The Case for Banning Lead in Gasoline

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PREFACE

Leaded gasoline presents a serious inherited public health problem thrust upon the leaders of this generation. This paper makes the health, technical, economical, and moral case for those leaders to act to ban leaded gasoline. The paper focuses on the following points:

- Airborne lead is a cumulative neurotoxin ingested by humans, adversely affecting the mental and physical health of children, and causing elevated blood pressure, hypertension, and other cardiovascular conditions in adults.

- Unleaded gasoline, known as a clean fuel, makes economic sense as it improves engine and component durability alike and reduces maintenance costs.

- Those supplying lead for gasoline argue that unleaded gasoline contributes to valve wear and higher benzene emissions and, therefore, justifies the continued use of leaded gasoline. Countries that have eliminated lead in gasoline have considered and rejected these arguments.

- There is economic justification to switching immediately to 100% unleaded gasoline. China and India are doing this now.

Unleaded gasoline is now used in much of the world, but leaded gasoline still remains in many populous world countries and major world cities. Eighty percent of airborne lead comes from combustion of leaded gasoline, and airborne lead is found responsible for adversely affecting the mental and physical development of children. Many countries, putting health costs into the equation, have realized economic benefits from the conversion to unleaded gasoline.

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0.0 EXECUTIVE SUMMARY

0.1 Effects of Leaded and Unleaded Gasoline on Human Health

Numerous and highly respected health studies have confirmed the serious health threat posed by leaded gasoline, even at very low levels. Lead is a cumulative neurotoxin that adversely affects the mental and physical development of children and causes elevated blood pressure, hypertension, and other cardiovascular conditions in adults.

Studies have conclusively correlated levels of lead in gasoline to elevated lead blood levels and have found that decreasing lead in gasoline causes blood lead levels to fall.

The introduction of unleaded gasoline, and subsequent decrease in blood lead levels, have been shown to have significant economic value, primarily in the form of avoided health care costs and wage losses due to lower intelligence and illness. For instance, a one microgram per deciliter reduction in blood lead level for one year's cohort of children (all children born in the same year) translated to a gain of approximately US $6.9 billion.

0.2 Effects of Unleaded and Leaded Gasoline on Vehicle Components

Unleaded gasoline is a clean fuel that does not produce corrosive compounds. The vehicles maintenance savings from unleaded gasoline use outweigh any negative side effects, such as potential for valve wear, if any, on some older susceptible pre-1980 engines.

Leaded gasoline increases vehicle maintenance costs in the range of US $0.05 per gallon (US $0.013 per liter) of gasoline. The components formed in leaded fuel combustion are corrosive and harm engines, spark plugs, and exhaust systems. Leaded gasoline, even in trace amounts, deactivates the catalytic converter used for emissions control. Additives used to prevent the accumulation of lead in the combustion chamber cause lead to stick to active catalyst sites, deactivating them.

0.3 Options for the Elimination of Leaded Gasoline

Approach #1:

Immediate, 100% conversion from leaded gasoline to unleaded. The most cost effective and health effective approach. Avoids the huge cost of an additional gasoline distribution system, because the existing gasoline station tanks and pumps are used. Achieves elimination of ambient lead in the shortest time. This approach has recently been taken by China. The city of Delhi, India converted to unleaded gasoline in September 1998.

Approach #2:

Rapid phase-out of leaded gasoline by incrementally reducing lead concentrations from higher to lower levels, followed by the introduction of unleaded gasoline and then the banning of lead. Gives more time for refinery upgrade. Requires a dual distribution system for a period of time. Takes 4 to 6 years to obtain zero lead levels.

Approach #3:

Phase-in unleaded gasoline to coincide with introduction of new vehicles designed for that fuel, and **phase-out** leaded gasoline as older vehicles are retired. A success in the United States and Canada, but it took 20 years, which is too long.

0.4 Issues and Solutions Concerning Unleaded Gasoline Use

Higher valve seat wear can occur in some pre-1980 design engines at operating conditions of 120 km/hour with unleaded gasoline. This problem, although increasingly unlikely, can occur in certain engines with non-hardened valve seats and high valve rotation design. Not all engines are susceptible - Honda stated that none of its engines were susceptible nor are any U.S. design engines. Valve wear with unleaded gasoline has not been found to be a problem in susceptible engines under normal driving conditions and operation at 100 km/hour. Anti-valve wear additives in the unleaded gasoline used in Europe and Thailand have been shown to completely eliminate valve wear.

Benzene emissions are to be avoided - the concern is that some refinery processes used to increase the octane rating of unleaded fuel might cause increases in emissions of the aromatic gases. However, many cost effective refinery techniques exist that increase the octane number without increasing benzene emissions. Furthermore, vehicles equipped with catalytic converters destroy 90 to 95% of benzene and other aromatics in the exhaust stream.

Octane enhancement is also not a problem. Many efficient refinery procedures exist that can cost effectively increase the octane rating of gasoline without using lead.

0.5 Costs of Producing and Using Unleaded Gasoline

The most significant costs incurred in removing lead from gasoline are cost of alternate octane values and modifying refinery production facilities. The cost of eliminating leaded gasoline has been estimated in the modest range of only US $0.038-0.076 per gallon (US $0.01-0.02 per liter) of gasoline in the majority of refineries, and the refinery upgrade cost pays for itself in a short period through increases in productivity and efficiency. The World Bank offers support through low cost loans.

0.6 Worldwide Experience with Regulating Lead

Countries around the world are at various stages of tackling the problem of human exposure to lead emissions. The World Health Organization has called for a lead ban by 2001. The United States began to phase out leaded gasoline in 1970 and completely eliminated it 20 years later. Since 1975, many countries have introduced unleaded gasoline, including Japan, Canada, Mexico, Central and South America, all of Western Europe, Korea, Australia, China, Thailand and Taiwan. In the United States, health concerns of leaded gasoline peaked about the same time as the need to clean up pollution from automobiles. In other countries, the regulation of lead levels in gasoline because of health concerns preceded the widespread use of catalytic converters to clean up automobile exhaust pollution.

0.7 Conclusions

The ban of leaded gasoline provides immediate and significant human health benefits and reduced vehicle maintenance costs. The most effective policy approach in working towards the removal of lead in gasoline is either an **immediate 100% conversion** to unleaded gasoline or a **rapid phase-out-of-lead** approach. All issues raised by lead supporters have easy and cost effective solutions and are vastly outweighed by the well-documented health and vehicle-related benefits. Each country needs to formulate a plan for banning leaded gasoline that reflects the needs and recommendations of its parent/teacher groups as well of those of health organizations and industry. Protection of children's mental development is paramount and dictates the approach all countries must take. Leaded gasoline must be eliminated at all possible speed.

1.0 INTRODUCTION

The primary source of human lead exposure is leaded gasoline emissions, which are inhaled and ingested resulting in a steady accumulation of lead within the body. Many nations have switched to unleaded gasoline and have avoided this serious situation. However, other nations still use leaded gasoline as the main fuel for the spark-ignited engines used in passenger cars, light-duty trucks, and two-wheeled vehicles. Consequently, large populations of these nations suffer unnecessary and serious health effects.

Leaded gasoline has serious negative effects on health and the environment. The accumulation of lead in the body, known as the human lead burden, has been found to pose a significant risk to humans even at very low levels. The major source of human lead accumulation in developing countries was found to be airborne lead, 90% of which come from leaded gasoline [12]. The World Health Organization recently has determined that 1.9 billion humans still suffer health problems due to this source of lead and has called for the complete elimination of leaded gasoline by 2001. Lead in gasoline also severely limits exhaust emissions control options because it completely destroys the effectiveness of catalytic converters, the most commonly used exhaust emissions control system. For both reasons, a growing number of nations around the world have moved, or are moving, to completely eliminate lead in gasoline. Although the negative impact on health and emissions control is well known, leaded gasoline is still widely used in a number of countries worldwide. Leaded gasoline remains a transportation fuel partly because several easy and cost effective ways to quickly switch to unleaded gasoline are not fully understood. The World Bank offers low interest loans to oil companies to help offset the cost of switching to unleaded gasoline.

This paper presents the case for quickly and cost effectively eliminating lead in gasoline for all countries still using leaded fuel. Lead impairs children's intellectual development and hurts their chances to compete in the ever-expanding global economy. Nations rely on the next generation of children for their future, and by harming children, the use of leaded gasoline puts future economic and social advancement in jeopardy. MECA considers protection of children's health, welfare, and intellectual development the most important reason to remove lead from gasoline.

By contrast, opposing arguments stating that lead is necessary to protect old automobile engines are greatly overstated. Even considering old engines, the overall cost benefits of lead elimination are positive. The argument that benzene emissions will increase if unleaded gasoline is used for old vehicles is also flawed. A quick and complete ban on lead in gasoline for all nations still utilizing leaded gasoline is the most beneficial and cost effective course of action.

