. Once these high-risk individuals are identified, they or their parents can be counseled to reduce their exposure, and medical treatment can be initiated if the blood lead concentrations indicate that treatment is warranted.

Recommendations for blood lead screening have been given by the American Academy of Pediatrics (1998). The standard procedure for blood lead measurement requires a blood sample collected by venipuncture. With

Blood lead laboratories should establish careful procedures to ensure that their blood samples are accurate.

suitable precautions, capillary (fingerstick) blood samples can also be used, but these carry a greater risk of contamination by environmental lead that may be present on the skin (Parsons et al., 1997). The glassware, needles, and chemical reagents used for collecting and storing blood must be lead-free, and each batch should preferably be checked for lead contamination before use. Suitable supplies are available from a number of commercial medical suppliers.

Because of the ubiquity of lead in the environment, the contamination of blood lead samples is a common problem, and careful quality assurance and quality control procedures are essential. These should include analyses of blank samples to identify contamination in the sampling and analysis process. Blood lead laboratories should establish careful procedures, and participate in routine proficiency testing to verify the accuracy and precision of their blood lead measurements. The U.S. Centers for Disease Control operates a blood lead level laboratory reference system; it provides blood samples having accurately known lead concentrations to more than 250 laboratories around the world (CDC, 1998). These can be used to verify calibrations and as reference samples for quality control purposes. A list of blood lead laboratories certified by the U.S. Occupational Safety and Health Administration is available on the World-Wide Web at www.osha-slc.gov/OCIS/toc_bloodlead.html.

The World Health Organization has summarized analytical techniques for lead in blood (WHO, 1995). Commonly used techniques include atomic absorption spectrometry, graphite-furnace atomic absorption spectrometry, anode-stripping voltimetry, and inductively-coupled plasma atomic emission spectrometry. X-ray fluorescence spectroscopy can also be used. The National Institute of Standards and Technology uses isotope-dilution mass spectrometry to establish accurate target values for its blood lead reference materials. The U.S. Centers for Disease Control uses a similar method – inductively coupled plasma isotope-dilution mass spectrometry (U.S. CDC, 1998).

9.2 Measuring Lead In Ambient Air

Lead concentrations in ambient air are measured by collecting total suspended particulate matter on a glass-fiber filter for 24 hours using a high-volume air sampler, and then analyzing the collected particulate matter for lead. The analysis of the 24-hour samples may be performed either for individual samples or composites of the samples collected over a calendar month or quarter. Lead in the particulate matter is solubilized by extraction with nitric acid (HNO_3), facilitated by heat or by a mixture of HNO_3 and hydrochloric acid (HCl) facilitated by ultrasonication. The lead content of the sample is analyzed by atomic absorption spectrometry. The ultrasonication extraction with HNO_3/HCl will extract metals other than lead from ambient particulate matter. For a complete description of this method, refer to the United States Code of Federal Regulations Part 50, Appendix G.

The typical range of lead concentrations that can be analyzed using this method is 0.07 to 7.5 µg Pb/m^3, and the typical sensitivity (for a 1 percent change in absorption) is 0.2 and 0.5 µg Pb/ml for the 217.0 and 283.3 nanometer lines, respectively. A typical lowest detectable level is 0.07 µg Pb/m^3.

10. CONDUCTING PUBLIC EDUCATION

The success of a lead phaseout strategy hinges on public acceptance.

If a lead phaseout strategy is to be successful, it must gain the public's understanding and acceptance. For this reason, implementers commonly include public education programs as part of their lead phaseout strategies. These programs consist of efforts to generate public interest in, and understanding of, a particular message. They can be designed and conducted by the government alone or in cooperation with non-governmental organizations (NGOs) and/or the private sector. While they are often developed for a broad audience, they can also include media communications targeted to a range of differing public opinions. More specific outreach and training programs can be targeted to auto mechanics and service station attendants (Lovei, 1998).

> This chapter describes how to establish goals and develop specific strategies for implementing a public education program for lead phaseout. It also reviews media and other techniques for public communication.

The Steps In A Public Education Program

1. Define public education goals
An effective public education program will help assure public support for the lead phaseout policy. The program goals ("the desired results") should include: 1) increasing awareness and understanding of the health and developmental problems caused by exposure to lead and 2) changing public perceptions about the ability of older vehicles to use unleaded gasoline and the maintenance benefits of reducing or eliminating lead.

