An Analysis of Alternatives for Unleaded Petrol Additives for South Africa

Dr. Michael S. Graboski

May 2003

Disclaimer:

This report is based upon publicly available information and information provided by South African companies and government entities through private communications. Analyses derived from the data and conclusions drawn assume that the information database represents an accurate picture of the South African motor fuel situation.

Executive Summary:

The US EPA and CERF/ IIEC are jointly assisting South Africa with its phase out of leaded petrol . The primary focus of the exercise is to provide technical assistance and business linkages to South African government and industry that will facilitate the country's phase out of leaded petrol . One part of this effort is to evaluate the various additives that could serve as an alternative octane booster in South Africa after lead is removed the country's petrol . An important aspect of the analysis is the potential impact on petrol supply. The purposes of this white paper are to provide a preliminary analysis of the South African transportation fuels sector and analyze alternative additives and their technical feasibility, including a discussion of issues related to environment and some aspects of their costs and benefits.

The analysis represents a snapshot of the current fuels situation in South Africa. A quantitative comparative economic assessment of alternatives is beyond the scope of this report and is not included. One important aspect of this study is to assess what data are required for more detailed future analyses as well as to evaluate the quality of those data sources. The report is likely to identify data gaps that will need to be filled.

Currently, the industry is transitioning to unleaded gasoline, and refiners indicate that 30% of all gasoline sold is now unleaded. This is being accomplished using MMT and aromatics including benzene. The industry is committed to eliminating lead by 2006, however the methods they will employ have not yet been described. However, they are also committed to changing to a zero metallic additives specification by 1 January 2004, which will effectively eliminate MMT from petrol sold in South Africa.

The unleaded Research Octane specification is 95 at the coast and 93 inland. Based upon the specification, the pooled octane requirement is about 94.4. There are not many additives available to raise the RON to such high levels. It would seem that an analysis of the actual RON requirements for the fleet should be made to determine whether multiple grades of unleaded could be offered that would more efficiently use the existing octane production capabilities. This would need to be done in conjunction with a public awareness program related to the significance of octane.

South African gasoline is produced from crude oil, coal and natural gas. Synthetic petrol from coal and natural gas represents about 39% of the supply. It is very high in olefins and aromatics. If synthetic petrol that meets the octane specification is to be produced, an additive must be used because the Fisher-Tropsch technology employed produces a fixed composition product. The Sasol product can meet the inland RON specification with 11% ether additive.

The octane requirements can be met through refinery modifications and or the use of additives. In the refinery, increasing the use of aromatics is a likely. Additives such as MMT (a manganese organometallic compound that functions like tetraethyl lead), ethers like MTBE and alcohols like ethanol are likely candidates.

The South African refining industry is capable of producing sufficient gasoline to satisfy the South African demand. However, it must export a substantial quantity of distillate. The industry has suggested that the cost of modernization to meet the RON specifications and desulfurized diesel fuel is about $1.25 billion.

One approach to meeting the RON specifications is to increase the use of isomerate and aromatics. Producing isomerate is relatively inexpensive and the product is benign, however the aromatic content of petrol then might need to be raised from 34% to 40% after lead removal to satisfy the RON specifications. If aromatic concentrate were used, about 19,000 barrels per day would be required from additional reforming capacity or through purchases. Aromatics and some of their combustion byproducts are toxic and carcinogenic. Benzene is a known human carcinogen and other aromatics are known to decompose in the exhaust to benzene. Aromatics also are converted via the combustion process into exhaust particulate that contains a substantial fraction of diesel-like polycyclic hydrocarbons that are more carcinogenic than benzene. Light aromatics in the exhaust are potent ozone formers and a portion of the light aromatics are converted into fine particulate aerosols by sunlight.

MMT alone cannot replace lead. A combination of isomerization and MMT at 18 mg/l would be satisfactory. MMT may be the lowest cost alternative to the refiner, however MMT use may reduce vehicle mileage by 2%. In addition, MMT use may raise the cost of vehicle maintenance. In addition, there are un-quantified health and environmental effects associated with MMT. Manganese compounds are known to be neurotoxins. However, the impact of low-level long-term exposure by inhalation is not known. Blending MMT increases hydrocarbon emissions that are ozone precursors. Exhaust air toxics are likely to increase due to the increase of hydrocarbon emissions. The emissions of ultra-fine particulate manganese oxides also represent a health issue.

Blending either MTBE or ethanol into refinery petrol can satisfy the Research Octane specification. Approximately 18,000 barrels per day of MTBE or 12,000 barrels per day of ethanol would be required to satisfy the octane demand.

MTBE would have to be purchased. South Africa does not have adequate supplies of methanol and natural gas liquids to produce that quantity of MTBE.

Ethanol from the synthetic petrol plants could supply a substantial portion but it is currently exported as high valued chemical grade alcohol and converted into ethyl acetate. Agricultural feedstocks including maize, cassava, sugar and molasses could yield substantially more alcohol than required. However, an investment of near $300 MM might be necessary.

The cost of production of petrol with MMT might be lower than that based on MTBE or ethanol. Assuming $25 per barrel crude, lead at 1.5 cents per gram, MMT at 1 cent per gallon treatment cost, MTBE valued over gasoline at octane based upon 1 cent per octane gallon and ethanol at $1.25 per denatured gallon, the cost premiums are estimated to be

0.4 cents for MMT, 2.11 cents per gallon for MTBE and 3.07 to 3.95 cents per gallon for ethanol depending on the final vapor pressure specification for ethanol containing petrol.

The use of MTBE and ethanol may have health and environmental impacts. Oxygenates generally reduce carbon monoxide and hydrocarbon emissions. They also reduce fine particulate exhaust. MTBE is converted to formaldehyde and ethanol to acetaldehyde in the exhaust. The aldehydes can irritate the respiratory system. They are also weak carcinogens. MTBE is non-biodegradable and has caused water pollution problems in the United States. Ethanol increases gasoline vapor pressure and is easily transported by permeation through some fuel tanks and hoses. To use ethanol without increasing evaporative emissions, the petrol blendstock must be modified to lower its vapor pressure raising the cost. Ethanol petrol also cannot be pipeline transported. Ethanol must be blended at the terminal prior to distribution.

During the transition, refiners may use approaches that are not in the best interests of the public. In setting policy, the South African government might want to consider not only cost of production of petrol but also external costs. The long-term costs for health and welfare are different for the various alternatives. Consumers may have different maintenance costs associated with the various alternatives. Domestic production of ethanol could provide a source of rural income.

Introduction:

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The analysis represents a snapshot of the current fuels situation in South Africa. A quantitative comparative economic assessment of alternatives is beyond the scope of this report and is not included. One important aspect of this study is to assess what data are required for more detailed future analyses as well as to evaluate the quality of those data sources. The report is likely to identify data gaps that will need to be filled.

Local Petrol Grades, Specifications and Issues

South Africa has committed to removing lead from the bulk of the petrol supply in 2006. The specification for unleaded fuels is published by the South African Bureau of Standards as SABS 1598:2001 and allows for two grades of unleaded petrol . These are 93 and 95 research octane number, RON. The unleaded specification allows for a minor level of lead that may be picked up in the distribution system. The specification does not permit the purposeful introduction of lead into petrol. Currently, most motor petrol is leaded according to SABS 299:1995 which allows for three grades, 97, 93 and 87 RON. Petrol can have up to 0.4 g/l of lead. Both specifications allow for the use of oxygenates.

Stoichiometric petrol engines equipped with oxygen sensor controls are insensitive to fuel composition and altitude. The controls correct for winter/ summer fuel variations and the presence of oxygenates. Emission controls are relatively unaffected by these variables. This is not true for older carburetor type engines.

The petrol specifications also include other data relating to drivability of automobiles such as distillation properties, vapor pressure, gum formation and corrosion requirements. Detergent additives are very important in controlling engine deposits and enforcement to insure the presence of detergent additives is important. Removing lead from petrol should not alter these requirements. The octane specifications are related to location, particularly altitude. It is commonly accepted that the octane requirement for non-turbocharged vehicles decreases with altitude due to derating of the engine. However, if the specification is intended to relate to the future fleet where turbocharged petrol vehicles are present in large numbers, the octane derating for altitude needs to be reconsidered. Geographically, the specifications are as follows:

- Coastal Leaded, 97 RON
- Coastal Unleaded, 95 RON
- Inland Leaded, 93 RON
- Inland Unleaded, 93 RON

It is possible to drive from the inland area to the coastal area on a single tank of fuel. This suggests that the RON specifications should not be altitude compensated and for each grade, there should be a national specification.

South Africa is currently developing its clean air program. The fuel specification needs to be coordinated with clean air requirements as well. This might include Reid Vapor Pressure controls during hot weather and the addition of oxygenates for carbon monoxide control.

In 1999, the DME reported that the total consumption of Coastal petrol was 4.61 MM kiloliters (kl), while the Inland consumption was 6.22 MM kl. Only 11% of the petrol sold was unleaded. More recent reports[1] suggest that 30% of the petrol currently sold is unleaded. The unleaded fuel is reported to contain 5% benzene compared to 2% benzene in leaded petrol . The total aromatic content was not reported but this suggests that refiners are producing their unleaded fuel with a very high BTX content derived from catalytic reforming. The RON of BTX components including benzene, toluene, p-xylene, o-xylene and m-xylene are 106, 114, 120, 105 and 120 respectively. South African drivers need to be educated about octane requirements. It has been proposed that the main reason for the increase in use of unleaded gasoline from 1999 was the increase in Inland unleaded research octane from 91 to 93.

Octane:

Three octane ratings are commonly utilized. These are Research (RON), Motor (MON), and Road. In spark-ignited engines, a timed spark at close to the top dead center piston position on the compression stroke detonates the fuel. Knock occurs if the fuel detonates due to compression heating on the compression stroke prior to the spark being actuated. The higher the octane number, the more difficult it is to detonate by compression heating.

The research and motor octane ratings are determined by engine testing. The research rating is characteristic of a vehicle operating under light load city driving. The motor rating is related to heavy load highway operation.

The road octane rating is also called the Antiknock Index, AKI. The road octane number is the average of the RON and MON ((R+M)/2). Petrol may be blended to produce the same AKI with very different RON values. The difference between RON and MON is termed sensitivity. Good petrol has a low sensitivity. Refiners can control sensitivity during blending of petrol , but the degree of control is related to their refinery configuration. Some blendstocks, such as alkylates, have very low sensitivity (1 or 2

[1] Data reported at the CERF workshop on lead phaseout, Johannesburg SA, 1/27/03.

octane numbers), while other streams like FCC naphtha exhibit sensitivity values of up to15 units.

The octane requirement of an engine is a function of its compression ratio. Since 1971, essentially all US cars have been designed to operate with 91 RON petrol. Later, a road octane design limit of 87 was also imposed for "regular grade" petrol at sea level. In the US refining sector, the actual RON supplied by the refining sector is about 5 units higher than the road octane number, or 92 RON. Some older cars and specialty vehicles require premium petrol with a road octane number of 91. While about 25% of US petrol sales are for premium grades, the actual requirement for non-regular petrol is considerably lower. Most premium petrol sales are based upon lack of understanding of the meaning of octane by the US public. Factually, as long as petrol has sufficient octane, more octane does not yield better performance.

The octane requirement of vehicles can also increase with age. The primary problem is combustion deposits. Heavy deposits on intake valves can retain heat and cause premature detonation of the fuel during compression. Lead deposits on valves may result in greater octane requirements. US petrol must contain detergent additives to cleanup carbon and organic deposits. Detergent additives do not, however, affect metal oxides.

It is important to understand why the South African research octane specification is set at 95 at sea level. Attaining such an RON for unleaded petrol requires the addition of very high RON blendstocks that are expensive and might be technically unnecessary.

In many driving situations, especially those involving heavy loads and high ambient temperatures, the MON may be the limiting performance variable. The South African specification may not adequately address MON.

Historical Use of Oxygenates as Octane Additives:

In the U.S., essentially all automobiles produced after 1980 can run successfully on petrol containing 10% ethanol or 15% MTBE. There are two issues. First, elastomers and seals have been upgraded so they are not affected by the greater solvent power of ethers and alcohols. Second, vehicle control systems have been developed to account for the different air to fuel ratios necessary to burn oxygenated and non-oxygenated fuels ("closed loop").

In 1999, NAAMSA (National Association of Automobile Manufacturers of SA) agreed to the use of 12% ethanol blends (85% ethanol minimum) splash blended into 93 RON leaded petrol in several South African states[2]. Toyota has expressed concern that older vehicles, certain imports and those with after market engine replacements could experience problems. Reports of major problems since 1999 were not discovered, however, it is not known exactly how much ethanol Sasol actually blended into petrol.

[2] Robertson, D., "Toyota Warns Against Use of Alcohol Blend", Business Times (South Africa), 7/25/99.

Simultaneously, Sasol began to produce ethyl acetate and chemical grade ethanol from its crude alcohol supply, using only a small quantity for fuel[3].

An understanding of the technology of the fleet is necessary to understand the impact of oxygenate blending on performance and emissions. Sasol had previously marketed an oxygenate with 65% ethanol that caused problems because some vehicles contain metallic fuel system parts that are subject to corrosion by oxygenated fuel blends[4]. The problems appear to be related to the presence of organic acids present in the oxygenate stream, which would not normally be found in fermentation alcohol. This clearly points out the need to have an adequate specification for alcohol fuel additives.

Older "open loop" automobiles (pre 1980 US technology) must be manually adjusted to operate on oxygenated fuels. If they are set up to run on hydrocarbon fuels, the fuel to air ratio will be very lean, on oxygenated fuels resulting in performance issues including stalling, hesitation and misfire. In the Inland region, open loop cars don't seem to have suffered such performance problems. The South African industry has not apparently adjusted vehicles for altitude; thus in practice they run very rich. Adding oxygenates would thus improve fuel economy and reduce emissions by leaning the combustion.

The South African fuel standard currently allows oxygenates, including the Sasol 85% ethanol additive to be blended into petrol.

Petrol Distribution:

Lead removal need not complicate petrol distribution. The distribution issue is not related to the fleet requirement for lead, but the ability of the refining industry to alter its manufacturing capability. The industry will require lead-time to eliminate lead. At the same time, it is expected that the population of cars requiring unleaded petrol will grow continuously during lead phase-out necessitating an increase in supply of unleaded petrol. Currently the distribution system handles a leaded grade and an unleaded grade in each region (coastal and inland), but the volume of unleaded petrol is small. When a complete switch is made, the distribution issue no longer applies.