Since the introduction of unleaded gasoline in the United States, airborne lead has been reduced more than 95% which is a major achievement in air quality improvement.

2.0 ADVERSE IMPACTS OF LEADED GASOLINE VS. POSITIVE IMPACTS OF UNLEADED GASOLINE

2.1 Adverse Health Effects of Lead

The adverse health effects of exposure to lead have been known for centuries. When lead was introduced in gasoline in the late 1920s, the knowledge of the lead exposure health risks sparked a growing concern among scientists and others. The subsequent health risk studies were one of the primary reasons the United States decided to switch to unleaded gasoline in 1970.

Since then, many highly-respected scientific studies have confirmed the seriousness of the threat posed by lead. These studies have reported several significant health threats resulting from both low and high blood lead levels, including neurodevelopmental effects in children and increased blood pressure and related cardiovascular conditions in adults [3]. Lead has also been identified as a possible carcinogen. Of these three effects, the neurodevelopmental effects of lead exposure to unborn children and small children are viewed by health experts as the most significant public health hazard [3].

Worldwide, a large number of health and government agencies, including the World Health Organization, the U.S. Environmental Protection Agency, the International Agency for Research on Cancer, and the California Air Resources Board (which in April 1997 identified inorganic lead as a toxic air contaminant), have determined that lead poses a serious health hazard [3]. The scientific evidence and concern for health risks posed by lead have caused a growing number of countries to ban lead in gasoline (see Section 6.0 below).

2.1.1 Measuring Lead Levels in Humans

Human lead levels are measured by an analysis of teeth, bone, and/or blood. Teeth and bone are cumulative indicators of lead exposure; cumulative indicators show the degree to which a person has been exposed throughout his or her life. In the case of teeth, lead concentrates in tooth dentine. Needleman [14] and others have studied dentine lead levels by analyzing shed children's baby teeth.

Measurement of blood lead level, or the concentration of lead in blood (measured in micrograms per deciliter, µg/dL), is more representative of recent exposure (within the past 3 months), while simultaneously indicating cumulative exposure (since some lead is mobilized in the blood from bone and other storage areas) [3]. A study by Billick found that blood lead increased and decreased with the seasonal use of gasoline [2].

2.1.2 Neurodevelopmental Effects in Children

Studies have shown the adverse neurodevelopmental effects lead exposure has on children. Some have concluded that children with elevated levels of lead accumulated in their baby teeth, even with relatively low levels of lead in their blood, experience more behavioral problems, lower intelligence quotients (IQ), and more concentration problems than their counterparts without significant lead accumulation [14, 23]. One study found that children with prenatal umbilical-cord blood lead levels at or above 10 µg/dL consistently scored lower on standard intelligence tests than those with lower levels of lead [3].

Several factors make children more susceptible to lead exposure than adults:

- Children easily assimilate lead in the stomach, resulting in greater distribution levels throughout the body.
- Children possess greater metabolic rates, resulting in a higher intake of lead through food.
- Children have greater neurologic sensitivity.
- Children have a higher breathing frequency through the mouth and tend to be more active which translates to greater volumes of air (with airborne lead) inhaled during the course of a day.
- Children have a higher hand-to-mouth frequency resulting in higher ingestion rates of lead deposited on various surfaces.

These inherent characteristics of children require that special attention be given to the potential of child lead exposure.

Economically disadvantaged children are highly susceptible to lead exposure. Often they reside in urban areas where the general population has higher than average lead exposure levels and play in places where nearby road traffic emits high levels of airborne lead. Poorer children are also likely to have diets deficient in lead-suppressing minerals, such as calcium and iron, which makes them more vulnerable to lead exposure [3].

2.1.3 Relationship Between Leaded Gasoline and Blood Lead Levels

Studies from the mid-1970s to the present have shown the relationship between decreases in airborne lead levels and blood lead levels in humans. Scientists recognize these two trends and are confident that they are significantly correlated.

The U.S. Center for Disease Control (CDC) used evidence from two cross-sectional surveys, versions of the National Health and Nutritional Examination Survey (NHANES), to investigate the distribution of blood lead levels in the U.S. population. The results showed a 78% decline in blood lead levels for persons aged one to 74 years of age in the 10 years between the surveys. Data from the NHANES II survey, conducted between 1976 and 1980, suggests that approximately 88.2% of children aged one to five exhibited a blood lead level greater than or equal to 10 µg/dL during this period. Subsequently, NHANES III reported that only 8.9% of the same age group showed such high blood lead levels between 1988 and 1991. Similar declines were found in other subgroups determined by race, ethnic background, gender, urban status, and socioeconomic levels.

This substantial reduction in overall blood lead levels in the U.S. coincided with a decline in lead exposure from environmental sources, most notably from the reduction of lead in gasoline. The amount of lead used in gasoline decreased 99.8% nationally between 1976 and 1990. In addition, food and soft drink cans containing lead solder diminished from 47% of cans in 1980 to 0.85% in 1990.

The highly significant correlation between blood lead levels and the amount of lead used in gasoline led the NHANES II and III authors to conclude that lead in gasoline was most likely the largest determinant of blood lead levels during the entire survey period and that leaded gasoline phase-out probably resulted in the decreased blood levels detected in the latter survey [3]. This conclusion is re-enforced by experiences in California between 1976 and 1980 when average ambient air lead levels decreased 30-fold, precipitating a 37% drop in average blood lead levels during the same period.

2.2 Economic Health Benefits of Unleaded Gasoline Use

In 1994 Professor Joel Schwartz of the Harvard School of Public Health quantified the economic health benefits of reduced lead exposure in the U.S. Schwartz related lead exposure to decrements in IQ and decrements in IQ to earnings lost over a human life span. He estimated that a 1 µg/dL reduction in blood lead level for one year's cohort of children (all children born in the same year) translated to a gain of approximately US $6.9 billion, the majority of which is attributed to avoiding lost future earnings ($5.060 billion) [17]. A summary of Dr. Schwartz's estimate is shown in Table 1.

A 1995 report by Dr. David Salkever of the Johns Hopkins School of Hygiene and Public Health asserted that Dr. Schwartz's estimations were significantly conservative in relating earnings to the marginal productivity of labor in the market. Salkever estimated that earnings losses averted by a 1 µg/dL reduction in blood lead level in children was approximately 50% greater than Schwartz's estimation of $5.060 billion [16] and that such benefits would only continue to grow as education and cognitive skills become increasingly more important in our economy.

Another study estimated the health costs to society in economic terms, based solely upon the effects of lower IQ's in children, might be as high as 45 cents per gallon or $45 billion dollars annually [18].

Table 1. Annual Health Benefits of Reducing Mean Blood Level by 1 µg/dL in the Population of the U.S.

Benefit	Amount (millions of US $)
Children	
Medical Costs Avoided	189
Compensatory Education Avoided	481
Earnings Loss Avoided	5,060
Infant Mortality Avoided	1,140
Neonatal Care Avoided	67
Children Sub-total	**6,937**
Adults	
Medical Costs Avoided	
Hypertension Avoided	399
Heart Attacks Avoided	141
Strokes Avoided	39
Lost Wages Avoided	
Hypertension Avoided	50
Heart Attacks Avoided	67
Strokes Avoided	19
Mortality Avoided	9,900
Adult Sub-total	**10,215**
Total	**17,152**

The table above shows the breakdown of the implied economic health benefits (in 1989 US$) related to lead exposure reductions for both children and adults as determined by Schwartz [12].

Human lead burden is directly related to increased blood pressure. A similar relationship exists between high blood pressure and the costs associated with strokes, heart attacks, and deaths attributed to increased blood pressure. In this case, it was estimated that a 1 µg/dL reduction in blood lead level is valued at approximately US $57 per year per person [18].

2.3 Adverse Impact of Lead on Emission Control Equipment

Leaded gasoline has many negative effects on both vehicle parts and emission control equipment. The nature of the chemical components resulting from the combustion of leaded gasoline cause high engine wear, short spark plug life, corrosive wear of the exhaust system, and high maintenance costs. Leaded gasoline also deactivates the catalytic converter. Alternative non-catalytic methods of exhaust emissions control that are compatible with leaded fuel are fuel inefficient, resulting in a 30% decrease in fuel economy, and cannot achieve the same low emission levels of catalyst-equipped vehicles.

