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Ethanol as a lead replacement: phasing out leaded gasoline in Africa

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Abstract

The rising cost of lead additives and of gasoline, and the falling cost of ethanol and sugarcane, have created favorable economic conditions for fuel-ethanol production. In Africa, where lead additives are still heavily used and where sugarcane production is high, ethanol can be a cheap source of octane. More than enough sugarcane is produced in Africa to replace all the lead used in African gasoline; this would require Africa to produce about 20% of amount of ethanol currently produced in Brazil, and would require the shift of some sugar production to ethanol production. At a more modest scale, African countries that could replace lead with ethanol using primarily their by-product molasses production include Zimbabwe, Kenya, Egypt, Zaire, Zambia, Sudan, Swaziland, and Mauritius. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Ethanol; Lead; Africa

This article seeks to address two audiences: those interested in fuel-ethanol in developing countries, and those interested in the international phase-out of leaded gasoline. Ethanol proponents have typically focused on the benefits of ethanol in terms of greenhouse gas emissions, local energy security, and stabilization of the agricultural sector. Proponents of the phase out of leaded gasoline have typically focused on refinery modifications and the additive methyl tertiary butyl ether (MTBE) as strategies for replacing lead additives. The message to both audiences is the potential benefit of ethanol as a replacement for lead in gasoline, in terms of costs, public health, and potential international collaborations.

There is now virtually universal acceptance of the need to eliminate lead from gasoline. Its adverse neurological effects, especially on children, have been definitively established by numerous researchers in many countries (NRC, 1993). When lead is phased out of gasoline, the population's exposure to lead drops in a predictable manner (Thomas et al., 1999). Even the manufacturer of gasoline lead additives, Octel Ltd., now agrees that their product needs to be phased out (Octel, 1999).

In many areas of the world, there has been tremendous progress in reducing and eliminating the use of lead in gasoline. As shown in Fig. 1, most of both North and South America have eliminated or nearly eliminated leaded gasoline, as have much of Europe and East Asia. However, in most of Africa and the Middle East, there has been almost no progress in phasing out leaded gasoline.

There are a number of factors that can slow down the transition from leaded to unleaded gasoline. While uncertainty about the health impacts of leaded gasoline used to be a major question, now the main questions are cost and the choice of how to replace the octane.

Lead additives are used in gasoline because they have been the cheapest source of octane. The most common ways to eliminate the need for lead additives have been to upgrade refineries to increase production of aromatic and alkylated hydrocarbons, or to use the additive MTBE. The additional cost of unleaded gasoline is typically reported as a couple of cents per liter at most (World Bank, 1993, 1994). Numerous studies have shown that the costs of phasing out lead from gasoline are far outweighed not only by the health benefits to the population (Schwartz, 1994), but even by the reduced maintenance costs for automobiles (Wintringham et al., 1972; US EPA, 1985). While it is often thought that older cars need lead additives to lubricate the exhaust valves, a number of studies have shown that the lead

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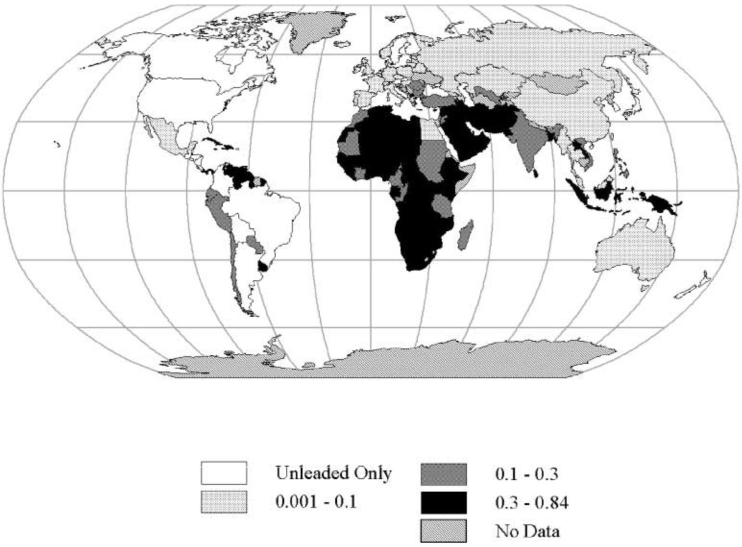

Fig. 1. Concentration of lead in gasoline, as of the late 1990s.

additive compounds actually do more harm than good (Thomas, 1995).

Despite the extensive experience with phasing lead out of gasoline in many countries, questions remain concerning how to replace the octane. Refinery upgrades do require major capital outlays. Increasing the concentration of aromatic compounds in gasoline can increase risks from benzene exposure. The additive MTBE has been found to be a threat to groundwater supplies, and may be phased out in the United States (EPA, 1999). All gasoline blends seem to have some drawbacks, and the relative merits of different blends remain an area of active scientific research and policy debate (Calvert et al., 1993; NRC, 1999).

Here we discuss the potential to replace lead additives with ethanol manufactured from sugar or molasses. While long recognized as a good source of octane, and used in a number of countries, including the United States, ethanol has almost never been discussed as a lead replacement. This may be because most of the discussions of leaded gasoline phase-out have been based on the experience of the United States and western Europe. Neither the United States nor western Europe is well suited for extensive sugar-based ethanol production. The United States does in fact produce fuel ethanol from corn but, as will be discussed below, ethanol can be produced more economically from sugar crops than from starch crops such as corn.