2. Develop public education strategy
Once the goals are established, implementers must devise specific strategies for achieving these goals. Because strategies are likely to differ for different audiences, it is important to categorize "the public" so that messages can be tailored to the specific needs and concerns of different groups (e.g., parents, taxi cab drivers, service station operators).

3. Identify potential communication media
Next, implementers should identify appropriate communication media, choosing the most effective media for each audience they want to reach.

4. Assign responsibilities for communication and public education
In this step, implementers assign responsibilities for communication and public education to the appropriate organization. The organization(s) can include government agencies, NGOs, public relations firms, and others.

5. Follow up to assess the program's effectiveness
During and after the public education process, followup studies should be conducted. These should assess the effort's effectiveness and determine whether further public education efforts are required.

6. Begin public education activities
To obtain the best results, implementers should initiate these activities well in advance of the actual lead phaseout program.

10.1 Defining The Goals Of The Public Education Strategy

A public education strategy can both build public support for phasing out lead in gasoline and reduce opposition to the phaseout strategy.

The public's understanding of a lead phaseout strategy's policies and programs is important in building political support for the strategy and educating consumers to change their fueling and auto maintenance habits. Public education programs for lead phaseout generally have two important goals:

- Increasing awareness of the health risks associated with using leaded gasoline and the significant social benefits of policy measures to phase out lead from gasoline.
- Changing public perceptions that unleaded fuel will adversely affect vehicle performance and reduce gas mileage.

It is recommended that implementers evaluate the public's general level of awareness of lead's adverse health effects as well as the level of concern and misperception about the effects of unleaded fuel before significant resources are spent on the lead phaseout program itself as well as related public outreach efforts. Because resources are typically limited for outreach activities, it is important to understand the audience's level of awareness and understanding as fully as possible before committing to a specific strategy or approach. For example, if it is determined that opposition to unleaded fuel is less than anticipated, then relatively fewer dollars will need to be devoted to dispelling the myths related to poor performance.

Before spending large sums on a public outreach effort, implementers should evaluate the public's general awareness about lead's adverse health effects and their concerns and misperceptions.

Several tools exist for gauging public awareness and attitudes, including public opinion surveys and focus groups.

Public opinion surveys. These can be expensive and time consuming, but offer a systematic way to assess widespread public attitudes as well as to evaluate the reactions of different segments of the public to proposed policies or programs. A formal effort involves administering a survey to a sample of people through a written questionnaire or through in-person or telephone interviews. The sampling method is carefully chosen to be statistically representative of the public, and the survey results require statistical analysis. The results can be used to identify public concerns, gather information on the likely level of public acceptance of a policy or program, and also to develop effective messages for public information materials and a media strategy. When public opinion surveys are repeated over time, they can help keep the government informed of changes in public knowledge of a policy or program, as well as any accompanying changes in public preferences.

An informal survey is less expensive and can also be useful in identifying public attitudes. However, its results may not be statistically valid.

Focus groups (small group discussions with professional facilitators who gather opinions or perspectives) are an effective way of gathering information on public opinions and concerns regarding broad policy or program goals and impacts. They can be especially useful for obtaining more detailed information when designing a media strategy or strategies for specific groups (see Section 8.2). Focus groups are not a suitable method for wide public participation or to disseminate information.

10.2 Developing A Public Education Strategy

Once implementers articulate the goals and develop a sound understanding of the public's current level of awareness, they can begin to develop approaches to increase awareness and understanding.

The audiences. For a strategy to be most effective, it is useful to break up the general public into different groups or "audiences," defined on the basis of their specific concerns, driving or vehicle use patterns, and access to information. Implementers should also review who is affected by the lead phaseout strategy indirectly, as well as those social groups or businesses that may be difficult to reach.

The table below characterizes the types of audiences that should be targeted in the public education program. Each audience segment has different concerns or issues, and each plays a different role in the overall success of the lead phaseout program.