2.3.1 Catalytic Converter

The effects of leaded gasoline on engines and catalytic converters have been studied for many years. Research has confirmed that lead in fuel rapidly deactivates the performance of the catalytic converter [4]. At lead levels of 0.125 grams per liter (g/l) or greater, the deactivation occurs after only a few tankfuls. Even trace lead levels (less than 0.003 g/gal (0.0008 g/l)) in unleaded gasoline will cause lead poisoning of the catalyst and will negatively influence its performance in an automotive catalytic converter. Gasoline with zero residual lead provides the most flexibility in catalyst design and the greatest potential to utilize the most cost-effective catalyst materials [4]. Consequently, the United States Federal Code regulations does not allow the addition of lead compounds at the refinery to gasoline that will be sold as "unleaded." The maximum lead specification for unleaded gasoline is 0.014 g/l (0.05 g/gal), but this maximum does not reflect the lead level of actual commercial gasoline sold at the pump. In the United States, lead in commercial gasoline has been approaching zero (nondetectable limits) for several years.

2.3.1.1. Lead Deactivation of the Catalyst

Ford Motor Company published the definitive study on the mechanism by which leaded fuel poisons a catalyst [7]. Tetraethyl lead (TEL), along with ethylene dibromide (EDB) or ethylene dichloride (EDC) are gasoline additives. EDB, the most common additive, minimizes lead accumulation within the combustion chamber, on the spark plugs, and on the valve seats by providing a compound that reacts with lead to form the volatile lead bromide upon combustion. Gaseous lead bromide is exhausted with other gases into the exhaust system and diffuses to the active catalyst sites. It finds the active catalyst sites, sticking to these sites and remaining there as solid lead compounds - thus deactivating the catalyst site for further reactions. This phenomenon is known as lead poisoning.

The Ford scientists analyzed lead poisoned catalysts and found lead concentrations only on the precious metal catalyst sites. No lead was found associated with the aluminum oxide and other base metal oxides used to disperse the precious metal throughout the catalyst support. Ford scientists also found that various precious metals were affected differently by lead. Platinum (Pt) was more resistant to lead poisoning because it is somewhat protected by sulfur in the fuel. Pt oxidizes sulfur dioxide to sulfur trioxide and then reacts with lead compounds to form lead sulfate which is not a catalyst poison. The protection is short lived, however, as additional lead sulfate clogs up the site area and eventually renders the area inactive. Nevertheless, Pt is the preferred catalytic material for initial catalyst formulations in catalytic converters directly after the switch to unleaded gasoline. The Ford researchers also studied palladium and rhodium, which are more strongly poisoned by leaded gasoline.

At higher temperatures (above 750°C), lead sulfate decomposes into lead oxide which chemically deactivates the catalyst. High temperature conditions nonetheless minimize physical plugging of the catalyst because particulate lead retention is significantly reduced [4].

2.3.1.2. Lead Deactivation Occurs Rapidly

One tank of leaded gasoline causes a rapid decline in catalyst performance, which increases emissions significantly. A return to unleaded gasoline will return some of the lost catalyst performance. However, a permanent decline in catalyst performance will occur with steady use of unleaded gasoline. For example, in 1983 the U.S. EPA tested five vehicles, some equipped with oxidation catalysts and others with three-way catalysts. EPA researchers refueled each vehicle ten times with gasoline containing 0.28 g/l of lead [13]. For the five vehicles in the study, emission levels were reported to steadily increase with each fueling such that when the vehicle was refueled with unleaded gasoline after having been fueled with 10 tankfuls of leaded gasoline, hydrocarbon (HC) emissions were over four times the original levels and carbon monoxide (CO) emissions were nearly three times the original levels. For the three-way catalytic converter-equipped vehicles, NOx emissions nearly doubled. EPA reported that most deactivation occurred with four tankfuls of leaded gasoline. HC and CO emissions continued to increase with further fueling but not at the same rate [4].

2.3.2 Oxygen Sensor

Direct association of lead compounds with precious metals has been observed in laboratory studies on automotive catalyst support materials and zirconia exhaust-gas oxygen (EGO) sensors using electron microprobe and Auger electron spectroscopy [7]. After exposure of the zirconia EGO sensor at 730°C to combustion products from iso-octane containing 1.5 g Pb/gal, microscopic analysis indicated that the lead species were found directly associated with the platinum electrode surface, but not detected on the outer porous spinel barrier coating of the sensor. Thus, lead deactivation of catalyst supports and platinum electrodes in oxygen sensors are similar in that the halide-containing lead species specifically seek out precious metal surfaces that provide a catalytic site for dissociation resulting in lead deposits on the precious metal surface.

2.4 The Benefits of Unleaded Gasoline to Vehicle Maintenance

Unleaded gasoline considerably reduces the vehicle maintenance costs incurred with leaded fuel use. Unleaded gasoline is a clean fuel with less corrosive products of combustion than leaded gasoline. Consumers benefit from maintenance savings and fewer engine and exhaust system repairs due to corrosion. The additives EDC and EDB, needed in leaded gasoline, form corrosive acids upon combustion. They cause corrosion to engine parts, more frequent oil changes, and the replacement of spark plugs, mufflers and exhaust pipes. As a result of switching to unleaded fuel, several nations, including Australia, Canada, and the U.S., have reported maintenance savings in the range of US $0.189 per gallon (US $0.05 per liter) of gasoline [23]. The economic benefit in terms of savings in vehicle maintenance costs alone justifies the removal of lead from gasoline [18]; along with health benefits, the arguments become even more compelling.

3.0 OPTIONS FOR BANNING LEADED GASOLINE

There are three proven approaches a country can take to eliminate leaded gasoline. One choice, recently used by China and Central and South American countries, is **immediate, 100% conversion** of all gasoline from leaded to unleaded. China started switching individual cities to 100% unleaded gasoline in June 1997 and plans to have only unleaded gasoline throughout China by 2000. The city of Delhi, India, switched to 100% unleaded in September 1998. Thailand began a second type of approach in 1990, known as the **rapid phase-out** approach by incrementally reducing gasoline lead concentrations. Thailand introduced two grades of unleaded gasoline in 1991 and 1993 and then subsequently phased out leaded gasoline in 1996. The United States, Canada, Japan, and Western Europe chose the third approach, which was to **phase-in** unleaded gasoline coinciding with the introduction of new vehicles designed for unleaded fuel and to **phase-out** unleaded gasoline as older vehicles are retired.

The **immediate, 100% conversion** from leaded to unleaded gasoline appears to offer the most cost effective benefits as it most swiftly eliminates the negative health effects, avoids dual refinery and distribution system costs, and reduces vehicle maintenance costs. This approach gives realistic consideration to health needs and actual vehicle usage and is responsive to the protection of children's mental development. However, it requires a means to replace the equivalent octane value of the TEL removed - options are discussed in Section 4.3.

3.1 Approach #1: Immediate Conversion to Unleaded Gasoline

The **immediate, 100% conversion** from leaded gasoline to unleaded gasoline is a fast and attractive option. Ambient air lead concentrations are quickly reduced to zero. The source of negative lead health effects is quickly and effectively eliminated. Because unleaded gas completely replaces leaded gas, and since it is distributed through the existing leaded fuel system, countries avoid the complications and cost of both building a new distribution system with two separate pumps and storage tanks at the gasoline station and maintaining a dual fuel distribution system. Residual leaded gasoline in tanks and pipelines will be diluted to near zero after several refill replacements of the gasoline station storage tank. Older vehicles will also benefit from decreased maintenance costs because of increased spark plug and longer exhaust system and engine life. Since there is only unleaded gasoline, the unnecessary costs, and the potential for misfueling and lead contamination of unleaded gasoline, which can undermine the performance of the catalytic converter, are not even considerations.

China has taken the **immediate, 100% conversion** approach along with Central and South American countries (see Section 6.1). India started this approach in Delhi as of September 1998.

The **immediate, 100% conversion** approach requires a means of octane replacement. If imported octane is required this can be later phased out when the internal refinery system is upgraded.

3.2 Approach #2: Rapid Phase-out of Leaded Gasoline

The **rapid phase-out** approach is characterized by a transition period of 4 to 6 years from leaded to unleaded gasoline, during which concentrations of TEL in leaded gasoline are rapidly reduced, followed by the introduction of unleaded gasoline, and finally the ban of all leaded gasoline.

The **rapid phase-out** approach requires separate gasoline distribution systems and separate refinery storage facilities for each product. Some countries using this approach have added a valve seat wear prevention additive to unleaded gasoline, but whether preventive additives are actually needed is debatable. Lead contamination of unleaded gasoline and potential for misfueling remain a problem with this approach until leaded gasoline is finally banned.

As previously stated, Thailand took the **rapid phase-out** approach starting in 1990, and Figure 1 illustrates the effectiveness in reducing lead emissions with regard to the number of years over which a rapid phase-out occurs.