A number of major international organizations have issued publications advising countries how to phase-out leaded gasoline. While outstanding in most respects, they do not seriously discuss the ethanol option. For example, OECD (Organization for Economic Cooperation and Development) and UNEP (United Nations Environment Program) recently published an advisory on methods to phase out leaded gasoline that discusses only the refinery modification and MTBE options (UNEP, 1999). A World Bank survey of world-wide experience in phasing lead out of gasoline discusses the use of ethanol in Brazil, but primarily in a negative light (Lovei, 1996). Neglect of the potential for ethanol to replace lead in gasoline is almost surely not intentional, but rather a reflection of the experience of most experts on leaded gasoline phase-out. Jose Goldemberg, of the University of Sao Paulo in Brazil, has pointed out that sugar-derived ethanol is one of a number of technologies that could provide some developing countries with the opportunity to "leap-frog" past the experience of the northern industrialized countries (Goldemberg, 1998).

There is also the possibility that some countries are actually being discouraged from replacing lead in gasoline. Octel (the manufacturer of lead additive compounds) is widely reported to be advising developing countries to "go slow" on the phase-out of leaded gasoline (Kitman, 2000; Ottenstein and Tsuei, 1994a).

The relative costs of ethanol versus other octane enhancers and versus gasoline itself can vary greatly over time and for different countries and technologies. Depending on the local economics of gasoline, sugar, ethanol, and lead additives, ethanol can be as cheap or cheaper than lead as a source of octane for gasoline. In some situations, ethanol can even be as cheap or cheaper than gasoline. Moreover, ethanol prices can be expected to continue to fall as the technology and experience improves, while lead additive prices can be expected to continue to increase as its market shrinks (Ottenstein and Tsuei, 1994b).

Sugar cane is abundant in many of the countries that are still using leaded gasoline; some of these countries already produce ethanol for other purposes. International prices for sugar are now so low that many producers are in severe financial stress (Hannah, 1999).

Use of sugar-cane-derived ethanol to replace lead in gasoline would simultaneously eliminate a significant public health risk, help stabilize sugar markets, and provide a foundation for development and expansion of a biomass-derived fuel system.

Below we provide some background on ethanol as a gasoline blendstock and on production of ethanol from sugarcane or molasses, calculations of the amount of ethanol needed to replace a given amount of lead in gasoline, sample cost calculations, background on the international experience with fuel ethanol, and estimates of the potential to replace lead in gasoline in African countries based on the amount of lead used in gasoline and the amount of sugarcane produced.

1. Background on ethanol as a gasoline blendstock

Tetraethyl lead is added to gasoline to provide octane; the replacements for lead must therefore have good octane characteristics. "Octane" is a measure of the tendency of the air/fuel mixture to resist spontaneous combustion as it is heated during the compression stroke in the engine cylinder. This pre-ignition, or "knock", decreases the efficiency of the engine and increases engine wear. The high temperatures and pressures during the compression stroke in the cylinder cause fuel molecules to break down into free radicals (highly reactive molecules with an unpaired electron). Tetraethyl lead scavenges the free radicals, reacting with them before they can build up the chain reaction that causes the pre-ignition.

Instead of adding tetraethyl lead, one way to increase the octane value of a gasoline is to change its composition so that it is less likely to generate the free radicals that lead to knock. Molecules with stronger bonds are less likely to break down; strongly bonded hydrocarbons include low bond order hydrocarbons such as ethanol and MTBE, and hydrocarbons with branched or ring structures (Owen and Coley, 1995; Spiro and Stigliani, 1990; Brawley, 1972). Table 1 compares the features of standard refinery feedstocks and octane enhancers.

Gasoline is blended from a wide range of components, or blendstocks, depending on the intended use and conditions. While the majority of blendstocks are petroleum fractions of varying hydrocarbon chain length (e.g., light-straight run, isomerized LSR, fluid catalytic cracked, reformate etc., as listed in Table 1), ethanol has long been considered a good blendstock. In fact, several of Henry Ford's earliest automobile designs, including the famed Model-T, were designed for use with ethanol. During the great World Wars, alcohol fuel was occasionally used as a gasoline extender or as an outright replacement fuel in both the United States and Europe. Ethanol can be used in unmodified modern engines at volume concentrations of up to about 25%, or as a pure fuel in cars with minor engine modifications. The mileage performance of gasoline-ethanol blends is essentially the same as for normal gasoline (Nelson, 1969; Wyman et al., 1993; Unzelman, 1981; World Bank, 1980).

Use of ethanol as a blendstock has both positive and negative effects on emissions of air pollutants. A significant drawback to the use of ethanol is its high Reid vapor pressure (RVP), which is a measure of a gasoline's volatility. The RVP effect of ethanol on gasoline blends is not linear; ethanol blending at a 5–6 volume percent increases RVP by about 1.3 psi; additional ethanol blending does not further increase RVP (California Energy Commission, 1998). Gasolines with higher RVP have higher evaporative emissions, which are released during refueling and when the car is not operating. These evaporative emissions are ozone precursors, and the use of ethanol blends without compensatory blending to control RVP can result in increased ozone (smog) formation (NRC, 1999).