Audience Segment	Specific Concerns or Issues	Potential Role
General Public	Doesn't perceive lead as a health threat	Can be a powerful force lobbying for change
Parents	Concerned about their childrens' health and welfare	Can be instrumental in pushing for lead phaseout
Motorists	Concerned about keeping gasoline prices low Concerned about changes that would adversely affect vehicle performance or gas mileage	Account for major share of gasoline consumption as well as new/used car purchases, and demand for vehicles and maintenance services
Service Station Operators	Concerned that the need to supply unleaded gasoline will disrupt normal operations and increase costs of doing business	Because of role in the supply chain, can be key to delivering public education messages and to the overall program's success
Fleet Owners and Operators (e.g., taxi cab drivers, government agencies)	Particularly concerned about keeping operating costs low, vehicle performance, and access to supplies	Can represent a significant portion of the driving public

The message. Public education efforts should inform the general public and specific audience segments about the serious health risks from human exposure to lead. Education efforts should also inform the public that leaded gasoline is the main source of lead in the environment. Information about the neurotoxic impacts of lead in gasoline, especially its impacts on the IQ development of children, can be very powerful in influencing public opinion and consumer behavior. Increased public understanding of the significant social benefits expected from a phaseout strategy, in terms of greatly reduced health and developmental problems from exposure to lead, can influence consumer behavior and also alleviate public concerns.

Public education messages should stress both the negative health effects of lead in gasoline and the positive benefits society can realize from phasing it out. They should also address public concerns about automobile performance and the economic impacts of a lead phaseout strategy.

Sample Messages On Lead's Health Risks And The Expected Social Benefits From A Lead Phaseout Strategy

- Lead exposure in children results in neurodevelopmental damage, resulting in lower intelligence, increased incidence of behavioral problems, increased risk of learning disabilities, and increased risk of failure in school.
- The damaging effects of lead on the cognitive function of children begin to occur at very low levels of lead exposure.
- Reducing the adverse health impacts of lead exposure in children can be expected to result in an increase in average intelligence and improvements in the learning performance of future children, thus improving their lifetime productivity.
- Lead exposure in adults is linked to increased blood pressure, leading to increases in the incidence of hypertension, cardiovascular illness, stroke, and premature death.

A public education strategy should also identify and address public concerns about automobile performance and the economic impacts of a lead phaseout strategy. Many of the public's concerns may have been exaggerated by vested interests in continuing the sale of leaded gasoline, or by an initial lack of practical or scientific information to support the phaseout strategy.

Sample Messages On The Effects Of Unleaded Gasoline On Vehicle Performance

- Unleaded gasoline does not adversely affect an engine's performance, and generally reduces maintenance costs.
- Even older engines with soft valve seats are unlikely to suffer adverse effects unless they are driven continuously at high speeds for long distances. For the few engines that do suffer valve seat problems, replacing the cylinder head or valve seats will correct the problem and keep it from recurring.
- Catalytic converters are not necessary for a vehicle to use unleaded gasoline.
- Vehicles using unleaded gasoline require far less frequent spark plug changes.
- Price and supply information can help allay concerns that unleaded gasoline will be too expensive or unavailable.

Training. Last, targeted training programs for auto mechanics and service station operators can be an effective way to assist consumers in reducing the sensitivity of old cars to the use of unleaded gasoline. Such training can facilitate the proper engine modifications and maintenance of older cars with engines not designed for unleaded gasoline. Mechanics and service station operators can also help disseminate information to consumers about proper fueling practices.

10.3 Media And Other Techniques For Public Communication

A wide variety of media and other techniques are available to communicate with the public, as well as specific groups, and deliver public education strategies. Agencies should develop attractive public information materials that convey the appropriate messages or information in a fast, concise, and clear way. The wider availability of desktop publishing and increasingly accessible communication technologies offer government agencies more varied ways to capture the public's interest effectively and educate them about policies and programs.

Agencies should develop attractive public information materials that convey the messages quickly, concisely, and clearly.

Some Of The Techniques Available For Public Education Programs

- Newspaper inserts and articles
- Public service announcements and media advertising
- Brochures, fliers, and fact sheets
- Posters and billboards
- Information hotlines
- Special techniques

Public information materials are often designed to reach a broad public beyond those who are directly affected. An emphasis on concise, informative, visual presentations makes it easier to reach people who have only a few moments to catch the message. Technical information and issues should be translated into terms that the public can easily understand. In countries where language may be a political issue, using multilingual materials can demonstrate that the government is trying to reach out to all social groups.