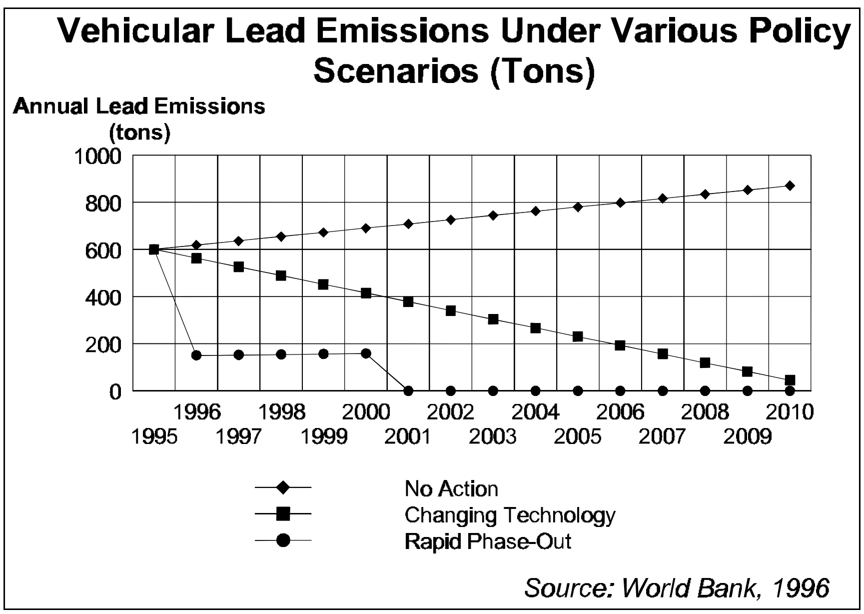

Figure 1. Annual lead emissions are reduced and eliminated far more quickly under rapid phase-out than under other policy scenarios.

It was found that some Thailand motorists used unleaded gasoline in older vehicles which contributed to the effectiveness of the program. These motorists also obtained the economic benefits without apparent negative effects.

3.3 Approach #3: Phase-in, Phase-Out

The **phase-in, phase-out** approach requires the maintenance of a dual distribution system for many years. New vehicles are designed for unleaded fuel, and as older vehicles are retired, the demand for leaded fuel diminishes. Finally, leaded fuel is banned. This approach was taken by the United States, Canada, Australia, Japan and many European countries.

Since ambient lead in the air is now near zero in the U.S., the approach is considered successful. It took nearly 20 years for the complete transition, however, which was unnecessarily long. Most experts agree that, in retrospect, the better approach is to ban lead completely or to require a rapid phase-out. Notably, older vehicle owners tended to use leaded gasoline when the pump price was lower, but some did choose to use unleaded gasoline and realized reduced maintenance costs and improved engine life.

3.4 All Groups Affected by the Lead Issue Should Be Consulted

National governments are not the only entities to have a proper role in the process to eliminate leaded gasoline. Parents and teachers, in addition to the important roles of health and environmental organizations, fuel manufacturers, vehicle manufacturers, are all also crucial to the successful plan to eliminate lead from gasoline and the subsequent protection of public health, particularly children's physical and mental development. The demand for lead elimination is peaking throughout the rest of the world. Parents want a healthy environment for their children. Through collaboration, these groups can achieve widespread support for and understanding of the importance of banning leaded gasoline.

Though the refinery industry has its economic limitations, it has had over 20 years of forewarning that lead poses serious health risks and must be eliminated from gasoline. It is very important to have a reasonable and timely plan to balance the concerns and interests of all parties.

3.5 Funding

The World Bank has committed itself to assisting nations with low interest loans for refineries and systems needing modification to assure an adequate supply of unleaded gasoline.

4.0 ISSUES AND SOLUTIONS CONCERNING UNLEADED GASOLINE USE

The overwhelming benefits of unleaded gasoline are undisputed. Four issues, however, have been raised by the lead additive industry concerning the use of unleaded fuel: 1) claims that engine valve wear with unleaded gasoline will occur, 2) claims that benzene emissions will increase if unleaded gasoline is used by older vehicles, and 3) claims that gasoline octane replacements will be more costly, and 4) claims that unleaded gasoline will result in loss of engine thermal efficiency and fuel economy. All of the above are discussed below, however regardless of the argument, any costs incurred cannot outweigh the health benefits of unleaded gasoline, especially with regard to children's mental health.

Since the 1920s, lead has been added to gasoline to increase its octane rating and reduce engine knock. Knock is a measure of how sensitive an engine is to pre-ignition. By reducing knock tendency (by raising octane rating), engines could be designed for more power. TEL/EDB additive, or leaded gasoline, was used as the primary octane additive for over 50 years. Engines had to be redesigned to accept TEL. To prevent the accumulation of lead on the valve seats, the valves were designed to rotate a few degrees per revolution [8]. It was found that lead deposits actually served as a lubricant between the valve and the valve seat. Other organic and fuel soluble fuel additives based on sodium or potassium have been found to also serve as effective valve lubricants.

Subsequently, in the early 1970s, engines were redesigned again for unleaded gasoline. Hardened valve seat inserts were introduced. Older engines were thought to be susceptible to valve seat wear if operated on unleaded gasoline. Actually, valve wear has been found in several studies of older engines but only at high engine speeds and loads in engine dynamometer studies. However, in actual use, older vehicles in the United States valve wear did not turn out to be a problem in this respect. Many older vehicles used the clean burning unleaded gasoline (a brand of AMOCO premium unleaded gasoline had been on the market since the 1940s). Also, many vehicles were converted successfully to LPG fuel (an unleaded fuel).

Proponents of leaded gasoline say that an increase in aromatic compound emissions, especially benzene, may result from older vehicles emissions with unleaded gasoline. They believe refinery methods that do not emit aromatic compounds may be unavailable, undesirable, or prohibitively expensive. Practical solutions exist, however, to address this issue (see Section 4.3.1).

One of the reasons lead was added to gasoline was to lower unit cost and to increase the fuel octane rating. Potential cost increases is a primary concern of switching to unleaded gasoline, but today there are many overall cost effective methods to increase the octane number of unleaded gasoline. Also, as noted earlier, there are economic health and vehicle maintenance factors which positively offset higher octane cost, if any.

With the introduction of unleaded gasoline in the United States for use in 1975 model year vehicles, the average fuel economy of passenger cars has increased from 13.5 miles per gallon to ~27.5 miles per gallon. One of the primary contributors to the overall gain in fuel economy was the re-tuning of the engine for unleaded gasoline, which maintains optimal ignition calibration (due to non-fouling and longer effective spark plug life) for extended periods. This also improved engine power and performance. Another primary contributor to the improved fuel economy was the development of the “stoichiometric” engine - an accomplishment that gave increased power and fuel economy as well as superior emissions control all of which could not have been achieved with leaded gasoline. Thus, the predictions of fuel economy and power losses have not been seen.

4.1 Impact on Existing Fleets

Very few older vehicles in the existing vehicle fleet will be adversely affected by unleaded gasoline. Hardened valve seats have been installed on all U.S. vehicles since 1971. Japan introduced them in the late 1970s. The few existing more susceptible older vehicles with non-hardened valve seats and high valve rotation design should restrict operation to 100 km/h or use non-lead, anti-valve wear additives.

4.1.1 Issue of Valve Wear

What is engine valve wear and why is it important to engine life? Valves are designed to allow inflow of the fresh air/fuel mixture and outflow of the exhaust gas and to seal off the combustion chamber during combustion and gas expansion phases of the engine cycle. Valves are designed to rotate a few degrees with each revolution of the engine to assure a smooth closure surface and to remove lead deposits. This slight movement of the valve face on the valve seat could cause valve wear. Excessive valve wear would result in valve recession and perhaps the escape of exhaust gas and resultant engine power loss.

Valve seat hardness and valve rotation design affect valve wear significantly. Since the early 1970s in the United States and a few years later in other countries, modern engines have been constructed with valve seat inserts constructed of metals with hardness rating greater than 300 Brinnell Hardness Value [1]. Such inserts are heat-shrunk into place. Older engines have non-hardened valve seats constructed of metals with lower hardness value and are more susceptible to wear. Older engines can be re-built with hardened valve seat inserts.

Lead deposits on the valve mating surfaces were found to have some high temperature lubricating properties. Unleaded gasoline does not contain lead and there has been concern that valve wear would be severe without either hardened valve seats or an alternative gasoline additive with solid lubricant properties. Fortunately, the incidence of excessive valve wear with unleaded gasoline is much less of a problem than anticipated. In actual vehicle use it has rarely been found. Studies have shown that it can occur only in older susceptible engines when operated continuously at high speeds and load and do not occur when operated below 100 km/hour. Also, alternate fuel additives have been developed that are now proven in actual use which completely protect the susceptible older engines using unleaded gasoline from valve wear even under extreme engine operating conditions.