In the United States, the RVP of gasoline is regulated based on the region and the time of year. RVP limits are strongest in the summer and in the south, because

Table 1
Blending characteristics of refinery feedstocks and octane enhancers[a]

Compound	Function	RVP (psi)	Octane (MON)	Octane (RON)
LSR gasoline	Blendstock	11.1	61.6	66.4
Isomerized LSR gasoline	Blendstock	13.5	81.1	83.0
FCC gasoline	Blendstock	1.4	77.1	92.1
Reformate, 100 RON	Blendstock	3.2	88.2	100.0
Ethanol	Octane enhancer	11	99–104	114–141
MTBE	Octane enhancer	9	98–105	115–123

[a] LSR is light straight-run (LSR) gasoline, FCC is fluid catalytic cracked gasoline. RVP is Reid vapor pressure. MON (Motor Octane Number) and RON (Research Octane Number) are two different measures of octane value. MON and RON for ethanol and MTBE are given as a range because their effect on octane value depends on characteristics of the baseline gasoline. *Sources*: Gary and Handwerk, 1994; Owen and Coley, 1995; Unzelman, 1981, 1991; Wyman et al., 1993; Hinkanp, 1983.

evaporative emissions are higher in hotter weather. Baseline summer gasoline is limited to an RVP limit of 9 psi in the northern states, and to 8 psi in the southern states, and ethanol-gasoline blends are allowed to have a 1 psi higher RVP. However, the state of California has a stricter RVP limit of 7.8 psi, which both gasoline and gasoline-ethanol blends are required to meet.

On the other hand, ethanol reduces carbon monoxide emissions. Carbon monoxide is a direct human health hazard, as well as an ozone precursor. While in the US carbon monoxide emissions are already largely controlled by vehicle emissions control systems (Calvert et al., 1993), the carbon monoxide benefits of ethanol could be greater in countries in which vehicles do not have effective catalytic converters.

2. Background on production of fuel ethanol from sugar or molasses

Ethanol can be produced from three main types of biomass raw materials: (a) sugar-bearing materials (such as sugarcane, molasses, and sweet sorghum) which contain carbohydrates in sugar form; (b) starches (such as corn, cassava, and potatoes) which contain carbohydrates in starch form; and (c) celluloses (such as wood and agricultural residues) whose carbohydrate form is more complex.

The main attraction of sugar-bearing raw materials for alcohol production is that their carbohydrate content is already in the fermentable, simple sugar form and that they also produce their own source of fuel for processing in the form of bagasse (the sawdust-like byproduct of milled sugar cane). Starches contain carbohydrates of greater molecular complexity, which have to be broken down to simpler sugars by a saccharification process, which adds another process step and increases the capital and operating costs. In addition, corn requires an outside source of fuel for the ethanol production process. (Thus, the corn-based US ethanol program is inherently less efficient than sugar-based ethanol programs). Carbohydrates in cellulosic materials have an even greater molecular complexity and have to be converted to fermentable sugars by a more complex acid hydrolysis or enzymatic hydrolysis process.

The economics of biomass ethanol production and use depend on a number of factors specific to the local situation. These factors include (a) the cost of biomass materials, which varies among countries, depending on land availability and quality, agricultural productivity, labor costs, etc.; (b) ethanol production costs, which depend on the plant location, size, and technology, all of which vary a great deal among countries; (c) the cost of gasoline in individual countries, which depends on fluctuating petroleum prices and domestic refining characteristics; and (d) the strategic benefit of substituting imported petroleum with domestic resources. The economics of ethanol production and use, therefore, will depend upon the specific country and project situation (World Bank, 1980).

Cane-derived ethanol can be produced either from sugarcane or from molasses. If the sugarcane is devoted to ethanol production, most sources report that about 70 l of ethanol can be produced per tonne of cane, although an average of 80 l per tonne of cane is reported in Brazil (Moreira and Goldemberg, 1999). However, if sugar is produced from the cane and ethanol is produced only from the end-product “C” grade molasses, then ethanol production per tonne of cane is correspondingly reduced, to as little as 9 l of ethanol (plus about 100 kg of sugar) per tonne of cane. Intermediate approaches are also possible, in which ethanol is made from sweeter, “A” grade molasses, producing correspondingly more ethanol and less sugar per tonne of cane. Distilleries can be designed to be able to switch back and forth from sugar to ethanol production depending on demand (Fulmer, 1991).

Molasses is mainly used as animal feed and for ethanol production and, in some countries, for human consumption. Most of the world’s molasses production is in developing countries, often in remote locations, while animal feed markets are primarily located in the US and western Europe. Because many sugar mills are located in remote areas and the transport infrastructure is inadequate to transport the bulky, relatively low-value by-product molasses to port for export, substantial quantities of molasses remain unutilized and in fact often cause disposal problems (World Bank, 1980). Prevention of water pollution from dumping of waste molasses was cited as one of the motivations for ethanol production in Malawi (Nyirenda, pers. comm., April 2000), and dumping of waste molasses is cited as a continuing environmental problem in Uganda (Wakabi, 1999).

3. Substitution of ethanol for lead in gasoline

The amount of octane that a given amount of lead provides depends on the baseline characteristics of the gasoline and the amount of lead that has already been added. As shown in Fig. 2, the octane benefits of lead are greatest for gasolines with low initial octane number (RON), and there are decreasing benefits as more lead is added.