Technical information should be presented in terms that people can easily understand.

In other instances, the wide distribution of public information materials is impractical. The government can make some materials (e.g., summaries of reports, videos, exhibits) available upon request. Other materials, such as point-of-sale information for service stations, can be targeted and customized for distribution to specific groups such as motorists.

Agencies are encouraged to seek professional assistance in crafting effective messages and completing the design and artwork needed to convey messages in the most powerful and effective manner.

All outreach materials should provide contact information so that individuals with additional questions can call for more information or assistance. More detailed descriptions of the various techniques are provided below.

Newspaper inserts and articles can be extremely effective in reaching the general public as well as specific groups. They are also an inexpensive way to disseminate information. By providing factual information in press releases, a government agency can help reporters assemble articles or news stories that can counteract

CONDUCTING PUBLIC EDUCATION

Media coverage creates opportunities for public education, but can also be used by vested interests or political opposition to seize on and distort issues related to a lead phaseout strategy.

misleading information put forward by special interest groups that may be opposed to lead phaseout.[6] Although government agencies have little control over news stories before they are published or broadcast, they may be able to avoid spending valuable resources explaining a message or trying to reshape public opinion if they hold events targeted at the media or issue press releases with easy-to-understand information.

Public service announcements. In addition to providing detailed information that can be used as "news" in articles, government agencies can place ads or public service announcements in newspapers and other media. Unlike articles, the ads would provide broad, simple messages on the benefits of lead phaseout or the specifics of the government's lead phaseout strategy (e.g., price information, location of service stations offering unleaded gasoline). Often, the news media will allow the government to place ads free of charge or at a discount. More elaborate media advertising schemes can to be expensive and must be used carefully and efficiently. A minimum media strategy would include a central message via a public service announcement. A more high-profile media campaign would involve a series of radio and television ads during prime time. As consensus builds for the lead phaseout strategy, stakeholders and government agencies can cooperate in a media strategy to inform and educate the public through features and ads on television and radio, and in newspapers

Brochures, fliers and fact sheets can be effective education tools and are usually targeted at a specific group. For example, fact sheets explaining the adverse effects of lead on the development of children can be prepared and distributed at schools, health clinics, daycare facilities and other locations serving the needs of parents and children. Brochures providing detailed information related to vehicle performance should be targeted at motorists and are best distributed at gasoline stations or to companies or agencies operating vehicle fleets.

Posters and billboards are also extremely good mechanisms for spreading the main themes of the phaseout strategy: positive effects on the neurological development of children, minimal effects on vehicle performance, etc. Messages must be presented in a simple, clear, concise form, and their effectiveness can be greatly enhanced by the use of color and artwork, or linkages to popular themes or personalities.

Posters can be widely distributed and effectively displayed in service stations, public buildings, buses and other mass transit, schools, and places of worship.

Information hotlines can be very useful, especially in the early days of the lead phaseout strategy's implementation. By providing a number motorists can call for information on everything from sales locations, price differentials, and timing, to engine performance, government agencies can reduce opposition to the program caused by uncertainty or lack of knowledge. However, it is extremely important

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[6] Government agencies should be aware of the opportunities that media coverage creates for public education, but also of the dangers if vested interests or political opposition seize on and distort issues related to a lead phaseout strategy and discredit the program in the eyes of the public. For example, in some countries, myths about engine damage from the use of unleaded gasoline have been fostered or promoted in the media by organizations with vested interests in the sale of leaded gasoline.

for information hotlines to be fully operational during the stated hours of operation and staffed by competent, knowledgeable individuals.

Special techniques, including hands-on-demonstrations, videos and other devices, can be effective for workshops and targeted outreach efforts. For example, workshops or training courses may be the most effective method of educating service station operators and mechanics on the effects of unleaded fuel on engine performance. Videos or hands-on demonstrations could instruct mechanics on how to perform vehicle maintenance to improve engine performance. Educational videos on the effects of lead on air quality and human health could be developed for use in schools or with parent groups. These techniques are generally more expensive, but are likely to be the most effective in increasing the awareness and building the support of such influential groups as service station operators and mechanics.