The amount of lead required to minimize valve wear in susceptible engines was found to be 0.05 g/liter which is much less than the amount of lead formerly in the United States in leaded gasoline (which was about 3 g/gallon) [12]. Thus, if valve wear was the sole concern, only a small amount of lead would be necessary to avoid it rather than necessitating the use of gasoline with a high lead content. Countries using very high lead content gasoline (0.4 to 0.8 grams/liter) should take note of the above.

4.1.2 Minimizing Factors

In light of several studies on valve wear, the nature of older vehicle operation, characterized by fewer miles driven, lower speeds, and lower load operation than newer vehicles, reduces the likelihood that the few older vehicles equipped with non-hardened valve seats would be adversely affected by using unleaded gasoline. The studies have determined that valve seat wear is only encountered on certain older engines when operated at higher vehicle speeds and that normal driving speeds do not cause valve wear. To further reduce the chance of valve wear, valve wear protection additives can be made available to older vehicles [11].

4.1.2.1 Nature of Older Vehicle Operation

Many engine parameters affect the degree to which an engine experiences valve wear. An engine with high rotating valve design coupled with non-hardened valve seats is considered to be the most susceptible to excessive valve wear. A slight rotating valve design was incorporated into engines (U.S. designs commonly rotated at 6 RPM at specific engine conditions) in order to remove lead deposits. In the early 1970s some Japanese automobile manufacturers increased their valve rotation above this value. Vehicles with this engine design experienced valve wear problems when fueled with unleaded gasoline. After studying the problem, Japanese engineers returned to the original valve rotation speed and hardened the valve seats. After the redesign, the problem no longer existed. Honda stated that all its engines are designed for unleaded gasoline and would not experience excessive valve wear with unleaded gasoline. The valve rotation of U.S. engines has remained relatively constant and U.S. vehicles have not encountered in-use valve wear problems [6].

When Thailand realized it was necessary to ban lead in gasoline it conducted a study of its on-road vehicle fleet to determine the effect of unleaded gasoline. First a screening program was necessary in order to identify which older vehicles were susceptible to valve wear. In the case of older engines, the results were mixed. For instance, the 1979 Mitsubishi and 1974 Datsun had hardened valve seats whereas the 1982 Mazda and 1977 Opel had non-hardened seats, yet none of these engines experienced high valve wear even when operating at high speeds (130 km/h for 15,000 km). However, a 1974 Toyota with non-hardened valve seats did experience high valve wear. Subsequent screening revealed that a 1976 Toyota experienced high valve wear and a 1977 Toyota did not when operating as described above. In tests run on several susceptible vehicles at more normal speeds of 100 km/hour continuously for distances between 3000 and 12,000 km, it was found that unleaded gasoline did not cause unusual valve wear on any valve seats. When susceptible vehicles were run at higher speeds (120 km/h), valve wear was measured [1]. Thailand estimated that the number of on-road vehicles possessing non-hardened valve seats was about 10% of the fleet and that their numbers would decline in the future. The information gathered prompted the government to go ahead with their lead ban program [1].

These studies suggest that vehicles with non-hardened valve seats will unlikely be adversely affected by using unleaded gasoline because older vehicles probably will not normally be operated at high speeds or loads for an extended time. Public information programs will be helpful in this respect.

In certain countries, engines are routinely rebuilt when they wear out in a process that includes cylinder reboring, refitting with cylinder sleeves, turning bearing surfaces, replacing pistons, and other items. During this rebuild process, valve seats can be replaced by shrink fitting them in place in the engine head. Therefore, valve wear, should it occur in some number of engines, can be either repaired or rebuilt with hardened seats.

The conclusion has been drawn, through many similar studies, that concern for valve seat recession has been substantially exaggerated [11]. The use of unleaded fuel has also introduced benefits such as improved fuel economy [5]. Most importantly, maintenance costs incurred from leaded gasoline use considerably exceed the maintenance costs due to exhaust valve recession caused by unleaded gasoline [5].

4.1.2.2 Valve Wear Protection Additives

Several anti-valve wear protection additives (VWPA) have been formulated for unleaded gasoline. Sodium or potassium-based alkenyl sulfonate or napthenate VWPA may be used. Phosphorus-based VWPA is not recommended for catalyst-equipped vehicles [1]. The sodium- and potassium-based additives have been used extensively in Europe for many years and have not been reported to negatively affect catalytic converter performance.

The effectiveness of such additives in preventing valve seat wear was recently studied in Thailand [1]. The tests were run on an engine dynamometer at very high RPM and load. Under these conditions, the effects on engines using unleaded fuel without the additives were compared to those on engines using unleaded fuel with the additives. The optimum treat rate, or the optimal concentration of additive in the fuel, that prevented excessive valve wear for extreme driving conditions in vehicles with non-hardened valve seats was determined. Results showed that under the most severe operating conditions (exhaust temperature of 650°C), AVSR additives were highly effective in preventing valve wear of susceptible engines at specific optimum treat rates [1].

4.2 Benzene Emissions

Benzene emissions are to be avoided. Benzene is a common aromatic compound found in gasoline and is listed as a toxic air contaminant as it has been identified as a carcinogen that increases the risk of leukemia. The lead industry argument concerns benzene emissions from older vehicles without catalytic converters. Vehicles equipped with catalytic converts destroy 90 to 95 percent of aromatics and benzene in the exhaust stream. Thus, even lower emissions of these compounds result from an unleaded gasoline fueled catalytic converter equipped vehicle than a car burning leaded gasoline with no converter. Unleaded gasoline incorporates non-lead octane improver components to achieve octane rating. Several choices are available - these include certain oil refining processes, or non-lead high octane additives. Some refining methods increase the benzene content of gasoline. Therefore, and increased risk of benzene emissions may exist depending on the refinery method used to increase the octane number of unleaded gasoline. However, as done in the U.S., petroleum refinery processes are chosen to limit the benzene and aromatic content [18] and non-lead octane additives are also used.

Health studies clearly suggest that the adverse health effects of lead exposure far outweigh those resulting from potential increases in benzene emissions. For example, the U.S. EPA's Carcinogen Assessment Group in 1976 estimated that benzene emissions from automobiles accounted for 47 cases of leukemia per year in the U.S. This is compared to 5,000 deaths, 6,000 first-time strokes and heart attacks per year due to lead in gasoline for white males aged 40 to 59 years [18]. Although benzene emissions are undesirable, the effects of emissions from leaded gasoline are undoubtedly more severe, and lead can be removed from gasoline in such a way as not to increase benzene emissions or one can use catalytic converters to offset these emissions. In addition, once unleaded gasoline is introduced, many high mileage all-day-use vehicles can be retrofitted with a catalytic converter or an evaporative recovery system. Such vehicles allow immediate benzene emission control within large cities.

4.3 Octane Enhancement

Numerous technological processes, other than the use of lead additives, are available to improve the octane rating of gasoline. They vary with the refinery technical specifications, environmental regulation considerations, cost, and health effects [11].

4.3.1 Refiner Options for Increasing Octane Rating

Refining processes for gasoline may be classified into two major groups: hydroskimming refineries and conversion refineries. The more simple hydroskimming refineries are capable of processes that include crude distillation, treating, blending, and upgrading processes; technically advanced conversion refineries are more common and modify the crude oil fractions to gasoline components via processes such as catalytic reforming and fluid catalytic cracking. Conversion refineries also have isomerization, alkylation, and polymerization capacity and may include oxygenate production. Procedures may be combined with upgrading processes in order to enhance the octane number. A brief description of each process is listed in Table 2 below [11].

Table 2
Upgrading Processes for Octane Enhancement

Process	Description
Catalytic Reforming	Increase in octane of heavy naphtha containing reformates which are high in octane (93-102 RON). Magnitude of increase is at the discretion of the refiner. The "severity" of the operation determines the potential of reforming; however an increase in severity normally includes an increase in the aromatic content of gasoline.
Isomerization	Increase in octane of light naphtha (to 85-90 RON) without an increase in the aromatic content of gasoline.

Table 2
Upgrading Processes for Octane Enhancement

Process	**Description**
Alkylation and Polymerization	Normally performed in conjunction with fluid catalytic cracking (FCC), which is a process that converts heavy fuel oil into a lighter product with greater value, such as gasoline at 90-93 RON. These processes take end-products of FCC and transform them into high value gasoline blending components (92-97 RON). Polymerization tends to increase gasoline olefin content.
Oxygenation	Blending of gasoline with oxygenated compounds such as methyl tertiary butyl ether (MTBE), ethyl tertiary butyl ether (ETBE), methanol, and ethanol which contain high octane values (up to 115 RON). Effective in reducing harmful CO emissions.
Blending	Mixing of blendstocks and additives which can increase octane (by 1-2 values) to produce finished products to meet desired specifications.