The volume of ethanol needed to replace the octane being provided by the lead additive can be expressed as

$$X_e = (O_{Pb} - O_0)/(O_e - O_0), \quad (1)$$

where O_{Pb} is the octane number of the leaded gasoline, O_0 is the octane number of the gasoline without added

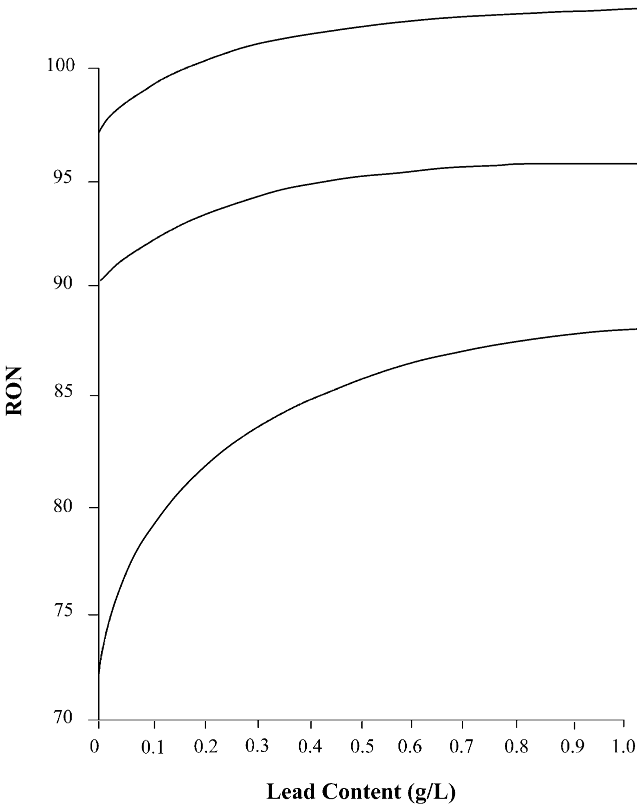

Fig. 2. Contribution of lead additives to gasoline octane (RON) for gasolines with different baseline RON values. *Source*: Owen and Coley, 1995.

lead, and O_e the octane number of ethanol. The net cost of substituting ethanol for lead can be expressed as

$$\Delta C = C_e X_e - C_g X_e - C_L L, \qquad (2)$$

where C_e is the ethanol cost, X_e is the ethanol volume fraction, C_g is the gasoline cost, C_L is the lead cost, and L is the lead concentration. The first term is the cost for the ethanol, the second term is the cost savings for the displaced gasoline, and the final term is the cost savings for the eliminated lead.

As countries around the world have reduced and phased out their use of gasoline lead additives, the market for lead additives has contracted. Octel's business strategy has been to increase lead additive prices to maintain its revenue stream as sales decline (Ottenstein and Tsuei, 1994b). As shown in Fig. 3, between 1980 and 1999 the price of lead additive has risen from 1¢ per gram of lead to about 2.5¢ (all in 1998 US$). The concentration of lead in leaded gasoline typically ranges from 0.15 g/l to a maximum of 0.8 g/l and thus the per liter cost ranges from about 0.4¢/l to 2¢/l, as of 1999.

The cost of ethanol depends on the costs of the raw materials, the technology of production, and market factors. In Brazil, the cost to produce ethanol is estimated to be about 21¢/l as of 2000 (Macedo, 2000). Despite a great deal of turmoil in the Brazilian ethanol program over the past several years, the average price paid to producers remained constant at about 34¢/l during the mid-1990s, but fell below the production cost to as low as 15¢/l at the end of 1999 due to a large surplus (Moreira and Goldemberg, 1999; Macedo, 2000), as shown in Fig. 4. In Malawi as of the late 1980s, ethanol was produced and delivered at an estimated cost of 26–34¢/l (US AID, 1989a, b). To evaluate a particular scenario, local costs must be determined. But for an illustrative example, a conservative ethanol price of 35¢/l will be assumed.

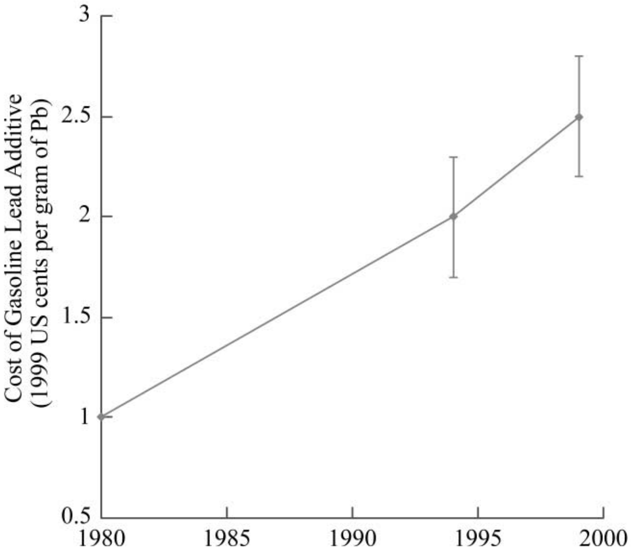

Fig. 3. Cost of gasoline lead additives (1998 USD). Note that the lead additive compound, tetraethyl lead (TEL) is about 40% lead. *Sources*: Frank, 1999; Ottenstein and Tsuei, 1994a; Unzelman, 1981.