It is necessary to develop an implementation plan showing how the distribution system can accommodate the switch to unleaded petrol in terms of tankage available at terminals and retail stations, and the sophistication of the supply system related to its ability to manage leaded and unleaded petrol in relatively large volumes. In addition, national standards for leak detection and ongoing monitoring will enable the industry to run a more efficient distribution network.

If the octane deficit is partially mitigated using an alcohol, such as ethanol, terminal blending facilities and tankage for alcohol may need to be added. Furthermore, if volatility control to protect air quality becomes an issue, blending of ethanol containing petrol with clear petrol in service stations would need to be controlled.

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[3] Berg, C., "World Ethanol Production 2001", www.distill.com, July 31, 2001.
[4] Dispatch On-Line, "Petrol with Alcohol Comes to SA", 7/23/99.

Other Issues Related to the Use of Unleaded Fuels:

Valve seat recession is often cited as an issue related to use of unleaded fuels. In the US, for example, all cars sold in the last 20 years, and most in the last 30 years were equipped with valves with hardened seats. (Even vehicles with older non-hardened valves exhibited few problems unless driven extensively at high speeds.) These vehicles were designed and warranted to operate on metal free petrol containing oxygenate such as ethanol. If leaded petrol is totally banned and there is a problem in the oldest vehicles, aftermarket products are available[5].

It is possible that ethanol blending will be at least a partial solution to the lead removal problem. Water management in the distribution system is crucial to eliminating problems related to fuel phase separation. The US distribution system has adapted to the trouble free handling of almost 20 billion gallons per year of ethanol blends.

The condition of tankage, especially retail tankage could be an issue if ethers like MTBE and TAME are a partial solution. The U.S. has experienced water pollution problems associated with spills and leaks of ether containing petrol . Ethers are highly resistant to biodegradation and have extremely low odor and taste thresholds causing drinking water supplied from wells to be unpalatable.

The South African Fleet:

The South African fleet is distributed approximately as follows:

Table 1
South African Motor Vehicle Statistics, December 2001

Vehicle Class	Count
Motor cars and station wagons	3,913,470
Minibuses	248,837
Buses	25,943
Light Commercial	1,297,383
Heavy Duty trucks	226,937
Motorcycles	158,606
Other	178,788
Total	6,049,964

Minibuses are typically 9-seat passenger vans designed for family use. Commercial vehicles consist of light duty cars, vans and pick-up trucks. Very few pickup trucks are purchased for personal use.

[5] Megnin, M.K., "The Transition to Unleaded Gasoline: Issues and Experience", Clean Air initiative-Regional Conference on the Phase-out of Leaded Gasoline in Sub-Sahara Africa, Dakar, Senegal, June 26-28, 2001.

The population is fueled with both petrol and diesel. Table 2 provides data on the fuel use by class[6] for 2001 projected from data for 1996. It was assumed that the fraction of vehicles in each class using petrol was constant, and the VMT and fuel consumption rates of the classes did not change.

Table 2
Fleet Fuel Use Data

Vehicle Class	% Petrol by Count	% Petrol Use
Motor cars and station wagons	99.3	68.9
Minibuses	99.4	7.6
Buses	0	0
Light Commercial	85.2	23.5
Heavy Duty trucks	0	0
Motorcycles	100	NA
Other	NA	NA
Total	-	100

Over a 10-year period (1990-1999), the average sales of cars and minibuses were 235,958 vehicles. Assuming this trend represents the long-term trend, this portion of the fleet will turn over every 17 years and exhibit an average age of about 8.5 years. The average sales of commercial trucks and buses are 82,157 vehicles. This fleet will thus turnover in 18 years and exhibit an average age of 9 years. The distribution of ages appears to not have been reported.

The Research Octane Number specification for South African petrol may have an impact on the ability of industry to supply unleaded fuel. The 93/95 unleaded specification appears to be related to the octane requirement of certain new European vehicles being added to the fleet. Most vehicles manufactured in the world operate well on 91 RON fuel. The current octane requirement of the in-use South African fleet has not been quantified but it is most likely lower than that required by the SABS 1598 specification. It might be most cost effective to supply two grades of unleaded gasoline as in other areas of the world; these would be a regular grade and a premium grade. If refiners elect to meet some or all of the increased demand for octane with aromatics or organometallic additives, lowering the pool octane could have a beneficial effect on gasoline quality.

Octane Study:

It might be useful to conduct a study of the distribution of vehicle need for Research Octane. Such a study might be based upon a stratified sample taken from the South African fleet as characterized by current registration data. These vehicles would be tested

[6] Prozzi, J.P., Naude, C., Sperling, C., Delucchi, M., "Transportation in Developing Countries, Greenhouse Gas Scenarios for South Africa", for the Pew Center on Global Climate Change, Feb 2002.

by professional drivers using a suite of unleaded fuels with varying RON values following an appropriate statistical design and test plan. These data would allow the establishment of a lower RON for a part of the fleet. Depending on the funds available, fuels with different octane enhancers could also be tested. Since demand for unleaded increased when Inland RON was raised form 91 to 93, there is a problem with public perception of octane and its benefits. The oil companies and the government would need to actively publicize the results and there might need to be incentives to encourage the public to try the lower octane fuel.

Petrol Supply:

In order to understand the implications of lead replacement, it is necessary to understand the existing liquid fuels industry. In South Africa, 61.3% of the transportation fuel (petrol and diesel) was reported to be supplied in the form of petrol. It is estimated that the percentage of petrol could fall slightly in future years due to the development of high efficiency passenger light duty diesels in Europe to 60.5% in 2005.

Overall Supply Balance for 1999

U.S. DOE/EIA has reported a reasonably current supply balance for petroleum fuels[7] for 1999. Table 3 presents the EIA data.

On the input side, South Africa has a limited supply of crude oil. In 1999, it was reported that crude oil reserves were only 29 MM barrels[8], less than one year of consumption. According to SAPIA, most of South Africa's crude is imported from Saudi Arabia and Iran. The qualities of those crude imports are not reported.

The refining sector includes both petroleum and synthetic fuel processing. In 1999, EIA reported that South Africa imported approximately 386,000 bbl/cd of crude oil. 29,400 barrels/day were exported. 35,000 bbl/cd of crude and natural gas liquids were supplied as a result of domestic production. SAPIA (South African Petroleum Industry Association) has also reported crude oil use. In 1999, the industry crude use totaled 17,637,000 metric tons of crude equivalent to 345,776 barrels per day. SAPIA reported a consumption of 385,476 BBL/day in 2000.

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[7] Energy Information Agency, U.S. Department of Energy, "Country Energy data Reports-South Africa", http://www.eia.doe.gov/emeu/world/country/cntry_SF.html. It would be useful to update this supply balance with more recent data. EIA will update the balance in 2003.

[8]http://www.eia.doe.gov/emeu/cabs/tbl3c.html

Table 3
Supply of Refined Products to South Africa, 1999
Thousands of Bbl/ calendar-day

	Production	Refinery	Imports	Exports	Consumption	Difference
Inputs						
Crude oil	25	381.5	385.9	29.4	0	0
Natural Gas Liquids	9.5	9.5	0	0	0	0
Other Oils	175	175	0	0	0	0
Outputs						
Petrol		180	13.9	12.9	183.3	2.3
Jet Fuel		37.9	0	3.5	34.4	0
Kerosene		21.5	0	3.59	18	0
Distillates		145.8	0.2	36.4	102.7	-6.9
Residual		104.6	5.67	41.0	67.5	1.8
LPG		10.0	0	0	10.0	0
Unspecified		51.3	2.1	4.26	49.8	0.5

In addition, EIA reports that 175,000 barrels per day of "other oils" were synthesized by Fischer-Tropsch from coal and natural gas. Sasol reports that liquid fuels (petrol and diesel) via Fisher-Tropsch from coal amount to 101,370 barrels per day, while it has been estimated that 22,500 barrels per day are produced from the PetroSA (Mossgas) natural gas GTL facility. Either EIA has overstated the quantity of "other oils" or has included other unquantified outputs such as waxes, oxygenated chemicals and LPG[9].

Table 3 also shows the fate of various refined products. Essentially all petrol produced by South African refiners is consumed within South Africa. However, significant quantities of distillates and residual oils are exported. EIA estimates that petrol makes up 64% of the transportation fuels used in South Africa. A substantial quantity of unspecified products are produced; these are likely to include lube oils, coke, waxes and asphalt, but they may also adjust for any overstatement related to other oils from synfuel plants.

Policy that promotes diesel use will extend the ability of refineries to supply refined products to domestic markets.

Natural Gas:

Understanding the natural gas situation is important because South Africa derives about 7% of its liquid fuels via gas conversion. Additionally, production of non-petroleum

[9] It would be worthwhile to obtain detailed data on product streams quantities and qualities from Sasol and PetroSA. Requests for data have been made.

based high-octane blending components such as Methyl tert-butyl ether (MTBE) depend on the availability of natural gas liquids.

Natural gas reserves amounted to 780 billion cubic feet in 1999. Some modest gas finds have been reported recently in Namibia and Mossel Bay that may extend reserves for a number of years based upon current usage. The PetroSA (Mossgas) synfuels facility consumes[10] about 60 billion cu/ft per year of gas plus 3.5 million barrels of condensates with resource sufficient to produce liquid fuels until 2007. This appears to represent most of the natural gas produced and consumed in South Africa. The Sasol synfuels plants produce about 24 billion CFY of pipeline gas from coal as a byproduct of liquid fuels production that is consumed by industrial and commercial users. Sasol is currently developing a pipeline project to import additional natural gas from Mozambique but it is unlikely that this gas will be available to increase transportation fuel supplies in the near term.

Coal:

South Africa is rich in coal reserves. Total coal consumed was 174.6 million tons in 1999 amounting to 75% of the country's energy consumption. 43 million tons were used to produce synthetic fuels.

Oil and Gas Industry View of Supply and Demand for 2000 to 2005

Table 4 shows supply and demand data for South Africa for the period 2000 through 2005 [11]. These data do not include exports and so should be compared with the consumption column of the EIA balance. These data are generally consistent with the EIA balance provided in the previous section. Comparing these data with EIA data, it appears that all distillates produced go to the diesel pool unlike in the US where considerable amounts of light (Number 2) distillates are used for home and industrial heating.

Demand for diesel and kerosene can be easily met under the high growth demand scenario projected by the industry.

[10] Asamoah, J., "The Sustainable growth of the Natural Gas Industry in South Africa", CEMSA Conference, August 2002, Johannsburg SA.
[11] SAPIA Annual Report 2001.

Table 4
Supply and Demand for Refined Products for 2000 and 2005
Barrels/cd

	Petrol	Diesel	Kerosene
2000			
Capacity	220,700	158,589	68,420
Demand	193,600	122,087	51,940
% Stream Factor	87.7%	77.0%	76%
2005			
Capacity	227,320	164,470	72,180
High Demand	224,920	147,770	61,320
% Stream Factor	98.9%	89.9%	85%
Low Demand	208,000	134,960	56,200
% Stream Factor	91.5%	82.1%	77.9%

Note: To convert from barrels/day to millions of liters per year, divide by 17.234. Capacity includes synfuels.

The following conclusions can be drawn:

- The oil and gas industry may meet demand through 2005 without major expansions. The industry expects a nominal 3% increase in supply capacity for petrol .
- Petrol demand is projected to grow between 7.4% and 16.2% between 2000 and 2005.
- Most of the increase in petrol demand will be met by increasing the operating stream factor of the industry instead of finding new supplies.
- Even with the high growth scenario, there will be excess diesel production capacity.

If the high growth scenario occurs, the ability to maintain a reliable supply of petrol from South African refineries could be at risk due to the high operating factor projected by the industry (99%). South Africa would then need to increase imports of finished gasoline as well as crude oil. The issue of supply needs to be carefully examined.

The Installed Capacity of the South African Refining Industry

As of January 1, 2002, the South African refining industry was able to fractionate 468,547 Bbl/cd[12]. According to SAPIA, the installed crude capacity in 2000 was 471,000 Bbl/ cd.

The Natref refinery near Johannesburg is being expanded from 87,000 bbl/day to 105,000 bbl/day. The details of the expansion are not known. The increase in refining capacity is about 3.7% and is consistent with the increase projected by SAPIA for the period 2000 to

[12] Oil and Gas Journal 2001 Worldwide Refining Survey

2005. There also are reports of plans to increase the Engen refinery by 50,000 barrels per day of capacity, but this is apparently only in the early planning stages.

In addition, there are two large producers of finished fuels utilizing Fisher-Tropsch technology: these are Sasol and PetroSA (formerly Mossgas). Each of these facilities has significant refining upgrading capability to produce finished petrol product. The petrol supply and demand data provided by SAPIA include the synfuels operations. SAPIA's report would lead one to believe that Sasol and PetroSA will not expand production in the recent future.

Crude Oil Refining Infrastructure

There are four major refining companies operating in South Africa. Table 5 provides the reported capacity data for each refiner by processing step and the industry totals (see note 12). The processes important to producing petrol and refined oils are described briefly in the following paragraphs. Figure 1 shows how the processes may be interconnected in a typical refinery.

Atmospheric Crude Distillation: The capacity of the atmospheric crude tower defines how much crude per day can be processed into various boiling ranges. Typical ranges include gases (methane through butanes), light straight run natural petrol , LSR (pentanes through 180F), heavy straight run petrol , HSR (180F through 380F for maximum reforming cut), kerosene (380F through 520F for maximum petrol production), and light gas oil distillate (520F through 650F). The quantity of each of the products is a function of the crude mixture supplied to the refinery.

Vacuum Crude Distillation: The vacuum crude tower is used to split the 650F+ boiling material that leaves the bottom of the atmospheric crude tower. The cut between 650F and 1050F is used as feed to the catalytic cracker, hydrocracker, and for lube oil and asphalt production. The heaviest material is sent to a thermal cracking operation; in this case visbreaking is used to produce petrol, diesel, and fuel oils.

FCC: Fluid Catalytic Cracking is used to convert the light vacuum oil primarily to petrol. In the FCC, generally the 650F to 1050F crude oil cut is processed to yield petrol, diesel (light cycle oil), residual fuel oil (heavy cycle oil) and a considerable quantity of light gases rich in propylene and butylenes. The FCC is the main tool the refiner has to vary the ratio of petrol to distillate and fuel oils. The refiner can adjust the conversion of feed to petrol and diesel by properly choosing the crude mixture fed to the refinery and the operating parameters of the FCC. This also impacts the production of light olefins in a predictable fashion.

Hydrocracker: South African hydrocracker capacity is based upon conventional high-pressure technology. The hydrocracker generally converts light vacuum oil from crude distillation to petrol and kerosene. The hydrocracker petrol is typically split into light and heavy fractions with boiling ranges comparable to LSR and HSR. These cuts usually exhibit an intermediate octane rating and can be upgraded by isomerization and reforming.