4.3.2 Health Concerns of Alternative Octane Enhancement Processes

Some refining processes, serving as alternatives to lead additives, increase the aromatic content of gasoline. Benzene emissions are of less concern than lead emissions, but environmentally beneficial blending processes still should be used to minimize aromatic emissions. Isomerization and alkylation enhance octane in gasoline increasing benzene. Oxygenation, with additives such as ETBE or MTBE, also is a favorable refinery option because it replaces aromatics and aids in the complete combustion of fuel, resulting in cleaner tailpipe emissions [11]. The manganese additive MMT is not recommended for octane enhancement, because it can negatively effect both health and emission control systems [9].

5.0 COSTS OF PRODUCING AND USING UNLEADED GASOLINE

Making the transition to unleaded gasoline requires some investments in infrastructure changes. The most significant cost of eliminating leaded gasoline is the replacement of the high octane values and the associated production and distribution costs. The modifications to refinery procedures that are necessary to efficiently use alternative octane boosters are discussed below. Distribution costs attributed to the excess storage and transportation of both unleaded and leaded gasoline are also an issue, but may be significantly reduced with careful planning or avoided by using the **immediate, 100% switch** approach (see Section 3.1).

5.1 Experience with Refiner Costs

A variety of technical options are available to both modern and older hydroskimming refineries to increase the octane rating of gasoline. The costs of switching from lead additives to one of the alternative methods (outlined in Table 2) are dependent upon the following: (1) the extent to which refineries are utilized and alternative octane enhancements are initiated; (2) the octane requirements of the vehicle fleet; and (3) the price of additives used for octane enhancement [5].

The cost of phasing out leaded gasoline has been estimated to be between US $0.01-0.02 per liter, which includes the costs of refinery investment, unleaded fuel production, and octane additives. Because of productivity improvement and refinery efficiency, investments in alternative refining techniques typically pay for themselves in the long run [5]. As a result, only investment costs attributed to expediting investments in refinery conversion and alterations in refinery infrastructure to produce unleaded fuel should be considered as a cost of conversion. For example, a 1996 study conducted by Abt Associates asserted that converting from leaded to unleaded gasoline at a hydroskimming refinery in Russia would cost between US $0.005 and $0.02 per liter of gasoline under the current production procedure. However, when changes in the refinery's procedure, which are expected to result in greater production, were considered, this estimate was cut in half [5]. Although this example is country-specific, refinery upgrading helps to minimize the costs of switching to unleaded gasoline in any country .

6.0 WORLD EXPERIENCE WITH REGULATING LEAD

TEL in gasoline was introduced in the 1920s and was used worldwide by the 1930s. Because of increasing health concerns about the dangers of airborne lead due to a growing body of related health studies [5], and the need to control automobile exhaust emissions by protecting catalytic converters, leaded gasoline use began to diminish after peaking in the 1970s. Unleaded fuel use then became more prevalent because of its benefits to health and vehicle maintenance.

6.1 Leaded Gasoline Use

As previously stated, many countries with high vehicle use have either eliminated leaded gasoline or significantly restricted its use in favor of unleaded fuel because of health and vehicle emission control concerns. In 1969 the United States was the pioneer in the switch to unleaded gasoline. At a time when health concerns of lead were peaking, the auto industry and government agreed to make significant reductions in vehicle emissions by 1975. They decided that this could be accomplished if clean unleaded gasoline was available. As a result, all U.S. engines were designed for unleaded gasoline starting in the fall of 1970, and unleaded gasoline was gradually introduced throughout the country so that it was available for new 1975 model vehicles. Since then, Japan, Canada, Mexico, Central and South America, all of Western Europe, Korea, Australia, China, Taiwan, and other Asian countries have introduced unleaded fuel. Soon after the introduction of unleaded gasoline, most of these countries also set vehicle exhaust emission standards to clean up the pollution caused by automobiles and trucks.

The United States, as well as other pioneers in switching to unleaded fuel, opted for the **phase-in, phase-out** approach. Completely eliminating leaded gasoline took about 20 years, which is much too long in respect to other alternatives. Japan followed suit and succeeded in eliminating leaded gasoline in 10 years [11]. Western European countries introduced unleaded fuel in the late 1980s, and several countries now only market unleaded gasoline, including Austria, Sweden, Denmark, and Germany.

All the Central America countries, as well as Colombia and China, have recently chosen to use the **immediate, 100% conversion** approach when switching to unleaded gasoline. The most recent to switch is Delhi, India. Thailand and Taiwan have used the **rapid phase-out** approach for eliminating leaded gasoline, and many other countries have reduced the amount of lead allowed in their leaded gasoline.

However, many nations with strong economies, such as Saudi Arabia and other Middle Eastern countries, have not yet introduced unleaded gasoline. Interestingly, many of these countries export petroleum and have the refining capabilities and expertise to convert to unleaded gasoline rapidly but lack the political will to take on the battle with the entrenched TEL industry. High octane unleaded gasoline is often exported, but leaded gasoline still remains in the domestic market in the absence of a government regulation.

Countries with weaker economies, such as those in Africa and the Caribbean, have not even begun to reduce lead concentrations in leaded gasoline. In fact, several countries during the course of the 1970s and 1980s nearly doubled the amount of lead used in gasoline. For example, lead concentrations in India jumped from 0.22 to 0.56 grams per liter of gasoline [11]. Several lower per capita income countries also possess the technical capability to make the transition to unleaded fuel but tend to produce unleaded gasoline only for the purpose of exporting.

With all the existing knowledge and understanding of lead health effects, especially its effect on children, it is incredible that lower-income countries tend to have much higher lead concentrations in their gasoline than do other countries. For instance, most countries in Africa allow 0.84 g/liter lead in gasoline whereas Asian countries have limited the maximum lead concentration to 0.15 g/liter (see Appendix II). The potential for adverse physical and mental health effects is higher with high lead gasoline than with the lower value. Higher lead concentrations imply more severe health risks, as well as diminishing improvement in octane value - most of the octane increase is obtained with 0.15 g/liter concentration [15]. With future projections of economic growth that will foster greater urbanization and motorization in these countries, high lead concentrations represent an increasingly major future health hazard.

Another cost factor to be considered by the above countries is the added cost to remove emission controls from cars and trucks imported into their countries. About 80% of new vehicles are manufactured for markets with emission controls and unleaded gasoline. Of the 20% of new vehicles destined for countries with leaded gasoline, many have to be revamped by removal of the emission control systems - an added complexity and manufacturing cost that may be added to the sales price of the vehicle.

6.2 Status of Lead Use Worldwide

Appendices I and II provide a comprehensive status of lead use in gasoline worldwide. Appendix I closely details the phase-out efforts of one particular region of the world, Central and South America and the Caribbean countries, and may offer insight into phase-out efforts suitable for other parts of the world. Appendix II provides a brief summary of the status of lead use in gasoline worldwide.

6.3 Case Studies of Lead Phase-out

Evidence from specific case studies where lead has been or is being removed from gasoline is useful when considering the costs and benefits of eliminating lead from fuel. Nations vary by government policy and political will in their efforts to address environmental problems. The countries selected below represent well-documented cases in which the elimination of lead from gasoline was achieved successfully, despite unique sets of circumstances.

<u>Thailand</u>

In response to the growing concern for airborne lead health hazards resulting from a rapidly growing vehicle population and severe traffic congestion in the Bangkok metropolitan area, the Thai Government implemented the rapid phase-out approach to switch from leaded to unleaded gasoline. In 1990, the maximum lead content of gasoline was reduced to 0.4 grams per liter and then to 0.15 grams per liter in 1994. Premium unleaded gasoline was introduced in May 1991, followed by regular unleaded in 1993. A complete switch to unleaded gasoline began in January 1996 when leaded gasoline was banned altogether [18, 21]. A grade of gasoline containing VWPA (see Section 4.1.1.2) also was introduced.

Quantities of aromatics in gasoline were controlled in the comprehensive environment program. To achieve the necessary changes to the country's three refineries and make other modifications, the Thai government received financial assistance from the World Bank, which resulted in increased production efficiency. The fuel reformulation in conjunction with the banning of leaded gasoline has resulted in the complete elimination of vehicular lead emissions in Thailand [11]. The record of ambient roadside lead concentrations in Thailand is shown in Figure 2.