For the example of a 16% ethanol blend to bring an 87 RON gasoline up to 94 RON, the direct cost of the ethanol would be 5.6¢ if ethanol costs 35¢ per liter. However, because ethanol displaces gasoline, the savings from the displaced gasoline are critical to the overall economics.

The cost of gasoline has fluctuated widely since the 1970s (Fig. 5). Even to relate crude oil prices to gasoline prices is difficult, since ex-refinery gasoline costs vary with a number of country specific factors, including the crude quality and source, refinery size and configuration, domestic petroleum products demand pattern, gasoline quality, etc. On average, however, the price of gasoline can be taken as roughly 1.3 times that of a unit volume of crude oil (World Bank, 1980; US DOE, 2000). Table 2 illustrates the cost of lead versus ethanol as an octane enhancer for various crude oil prices. Another octane option, shown in Table 2, is MTBE, which costs about 23¢ per liter as of 1999 (Moreira and Goldemberg, 1999), and also has a blending RON of about 120 (see Table 1).

The bottom line is that both ethanol and MTBE are more cost effective at higher gasoline prices, because both additives displace gasoline. In this particular illustration, MTBE is more cost effective than lead as an octane enhancer for crude oil prices over about \$15 per barrel, while ethanol remains a bit more expensive than lead additives even at high gasoline prices. If, however, ethanol costs were close to the lower costs reported in Brazil or Malawi, or if gasoline prices were higher due to high transport costs (as in Malawi), then the net cost of replacing lead with ethanol would shrink.

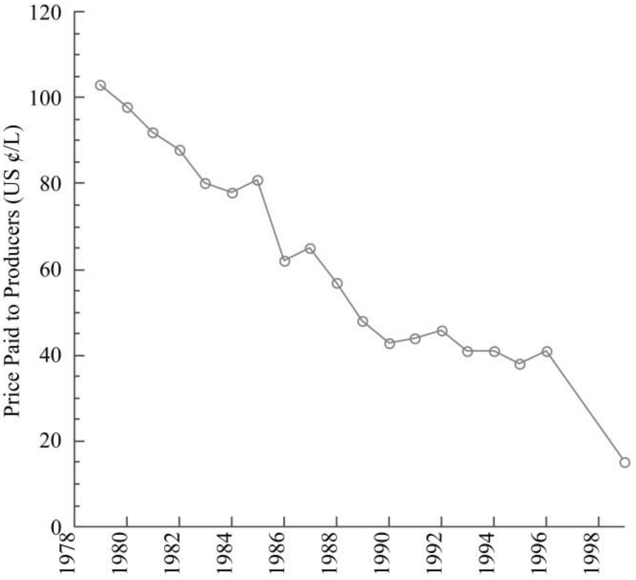

Fig. 4. Evolution of ethanol prices in Brazil. *Sources*: Goldemberg, 1996; Moreira and Goldemberg, 1999; Macedo, 2000.

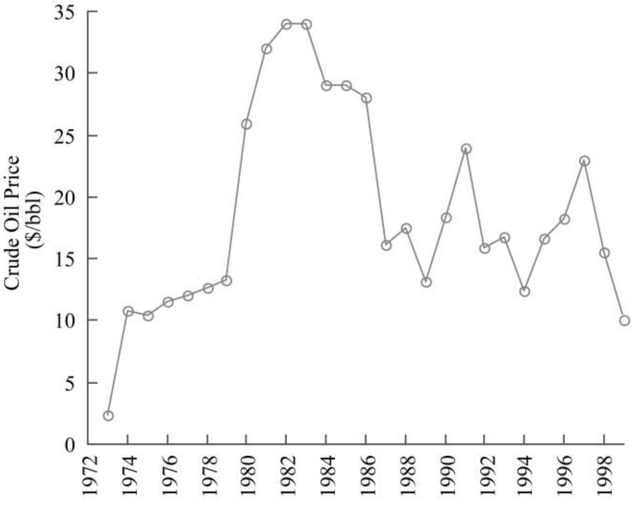

Fig. 5. Crude oil prices (Saudi Arabian Light) *Source*: US DOE, 1999.

For example, Table 2 also shows the case for Malawi, where high transport costs result in a wholesale gasoline price of 56 ¢/l (Pers. comm. Niyrenda, Asst. Prod. Manager, Ethco, 2000). In such a case, which may also exist elsewhere, ethanol is considerably cheaper than gasoline.

There could be a number of advantages to using locally-produced ethanol as a gasoline additive. First, it reduces the need to use foreign exchange to purchase gasoline. Second, it can provide a new source of income for the sugar industry, which is currently struggling with very low world market prices (Fig. 5). The low sugar prices indicate that ethanol prices could fall well below 35 ¢/l.

However, the foreign exchange savings due to ethanol's substitution for imported gasoline must be balanced against the lost foreign currency earnings from the export of molasses, ethanol or sugar. If hard currency is valuable or in short supply, this tradeoff needs to be estimated carefully. Molasses sales may be an important foreign exchange earner for the sugar company, whereas ethanol's foreign exchange savings may accrue to the economy as a whole (US AID, 1988). On the other hand, as previously discussed, in many locations substantial quantities of molasses remain unutilized because of high transport costs and weak markets (World Bank, 1980).