Catalytic Reforming: Catalytic reforming is used to upgrade petrol octane by converting low octane heavy straight run (HSR) petrol boiling typically between 180F and 400F to a high aromatic blendstock. Heavy straight run is typically low in aromatics and exhibits an octane number between 60 and 70. Two types of reformers are in use today. These are older semi-regenerative units and newer continuous regenerative units. The reformate octane level is adjustable according to the "severity" of reforming. Typically, the semi-regenerative reformers available in South African refineries are limited to 100 RON products with a MON of 89 and an aromatic content of about 70% by volume. The benzene content of reformate can be controlled by adjusting the boiling range of the HSR. This is evidently not being practiced in South Africa as the benzene content of unleaded gasoline is reported to be very high (5% by volume). The quantity of reformate that can be produced is limited by the HSR fraction of the crude plus heavy naphthas derived from processing.

Alkylation: Alkylation is a chemical reaction that adds isobutane (and/or isopentane) to light olefins, propylene and butenes, to produce a highly branched paraffinic petrol. The two main technologies use HF and sulfuric acid. The South African refineries utilize HF alkylation exclusively. The light olefins are produced in the FCC. The quantity of alkylate that can be produced is limited by FCC capacity and conversion. The alkylate product exhibits an RON between about 90 and 97 depending on the mixture of olefins used. Alkylate petrols are valuable because they possess low sensitivity. Sensitivity is the difference between research and motor octane numbers. The motor octane number of alkylate is only 1.5 to 3 units lower than the RON.

Polymerization: Catalytic polymerization is used to combine light olefins, principally propylene, to yield heavy olefinic petrol. Typical polymer petrol has an RON of 97 and an MON of 84. The quantity of polymer petrol that can be produced is limited by FCC capacity and conversion.

Isomerization: Isomerization is used to increase the octane number of light natural petrol (LSR). LSR generally boils between about room temperature and 180F. Typically LSR exhibits a road octane number of 60 to 70. The simplest isomerate process, assumed to be available in South African refineries, exhibits a research octane number of 82 to 84 and a low sensitivity, typically 2 or 3 units. More complex isomerization processes using recycle schemes can achieve research octane numbers of 89 to 90. The quantity of isomerate is generally limited by the LSR fraction in the crude as well as low octane material produced during processing. Isomerate can also be produced from natural petrol derived from natural gas liquids processed in the refinery. However, isomerate exhibits a high vapor pressure; the quantity that can be blended into petrol may be limited by volatility restrictions in the petrol specification.

Hydrotreating: Hydrotreating is used to remove sulfur, nitrogen and oxygen that is chemically bound in the crude or blendstocks. Hydrotreating doesn't materially alter the quantity of petrol produced. However, sulfur removal can reduce petrol octane.

Other Processes: Lube oil, asphalt manufacture and coke production typically do not materially impact the production of petrol and diesel in a refinery.

Petrol /Distillate Ratio

Within the refinery, the ratio of petrol to distillate can be varied in two ways. First, the crude oil mixture fed to the refinery can be richer in naphthas to maximize petrol or in middle distillates to maximize diesel. Second, heavy oil can be processed to lighter products. Typically, petrol and middle distillates comprise 40% of the barrel. Nearly 60% of the barrel consists of heavy residual fuel oils. These are catalytically cracked (FCC), hydrocracked, and thermally cracked (visbreaking and coking) to convert a portion of the residual oils to petrol and middle distillates. The primary tool is the FCC. The severity of the FCC, termed conversion, is variable. As the conversion is increased, the ratio of petrol to fuel oils is increased. In addition, the quantity of light olefins, primarily propylene and mixed butenes increases with severity. The octane rating of FCC petrol is intermediate (RON 90 MON 79). The olefins can be alkylated or polymerized to produce additional high-octane petrol. The alkylation and polymerization capacity of a refinery is limited by the ability to produce olefins in the FCC, which in turn is limited by the FCC capacity.

It is useful to compare the overall US refining industry with the South African industry. The following observations are made:

(1) The fraction of crude capacity as vacuum distillation is similar indicating the heavy fraction of crude received is similar in both sectors.
(2) The US industry has more FCC and hydrocracking processing capability relative to crude input, and can thus produce a greater fraction of light products from crude compared to South Africa.
(3) South Africa has much more thermal cracking capability relative to crude that can convert the heaviest vacuum crude oil to lighter residual fuel oil.
(4) The relative ability to upgrade light naphthas is similar, but South Africa has less reforming capability.
(5) US refineries can produce much more high-octane petrol from olefins. Considering olefin processing for petrol relative to FCC capacity, the US fraction is 23.1% while the South African fraction is 12.6%.

The comparison leads to the following conclusions:

Table 5
Refining Capacity January 1, 2002
Barrels/CD unless noted

Operator	Location	Crude	Vacuum	Visbreak	FCC	Reforming	Hydrocrack	Hydrotreat	Alkylation	Polygas	Aromatics	Isom
Caltex Oil SA	Capetown	105,000	53,000	11,500	24,000	14,500	0	46,000	0	4,000	0	5,000
Engen Petroleum LTD	Durban	104,000	39,000	34,000	22,600	20,750	0	72,900	2,623	530	1,500	6,290
National Petroleum Refiners Of SA Pty Ltd	Sasolburg	87,547	34,475	0	25,660	14,642	11,774	24,392	3,295	0	0	0
Shell & BP Petroleum Refineries Pty LTD	Durban	172,000	71,000	27,000	35,000	29,000	0	128,370	3,100	0	0	0
		468,547	197,475	72,500	107,260	78,892	11,774	271,662	9,018	4,530	1,500	11,290

Operator	Lubes	Coke tonnes/d	Sulfur tonnes/d	Asphalt
Caltex Oil SA	0	0	82	0
Engen Petroleum LTD	2,739	0	130	4,830
National Petroleum Refiners Of SA Pty Ltd	0	240	120	0
Shell & BP Petroleum Refineries Pty LTD	3,200	0	140	0
	5,939	240	472	4,830

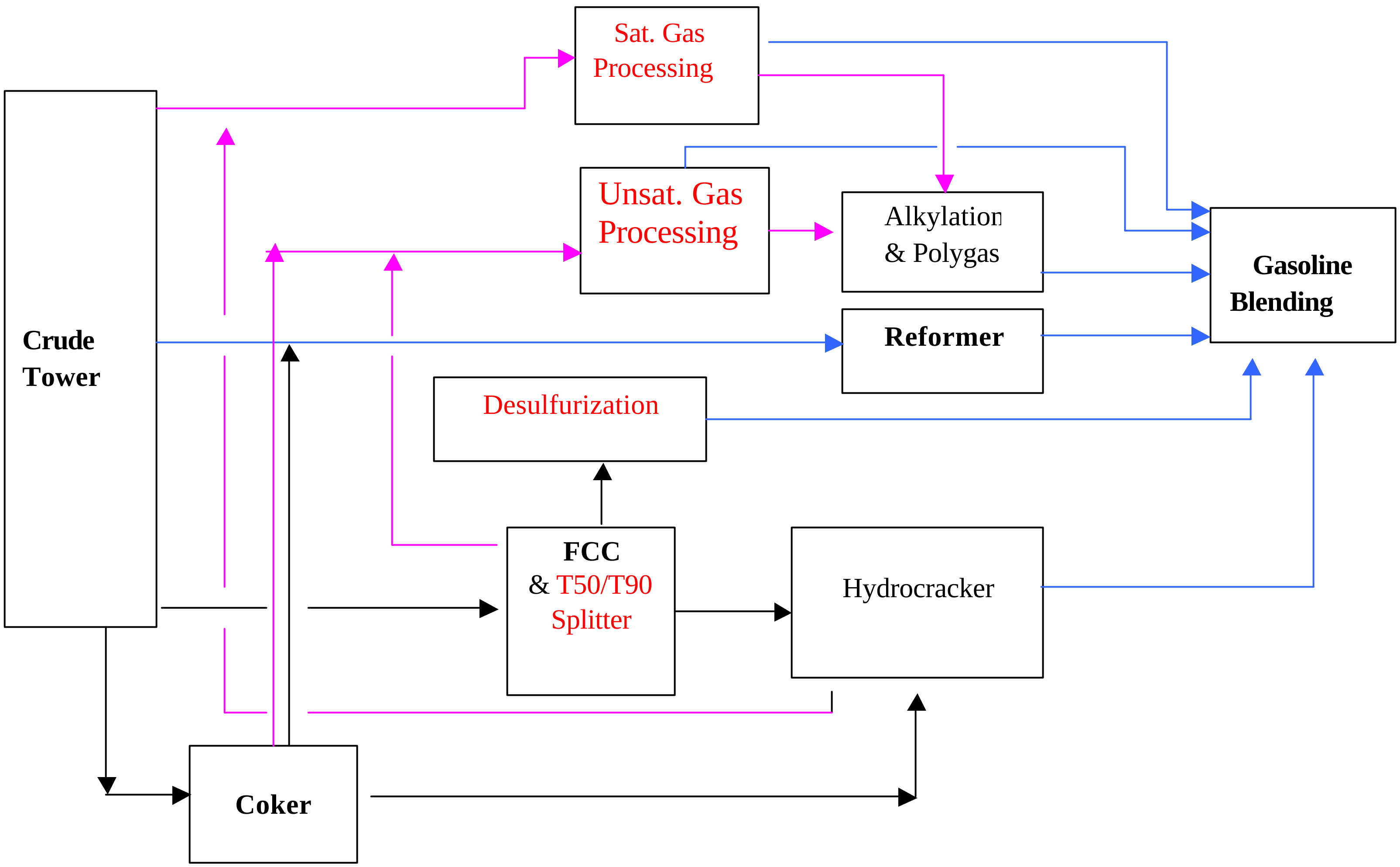

Figure 1 Typical Refinery Configuration
Only Gasoline production Shown

- The US refining model produces sufficient octane without lead.
- The South African refining industry cannot produce as much petrol as the US industry per barrel primarily due to a lower availability of FCC and hydrocracking capacity per barrel of crude distilled.
- South African refineries cannot produce much very high clear RON petrol.

Mode of Operation of South African Refineries:

In order to understand the fuel suite produced in refineries, the overall supply needs to be adjusted for petrol and distillates produced by the synfuels industry. It is estimated that coal and natural gas processing facilities produce about 63,200 bbl/d of petrol and 69,800 barrels of distillates/day. Thus, in 2000, the quantities of fuels produced in refineries were 130,558 bbl/day petrol, 104,232 bbl/day light distillates and 112,000 barrels/day of residual fuel oil. Table 6 compares the relative production of petrol, lighter distillates and residual fuel oil in the US and South Africa. South Africa produces a greater portion of its fuels in the form of light distillates, primarily diesel, and residual fuel oil. Based upon these data, the refining industry produces significantly less petrol and diesel per barrel than the US industry and considerably more residual fuel oil.

South Africa consumes essentially all of the petrol and light distillates it produces but exports a significant fraction of its residual oil. Thus, one option open to South Africa is to increase investment and better utilize crude oil conversion to process more residual oils to light products for domestic use. In fact, the South African refiners have indicated that they would need to make an investment of 10 to 15 billion Rand by 2006 (about $1 to $2 billion US) to modernize the industry so it can meet both the SABS 1598 octane specification and desulfurized the diesel pool. The details of this proposal are not public and there is no way to validate the proposition.

Table 6

South African Refining Sector Operating Mode

	US	SA	
		Total	Refining
Petrol	55.6%	36.7%	37.6%
Jet, Kerosene, Light Fuel oil	35.5%	41.0%	30.1%
Residual Fuel oil	8.9%	21.4%	32.3%

Petrol Blending:

Petrol is manufactured according to a specification that includes physical property ranges and limits necessary to ensure good performance in vehicles. A number of the specifications impact emissions and especially the tendency to form atmospheric ozone.

Some of the properties, RVP and distillation for example, are seasonally dependent. The octane specification is dependent on the vehicle. All petrol that meets the specification, regardless of its composition, is interchangeable or fungible.

In the refinery, a number of different petrol streams are produced. These are called blendstocks. They can be mixed in proportions necessary to satisfy the specification. Because of processing capacity and flexibility, the refiner can within limits vary the quantity and properties of the blendstocks. For example, to satisfy petrol distillation requirements for the 90% boiling point (T90), the refiner may have to reject heavy petrol components to the distillate pool. The refiner will blend finished petrol from the blendstocks as well as octane additives like lead so as to satisfy his demand scenario and minimize the cost of production within the constraints imposed by the petrol specifications.

From this brief discussion, the following should be evident:

- The refiner can control to some degree the relative amounts of petrol, kerosene, and diesel produced in the refinery by properly matching the mixture of crude oils for the demand scenario as well as by altering the operating conditions of the processing units, especially the FCC.
- There are limits to how much up-graded petrol can be produced by further processing such as reforming and alkylation.
- The petrol specification including olefin, aromatic, and sulfur contents as well as the maximum boiling point of the petrol impacts the quantity of petrol that can be produced as well as the octane level.

South African Alternative Liquid Fuels:

In addition to crude oil refining, considerable quantities of liquid fuels are produced from coal and natural gas. In each case, the feedstock is gasified to produce a mixture of carbon monoxide and hydrogen that is subsequently converted to gases and liquids by Fischer-Tropsch technology. The Sasol and PetroSA operations are directed at producing mainly finished petrol meeting the petrol specifications and distillate.

Sasol:

The Energy Research Institute reports that Sasol, which operates synthetic fuel plants in Sasolburg and Secunda, converts approximately 43 million tons per year of coal to liquid fuels and chemicals[13]. The reported production of liquid fuels is 39.3MM barrels per year or 107,670 barrels per day. Approximately 3276 bbl/day of residual fuel oil are produced resulting in a petrol and diesel production of 104,395 barrels/day. Sasol[14] reports current production of 58,795 barrels per day of petrol and 42,575 barrels of diesel (total 101,370), in good agreement with the data reported by the Energy Research Institute.

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[13] Energy Research Institute, "Preliminary Energy Outlook for South Africa", Department Mechanical Engineering, University of Capetown, October 10, 2001.