10.4 Assigning Responsibility For Public Education

The agency responsible for implementing lead phaseout should also retain overall responsibility for the public education program to ensure that the outreach activities and messages support the technical strategy, both in terms of the timing of specific messages and activities, and the content of these messages. However, the responsible agency should seek the assistance of relevant public affairs agencies, non-governmental organizations, industry associations, and the communications departments of universities. These groups typically have access to particular audience segments as well as expertise in managing public education programs or media campaigns. They can be useful, as well as inexpensive, sources of assistance to government agencies, which often lack the technical expertise and resources to carry out elaborate public outreach programs.

The responsible agency should consider setting up a special "public education committee" consisting of senior representatives from the various groups listed above. This committee would oversee the development of the outreach strategy and manage the activities carried out by individual group members.

10.5 Tracking Progress And Measuring Effectiveness

It is important to evaluate the program's effectiveness so that activities can be reshaped or revised as necessary over the course of the program.

A number of methods can be used to monitor progress and measure the program's effectiveness. Certainly, purchases of unleaded gasoline may be a direct measure of the program's effectiveness. If an outreach program is successful (and the overall phaseout strategy is logical and effectively addresses key pricing and supply issues), then purchases of unleaded gasoline should increase over an initial start-up period, while the total consumption of lead additives should decline.

The government also may want to conduct additional public opinion surveys six months to one year after the start of the public outreach program to determine the program's effect on public attitudes and awareness. If an initial survey was conducted, the agency can use the same survey instrument to evaluate effectiveness.

Telephone hotlines can be very useful in reducing opposition to a lead phaseout program, but they must be fully operational during their stated hours of operation and staffed by competent, knowledgeable individuals.

10.6 The Timing Of Public Education Activities

It is recommended that agencies begin public education efforts as early as possible – well before actual implementation of the lead phaseout program, so that the public is informed in advance of the changes that will take place, has time to adjust to these changes, and can accept them as improvements and benefits rather than needless inconveniences or, worse, expensive burdens to be avoided. Even the best phaseout program can be a total failure if it comes as a surprise to the general public.

Public education efforts should begin well before the implementation of the lead phaseout program starts.

Ideally the outreach program should evolve in concert with the development of the lead phaseout strategy itself so that the public is kept informed of the strategy's key elements. Over time, the outreach program should incorporate more and more information on the specifics of the phaseout strategy itself and the basis for the decisions that are made. Preferably, these decisions will be based on input from key stakeholders (see Chapter 11), which will reduce public opposition.

General education effort can start with the use of broad messages conveyed through public service announcements, posters and billboards that are widely distributed. These messages should convey the broad themes – improved childrens' health and welfare; and no adverse effects on vehicle performance. These broad messages can be supported by more detailed press articles that provide the rationale for phaseout, the benefits, the timing, and descriptions of the program (timing, availability, price, etc.).

By the time the phaseout strategy is put in place, the education program should be focusing on providing information that enhances implementation (e.g., providing locations where unleaded fuel is being sold, providing price information) and monitoring effectiveness.

11. INVOLVING KEY STAKEHOLDERS IN THE DEVELOPMENT OF A LEAD PHASEOUT STRATEGY

Gaining the concensus of the stakeholders in a lead phaseout program is critical to the program's success.

Stakeholder involvement is an essential part of a lead phaseout strategy, and should be incorporated into the process from the very beginning. Although stakeholder involvement is closely linked to public education and outreach (see Chapter 10), it differs in that it seeks to involve key parties in the decision making process. Public education and outreach, on the other hand, seek to inform the public and key groups about the need for the program and how it will work.

Many of the key stakeholder groups are the same as the audiences identified in the previous chapter and include parties that are most interested in, and affected by, a lead phaseout program, including government agencies, gasoline refiners and distributors, service stations owners and operators, and non-government organizations (NGOs). Gaining the support of these stakeholders is critical to the successful development and implementation of a lead phaseout strategy. By consulting these parties and involving them in the decision-making process, stakeholders will feel that they "own" both the process and its outcomes, and are less likely to oppose the program once it is implemented.

This chapter summarizes stakeholder involvement strategies, which include both stakeholder identification and outreach components.

The Steps In Stakeholder Consultation And Involvement

1. Identify stakeholders
Here, implementers should identify the program's stakeholders: the individuals and organizations whose interests will be most affected.

2. Identify strategy for stakeholder involvement
Implementers should next design a process for including the program's stakeholders in the strategy's development and implementation.