4. International experience with fuel ethanol

A number of countries have fuel ethanol programs (Table 3). All of them have been subsidized and are highly dependent on government policy for their continuation. While the economics of ethanol production is important, the real incentives for fuel ethanol

Table 2
Illustrative costs of ethanol and MTBE to replace lead additives[a]

Crude oil	Gasoline cost	Lead cost	Direct cost 16% blend		Net cost (¢/l gasoline)	
\$/bbl	¢/l	0.6 g/l at 2.5 ¢/g	Ethanol 35 ¢/l	MTBE 23 ¢/l	Ethanol 35 ¢/l	MTBE 23 ¢/l
10	9	1.5	5.6	3.7	2.7	0.7
20	17	1.5	5.6	3.7	1.4	− 0.5
25	22	1.5	5.6	3.7	0.6	− 1.3
—	56 (Malawi)	1.5	5.6		− 4.9	

[a] Baseline: 87 RON gasoline with 0.6 g/l lead versus 16% ethanol blend. Gasoline is assumed to cost 1.3 times the crude oil price.

Table 3
World production of fuel ethanol[a]

Country	Quantity (Bl)	Source
Current production		
Brazil	14	Sugar cane
United States	4	Corn
France	0.12	Sugar beets, etc.
Malawi	0.1	Molasses
South Africa		Coal, natural gas, molasses
Argentina		Molasses
Paraguay		Molasses
Cuba		Molasses
Costa Rica, El Salvador, Guatemala, Jamaica.		Wine distillate imports from Europe; export fuel ethanol to US In the past, El Salvador's gov. operated 4 fuel-ethanol plants.
Planned		
Sweden	0.5	Wheat
Netherlands	0.3	
Spain	0.1	
Ethiopia	0.08	Molasses
Canada		Corn
Fuel ethanol discontinued, ethanol now used for other purposes		
Zimbabwe	0.3	Molasses
Haiti		Largest distillery was originally designed for fuel ethanol, now converted to beverage molasses.

[a] *Sources*: Murtagh, 1997, Berg, 1999.

production have been support for the agricultural sector, national energy security, and environmental benefits.

Brazil. Brazil is the world's largest producer of cane-derived fuel ethanol. In 1975 the Brazilian government created the Proalcool program, in order to reduce the dependence on foreign oil imports in the wake of the first worldwide oil crisis in 1973 (Fig. 5), as well as to find alternative markets for sugar products, because world sugar prices were declining rapidly at that time (Fig. 6) (Moreira and Goldemberg, 1999). The use of ethanol both as a neat fuel and a gasoline additive was promoted. In response, the production of ethanol jumped from less than 1 Bl in 1976 to 12.6 Bl in 1995 (Moreira and Goldemberg, 1999; Goldemberg, 1998). During this time, the price paid to producers fell by a factor of eight (Fig. 4) (Goldemberg, 1996).

While the Brazilian ethanol program is often viewed as a success in environmental policy circles, it has faced a great deal of domestic criticism (Lizardo and Ghirardi, 1987). Between 1975 and 1996 the program was heavily subsidized by the government. Deregulation of the ethanol industry began in 1996, which resulted in turmoil in the Brazilian ethanol market, and increased sugar exports, which may have contributed to the current low world market prices for sugar (Fig. 6) (Hannah, 1999). Despite deregulation, industry experts predict that Brazilian fuel ethanol production will continue to expand, but at a slower pace. Brazil is actively seeking export markets for its fuel ethanol.

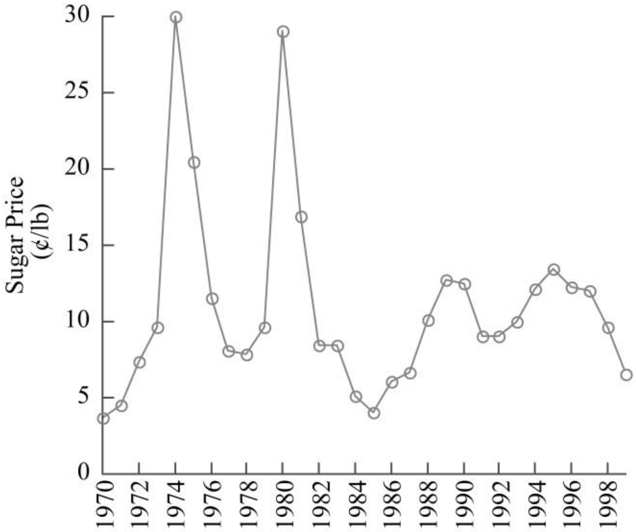

Fig. 6. Sugar prices from 1970 to 1999. *Source*: New York Coffee, Tea and Cocoa Exchange, 2000.

United States. The United States' fuel ethanol program also began in the 1970s, and is currently supported by the requirements of the US Clean Air Act of 1990, which has provisions that effectively mandate the use of some ethanol in fuels. The program receives federal tax exemptions, and a number of state-level incentives (Berg, 1999).

US fuel ethanol is produced from corn, which is considerably more expensive than production of ethanol from sugar cane. Ethanol production costs in the US have ranged from about \$0.20/l to about \$0.50/l (in 1989\$), depending on the cost of corn (Wyman et al., 1993). To make this corn–ethanol competitive with gasoline, ethanol has a \$0.54/gallon (\$0.14/l) tax subsidy (DiPardo, 2000).