[14] Louis Bosch, Sasol Inc, private communication

Sasol has considerable petrol octane upgrading capacity including alkylation, pen-hex isomerization, and catalytic reforming. In addition, Sasol produces a large quantity of oxygenated chemicals that could be used as octane boosters in the petrol marketplace. Typical Fisher-Tropsch conversion might produce 0.125 mass units of chemicals per mass unit of petrol [15] of which about 84% are alcohols and the remainders are acids, aldehydes and ketones. From these data, the quantity of alcohols produced is estimated to be 4,800 barrels per day. The alcohol mixture is typically 2% methanol, 66% ethanol, 4% isopropanol, 15% n-propanol and 13% butanols and higher alcohols but the exact yield and mixture varies depending on processing conditions. The estimated neat ethanol production from coal liquids is thus 3,200 barrels per day. Sasol can supply an 85% ethanol mixture, presumably by incorporating heavy alcohols, that meets the South African fuel specification. The potential supply of 85% ethanol would then be 3,765 barrels/day. Berg (see reference 2) reports that Sasol's ethanol capacity is greater than estimated from Meyer being 220,000 MT per year, or 4,800 barrels per day. Apparently, most of the ethanol is used for petrochemicals. The majority of this ethanol is being exported as 99.99% chemical grade alcohol or being converted to ethyl acetate[16]. Data on the quantity and composition of these streams would be useful in evaluating lead replacement alternatives.

It is unlikely that Sasol has the flexibility to alter the mixture or quality of refined products because the raw oil stream from the Fisher-Tropsch facility is fixed, and Sasol does not appear to have any cracking capability. The octane quality of coal liquid based petrol is extremely poor. An octane number of 40 has been reported for the raw petrol. The type of upgrading at Sasol is directed at increasing supply through alkylation of light ends and by raising octane through isomerization and catalytic reforming.

Myburgh et al[17] report that Sasol FT petrol can be produced to satisfy SABS 1598 for 93 RON Inland unleaded petrol using 11% ethers providing 1.7% oxygen. Sasol markets essentially all of its petrol inland to meet the 93 RON specification. The petrol will exhibit a 93.4 RON and 83.3 MON. Assuming the ether is Tertiary Amyl Methyl Ether, TAME (assumption compatible with volume and oxygen content reported by Myburgh), which has a RON of 111 and a MON of 98, the base petrol from Sasol exhibits octane ratings of 91.2 RON and 81.5. In addition, the petrol is rich in olefins (16.2%), aromatics (34.1%), and benzene (3.2%). The petrol sulfur content is on the order of 1 ppm, a level unachievable through petroleum refining.

In the Sasol process, the olefin content of the products is about 75%. C5 hydrocarbons constitute about 7.7% of the raw C5+ gasoline that in turn is about 39% of the FT products. Incorporating the C4 streams into the finished gasoline raises the gasoline yield

[15] Meyers, RA, "Handbook of Synfuels Technology", chapter 2 , McGraw Hill, NY.
[16] Alexander's Gas and Oil Connections, "Sasol to Build High Purity Ethanol Plant", www.gasandoil.com/goc/company/cna90661.htm and "Secunda Alcohol and Acid Chemical Plant, South Africa", www.chemicals-technology.com/projects/secunda/
[17] Myburgh,I.S., Schaberg, P.W., Botha, J.J., "Sasol's Synthetic Fuels developments-Meeting the Clean Air Challenge", 3rd International Conference on Environmental Management, South Africa, August 2002.

to 50%. The mass ratio of TAME to pentenes is 102/70. If all of the olefins can be converted to TAME, it could be blended at about the 6% level. Tentatively, it is concluded that Sasol has insufficient resources to produce adequate TAME to oxygenate its entire gasoline pool.

PetroSA (Mossgas) :

PetroSA, previously called Mossgas, converts natural gas to liquid fuels and chemicals. The production of liquid fuels by FT synthesis is approximately 22,500 BBl/day[18]. The output mix is reported to be 66.6% petrol, 31.9% diesel, 1.5% paraffin and 0.5% LPG. In addition, about 2,400 barrels per day of alcohols are produced that could be used as petrol extenders or octane boosting additives. More accurate data on the quantity and quality of these as well as the current disposition would be useful in evaluating alternatives.

The PetroSA facility is reported to include octane-upgrading capability similar to that at Sasol. Since the FT conversion technology used at Mossgas is the same as that used at Sasol, it is expected that the Mossgas petrol product is similar to the Sasol product in terms of octane quality.

The Octane Production Capability

Based upon refining units and production data from SAPIA and the South African Government, an approximate lumped material-balance analysis of the refining sector was developed that provides an estimate of the current clear pool octane for South African petrol. The proprietary model was developed from processing data provided in the literature[19] along with product supply requirements and synfuel input data. The model was also used for estimating the impact of various alternative octane scenarios.

The model was not used to examine transition scenarios but rather to look at the industry in 2006 when lead is fully removed.

The analysis examines simple refining upgrades and the use of purchased additives. The analysis does not consider major refining investments that could be made. There are several reasons for this assumption.

- Refiners have indicated that they will be able to meet the 2006 requirement whether they modernize refineries or not.
- Refiners are generally averse to making large investments. In fact, the South African refiners have asked the government for financial assistance because the fuel pricing structure does not allow refiners to earn a premium for supplying unleaded gasoline.

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[18] Jerry Sinor Consultants Inc website, edj.net/sinor/

[19] Maples, R., "Petroleum refinery Process Economics", Penwall Books, Tulsa Ok, 1993 and Gary, J., Handwerk, G., "Petroleum Refining Technology and Economics, third edition", Marcel Dekker, NY, 1994.

- South Africa might impose Euro3 or Euro4 fuel standards on the industry by 2010 to 2012. Refiners will want to target investments toward those standards while delaying investment as long as possible.
- Refiners indicate that there is no need to increase gasoline supply in the near term; there is sufficient capacity to meet 2006 demand.

Estimate of Lead Use and Octane Impact:

In 1999, the inland specification for unleaded petrol was apparently 91 RON. Based upon 1999 petrol statistics from the DME, Table 7 provides an estimate of the octane quality of clear petrol supplied by refineries. To allocate supply to the two regions, it was assumed that synthetic petrol produced by Sasol was marketed inland while the petrol produced by PetroSA was marketed in the coastal area. The impact of lead on petrol octane is a function of the blendstocks employed. In Table 7, the lead susceptibility was estimated for typical petrol formulations[20]. Typical motor octane numbers were provided by SAPIA[21]. The estimated impact of lead for 97 RON/ 87 MON is 5.4/7.0 numbers respectively. For 93 RON/83MON petrol, the lead susceptibility is estimated to be 6.1/8.5 numbers.

In Table 7, All-UL refers to quantity and clear octane for either all coastal or all inland petrol (with the lead effect removed). It thus represents the blendstock that must be upgraded to meet the unleaded specification in each region. The overall pool for all of South Africa is also estimated in Table 7.

Based upon the estimated quality of the Sasol (and thus Mossgas) petrol, the octane quality of refinery-produced gasoline was estimated. The pool of petrol produced by refiners appears to exhibit a RON of 90. The pooled requirement for RON without lead is estimated to be 94.2. Thus, refiners may have to increase the research octane numbers of their petrol pool by 4.2 plus a compliance margin to meet the unleaded petrol requirement. PetroSA (Mossgas) will have to increase octane by 3.8 units to satisfy the Coastal unleaded requirement. The need for a compliance margin is related to the nature of the standard (voluntary compared to enforced) and individual refiner business practices. Because of the repeatability of the RON test, a margin of 1 unit might be necessary under an enforcement scenario. In this analysis, an arbitrary 0.2 RON margin is assumed.

Octane Properties of Blendstocks:

Table 8 presents typical properties of petrol blendstocks. From the table, it is evident that the low RON streams need to be upgraded if the refining sector has any chance of producing 100% of its unleaded petrol with a RON of 94. As an alternative, ethers and

[20] Gary, J., Handwerk, G,. "Petroleum Refining and Economics", Marcel Dekker Inc, New York 1975. Page 168 provides a blending chart for lead developed by Ethyl Corp. Note that the third edition dropped the lead blending chart.
[21] McClelland, C., SAPIA, Private Communication, 9/25/02.

ethanol offer very high RON. Other metallic additives besides lead such as MMT may also be considered to blend up octane.

Table 7
Octane Capability of the Refining Sector
Octane Boost for Upper Bound of Lead Blending for 1999

	Refinery Bbl/day	g/gal Pb	Leaded		Clear	
			RON	MON	RON	MON
97-octane	57,558	1.51	97	87	91.6	80
95-octane UL	7,013	0.05	95	85	95	85
95- All UL	64,571	0.00	95	85	92.0	80.5
93-octane	43,235	1.51	93	83	86.9	74.5
91-octane UL	5,238	0.05	93	83	91	83
93- All UL	48,473	0			87.3	75.4
Total Pool					90.0	78.3

Octane Properties of Additives:

Organometallic: MMT (Methylcyclopentadienyl manganese tricarbonyl) and Ferrocene

One approach to meeting the RON specification is to octane treat using an organometallic. Two different additives, MMT and ferrocene, have been proposed, although it appears that neither is as effective as lead in raising RON. Thus, a scenario based upon metallic additives might also require refinery upgrading. Octel, the manufacturer of ferrocene, has not reported octane-boosting data for ferrocene or recommended treatment rates.

The United States Clean Air Act requires that fuels and fuel additives cannot be marketed unless the fuel or additive manufacturer provides substantial proof that their product will not cause a vehicle to fail to meet applicable emissions standards during its useful life. Ethyl was able to satisfy the EPA criteria at 9 mg/l (1/32 g/gallon) but not at higher treatment levels. The legal limit in Canada is 18 mg/l. Ethyl Corp recommends a treatment rate of 18 mg/l outside of the United States.

The octane boosting capability of MMT depends on the RON and MON of the untreated fuel, aromatic content of the fuel and the manganese treatment level. Generally speaking, low octane fuels respond better to MMT than high-octane fuels.

Figure 2 shows the octane response for MMT blended into 92.5 RON clear petrol [22]. The octane value of MMT at 18 mg/l is estimated to be approximately 1.5 RON units and 0.8 MON units. The MMT octane boost does not appear sufficient to produce unleaded petrol from the South African clear petrol pool without some additional processing of the pool.

Table 8
Octane Properties of Refinery Streams

Stream	RON	MON
FCC, Full range	90.5	79.0
Visbreaker	62.0	59.5
Isomerate	83.0	81.1
LSR	66.4	61.6
HSR	62.3	58.7
Lt Hydrocrackate	75.5	74.0
Heavy Hydrocrackate	65.0	64.0
Full Reformate, 100RON	100	89
C3 Alkylate	90.8	87.3
C4 Alkylate	95.5	92.0
Polymer	94.0	82.0
MTBE	118	100
TAME	111	98
Ethanol	130	96

MMT does not increase petrol supply directly through its addition to petrol. Ethyl Corp has reported that use of MMT reduces the need to process crude oil; this has a slight positive impact on refining efficiency. However, in this instance, petrol octane had to be raised by increasing processing that reduces petrol supply.

Lead is known to increase the octane requirements for a vehicle due to the formation of deposits. There does not seem to be any data reported on the effect of MMT on octane requirements although MMT forms deposits. It is necessary to quantify this effect to properly gauge the value of MMT as an octane additive. However, it is important to note that the World Wide Fuel Charter recommended that petrol specifications restrict metal-based additives down to zero in any grade of petrol. This would include not only manganese, but also lead, iron, and others

[22] Based upon blending model for MMT provided by Ethyl Corp.

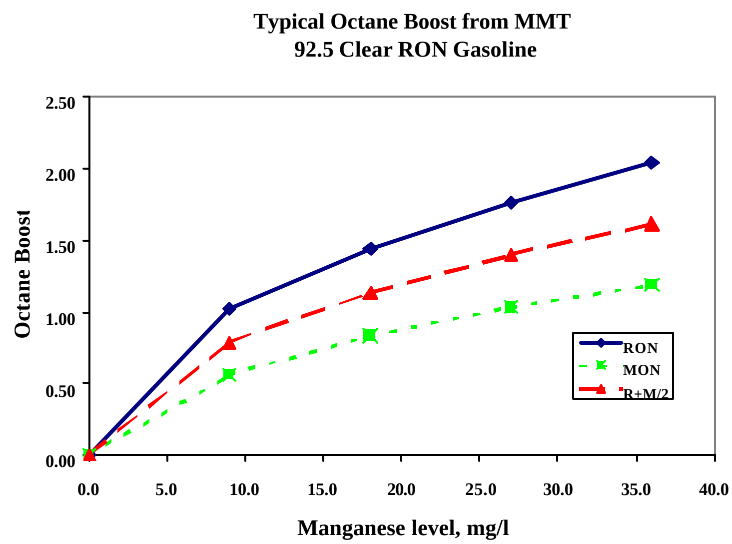

Figure 2

Oxygenates:

Properties of oxygenates that might be used in South Africa are provided in Table 9. In the U.S., oxygenates may be blended up to 2.7 weight percent oxygen in petrol except for ethanol which may be blended to about 3.5% oxygen (10% by volume denatured ethanol).

Data for alcohols ranging from methanol to n-octanol are included. As the alcohol molecular weight increases, the octane number decreases. Beyond butanol, the Research Octane Number becomes too low to be useful for petrol octane blending. Beyond propanol, except for t-butyl alcohol, the boiling point of the alcohols is such that blending them will negatively impact the petrol drivability index. Data for several ethers are also included. The ethers have relatively high Research Octane Numbers and lower boiling points than the alcohols with comparable molecular weight.

Supply of Additives:

MMT, Ferrocene, Lead:

The organometallic additives are manufactured and sold by international chemical companies. South Africa currently imports tetraethyl lead, therefore in a scenario that replaced lead with another organometallic, South Africa would simply import the replacement. The treatment rates are low and it is expected that there will be no limitation on supply.

Oxygenates:

Ethers:

MTBE is produced by the reaction of methanol with isobutylene while ETBE is made from ethanol and isobutylene. Methanol is produced from natural gas.

The two main feedstocks for production of ethers are refinery olefins and natural gas liquids. With the existing refinery infrastructure, there is little potential supply of MTBE or ETBE from FCC isobutylene. Based upon FCC capacity, it is estimated that about 2,800 barrels per day of MTBE could be produced in the refining sector, but this would come at the expense of alkylate as well as require investment.

Table 9

Properties of Oxygenates

	BRVP, psi	Oxygen, wt%	RON	MON	NBP, F
Methanol	31	50	136	104	149
Ethanol(denatured)	17	33	130	96	172
n-Propanol		27.6	118	90	208
Isopropanol	14	27.6	118	98	180
n-Butanol		21.6	96	78	243
t-Butyl Alcohol	9	21.6	105	89	160
Sec-Butyl Alcohol		21.6	101	32	211
t- Amylalcohol	7	18.2	97(1)		216
n-Hexanol		15.7	56	46	315
n-Octanol		12.3	28	27	383
MTBE	8	18.2	118	100	132
ETBE	4	15.7	118	102	162
TAME	1.5	15.7	111	98	187
DIPE	5	15.7	105(1)		155

(1) Blending R+M/2

South Africa has no large source of domestic natural gas that can serve as a feedstock resource for MTBE or ETBE production. To produce ethers in this case, butanes are recovered from natural gas and dehydrogenated to isobutylene.