<u>Sweden</u>

In Sweden, lead emissions from traffic accounted for nearly 80 percent of total atmospheric airborne lead in the late 1980s. The government of Sweden reacted to this fact by deciding to accelerate the phase-out of leaded gasoline. The first reduction of lead in gasoline occurred in the 1970s, from 1.2 g/l to 0.8 g/l; this reduction was followed quickly by decreases to 0.4 g/l and 0.15 g/l. In addition, tax incentives designed to promote the production of unleaded gasoline were introduced by imposing a tax differentiation on leaded and unleaded fuels (unleaded had a lower pump price) [11].

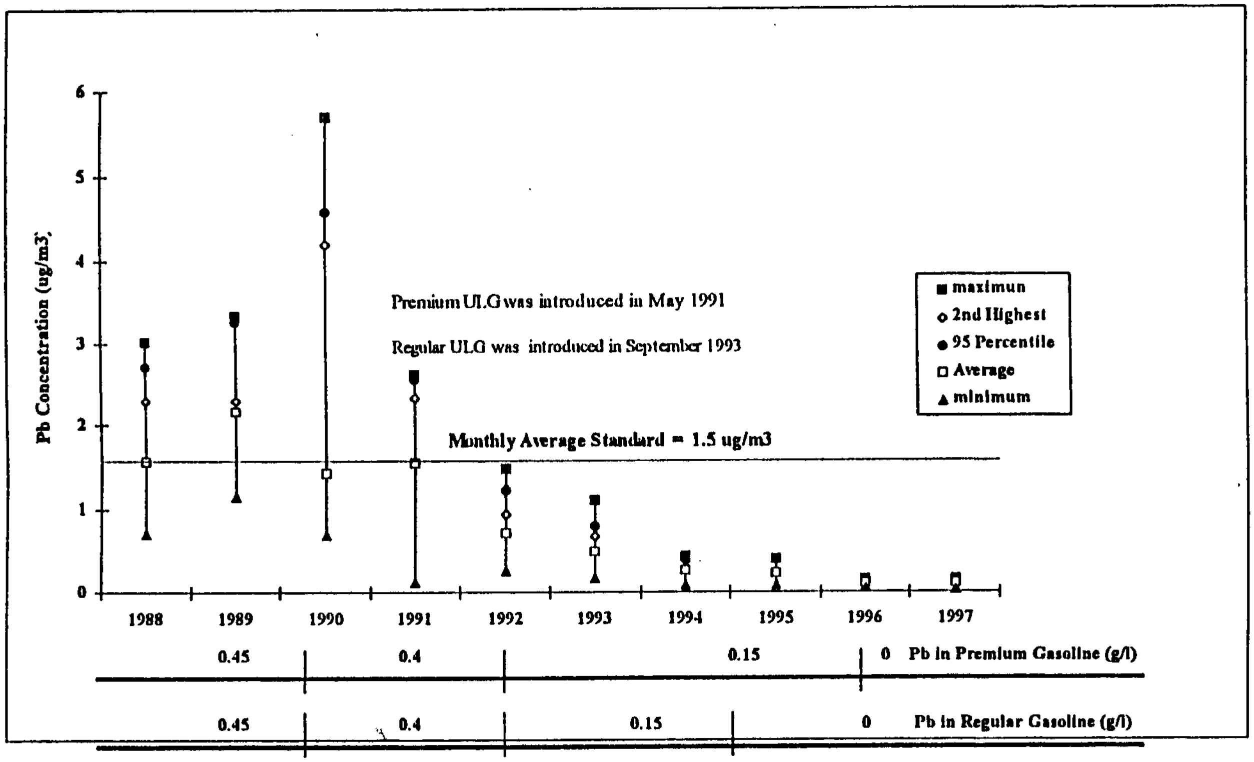

Figure 2. Trend of Monthly Average Lead Concentrations in Roadside Ambient Air in Bangkok from 1988 to 1997 (Values in 1997 are from January to July)

A switch to unleaded gasoline occurred in 1992 as a result of extensive market research, which indicated that lubricity additives could be effectively used in older cars with non-hardened valve seats. For these cars, an unleaded gasoline containing a sodium additive to prevent valve seat recession was introduced.* During this period, the government promoted the purchase of unleaded fuel by ensuring the price for leaded gasoline always exceeded that of unleaded gasoline, with the differential reaching 16% in 1993. Since 1994 all gasoline sold in Sweden has been unleaded.

Slovak Republic

In 1992, vehicular traffic represented the second largest source of lead emissions in the Slovak Republic, accounting for roughly 29 percent of airborne lead levels. In comparison to other European countries, the majority of industrial cities in the Slovak Republic did not have excessive ambient lead levels, being typically below 0.3 μg/m^3 as opposed to a range of 0.5 - 3.0 μg/m^3 for most European cities. Nonetheless, a project was conducted in the Republic between

*Author's Note: Swedish authorities apparently judged that there was greater chance of older vehicles being operated at high speed on Sweden's road system.

1986 and 1991, which revealed that children's neurological development was influenced by blood lead levels lower than 10 µg/dL. As a result, Slovak policy makers immediately addressed the problem, noting positive experiences of other countries from eliminating lead from gasoline.

The Slovak Republic encountered some unique obstacles en route to banning lead from gasoline. Three major obstacles were encountered by the Republic in implementing these policies: (1) composition of the vehicle fleet to be addressed, (2) lack of accessibility to unleaded gasoline, both in production and purchase, and (3) limited knowledge of the general population in using unleaded gasoline [11].

In 1993, only 0.4 percent of all vehicles in the Slovak Republic were equipped with catalytic converters. Legislation implemented during that year required that only cars with three-way catalytic converters be imported or manufactured, but the turnover of the vehicle fleet was expected to take a long time. Vehicles are operated longer, and due to the high price of vehicles and the low relative income level of the population, the age of the vehicle fleet in the country is much older than that of most Western countries. Use of unleaded fuels to protect catalysts was not needed - the health issue was most important. Only one producer of gasoline exists in the Slovak Republic and that producer did not possess the technical capability to switch completely to unleaded gasoline. Additionally, it was discovered that motorists knew very little about the use of and differences between leaded and unleaded gasoline. For example, 90% of the respondents to a particular survey believed incorrectly that unleaded gasoline could only be used in cars equipped with catalytic converters [11].

The first step in remedying the situation in the Slovak Republic was public education. This was accomplished through the dissemination of information regarding the adverse health effects of lead (especially to children) and the environmental quality status of the country. The Ministry of Environment, established as the country's sole Environmental Agency since the breakup of the former Czechoslovakia, distributed brochures on the negative effects of heavy metals and high lead levels in children. This forced an adjustment by the Slovnaft refinery (the only refinery in the Slovak Republic) through three distinct steps to a complete transition to unleaded gasoline production in 1995 [19].

7.0 CONCLUSIONS

Worldwide leaded gasoline phase-out would provide significant health and economic benefits. The primary benefit of unleaded gasoline is the elimination of the lead health hazards, one of which is the impairment of children's mental development. All pro-lead arguments pale in comparison to the need to protect children's mental development, making this a powerful reason to eradicate lead from gasoline. The general population also suffers from the effects of lead, in terms of high blood pressure and related cardiovascular conditions. Health studies show the correlation between a decrease in lead content of gasoline and a corresponding decrease in blood lead levels. These studies conclude that the major human lead burden source is via exhaust emissions from vehicles using leaded gasoline.

The introduction of unleaded gasoline also provides substantial benefits to vehicle operation by permitting the use of catalytic converters, which can reduce up to 90% of harmful air pollutants - hydrocarbon, carbon monoxide, and nitrous oxide emissions.

The economic benefits of unleaded gasoline, include significant reductions in vehicle maintenance costs and averted earning losses by the prevention of health ailments. These cost benefits easily outweigh the costs of refinery upgrading and alternative octane additives. Arguments to sustain leaded gasoline use to protect the valve seats of older engines are overstated - even older engines benefit from a switch to unleaded gasoline. The few engines that are susceptible to valve wear are decreasing dramatically in number, and their valve seats can be protected with modified operation to avoid very high speeds. In any event, alternative non-lead additives exist that can be employed, which are proven to protect valve seats. Many countries also routinely rebuild old engines, and during the rebuild process, hardened seats can be shrunk-fit into the engine head.

The most effective policy approach of introducing unleaded gasoline and eliminating leaded gasoline is either an **immediate, 100% conversion** approach or a **rapid phase-out** approach. Related refinery upgrading costs are recovered over the life of the investment.

The **immediate, 100% conversion** approach achieves reduced lead exposure levels in the shortest amount of time and avoids the capital cost burden of a second fuel distribution system. It requires refinery capability to replace TEL with alternative equal grade gasoline or temporary reliance on outside sources.

The **rapid phase-out** approach achieves a rapid decline in lead content of leaded gasoline, and provides time for refineries to phase-in modifications necessary for the total “unleaded” system. The goal of lead elimination is usually reached within 4 to 6 years under this approach.