Europe. In the European Union, currently only about 0.01 Bl of ethanol are used as fuel. In 1994 the European Union decided to allow tax concessions for the development of fuel ethanol and other biofuels, and as a result a number of ethanol projects have been announced in the Netherlands, Sweden and Spain. France has the most developed fuel alcohol program in the European Union. A 1996 law requires the addition of oxygenate components in fuel, and ethanol was given an early exemption from the gasoline excise tax (Berg, 1999).

South Africa. There are four major ethanol producers in South Africa. The largest is the South African Coal, Oil and Gas Corp. (Sasol), which produces up to 400 Ml/yr of ethanol from coal. This capacity was developed during the 1950s to reduce South Africa's dependence on oil imports during the apartheid era. Sasol's synthetic ethanol production can top 400 Ml per year, but usually fluctuates with demand on the world market in general, and on the Brazilian market in particular. The decline of exports to Brazil meant that the company had to find markets for its products elsewhere (Berg, 1999). Since the mid-1990s, Sasol's efforts to introduce coal-derived ethanol into gasoline have repeatedly failed because of petroleum and automobile industry complaints about the low quality of the Sasol ethanol (Robertson, 1998). Coal-derived alcohols are not pure ethanol. The original alcohol additive contained only 65% ethanol, which caused significant engine problems. As of mid-1999, the quality issues seem to have been resolved through development of an 85% ethanol blend, and the coal-derived ethanol will be used in South Africa as a 12% blend with gasoline (Xinhua News Agency, 1999; Sapa 1999).

South Africa also produces ethanol from natural gas, about 140 Ml/yr; the plant has been identified as "one of South Africa's most expensive white elephants." (Soggot, 1998) In addition, there are Illovo Sugar (43 Ml) and National Chemical Products (NCP), both of which use molasses as a feedstock.

Zimbabwe. Fuel ethanol has been produced in Zimbabwe since 1980. The economic and trade sanctions imposed on Rhodesia (the colonial name for Zimbabwe) in the 1970s generated the need for an independent, self-sufficient source of automotive fuel. Accordingly, a molasses fermentation and distillation plant began operation in 1980, shortly after the state of Zimbabwe was declared, at the Triangle sugar refinery. The total annual ethanol production of the plant was about 30 Ml throughout the 1980s (Rosenschein and Hall, 1991).

In the early 1990s, Zimbabwe experienced severe drought, and the Triangle sugar refinery was temporarily shut down (BBC, 1992). During the hiatus, Triangle's contract to supply fuel ethanol to the government expired. When the Triangle refinery restarted operations, the managers realized that they could get a better price by exporting the ethanol (Woods, pers. comm., February 2000). So now Zimbabwe's ethanol is exported.

Malawi. Malawi has very favorable economic conditions for ethanol. Like Zimbabwe, Malawi was on the forefront of fuel alcohol development, and has blended ethanol with its gasoline continuously since 1982, and has thereby eliminated lead. Because of high freight costs, the wholesale price of gasoline is about 56¢ per liter as of April 2000, and about 69¢ (US) per liter retail. Moreover, Malawi's molasses has a low value because the cost of shipping it to a port for export typically exceeds the world market price (US AID, 1989b). Malawi's Ethanol Company Ltd. produces about 10–12 Ml per year, providing a 15% blend for gasoline (US AID, 1988, 1989a, b; Pers. comm., Niyrenda, Asst. Prod. Manager, Ethco, 2000).

Ethiopia. In Ethiopia, the Finchaa sugar factory opened in April 1999 and has the capacity to produce 8 Ml of ethanol per year from molasses (The Reporter, Addis Ababa, 1999).

Thailand. In 2000 Thailand launched a program to mix 10% ethanol with gasoline. Ethanol will be produced from molasses, sugar cane, tapioca and other agricultural products. The goal is production of 730 Ml per year by 2002 (Deutsche Presse-Agentur, 2000; Bangkok Post, 2000; Business Day, 2001).

Zambia. A recent study assessed the role of sugarcane as a renewable resource to support sustainable development in the Luena region of northern Zambia. The analysis showed that ethanol became competitive at a price of 45–50 cents per liter, which was 5 cents above the expected price for gasoline. Among the reasons that ethanol was uncompetitive at lower prices was the fact that sugar prices continue to be supported at levels well above the international price. Future trade agreements could lower such price supports, making ethanol more competitive in the future (Cornland et al., 2000; BBC, 1982; Phiri, 1999).

There has also been interest in fuel ethanol in Cuba (BBC, 2000) and Uganda (Wakabi, 1999).

5. The potential for fuel ethanol to replace lead in gasoline

Roughly speaking, gasoline lead additive at a concentration of about 0.6 g/l can be replaced with a 20% blend of ethanol in gasoline. Thus in bulk, to replace a tonne of lead would require about 0.3 Ml of ethanol. As shown in Table 4, about 9000 tonnes per year of lead is used in gasoline in Africa, with more than half of this used in South Africa and Nigeria. To replace all the lead currently used in gasoline in Africa would require about 2.4 Bl of ethanol. For comparison, ethanol production in Brazil peaked at 15 Bl in 1997 and is about 12 Bl as of 1999 (Macedo, 2000).