It is likely that South African refiners can purchase sufficient MTBE on the world market to upgrade their petrol.

ETBE has not been widely used because it is more costly to produce than MTBE.

TAME is generally made in refineries. The volume of TAME that can be produced is generally smaller than the volume of refinery MTBE. At Sasol and PetroSA, the propylene and butenes are alkylated to petrol. There is potential to produce TAME from the C5-olefins in synthetic petrol. The capability to produce TAME needs to be quantified.

The synthetic fuel plants produce alcohols that can be blended or converted to ethers. The use of these as fuels would depend on economics and or fuel policy.

DIPE is manufactured by converting isopropanol or mixtures of isopropanol with propylene. There appears to be feedstock available within Sasol and Mossgas to produce DIPE. It is estimated that 3,000 barrels per day of propanols might be produced by the synthetic fuels facilities. If 50% is isopropanol, between 1,500 and 2,500 barrels of DIPE might be produced. The potential supply of DIPE needs to be quantified.

The price of MTBE and other ethers is generally related to the price of petrol plus freight. In the US, MTBE has generally been priced based upon its octane value. As an example, at 1-cent per octane gallon, MTBE would be priced at about 22 cents per gallon above the wholesale price of regular 87-octane petrol plus any freight charge. For $25 per barrel crude oil, the price of MTBE might be $43 per barrel. Depending on government policy, ethers produced within South Africa for petrol blending may have to compete economically with imported MTBE and organometallics.

Alcohols:

Ethanol is potentially available form a number of indigenous sources.

Based on the estimated output of alcohols from Sasol and Mossgas, about 6,200 barrels per day of ethanol are produced in synthesis. Additional ethanol is or can be produced from the ethylene by-product by hydration. This ethylene may yield as much as 8,000 bbl per day of chemical grade ethanol. Much of the chemicals are consumed in the chemical market.

Ethanol can be readily produced from starch and sugar. In South Africa, the likely choices are corn, sugar cane and cassava[23]. The potential for ethanol from corn is substantial since the annual crop is on the order of 8 million metric tons equivalent to about 315 MM bushels. In the US, new ethanol dry mills are capable of converting 1 bushel of corn to 2.8 gallons of ethanol. Along with ethanol, DDGS (distillers dried grains with solubles) is typically produced. DDGS contains most of the corn energy, protein and other nutrients since ethanol is produced only from the cornstarch. In the US, the ability to produce ethanol from corn is related to the ability to integrate ethanol production into corn-based livestock feeding. In South Africa, 80% of corn is fed to livestock. DDGS might also be integrated into the human food supply as a high energy

[23] Thomas, V., Kwong, A., "Ethanol as a Lead Replacement: Phasing Out Leaded Gasoline in Africa", Energy Policy V29, pp 1133-1143, 2001. and World Energy Council Energy Info Center, South Africa, Survey of Energy Resources 2001.(www.worldenergy.org/wec-geis/edc/countries/SouthAfrica.asp)

and protein supplement. In recent years, corn prices have been low and the planted land has declined by about 1 MM hectares. Planting this area in corn would result in the potential to produce about 18,000 barrels per day of ethanol on idled land without compromising food supply.

South Africa is capable of producing approximately 1,900 to 3,400 barrels per day of ethanol from “C” grade molasses. In addition, the potential from sugarcane may be an additional 9,000 barrels per day.

The potential to produce ethanol from other starch crops such as cassava has been estimated to be 58,600 barrels per day, but the basis for the estimate is unknown. 11,000 barrels per day may be produced from bagasse and straw but this technology is not commercially available.

The cost of production of agriculturally based fuels is greater than the cost of production of petrol, organometallic additives and natural gas based ethers. In the US, the cost of production of ethanol from corn including capital charges is less than $1.25 per gallon for denatured ethanol (containing 5% petrol as a denaturant) in current dollars. The variable cost is near 95 cents per gallon.

In Brazil[24], the actual cost of production of anhydrous alcohol in 1990 US dollars including capital charges is reported to be 86.7 cents per gallon. Recently there have been substantial reductions in cost due to a variety of factors. Even with inflation, the cost of production in Brazil is not likely to result in an ethanol cost of production that exceeds the US cost. Furthermore, Brazil exports ethanol for use as a petrol additive.

The overall economics of ethanol use is complicated by the impact of production on the rural economy since ethanol can create rural jobs and increase farm commodity prices. While it possesses a high octane rating, the energy content of ethanol is only about 2/3 that of petrol. Auto mileage is directly proportional to fuel energy. With a 10% ethanol blend, a car can travel about 0.97 km compared to 1 km on an all hydrocarbon fuel.

In the US, ethanol receives an excise tax exemption that effectively reduces the selling price by about 50 cents per gallon. There is a small producer tax credit as well as state incentives that helps new farm coop plants be competitive with the large wet mills. The price of ethanol commanded by producers is set by the price of regular petrol plus the excise tax exemption. Thus, in recent years, with wholesale petrol ranging from 50 cents to $1.00 per gallon, ethanol market prices have ranged from $1.00 to $1.50.

In Brazil, cross subsidies are used to pay ethanol producers for the excess of cost of production relative to petrol.

As with indigenous ether production, ethanol produced from coal and agricultural products might have to compete economically with imported MTBE and organometallics. However, domestic production has beneficial effects on the local economy. A cost benefit

[24] Convention on Climate Change, “The Cost of Ethanol”,

analysis of domestic supplies compared to imports is necessary to determine what subsidy level might be justified.

Lumped Refining Analysis:

The purpose of the lumped modeling analysis is to determine what scenarios may be used to meet unleaded petrol demand in the future. Lumping of refinery capacity based upon Table 5 assumes that refiners can freely exchange blendstocks. The analysis is non-optimal; that is, it satisfies the material balance but does not find the least cost option for the individual refiner. Simplified process descriptions are employed from the literature. Meeting the full specification would reduce flexibility and thus solutions that do not provide much octane upside might not be workable.

Petrol properties and relative capacity are reported in the following tables. Relative capacity is the energy in petrol for the scenario compared to the energy in base case petrol. This ratio should represent the potential relative miles traveled in each scenario.

Base Case:

The ultimate octane and petrol volume production capability was estimated using the simplified lumped model for the refining sector. The PetroSA petrol is treated as a blendstock since they have not reported a plan to produce unleaded petrol. Sasol petrol is assumed to be lead free using TAME for which Sasol claims a secure supply. The model was used to predict the clear petrol octane rating based upon the existing refining capacity. The energy in the petrol pool is used as a basis to estimate the potential impact of the scenario on the supply of petrol. The properties of the base-case petrol are shown in Table 10. While it is currently estimated from the lead standard that refiners currently produce 90 RON base petrol for lead blending, the model suggests production of clear 90.8 RON petrol.

In the scenarios to follow, only pooled data are reported. Petrol RVP is constrained to 9 psi in all cases and RON is set to 94.4 or, if less, the maximum that can be achieved. In the following scenarios, it is assumed that Sasol is blending 7,267 barrels of TAME per day or a lesser amount while addding MMT. If this resource is not available, the octane demand will increase above that estimated in the following sections.

In Refinery Scenarios:

The first set of cases examines the impact of investment within the refinery to upgrade the petrol RON. Table 10 provides the estimated impacts of refinery processing on petrol RON.

Isomerization:

The present industry appears to be capable of isomerizing only about 50% of its light naphtha petrol. Investment was assumed to increase isomerization capacity to 100%

based upon single pass isomerization technology such as the UOP Penex process. This requires the addition of about 9,700 barrels per day of capacity. The inside boundary limits investment is reported by UOP to be $8MM US ± 50% in 1998 dollars.

With full isomerization, the research octane number of the pool is increased by about 1.0 to 91.8 and there is about a 0.5% reduction in petrol supply. A portion of the decrease in supply comes from the need to reduce the quantity of butane blended to maintain 9-RVP petrol. Simple isomerization alone does not produce a sufficient RON increase. Increasing the complexity of the isomerization process by incorporating a recycle scheme to raise RON could raise the pool RON to 92.7. The investment cost has not been identified.

Catalytic Reforming and Aromatics:

In the analysis of additives, it is assumed that all catalytic reforming is operated at 100 RON. This is at or above the practical limit for semi-regenerative reformers. There appears to be no additional octane available from reforming. Additionally, the scenarios do not impact the plant hydrogen balance.

However, the usual approach by refiners to increasing RON is to blend aromatics. Therefore, a case is presented that looks at the required increase in aromatics to satisfy the 94.4 RON average. For simplicity, the aromatics are purchased. In this case, full build-out of isomerization with recycle is assumed. The aromatic content must be raised to about 40.1% from 34% when blending a BTX aromatic concentrate.

Olefins Processing:

The model analysis suggests that at a typical FCC conversion of 60%, a level necessary to meet the supply requirement for petrol and diesel, FCC olefin production at that level satisfies all polymerization and alkylation capacity. No additional capacity can be added without changing the mode of operation of the refinery. It is not known how easy it is to expand FCC capacity in the SA refining sector. In addition, adding alkylation capacity is very expensive. A 10,000 BBL/cd facility can cost between $30MM and $80MM. Without major FCC modifications, it is probably not feasible to add new alky or poly capacity.

MTBE:

It is possible to modify the refinery system to add MTBE capacity ahead of alkylation. This scenario is reported as column 5 in table 10. This requires refinery investment that will produce two impacts. First, removing isobutylene from the alkylate feed will increase the octane quality of C4 alkylate. Second, MTBE possesses a much higher RON than alkylate. Incorporating an MTBE system to produce 2,800 Bbl/d MTBE increases the RON by 0.4 units. With full simple isomerization, this yields a RON of 92.2 and supply of 98.7% relative to the base case. The capital cost of adding MTBE capacity might be $5 MM US ± 50%. However, alkylation capacity becomes underutilized.

The estimated quantity of MTBE that can be produced from FCC isobutylene is 1.7% of the refinery petrol pool. There are no other obvious indigenous sources of isobutylene available for etherification, therefore any additional MTBE must be imported.

An alternative to MTBE is to incorporate indirect alkylation of isobutylene to produce either isooctene or isooctane with higher capital cost. This approach provides lower RON than MTBE as well as less volume.

Table 10
Possible Properties of South African Clear Petrol From Crude Oil in 2005

Property	Base Case	100% Simple Isomerization	100% Isom w recycle	100% Isom w recycle + Aromatics	100% Simple Isom + MTBE
Relative Capacity	1.00	0.995	0.995	1.126	0.987
Quantity, BBL/day	165,551	165,088	165,088	185,553	164,135
RON	90.83	91.80	92.69	94.4	92.19
MON	81.8	82.9	83.6	85.2	83.0
RVP, psi	9.00	9.00	9.00	9.00	9.00
T10, F	128	130	130	129	130
T50	213	214	214	224	211
T90	321	322	322	316	321
Olefins, vol%	13.6%	13.6%	13.6%	12.2%	13.7%
Aromatics, vol%	34.0%	33.8%	33.8%	40.1%	34.0%

MMT Blending

Table 11 reports the result for blending MMT into petrol with simple isomerate plus MTBE and full isomerization with recycle. In the first case, petrol RON could be 93.9 with MMT blended at 18 mg/l while in the latter case it is 94.3 at 18 mg/l. Since MMT is energy neutral in the refinery, the available fuel energy is the same as for the refinery case without MMT. But recent tests with new vehicles suggests that the mileage will decline by about 2% after break-in due to degradation of the fuel system resulting from MMT contamination. This factor is included in the supply.

Blending MMT has no impact on petrol olefin or aromatic levels that are relatively high in South African petrol. In addition, the distillation index (DI, 1.5*T10+ 3*T50+T90) of the petrol is unchanged. In the US, automakers are asking to have DI capped at 1200F to limit hydrocarbon emissions due to improper vaporization of the fuel in the intake manifold. The impact of DI on hydrocarbon emissions is additive to the effects of MMT blending. Since the pool DI of 1157 is close to the proposed DI cap, it would appear that some petrol would certainly be produced with a DI higher than the cap with a possible emissions consequence.

Purchased Ether Blending (MTBE):

South African refiners can purchase MTBE. By blending 16,800 barrels per day of MTBE into the refinery clear petrol stream as required for equal supply compared to lead and adding full simple isomerization, a RON of 94.4 can be achieved as shown in Table 12. The overall supply is increased by 8.3% due to a combination of MTBE and butane to trim RVP to 9 psi. The MTBE concentration is 9.9% and the final oxygen content of the petrol is estimated to be 1.9%. There is additional ability to raise the pool octane with MTBE while limiting the oxygen content to no more than 2.7%.

Table 11
Petrol with MMT Blending

	Simple ISOM+ MTBE	ISOM w Recycle
MMT Level, mg/l	18	18
Relative Capacity	0.962	0.975
Quantity, BBL/day	164,135	165,088
RON	93.85	94.30
MON	83.9	84.5
RVP, psi	9.00	9.00
T10, F	130	130
T50	211	214
T90	321	322
Olefins, vol%	13.7%	13.6%
Aromatics, vol%	34.0%	33.8%

Table 12
Petrol with Purchased MTBE

Relative Capacity	1.083
Quantity, BBL/day	183,554
RON	94.40
MON	84.6
RVP, psi	9.00
T10, F	131
T50	202
T90	316
Olefins, vol%	12.3%
Aromatics, vol%	30.4%

Adding MTBE to 1.9% oxygen does not alter the demand for aromatics and therefore reduces olefins and aromatics only by dilution.

The maximum level of MTBE allowed in the US is 15% (2.7% oxygen). Increasing MTBE beyond 1.9% oxygen would allow refiners to decrease reformer severity and hence further decrease aromatics and benzene production for octane. Thus aromatics would be reduced in a percentage significantly greater than by mere dilution. Thus would further increase petrol supply by a combination of increased MTBE use and reduced loss of supply in the reformer.

Blending MTBE decreases the DI by about 40 degrees F producing a substantially better petrol pool.

Ethanol Blending:

Ethanol may be purchased or produced from indigenous resources. Due to its high research octane number, the pool necessary to replace the quantity of leaded petrol would receive about 12,050 barrels of denatured ethanol (95%), amounting to 6.9% by volume. In this case, the refineries would upgrade to full simple isomerization. The petrol properties are shown in table 13. The oxygen content of this petrol is about 2.4% by weight. The petrol was blended to have no RVP increase. Thus, butane was removed from the blendstock. The relative energy output of the refinery system is 103.4%. Thus potential petrol supply is increased by 3.4% using ethanol.