The conclusions are clear. Protection of children’s mental development is paramount and makes removing lead from gasoline a national and international priority. Leaded gasoline must be eliminated at all possible speed. The **immediate, 100% conversion** approach achieves this objective, and therefore MECA highly recommends consideration of it. If protection of children’s mental development were not considered, then the **rapid phase-out** approach would be a more reasonable and rational approach. Given the immediate, significant health benefits, however, to a total ban of lead in gasoline, the **rapid phase-out** approach is clearly second best. In either case, the valve wear potential of older engines when operated on unleaded gasoline can be dealt with through a public education program. The claims regarding benzene emissions can be avoided through the selection of various low benzene refinery processes or non-lead additives. Both of these arguments should not enter into the discussion as reasonable arguments against the ban of leaded gasoline. The **phase-in phase-out** approach is too lengthy a process and should not be considered. All countries which now have high leaded gas concentrations beyond 0.12 g/l should immediately take steps to reduce to this level for the protection of their citizens - especially their children.

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9.0 APPENDIX I

Detailed Status of Lead Elimination in Central and South American and Caribbean Countries				
Countries	**Target Year**	**Unleaded Gasoline Consumption, %**	**Maximum Allowed Lead Level, g/l**	**Current Methodology/ Future Strategy for Supplying Unleaded Gasoline**
Anguilla	n.d.	46	--	*Import
Argentina	1996	100	0	*Refinery upgrading: -reformer modification -new isomerization unit -new alkylation unit -new polymerization unit -new MTBE unit *Tax incentive on gasoline pricing *Major addition of MTBE *Transition in 7 years
Barbados	2000	40	0.79	*Same price for leaded and unleaded gasoline *Purchase from outside country *MTBE addition
Bermuda	1990	100	0	*Purchase from outside country *2-year transition
Bolivia	1995	100	0	*Eliminated production of leaded gasoline in 2 small refineries (1991 and 1995) *No specific strategies identified
Brazil	1991	100	0	*Production of ethanol/gasoline blend
Chile	n.d.	28	0.60	*New/modified catalytic reformers, alkylation, and Catalytic cracking units (CCUs) in 1996
Colombia	1990	100	0	*Import 25% of unleaded needs
Costa Rica	1996	100	0	*MTBE addition to Super in 1995 *Import high-octane gasoline to mix with own production of 75 Research Octane Number (RON) to produce unleaded 88 RON and 94 RON
Dominican Republic	n.d.	31	0.40	*All unleaded (95 RON) is imported *50-60% of leaded gasoline is imported
Ecuador	2000	24	0.50	*Refinery upgrades, CCU modifications as of 1994
El Salvador	1996	53	0.84	*Possible MMT addition as of 1996 *Import high-octane gasoline, mix with own production *Gradual reduction of lead concentration in gasoline

Detailed Status of Lead Elimination in Central and South American and Caribbean Countries				
Countries	**Target Year**	**Unleaded Gasoline Consumption, %**	**Maximum Allowed Lead Level, g/l**	**Current Methodology/ Future Strategy for Supplying Unleaded Gasoline**
Guatemala	1991	100	0	*>70% of unleaded gasoline is imported
Honduras	1995	65	--	*Imported, since refinery shut down in 1992
Jamaica	2001	30	0.77	*Refinery upgrades: -new CCU in 2000 -new isomerization unit in 2000 *Possibility of reducing octane of Super leaded to reduce lead concentration
Mexico	1999	56	0.26	*Major upgrades to refineries: -4 new alkylation units -4 new isomerization units -1 new CCU -6 MTBE units
Netherlands Antilles-Aruba	n.d.	50	--	*Production almost entirely for export
Nicaragua	1996	100	0	*Import high-octane gasoline and mix with own production to produce 90 RON unleaded
Panama	2002	93	0.82	*Possible import of high-octane blending components *Refinery upgrades -new semi-regen reformer -reformer modified to isomerization unit
Paraguay	n.d.	1	0.20	*Import 100% *Interested in importing blending components *Possibly supply from within if new refinery is built
Peru	n.d.	25	0.75	*Phased supply of 1 then 2 grades of unleaded gasoline as of 1995 *MTBE addition *Interested in purchasing blending components
St. Lucia	2001	16	--	*Purchase from outside the country
Suriname	n.d.	0	--	
Trinidad & Tobago	2000	1	0.40	*Refinery upgrades: -expansion of CCU and alkylation units in 1996 -new polymerization unit in 1997 -new MTBE unit in 1996

Detailed Status of Lead Elimination in Central and South American and Caribbean Countries				
Countries	**Target Year**	**Unleaded Gasoline Consumption, %**	**Maximum Allowed Lead Level, g/l**	**Current Methodology/ Future Strategy for Supplying Unleaded Gasoline**
Uruguay	n.d.	6	0.30	*Refinery upgrades -new refinery in 1999 -new isomerization unit in 2000
Venezuela	2007	0	0.85	*Major upgrades to refineries: -reformer expansion(1999) -new reformers (2001) -alkylation expansion.(2001) -new isomerization units (2001) -new TAME units (1999)

n.d. = no data

Source: World Bank, December 1996.

10.0 APPENDIX II

Status of Lead Use in Gasoline Worldwide		
Countries	**Maximum Lead Content of Lead in Gasoline, g/l**	**Market Share of Unleaded Gasoline, %**
Africa		
Angola	0.77	0
Benin	0.84	0
Botswana	0.44	0
Burkina Faso	0.84	0
Burundi	0.84	0
Cameroon	0.84	0
Chad	0.84	0
Ethiopia	0.76	0
Gabon	0.80	0
Ghana	0.63	0
Ivory Coast	0.26	0
Kenya	0.40	0
Liberia	0.77	0
Madagascar	0.80	0
Malawi	0.53	0
Mali	0.80	0
Mauritania	0.25	0
Mauritius	0.40	0
Mozambique	0.65	0
Namibia	0.40	0
Niger	0.65	0
Nigeria	0.66	0
Senegal	0.60	0
South Africa	0.40	--
Uganda	0.84	0

Status of Lead Use in Gasoline Worldwide		
Countries	**Maximum Lead Content of Lead in Gasoline, g/l**	**Market Share of Unleaded Gasoline, %**
Zimbabwe	0.84	0
Asia		
Australia	0.25-.045	45
Bangladesh	0.80	0
Brunei	0.11	43
China	0.45	--
Hong Kong	0.15	80 (1995)
India	0.42	--
Indonesia	0.45	--
Japan	0	100
Korea	--	83 (1992)
Laos	0.40	0
Malaysia	0.15	50
New Zealand	--	44 (1995)
Pakistan	0.42	0
Philippines	0.15	30 (In Manila, 1994)
Singapore	0.15	60
Sri Lanka	0.20	0 (1995)
Taiwan	0.15	45
Thailand	0.15	63
Vietnam	0.40	0
North Africa & Middle East		
Algeria	0.60	0
Bahrain	0.40	0
Egypt	0.26	--
Iran	0.19	0
Iraq	0.50	0

Status of Lead Use in Gasoline Worldwide		
Countries	Maximum Lead Content of Lead in Gasoline, g/l	Market Share of Unleaded Gasoline, %
Israel	0.15	10 (1994)
Jordan	0.30	0
Kuwait	0.53	0
Lebanon	0.84	0
Libya	0.80	0
Morocco	0.50	0
Oman	0.63	0
Saudi Arabia	0.40	0
Syria	0.60	0
Quatar	0.15	53
Tunisia	0.50	0
UAE	0.40	0
Yemen	0.45	0
Western Europe		
Austria	0	100 (1994)
Belgium	0.15	57
Cyprus	0.40	4
Denmark	0	100
Finland	0	100
France	0.15	41
Germany	0.15	89
Greece	0.40	23
Iceland	0.15	70
Ireland	0.15	38
Italy	0.15	24
Luxembourg	0.15	69
Netherlands	0.15	75

Status of Lead Use in Gasoline Worldwide		
Countries	**Maximum Lead Content of Lead in Gasoline, g/l**	**Market Share of Unleaded Gasoline, %**
Norway	0.15	50
Portugal	0.40	21
Spain	0.15	14
Sweden	0	100
Switzerland	0	100
Turkey	0.40	2
UK	0.15	53
Central & Eastern Europe		
Bulgaria	0.15	13 (1995)
Croatia	0.60	--
Czech Republic	0.15	18
Hungary	0.15	50 (1994)
Poland	0.15	21 (1994)
Romania	0.60	6 (1995)
Russian Federation	0.37	45 (1995)
Slovak Republic	0	100

Source: World Bank, January 1998.