3. Communicate risk assessment and benefit estimates
Education is a key component of stakeholder involvement. Stakeholders must understand the need for the program, its benefits and its costs.

4. Communicate/consult on alternative phaseout strategies
Ideally, implementers should be willing to consider alternative phaseout strategies that address stakeholder concerns and constraints.

11.1 Stakeholder Identification

A first step in developing a stakeholder involvement program is to identify the various stakeholders whose interests will be affected by a lead phaseout strategy. Often, the key stakeholders are the same organizations or people as the key audiences identified for a public education strategy (see Chapter 10). The

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focus here, however, is engaging key stakeholders in a collaborative decision-making process. Potential stakeholders include:

- Government agencies and ministries (e.g., energy, environment, health, industry, transportation, finance, trade).
- Petroleum refiners.
- Automobile manufacturers and importers.
- Gasoline distributors and retailers.
- Fleet owners and operators.
- Non-government organizations.
- Motorists.

The key stakeholders for a lead phaseout program are often the same as the audience for the program's public education strategy (Chapter 10).

Each group is described briefly below.

Government agencies. Typically, many government agencies and ministries – both at the national and local levels – play a role in the phaseout of leaded gasoline. These include agencies that set and control tax policies, environmental programs, vehicle registration, vehicle inspection and maintenance programs, and tariffs and duties on vehicle imports and fuel imports, and regulate refiners. These agencies need to be involved in the process so that they understand what implications (if any) a phaseout program will have on their programs and vested interests.

Petroleum refiners. Oil refiners have a large stake in the decision making process for a lead phaseout strategy. It is important to involve such powerful stakeholders in the consensus building process to reduce their opposition to a lead phaseout strategy. Timing as well as the technical aspects of the phaseout options considered are significant issues for oil refiners because converting from leaded to unleaded fuel can have enormous cost implications for them. Implementers should be sensitive to their issues and be willing to consider various incentive schemes or schedules to facilitate the conversion process.

Automobile manufacturers and importers. Auto manufacturers are not likely to be affected much by lead phaseout per se. However, many countries may decide to take advantage of the opportunity presented by lead phaseout to introduce vehicle emission standards that are strict enough to require catalytic converters. In this case, auto manufacturers will be very much affected, and it will be critical to obtain the support (or at least the acquiescence) of this stakeholder group. Working with automobile manufacturers to devise a practical schedule for incorporating emissions controls in their automobile designs can promote broad support and reduce the potential for opposition from certain segments (those less able to quickly add controls or increase imports of vehicles so equipped). Auto manufacturers can actually support a phaseout strategy by endorsing the use of unleaded gasoline.

Gasoline distributors and retailers. These groups provide an important link in the supply chain and their support can greatly enhance the operation of a lead phasedown program. Retailers also play an important role in the public education process because of their direct access to motorists, so their issues should be carefully considered in the development of a strategy. Retail service station owners and operators should be involved in the consensus building process because gaining their support for a lead phaseout strategy can assist in securing support from vehicle owners and operators. Service station attendants or mechanics can assist with the public education strategy by disseminating information to motorists when they purchase gasoline or auto maintenance services.

Fleet owners and operators, particularly government vehicle fleets, can play a key role in a lead phaseout program by implementing measures first and demonstrating their effectiveness.

Non-government organizations (NGOs), such as medical or public health associations, educational or teachers' associations, or environmental organizations, can facilitate consensus building. Working with concerned members of the public, NGOs generally will support the significant social benefits of policies and programs to phase out lead from gasoline. They can help explain the health risks associated with using leaded gasoline and build political support for a lead phaseout strategy.

Motorists are also key stakeholders. They must pay any price differentials or bear any service inconvenience that result from the strategy. Motorists (or groups of motorists such as taxi cab drivers) may be represented by an NGO or association. If so, representatives of these groups should be invited to participate in the decision making process.

11.2 Stakeholder Involvement Strategies

After stakeholders are identified, implementers should design a process for disseminating information to them and involving them in the decision making process for the lead phaseout strategy. The nature and extent of stakeholder involvement will vary depending on the institutional arrangements and industry practices in each country.