In the United States, ethanol is allowed a volatility exemption of 1-psi due to its high RVP blending number. If ethanol is used in attainment areas, the extra evaporative emissions due to the volatility increase are deemed not harmful. If the RVP is increased to 10-psi for petrol with ethanol, the supply increases to 104.6% due to increased butane blending.

Regardless of whether or not a volatility allowance is allowed, it is possible to produce varying octane grades of gasoline with ethanol once ethanol is present at about 2% by volume since the RVP of the fuel is essentially constant for ethanol levels from 2% to 10%. This means that blenders can provide several octane grades by splash blending ethanol on top of a blendstock in the terminal or service station.

With an ethanol blend level of 6.9%, the olefin content and aromatic content of the finished petrol are reduced by dilution only. Blending ethanol to a higher level than 6.9% would allow a reduction in aromatics. As with MTBE, ethanol has a favorable impact on petrol DI.

Ethanol must be blended at the terminal prior to retain distribution. The levelized cost of upgrading terminals for ethanol blending is about 0.1 cent per gallon.

Table 13
Petrol with Ethanol
9-Psi RVP

Relative Capacity	1.034
Quantity, BBL/day	175,547
RON	94.40
MON	82.8
RVP, psi	9.00
T10, F	123
T50	201
T90	319
Olefins, vol%	12.8%
Aromatics, vol%	31.8%

Environmental and Health Summary:

When evaluating additives, the full environmental effect should be considered. This includes exhaust emissions, evaporative emissions, air-toxic emissions, and environmental hazards including groundwater degradation.

Table 14 qualitatively compares the options of MMT, ethers, and ethanol. In addition, the hydrocarbon streams that may be manipulated are also considered. The analyses used to develop the ratings are discussed in the following sections.

Motor Vehicle Emissions:

Vehicle emissions can be divided into several categories:

- "Regulated" exhaust mass emissions (g/mile) from the vehicle fleet including nitrogen oxides (NO_X, a mixture of NO and NO_2), carbon monoxide (CO) and total hydrocarbons (THC)[25].
- Evaporative emissions including refueling, running loss, diurnal and hot soak emissions. Evaporative emissions are a function of the petrol Reid Vapor Pressure.
- Other mass emissions, (mg/mile) from the vehicle fleet including toxics (formaldehyde, acetaldehyde, benzene, 1,3-butadiene, and polycyclic hydrocarbons) and fine particulate les than 2.5 microns (PM 2.5).

Emissions depend on the fuel and the vehicle. Some important vehicle issues are the following:

- Cars with oxidation catalysts control hydrocarbon and carbon monoxide emissions only.

[25] Several measures of hydrocarbon emissions are reported for vehicles. In addition to THC, non-methane hydrocarbons (NMHC), volatile organic compounds (VOC), and non-methane organic gases (NMOG) are cited.

- Cars with 3-way catalysts control nitrogen oxide emissions as well as exhaust THC and CO.
- Both oxidation and 3-way catalysts reduce air toxic emissions and can also reduce white smoke.
- The exhaust emissions from properly running cars without emissions control systems or with malfunctioning systems can be ten or more times greater than cars with functioning controls.
- The exhaust THC and CO emissions from cars running fuel rich may be several orders of magnitude greater than cars with properly functioning controls.
- Evaporative emissions are highly variable and depend on the tightness of the fuel system and the existence of a gas cap.
- The NO_X emission is dependent upon the in-use fuel as well as the fuel used to calibrate the emission control system. Recent data developed by the Automakers[26] has shown that with new model cars calibrated on oxygenated California reformulated fuels, NO_X, THC and CO emissions are lower than for non-oxygenated reformulated fuel.
- Particulate from motor vehicles comes from fuel and lube oil. Smoke from oil can only be controlled through maintenance. Particulate from fuel rich vehicles is also reduced substantially through maintenance that minimizes rich operation.

Some believe that the best way to control emissions is with a good inspection and maintenance system. However, others believe that public awareness is equally important. Routine maintenance related to ignition quality (wires, sparkplugs, etc) will help maintain mileage and reduce emissions.

[26] The Alliance, AIAM, Honda, "Industry Low Sulfur Test Program", presented at ARB Workshop, 7/2001.

Table 14
Environmental Exposure Due to Increased Use of Various Octane Alternatives

	Criteria pollutants				Air Toxics			Environment		
Additive	CO	Ozone	PM	NO2	Benzene	PAH	Aldehydes	Water Pollution	Human /Animal	Total
Isomerate	-1	-1	0	0	-1	-1	0	0	0	-4
Alkylates	0	0	0	0	-1	-1	0	0	0	-2
Reformate	+1	+1	+1	-1	+2	+2	0	+1	0	7
MMT	0	+2	+1	-1	+1	+1	0	0	+2	6
Ethanol (alcohols)	-2	-2	-2	+1	-1	-2	+1	0	0	-7
MTBE (Ethers)	-2	-2	-2	0	-1	-2	+1	+2	0	-6

Score: +2 Significant increase, +1 small or moderate increase, 0 little or no effect, -1 moderate decrease, -2 significant decrease
Criteria pollutant refers to impact due to increasing additive
Air toxics refers to effect of fuel component on exposure to given toxic.
Water pollution refers to exposure due to contamination of ground water
Human animal refers to exposure due to inhalation.
Ethanol fuel is match blended so as to not elevate evaporative emissions

Fuel affects emissions as well. Clean fuels should improve emissions from all vehicles regardless of their maintenance status.

- Carbon monoxide and exhaust hydrocarbon emissions are reduced substantially using petrol blended with oxygenates.
- Hydrocarbons are emitted through evaporation. The major components of evaporative emissions are the light hydrocarbons including light olefins from FCC petrol and benzene. FCC olefins are very potent ozone formers[27].
- Hydrocarbons themselves are not criteria pollutants, but enter into the ozone forming process. The composition of the emission as well as the rate is important to ozone formation. Olefins and aromatics are the most potent ozone forming hydrocarbons.
- The exhaust hydrocarbon emission is important because the mass emission of air toxics is approximately proportional to the hydrocarbon emission rate.
- Toxic emissions also depend on the fuel composition. Specific decomposition products are formed from fuel components. For example, decomposition of ethanol in the exhaust results in formation of acetaldehyde.
- Exhaust particulate and diesel-like toxics, commonly referred to as polycyclic organic matter (POM) are preferentially controlled through the use of oxygenates.
- Fuel effects on NO_X emissions are generally minor. The exception is sulfur, which is a temporary poison for emissions control catalysts. Reducing sulfur in the fuel increases catalyst efficiency and lowers NO_X as well as other emissions.

Carbon monoxide and nitrogen dioxide (NO_2) are considered to be criteria pollutants in the United States and many other countries. Most carbon monoxide in the air comes from motor vehicle exhaust. Nitrogen oxides are emitted by petrol and diesel powered engines, as well as other combustion sources primarily as nitrogen monoxide that is converted to nitrogen dioxide readily in the atmosphere.

Other criteria pollutants are ozone, particulate matter (PM2.5 and PM10[28]). Ozone is formed completely through atmospheric reactions involving hydrocarbons and nitrogen oxides. Fine particulates in the air result from a combination of direct emissions and secondary reactions occurring in the atmosphere involving emissions of nitrogen and sulfur oxides and aromatic hydrocarbons. Essentially all of the PM present in automobile exhaust is 2.5 microns or less.

[27] Evaporative emissions are a strong function of gasoline vapor pressure. While the mass of evaporative emissions increases with RVP, the emission rate of specific hydrocarbons is a function of their individual vapor pressures. Thus, for a given fuel, increasing its RVP will increase the emission rate of the pressurizing agents, typically butanes, but not the emissions rate of the heavier hydrocarbons present in the fuel. “Evaporative Emissions” based upon fuel leaks do not show such a differentiation; their composition is more like that of the whole fuel.

[28] The number refers to the maximum size of particulate. PM10, for example, refers to particulate less than 10 microns.. These are considered as different pollutants since larger particles are collected in the upper respiratory system while smaller particles penetrate deep into the lungs. The physiological effects are different.

Lead is emitted directly as ultrafine particulate. The typical emission rate is on the order of 100 mg/mile.

While controlling direct emissions is crucial to improving air quality, there is not a direct proportional link between emissions and air quality because the chemistry is complex and non-linear. Generally, the impact of emissions changes on air quality is assessed through atmospheric modeling.

Air Toxics:

Exposure to low levels of vehicular air toxics is considered to be an important public health issue. The most potent cancer promoters are benzene, 1,3-butadiene and polycyclic aromatic hydrocarbons (PAH) such as normally found in diesel smoke. 1,3-butadiene has a short half lifetime in the atmosphere while the aromatics are much more persistent. The aldehydes are not very potent cancer initiators but contribute to lung eye and respiratory problems. Table 15 shows two sets of data that have been reported that rank the potency or relative cancer risk of automobile air toxics. The table suggests that the risk of developing cancer from benzene, for example, is 10 to 14 times as great as the risk from acetaldehyde for the same exposure. The rate of production of toxic emissions is related to fuel quality. Determining the link between emissions and exposure is difficult.

- The olefin concentration in fuels is responsible for 1,3 butadiene emissions. The main sources of olefins in South African petrol are FCC and polymer petrol blendstocks.
- The aromatic content of fuels drives the exhaust emissions of POM. Aromatics are present in FCC and reformate blendstocks.
- Benzene emissions depend on both the benzene content and the total aromatic content. Benzene is emitted through evaporative emissions as a result of benzene in the fuel. Benzene is emitted from the exhaust because of the presence of benzene in the fuel as well as through dealkylation of fuel aromatics.
- Oxygenated fuels have been identified as precursors to direct aldehyde emissions. MTBE promotes formaldehyde emissions and ethanol promotes acetaldehyde emissions. Fuels without oxygenates also producer formaldehyde and acetaldehyde but to a lesser degree. Importantly, the majority of aldehydes found in the atmosphere are not a result of direct emissions; instead, they are produced in secondary reactions that form ozone[29].

Secondary Reactions:

The emissions related to fuels and additives contribute to air quality in the following manner:

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[29] Office of Environmental Health Hazard Assessment, "Potential Health risks of Ethanol in Gasoline", California EPA, December 1999.

- Reactions in the atmosphere to form ozone, irritants and fine particulate.
- Emissions of metallic additives and their derivatives.

Table 15
Relative Cancer Risk Parameters

Chemical	California	NESCAUM	Assumed for analysis
Acetaldehyde	0.10	0.07	0.10
Benzene	1.0	1.0	1.0
1,3 Butadiene	34.0	3.58	3.58
Formaldehyde	0.21	0.004	0.21
MTBE	0.018	Not reported	0.018
POM	Not reported	7.1	7.1

In many situations, the controlling variable for atmospheric ozone is the ambient concentration of hydrocarbons (high VOC/NO_X ratio)[30]. In this case, reducing hydrocarbon emissions reduces ozone, while changing NO_X emission levels has little effect on air quality. Hydrocarbons perform differently depending on their chemical structure. These are characterized using "reactivity", defined as grams of ozone produced per gram of hydrocarbon. The most potent ozone formers are olefins followed closely by aromatics. The reactivity of many olefins (FCC petrol and polymer petrol) and aromatics (FCC petrol and reformate) is in the range of 1.5 to 7.7 while the reactivity of paraffins (alkylate and isomerate) and oxygenates (MTBE and ethanol) range from 0.4 to 1.2.

Carbon monoxide is recognized as a weak ozone former. Since CO is present in very large amounts in the exhaust, its presence can have a significant impact on the concentration of ground level ozone.

There is not necessarily a simple relationship between air toxic emissions and atmospheric concentrations of toxics. Benzene and dienes like 1,3 butadiene are not manufactured during ozone formation and come primarily from automobiles; thus their concentration in ambient air is related to vehicle emissions rates, atmospheric mixing and transport and their atmospheric decay rates. Aldehyde exhaust toxics represent only a small portion of the ground level aldehyde inventory because a substantial portion of the inventory is produced by ozone forming reactions from hydrocarbons. POM levels are likely to increase due to secondary polymerization reactions involving aromatics.

[30] Bergin, M., Russell, A.G., Carter, W.P.L., Croes, B.E., Seinfeld, J.H., "Ozone Control and VOC Activity", Encyclopedia of Environmental Analysis and Remediation, V5, Meyers ed, J Wiley and Sons, NY, 1998.

Fuel Effects:

Isomerate:

Isomerate is composed of paraffins that are considered to be relatively benign. Because of its favorable effect on petrol distillation properties, isomerate will lower exhaust CO and HC emissions. Because of their low ozone reactivity, overall they will tend to form less ozone. Using isomerate for octane dilutes aromatics in the fuel reducing benzene and POM emissions. Isomerate is biodegradable and has no tendency to accumulate in the environment. Blending isomerate compared to natural or straight run petrol can raise the vapor pressure of the final petrol by a few tenths of a PSI.

Alkylate:

Alkylate is composed of paraffins that are considered to be relatively benign. Because of its higher boiling range, alkylate does not impart favorable characteristics to the petrol distillation characteristics. Alkylates have low blending vapor pressures and help control petrol RVP. There is an ozone benefit due to the low reactivity of paraffins. Using alkylate for octane dilutes aromatics in the fuel reducing benzene and POM emissions. Alkylates do not have a tendency to accumulate in the environment.

Reformate:

Reformate produces greater emissions of CO and hydrocarbons. When taking in combination with the high ozone reactivity of aromatics, the impact on CO and ozone is significant. Use of aromatics may reduce NO_X emissions and thus lower NO_2 concentrations in the ambient. Aromatics are readily converted to POM and $PM_{2.5}$ in the exhaust and by chemical reactions that occur in the ambient.

Benzene in the fuel is emitted through evaporative emissions. The mass of benzene emitted depends on the benzene content of the fuel and not the fuel Reid vapor pressure (RVP). Reid vapor pressure is the major variable affecting evaporative emissions.

Benzene exhaust emissions are dependent on the benzene in the fuel and the conversion of other aromatics to benzene in the combustion process. Exhaust POM is increased in proportion to the aromatic content of the fuel.

BTX, the class of compounds benzene, toluene and xylenes produced by catalytic reforming, is among the slowest hydrocarbons to biodegrade and can persist in groundwater close to the spill site.

FCC Petrol:

Full range FCC petrol is highly olefinic and aromatic. The olefins are present in the lower boiling fraction of the petrol. Aromatics tend to be present in the higher boiling fractions.