Table 4 also shows the production of sugar cane in Africa. If the sugarcane is used for ethanol production rather than sugar production, about 70 l of ethanol can be produced from each tonne of sugar cane. If the sugarcane is used to make sugar, ethanol can be produced from the by-product, "C" grade molasses at about 10 l per tonne of cane. The table shows that the ethanol production potential in Africa if all of the sugar cane were converted to ethanol is about 4 Bl. If only molasses is used, the production potential is about 0.5 Bl.

It is, of course, not particularly plausible that all countries in Africa would find it feasible to devote nearly half of their sugar production to ethanol. Situations vary tremendously across the continent, and fuel ethanol makes more sense in some places than others. Nigeria, the largest consumer of lead additives in Africa, has relatively low production of sugar cane. Being a major oil producer and exporter, it might consider refinery upgrades or petrochemical-derived MTBE as a source of octane. On the other hand, South Africa, the second largest consumer of lead additives in Africa, has the potential and the existing infrastructure to completely replace lead additives with ethanol, both cane-derived and from petrochemicals. The north African countries of Algeria and Libya are the third and fourth largest users of lead additives, but they do not produce sugar cane, so here again, a petrochemical-based approach to increased octane may be the most straightforward option.

Other countries, however, including Zimbabwe, Kenya, Egypt, Zaire, Zambia, Sudan, Swaziland, Mauritius, and Malawi, produce considerably more sugarcane than would be required to fulfill their octane needs, and so appear to be well suited for fuel-ethanol production.

Table 4
Potential to replace gasoline lead additives with sugarcane-derived ethanol in Africa[a]

Country	Pb used in gasoline tonnes/yr	Gasoline consumption Mtonnes/yr	Pb Conc. in gasoline g/l	Ethanol requirement Ml/yr	Cane prod Mtonnes/yr	Cane-ethanol potential[b] Ml/yr	Molasses-ethanol potential[c] Ml/yr
Nigeria	2600	3500	0.65	840	0.7	50	7
South Africa	2300	7000	0.33[d]	700	21	1500 + 350 syn	200
Algeria	1300	1700	0.6	400	0	0	0
Libya	900	1500	0.6				
Zimbabwe[e]	315	300	0.8	75	4.7	300	47
Ghana	300	400	0.6	100	0.15	10	1.5
Tunisia	200	300	0.5	60	0	0	0
Cameroon	180	250	0.6	50	1.4	100	14
Morocco	158	350	0.3	50	1.4	100	14
Ethiopia	168	160	0.84	50			8
Kenya[e]	150	400	0.4	50	5.2	350	52
Egypt[e]	100	1700	0.25	30	15.3	1000	150
Uganda	90	90	0.84				
Zaire[e]	80	110	0.6	25	1.8	130	18
Zambia[e]	80	100	0.7	25	1.6	110	16
Angola	70	70	0.7				
Sudan[e]	64	190	0.4	20	6	400	60
Swaziland[e]					3.7	250	37
Mauritius[e]	45	90	0.4	10	3.5	250	35
Malawi[e]	0	66	0	0			10
Total	9000			2400		4200	470

[a] *Sources*: FAO, 2000; Octel, 1998; US DOE, 1999.

[b] Assumes 70 l ethanol can be produced per tonne of sugarcane (Fulmer, 1991).

[c] Assumes 10 l ethanol can be produced from "C" grade molasses (Fulmer, 1991).

[d] Pers. Comm. Tracey Potter, South African Embassy, Washington DC, July 1993.

[e] Countries that could produce considerably more ethanol than required to eliminate lead from gasoline.

6. Conclusion

In summary, ethanol appears to be a good option for replacing lead in gasoline in a number of countries in Africa. The economics will depend on local conditions, but it is plausible that costs will be comparable to or lower than other octane sources.

Fuel ethanol has a number of advantages. It can provide an outlet for molasses that might otherwise go to waste; it can help to stabilize the agricultural sector, and it provides a domestic contribution to the fuel mix. Cane-derived ethanol also has low net emissions of greenhouse gases, and thus could be part of a country's strategy for reducing greenhouse emissions.

But fuel ethanol programs do not spring up on their own. Fuel ethanol programs, like almost every aspect of fuel and energy production worldwide, are tightly bound up with a host of local and international factors, including national energy policies, national security policies, competing interests within the energy, agriculture and transportation sectors, and the international markets for gasoline, sugar, and lead additives. On paper, fuel ethanol seems to be an attractive option for replacing lead in gasoline in Africa. To realize this potential will require carefully designed programs adapted to local conditions.

In the 1980s and 1990s there were a number of international efforts to develop and promote fuel ethanol in developing countries, notably including work by the World Bank (World Bank, 1980), the US Agency for International Development (US AID, 1988, 1989a, b), the Stockholm Environment Institute (Cornland et al., 2000), and Brazil (Moreira and Goldemberg, 1999). Beginning in the mid-1990s, there have been a number of international efforts devoted to the worldwide elimination of lead in gasoline, including initiatives at the World Bank (World Bank, 1996), the United Nations Environment Program and the Organization for Economic Cooperation and Development (UNEP and OECD, 1999), and the US EPA and US AID (US Mission to the United Nations, 1996). Coordination of international fuel-ethanol programs with international leaded gasoline phase-out programs could provide synergistic benefits.

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