The stakeholder involvement strategy should be closely linked with the public education strategy (see Chapter 10) to ensure a consistent and effective message. The inputs stakeholders provide may, in some cases, identify the need for more public education, but also may identify real problems that must be addressed in designing a lead phaseout strategy. Examples of issues where stakeholder involvement may help in building consensus for a lead phaseout strategy are:

- Identifying the best technical options for phasing out lead in gasoline.
- Evaluating the timing for implementing selected technical options.
- Assessing the economic and behavioral impacts of pricing decisions and incentive policies.
- Evaluating the "fit" between technical options and policy instruments.
- Identifying monitoring, compliance and enforcement needs.

The nature and extent of stakeholder involvement will vary depending on the institutional arrangements and industry practices in each country.

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Good organization and well-planned outreach are necessary for a stakeholder involvement program because they can help produce inputs that the government can use in decision making as well as facilitate consensus building. Implementers should identify specific strategies to gain the participation of stakeholders. Several methods are available to bring stakeholders together, provide them with information, and establish effective communications. Selected examples are summarized in this section.

Advisory groups. An advisory group is a way to bring together a core group of stakeholders who have a strong interest in a lead phaseout strategy. An advisory group should be composed of representatives from each of the key stakeholder groups (each should be given equal status in presenting and deliberating their ideas), along with representatives from government agencies. Advisory groups provide a forum for the government to present proposed policies and programs, and bring stakeholder feedback and ideas into the process.

Advisory groups usually meet regularly to discuss issues of concern and to reach agreement on recommendations as input to implementers. Advisory group meetings can serve to educate stakeholders on technical issues, update them on progress or new issues identified, and provide an organized way for the government to learn and understand the positions of different groups. An advisory group can also assist in outreach efforts to broaden a stakeholder involvement program.

Public meetings are more effective if they are held early in the decision making process.

Public meetings and hearings. Implementers can use these vehicles to present information to stakeholders and the public, and obtain input from participants. They can be tailored to specific issues or organized for specific groups of stakeholders with an interest in a lead phaseout strategy. While public meetings are useful for exchanging information, public hearings typically are more formal events held prior to a specific decision point in developing policies and programs. Public meetings are more effective if they are held early in the decision making process and if the government makes clear the link between the meetings' input and decision making. If held too late in the process and not accompanied by other stakeholder involvement opportunities, stakeholders and the public may feel that their ideas and concerns will not be addressed. A media strategy is important for effective public meetings to attract the widest possible audience. Public education materials (see Chapter 10) can be distributed at a public meeting.

Workshops. These are designed as special meetings to inform stakeholders and seek input on a specific policy issue or program. They usually involve a relatively small group of people, require advance registration or invitation, and provide an opportunity for people to participate intensively. Typically, participants work on specific issues or concerns and are usually sent materials in advance to prepare for the workshop. They can be very useful for educating groups on technical issues to enhance their ability to make informed decisions. Input from workshops can be integrated into the larger stakeholder involvement process.

The Role Of Public Awareness In Slovakia's Lead Phaseout

Slovakia's successful phaseout of leaded gasoline was due to the use of an incentive policy, which was later combined with a rapid phaseout approach to influence consumer behavior and to smooth the transition. Different programs were put in place to combine the incentive policy with regulations to ensure the reduction of lead content in gasoline, and to support the use and import of cars with improved pollution characteristics. Slovakia only has one refinery (Slovnaft), which facilitated the transition from the production of leaded to unleaded gasoline.

At the beginning of the phaseout program in 1988, Slovnaft introduced a lubricant additive ANABEX® 99, which helped ease the transition and achieve lead levels of 0.15 g/l by 1989 (down from 0.25 g/l). Beginning in 1993, the Slovakian government enforced and made catalytic converters mandatory for both imported and domestic cars. And beginning in 1995, only unleaded gasoline was sold at service stations. These policies were accompanied by registration standards for new and imported vehicles that included the:

- Capability to use unleaded gasoline without the use of lubricating additives.
- Presence of a three-way catalytic converter.
- Age of imported vehicles: manufactured in 1985 or later.

These initiatives were supported by strong information campaigns that informed and influenced consumers' behavior, and involved them in the lead phasedown process. This rigorous, multi-faceted approach helped to overcome the problem of old vehicle fleets (most of which were over 15 years old) and the respective low turnover rates, thus giving the public an incentive to buy cars with catalytic converters (REC, 1998).

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