In the South African refineries, propylene and butenes in the FCC product are polymerized and alkylated. However, pentenes and heavier olefins are left in the petrol. These are potent ozone formers.

Synthetic Petrol:

Petrol produced by coal and natural gas conversion is extremely olefinic. The light olefins are processed to alkylates but the C5+ fraction is not treated. Meyers[31] reports that the petrol fraction form coal gasification contains 75% olefins, 10% paraffins, 8% oxygenates and 7% aromatics. A substantial fraction of the olefins are converted to aromatics in the catalytic reforming used to upgrade the synthetic fuels naphthas. The olefin content of Sasol petrol is reported to be 16.2% (see Myburgh et al reference 17).

MMT:

Automobile and Light Truck Fuel Mileage, Maintenance and Emissions:

The understanding of the impact of MMT on vehicle emissions is evolving. In its initial petition of EPA, Ethyl requested that 18 mg/l of MMT be allowed in U.S. fuels. However, the body of emissions data available suggested that MMT negatively impacted emissions at that treatment level. Ethyl subsequently provided fairly extensive data to EPA demonstrating that hydrocarbon emissions were not increased in pre-1990 model vehicles when MMT was blended at 9 mg/l or 1/32 g/gal. They also suggested that MMT reduced NO_X emissions substantially. The automakers expressed concern at that time and provided some data that suggested that MMT might contaminate emissions control systems causing an increase in hydrocarbon emissions in catalyst vehicles as vehicles age. In 1993, EPA determined that, based upon available data, MMT at 9 mg/l (1/32 g/gal) would not cause or contribute to regulated emissions failures of vehicles. However, because of the nature of the emissions dataset, only detection of fairly large emission increases was possible. Sierra Research[32] has summarized a part of the literature related to the impact of MMT on vehicle emissions controls, emissions performance and health effects.

More recently, the Auto Alliance (a joint study by The Alliance of Automobile Manufacturers, The Association of International Automobile Manufacturers, The Canadian Vehicle Manufacturers Association) has reported[33] the results of two extensive fleet tests on newer Tier 2 low emitting vehicles operating with clear fuel and fuel with 9 mg/l of MMT. Testing allowed a paired analysis that increased the statistical power. In phase 1, 20 matched pairs (40 vehicles) of 1996 vehicles representing 5 manufacturers were emission tested at various intervals while accumulating 50,000 miles. In phase 2, an additional 16 vehicles encompassing 4 models from four manufacturers were divided into

[31] Meyers, R., "Handbook of Synfuels Technology", Mcgraw Hill, New York., chapter 2.
[32] Sierra Research, Inc, "Impact Associated with the Use of MMT as an Octane Enhancing Additive in Enleaded Gasolines-A Critical review", Report SR-02-07-01, July 2002.
[33] Alliance of Automobile Manufacturers, "The Impact of MMT on Emissions and Durability, Part 1, and Part 2", 2002. See also, SAE 2002-01-2894.

matched pairs and tested at intervals up to 100,000 miles accumulation. No emissions data have been reported for newer vehicles operating at higher MMT levels. However, the body of data suggests that emissions would have been impacted sooner at 18 mg/l treatment rate. There is no way to estimate the potential elevation in emissions at higher treatment rates.

Generally, Alliance studies show that the addition of MMT has at most a small impact on fuel mileage. Fuel economy data are reported for city fuel economy measured via the emissions test at various mileage accumulations and on-road fuel economy measured by direct fuel consumption measurements taken during mileage accumulation. For all mileages (up to 50,000 for Part 1 and 100,000 miles for Part 2), the city and on-road mileage was lower for MMT fueled vehicles. For the part 1 fleet, the loss in mileage was about 1%. For a combined part 1 and 2 fleet, the average reduction in fuel economy for the city test was 2%. Using on-road testing, MMT fuel economy was 2.3% lower. This factor might be added into the efficiency for the MMT case resulting in an effective petrol supply of 97.2% with MMT compared to clear base petrol. If deposits are responsible for reduced fuel economy, higher levels of MMT could reduce fuel economy to a greater extent.

No studies on the impact of MMT use on maintenance cost were identified. However, with lead, the life expectancy of spark plugs was typically 10,000 miles while it is 100,000 miles with unleaded gasoline. Since MMT is known to form deposits and the Alliance study reports problems with misfire, it is possible that plug replacement could be more frequent with MMT use.

The body of data is fairly conclusive that MMT raises exhaust hydrocarbon emissions. Ethyl's data on older cars at 1/32 g/gal suggests that the increase in hydrocarbon emissions is small and not statistically significant. The Alliance data suggest that at low mileage, MMT has no effect on hydrocarbons but the emissions increased progressively relative to clear fuel after 15,000 to 25,000 miles. In Part 1 of the Alliance study, it was found that fleet averaged hydrocarbon emissions increased by 21% at the 95% confidence level at 50,000 miles. In the Part 2 report, at 75,000 and 100,000 miles, hydrocarbon emissions on MMT fueled vehicles increased 24% and 37% respectively at the 95% confidence level.

MMT probably affects carbon monoxide emissions. In Part 1 of the Alliance fleet study, average emissions of CO from MMT fuel were numerically greater from 4,000 to 50,000 miles. Only the 6.2% increase at 50,000 miles was statistically significant at the 95% confidence level. In the Part 2 fleet, numerical fleet averages for CO emissions using MMT fuels were not always higher as mileage increased. However, at 75,000 and 100,000 miles MMT increased CO by 9.2% and 30.6% respectively at the 95% confidence level.

There is a general body of data that suggests that use of MMT does not increase nitrogen oxide emissions, and may actually reduce NO_X. On some older vehicles, Ethyl has reported that a 20% NO_X reduction occurs. EPA has concluded that the reduction is probably less than 10% for the older fleet.

In Part 1 of the Alliance study, NO_X emissions with MMT were numerically lower between 4,000 and 50,000 miles. The spread increased with miles and at 50,000 miles, the difference was –21.6% at the 95% confidence level. For the Part 2 fleet, MMT emissions were numerically lower from 4,000 to 75,000 miles, but higher at 100,000 miles. The spread in NO_X emissions increased through 35,000 miles where they were 15.1% lower with MMT at the 95% confidence level. However, at 50,000 miles, the difference narrowed. At 100,000 miles, NO_X increased 35.8% at the 95% confidence level.

The Alliance Phase 1 and Phase 2 data suggested a small loss of fuel economy when using MMT. This is generally consistent with lower NO_X emissions observed. The Phase 1 study suggested that engine deposits were the primary cause of increased emissions up to 50,000 miles. In the Phase 2 study, all emissions with MMT exceeded those for the fleet operating on clear fuel at 100,000 miles suggesting that at the highest mileage accumulation investigated, MMT was impacting the emissions control system as well as causing engine deposits.

MMT slightly increases particulate emissions due to the exhausting of fine manganese oxides. Since the treatment rate is low, the particulate emissions effect is minor. Compared to the lead case, particulate reduction will occur because the lead treatment level is much higher than the manganese treatment level.

Air born manganese from MMT will accumulate in humans and animals. The long-term impacts of such accumulation are not known.

There is little data available on the impact of MMT on exhaust toxic emissions. It is expected that for cars with catalyst systems, exhaust toxic emissions would vary in proportion to the change in exhaust hydrocarbons[34]. There would probably be no change in the potency of the toxics.

Oxygenates:

In general, oxygenates impact emissions several ways. First, it has been shown that the addition of fuel oxygen reduces exhaust emissions of hydrocarbons and carbon monoxide in old as well as new motor vehicles. Second, using oxygenates can result in the reformulation of the hydrocarbon portion of the fuel. Typically, aromatics may be reduced when oxygenate is added so as to not "give away" octane. Reducing aromatics

[34] EPA Complex Model, for example, shows that for 1990 technology vehicles, the main controlling variable for exhaust toxic emissions is the hydrocarbon emission. In addition, certain fuel specific properties also impact toxics. Newer vehicles have more efficient control systems that employ the same type of catalytic converters as used for the complex model development. Technically, there is no reason that the functional behavior exhibited by 1990 vehicles would be different than that observed in new vehicles.

has a beneficial effect on hydrocarbon and carbon monoxide emissions and also reduces the emission of benzene. Third, the addition of oxygenates has a beneficial effect on the petrol distillation properties and reduces olefins, sulfur and aromatics at least by dilution.

Their general performance of oxygenates in fuel is related to the oxygen content they impart, and their impact on vapor pressure and distillation characteristics of the finished petrol.

- Fuel oxygen reduces hydrocarbon, CO, particulate and POM emissions. The emissions reduction is generally in proportion to the oxygen content.
- The final vapor pressure of the petrol depends on the quantity of oxygenate added and its blending RVP.
- The addition of oxygenates altars the 50% and 90% boiling points of the petrol blendstock. Most oxygenates exhibit boiling points below the 50% boiling point of petrol. Thus oxygenates increase the overall petrol volatility and generally improve the drivability characteristic of the fuel. Fuels with low volatility have been shown to produce more hydrocarbon emission than higher volatility fuels[35].

Evaporative Emissions:

There are several types of evaporative emissions. These are the following: resting or diurnal, refueling, hot soak and running. In general, evaporative emissions are thermally driven and correlated against fuel Reid vapor pressure[36].

The use of ethers does not negatively impact vehicle evaporative emissions compared to all-hydrocarbon fuels. When ethers and petrol are mixed, the final vapor pressure is nearly the composition weighted average of the vapor pressures of the two unmixed blending components[37]. Thus, an 11% mixture of MTBE with a vapor pressure of 8-psi in a clear petrol having a 10-psi RVP will yield a 9.8-psi finished petrol.

The use of alcohols generally elevates the petrol RVP compared to the all hydrocarbon-fuel and thus can increase evaporative hydrocarbon emissions. While the Reid Vapor Pressure of pure ethanol is 2 psi, ethanol exhibits a 17-psi blending vapor pressure (BRVP) when added to petrol at 10 volume percent. If 10% ethanol is added to a 10-psi RVP clear petrol, the finished vapor pressure will be about 10.7 psi. The importance of the effect declines as the alcohol molecular weight increases.

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[35] Often the drivability index of the fuel is used as a measure of fuel quality. It is defined as (1.5*T10+3T50+T90). T10, T50 and T90 are the temperatures along the distillation curve that occur at 10%, 50% and 90% of the gasoline distilled over by the ASTM D-86 test. At about a DI of 1200F and less, hydrocarbon emissions are independent of gasoline volatility. Above 1200F DI, emissions increase.

[36] The Reid vapor pressure is a measure of gasoline volatility. In the US, it is used as a fuel standard for drivability and summer emissions control.

[37] A blending property is used to compute the final mixture property by weighting according to the volume fraction in the fuel. RVP =BRVP* vol frac + BRVP(oxygenate)*vol frac(oxygenate)

Estimating Fuel Effects on Emissions:

Two modeling tools for predicting the effects of fuels on US automobiles are available. These are the US EPA complex model and the California Predictive Model. Each respective model estimates evaporative hydrocarbon emissions and exhaust emissions of NO_X, hydrocarbons, and individual air toxics based upon fuel properties. The Predictive Model estimates carbon monoxide emissions as well. The EPA model relates the emissions from 1990 technology cars to fuel properties. The California Predictive Beta 3 model divides cars into three technology groups. These are pre-1986 (Tech 3), 1986 to 1995 (Tech 4), and 1996 to 2005 (Tech 5). Since the models are built to simulate the various segments of the US fleet, they might be used effectively to suggest trends that might be expected in the South African case.

In newer vehicles, the effect of oxygenates depends on the integrity of the emissions control system. In emissions analysis, the fleet is often parsed by emission levels into "normal emitters" and "high emitters". High emitters are considered to have defective emissions control systems. In the United States, although only about 10% of the vehicles are classified as high emitters, they contribute approximately 50% of the exhaust hydrocarbon and carbon monoxide emissions. The EPA complex model and the California Predictive Model both account for the emitter distribution in the US fleet.

In the following sections, the emissions trends for oxygenated fuels are examined using the emissions models in order to demonstrate the impact oxygenate blending might have on vehicle emissions. In this analysis, oxygenates are added to a typical base petrol [38] that might be manufactured in South Africa.

MTBE and Ethers:

A variety of ethers have been used as octane blending agents. The most common ones are MTBE and TAME. The ethers are highly desirable blending components in petrol because of their high octane and oxygen content, and their favorable impact on volatility. Importantly, petrol with ethers can be blended in the refinery and moved through common carrier pipeline. The ether containing petrol is fungible with other ether containing and all hydrocarbon fuels. Fungability implies that all mixtures of these petrol s meet the petrol specification and will provide equal performance. Ether-containing fuels are resistant to phase separation in the presence of water.

MTBE is expected to be the likely ether-blending component in South African petrol. When added at 11%, MTBE incorporates 2.1% oxygen into the fuel[39]. Table 16 compares estimated emissions for an MTBE fuel prepared from the clear fuel and the clear fuel based upon the complex model. The Phase 1 area B summer model was used for the calculations; the weighting factor for the total hydrocarbon emissions is 69% derived

[38] The non-oxygenated base fuel was assumed to be 9 psi RVP, 34% aromatics, 1.5% benzene, 13.6% olefins, 200 ppm sulfur, 213F T-50, equivalent to 45% E-200 and 321F T-90 equivalent to 82% E-300.
[39] When 11% MTBE is added, the oxygen content is 2.1%. The RVP is 9 psi. There are 30.5% aromatics, 1.34% benzene, 12.3% olefins, 178 ppm sulfur, 205 T-90 49.4% E-200, 315 T-90, 84.3% E-300

from evaporative and 31% from exhaust. Adding MTBE modestly reduces NO_X and total HC emissions. There is a very significant reduction of mass toxic and potency weighted toxic emissions.

Ethanol:

Ethanol is a highly desirable blending component for research octane. However, under some circumstances, ethanol-containing fuels are not fungible with other fuels. The same is true for other alcohols used as blending agents. The reasons are discussed later and are associated with the "commingling issue". Generally, ethanol blends cannot be transported by pipeline because fugitive water present in the pipeline system can result in petrol phase separation. Thus, ethanol is typically "splash blended" on top of a clear petrol stock at the terminal prior to distribution to the service station. In many instances, the properties of the blendstock are tailored at the refinery to accept ethanol. For example, a sub-RVP blendstock might be prepared so that the vapor pressure of the ethanol blend doesn't exceed some standard. The blendstocks for a specific ethanol content are generally fungible.

With the ethanol match blended fuel (9-psi), the complex model (Table 16) suggests there is about a 2% reduction in hydrocarbon emission due to the addition of 10% ethanol to petrol blendstock for the 1990 technology US fleet. To control the vapor pressure to 9-psi, approximately 1.4% butanes need to be avoided in the base petrol. NO_X emissions are predicted to decline by about 1.5%. If the vapor pressure elevation is permitted, the evaporative emissions increase from 9.8 psi fuel will result in a total HC emission increase of 21.6% relative to the 9-psi base stock.

Effect of Fleet Age:

The impact of ethanol and MTBE on motor vehicle exhaust emissions depends at least on the vehicle age, and emissions system condition. For the oldest vehicles in the California Fleet, addition of 10% ethanol to a base petrol [40] is predicted to reduce exhaust hydrocarbon emissions by about 7.5% and NO_X emissions by about 1.4% relative to the base fuel. The carbon monoxide reduction is estimated to be 8.9% due to the addition of 10% ethanol. Since the CO reduction depends on the oxygen content of the fuel, the CO reduction with MTBE is less.

[40] When 10% ethanol is blended, the oxygen content is 3.5%, and there are 31.3% aromatics, 1.35% benzene, 12.7% olefins, 180 ppm sulfur, 197 T-50, 51.2% E-200, 317 T-90 and 84% E-300. If the ethanol is splash blended, the RVP is 9.8 psi. In order to produce 9-psi gasoline, about 1.4% butane must not be blended into the base gasoline.

Table 16
Emissions and Emissions Reductions Estimated from the Complex Model, mg/mile, %
Phase 1, Class B Model

	Clear Petrol	11% MTBE	10% Ethanol (match blended at 9 psi)
HC Total	-	-1.7%	-1.9%
HC Exhaust	0.4296	0.4057	0.4027
HC Evap	0.9581	0.9581	0.9581
NOX	0.651	0.640 (-1.7%)	0.644(-1.1%)
Toxic			
MTBE, % Exhaust HC	0%	3.5%	0%
MTBE	0	14.28	0
Benzene, Exhaust	24.89	20.25	19.38
Benzene, Evaporative	10.55	8.43	9.49
Acetaldehyde	2.13	1.97	4.99
Formaldehyde	4.53	5.07	4.58
1,3,Butadiene	4.86	4.17	4.01
POM	1.44	1.36	1.35
Total (w/o MTBE)	48.40	41.26(-14.8%)	43.81(-9.5%)
Total Potency (w MTBE)	63.25	53.70(-15.1%)	53.46(-15.5%)

With the California Predictive Model adjusted to model the 2005 fleet, a fleet-wide exhaust hydrocarbon emission reduction of about 7% is expected with 10% ethanol. The carbon monoxide reduction is estimated to be 8.9% due to the addition of 10% ethanol. The NO_X emission is predicted to increase by about 1%.

Newly released data from an extensive study conducted by the Automobile Industry[41] but not factored into the California Predictive model show that the emissions performance of the most advanced U.S. cars operating on oxygenated fuels may be better than that estimated by the Predictive Model. For an 11% MTBE fuel and a 11% ethanol fuel, the NO_X emissions was found to decrease compared to an all hydrocarbon fuel. The NO_X emission was lowest for the MTBE fuel most likely because the car control systems were calibrated with 2% oxygen. Importantly, both CO and hydrocarbons declined in proportion to the oxygen level in the fuels. For 10% ethanol, the estimated reductions in exhaust hydrocarbon and CO were 10% and 30% respectively.

Off Road Engines:

“Off road” engines include 2-cycle and 4-cycle engines associated with construction, agriculture, and marine uses. They also are characteristic of uncontrolled motor scooters and bikes. The use of oxygenated fuels provides substantial reduction in carbon monoxide and hydrocarbons for these engines. While NO_X increases, the relative amount

[41] The Alliance, AIAM, Honda, “Industry Low Sulfur Test Program”, presented at ARB Workshop, 7/2001.

of NO_X compared to HC and CO is small for this type of equipment resulting in minor NO_X gains for large CO and HC reductions.

Aldehyde Emissions:

Aldehydes are strong eye and throat irritants. MTBE and Ethanol tend to increase direct acetaldehyde emissions by a large percentage, but most aldehydes are produced by secondary reactions in the atmosphere from all fuel components.

Commingling and Permeation:

When ethanol is blended into petrol, there is an increase in petrol Reid Vapor Pressure. Typically, ethanol exhibits a blending RVP of about 17 psi at 10% blend level. For typical petrol s, this translates to about a 1 pound per square inch increase in vapor pressure. Importantly, the same 1-psi RVP increase is observed over a range of ethanol concentrations from about 2% ethanol to more than 10% ethanol because the observed blending vapor pressure is inversely proportional to concentration. Based upon this observation, the approximate formula for a range of concentrations of ethanol is as follows:

$$RVP = \text{vfraction (Petrol)} * RVP \text{ (Petrol)} + 1.7$$

"Commingling" is the act of mixing ethanol blends with non-ethanol blends. With the above equation it can be shown that mixing an ethanol blend with a non-ethanol blend that may contain an ether or no oxygenate will result in an overall increase in vapor pressure of the mixture compared to the linear volumetric combination of the vapor pressure of the individual blends. (MTBE fuels blend linearly with other ether containing and all-hydrocarbon fuels). Segregation of ethanol fuels and non-ethanol fuels in the distribution system is important to controlling petrol RVP.

Another issue related to ethanol blends is permeation. In older cars, especially those equipped with less sophisticated hoses and seals and plastic fuel tanks, it has been found that petrol permeates through the fuel system components increasing the overall hydrocarbon emissions from the vehicles. When ethanol is present, the permeation rate increases. The effect has not been quantified. It is relatively insignificant for new U.S. cars.

Particulate Matter:

Ethanol and MTBE substantially reduce fuel-based particulate emissions from vehicles. Several studies suggest that 10% ethanol may reduce the emissions of fuel derived diesel-like particulate and polycyclic aromatic hydrocarbons (PAH) from automobiles by 30% or more. Even though the particulate emission from individual petrol fueled cars is much less than from diesel trucks and buses, the total auto emission can represent a significant portion of the mobile source inventory since cars represent more than 90% of the vehicles on the road.

Status of MMT in the United States:

Ethyl Corp, the supplier of MMT, applied for a waiver to use MMT in the United States in the early 1990's. The analysis of a waiver application concentrates on four major areas of concern--exhaust emissions, evaporative emissions, materials' compatibility, and driveability. The Administrator of EPA denied the waiver request even though the Agency found that Ethyl had met its burden to demonstrate that the use of MMT at 1/32 g/gal would not cause or contribute to a failure to meet emission standards; the action was a result of unresolved concerns regarding the potential impact of manganese emissions resulting from MMT use on public health. However, the US Federal Court ordered EPA to grant the waiver because EPA lacked the legal authority to deny it based on public health considerations.

In the U.S., MMT can be blended into conventional petrol but not reformulated petrol . Congress banned the use of metal additives in the latter fuel. While blending of MMT is legal in the U.S., it is not present in the petrol supply except along the Canadian border, and then in only a small part of the petrol. MMT is legal and used in Canada and some petrol is imported to border locations.

U.S. and Canadian automobile manufacturers are opposed to the use of MMT and don't recommend its use. The automobile manufacturers have consistently argued that MMT harms emissions control systems, especially on new low and ultra-low emitting cars.

MMT is not exempt from the requirements of Tier 2 health effects testing required of all fuel additives under the Clean Air Act. As with other fuels and fuel additives, health effects testing is being conducted on MMT in accordance with the registration requirements for fuels and fuel additives.

Health Effects of MMT:

Acute Effects:

The overall program is directed at facilitating the introduction of clean cars into South Africa. To the extent that MMT permits the change, the overall effect of its use would be to lower ozone and irritants compared to the base case with lead.

Chronic effects:

Compared to leaded petrol the exhaust emissions of toxics and fine particulate will be reduced with MMT. To the extent that MMT permits the change, the overall effect of its use would be to lower the exposure to air toxics like benzene and fine particulate compared to the base case with lead because of the emissions reductions associated with catalytic converters.

Removal of lead is important to public health. There is concern that replacing one metal additive with another could cause unanticipated health problems in the future.

There is concern that sufficiently high doses or long term low doses of inhaled manganese can cause Parkinsons-like symptoms in humans. Manganese can be ingested safely. However, when inhaled, it can successfully pass to the brain with relatively high efficiency. The precise mechanisms of manganese neurotoxicity are not well understood, but it appears that manganese can affect several different aspects of central nervous system function and structure. There is a wide range of opinions based upon the health effects literature regarding the NOAEL (no-observed-adverse effect level) and the LOAEL (lowest-observed-adverse effect level) for manganese. Additionally, based upon the poor understanding of manganese neurotoxic effects, estimating the exposure of the population to "reactive" manganese is not possible. While MMT has been used in Canada for more than 20 years, no definitive studies have been carried out to evaluate whether low-level chronic effects of manganese exist in the general population.

Ferrocene:

Ferrocene is another metallic additive that could be used to boost octane. It is a coordination compound of iron and two molecules of cyclopentadiene. Octel, the manufacturer of ferrocene additives, had not provided information on the octane boosting properties. The main utility of ferrocene seems to be as a diesel additive for improving combustion and suppressing smoke.

Data on emissions from a substantial fleet of light duty vehicles have not been identified. The Automobile Manufacturers are opposed to ferrocene for the same reasons they oppose MMT. Without octane blending data, it is not possible to estimate the level of ferrocene required to produce the requisite RON petrol.

Health Impacts of Ferrocene:

The combustion products from fuels with ferrocene appear to be similar to those of clear fuel.

The majority of the work on ferrocene has been carried out at the Fraunhofer Institute to characterize exhaust with and without ferrocene in fuel and to evaluate toxicity[42].

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[42] The Health Effects Institute," Summary Of A Workshop On Metal-Based Fuel Additives And New Engine Technologies"1998. More information about toxicity studies of ferrocene can be found in the following references: (1) "Investigation of Otto Engine Exhaust Resulting from the Combustion of Fuel with Added Ferrocene," a report from the Fraunhofer Institut für Toxikologie and Aerosolforschung (July 1996); (2) "Thirteen-Week, Repeated Inhalation Exposure of F344/N Rats and $B6C3F_1$ Mice," Nikula, KJ et al., in Fund. Appl. Toxicol. 21, 127-139 (1993).

Data have been reported comparing a commercial fuel containing 30-ppm ferrocene with a fuel not containing ferrocene. This work involved chemical and physical characterization of exhaust, studies of exhaust fractions, mutagenicity and cytotoxicity assays, and animal inhalation studies of chronic toxicity and carcinogenicity. A VW Golf/Passat 1.8 l petrol engine with automatic transmission and catalytic converter produced the exhaust. The driving cycle employed both urban and freeway driving and had an average speed of 40 mph and a maximum speed of 80 mph.

Emissions testing quantified particle mass, size distribution and concentration, eight hydrocarbons, 16 polycyclic aromatic hydrocarbons, five aldehydes, the sum of phenols, ammonia, iron and platinum; and oxides of nitrogen and carbon. The exhaust did not appear to be changed by the addition of ferrocene, although durability seems to not have been addressed.

Exhaust condensate, particles, toluene-soluble extracts from the particles, and the gaseous phase of the exhaust were studied for mutagenicity and cytotoxicity. Under the testing conditions used, ferrocene did not affect the cytotoxicity or mutagenicity of exhaust. Animal testing involved exposure of rats to exhaust concentrations and a clean air control. Exhaust was diluted in order to avoid carbon monoxide poisoning. Animals were exposed for 18 hours/day, 5 days/week for 12 months (for chronic toxicity), or for 24 months + 6 months recovery (for carcinogenicity). Animals exposed to exhaust from ferrocene-containing fuel did not respond differently than those exposed to fuels not containing ferrocene. No toxic effects were observed after 24-30 months.

MTBE Toxicity and Water Pollution

There is a considerable body of data related to emissions and health effects of MTBE. In the United States, MTBE will probably be eliminated from the petrol pool within the next few years because of concerns related to water pollution. Refining companies are currently removing MTBE voluntarily.

Toxicity:

Data on the tendency for MTBE to cause cancer are highly controversial. At worst, MTBE presents a low risk. It is not toxic to humans or wildlife in concentrations generally found in the environment from fuel use except possibly in some groundwater situations. Because the odor and taste threshold of MTBE are much lower than any concentration that presents a risk to the public, the risk of excessive exposure by ingestion is low.

Water Pollution:

MTBE along with other ethers including ETBE (ethyl t-butyl ether), TAME (tertiary amyl methyl ether), DIPE (diisopropylether) and the alcohol TBOH (tertiary butyl alcohol) are extremely resistant to biodegradation. The ethers are soluble in water and if spilled, move rapidly to the aquifer where they accumulate. The taste and odor threshold of the ethers is very low. MTBE has been reported to be detected by humans at levels below 2 ppb. At these low concentrations, it gives the water a kerosene-like taste. A relatively small spill of MTBE can leave groundwater not potable. In the US, even with the required replacement of older service station underground storage tanks with new double walled tanks and leak detection systems, containment of MTBE has been a problem. Other significant sources of MTBE water contamination are pipeline leaks, and fuel spills.

Ethanol Toxicity and Water Pollution

Toxicity:

Ethanol is not considered to be a human carcinogen. There are no health effects data that support either chronic or acute health issues due to long term exposure to the low levels of ethanol expected to be present in the environment due to the use of ethanol in petrol.

Water Pollution:

A case has been made that ethanol can lead to ground water contamination. Two recent analyses[43] have been reported using ground water modeling techniques. Unlike ethers, ethanol biodegrades rapidly. There are no test data available to confirm the modeling results in either analysis. It has been proposed that microbes will preferentially attack ethanol in the groundwater plume resulting from a leak or spill. The plume length is defined by the rate of degradation of the chemicals. If the chemicals are all biodegradable, the plume attains a stable length if there is a continuous leak of contaminants. Malcolm Pirnie estimated via a "two dimensional model" that the stable plume could be 34% longer with ethanol present in the fuel. In the Surbec-Art Environmental analysis, a "three dimensional model" was employed where modeling parameters were available due to the considerable site research performed. Modeling was conducted assuming a BTEX spill without ethanol and one with ethanol. Acetic acid degrades considerably slower than ethanol. Since ethanol could biodegrade to acetic acid, a third set of model runs explored the impact of acetic acid production on plume length. In all cases, the plume was found to stabilize. The length of the BTEX plume was found to increase by about 10% if no acetic acid was produced during biodegradation and 80% if half of the ethanol degraded to acetic acid. The studies are in agreement that ethanol could increase the distance from a spill where BTEX would be detected but also suggests BTEX will still be purged from the environment.

Ethanol Energy Balance and Crude Oil Use:

In the United States, ethanol use in the petrol pool is increasing primarily because of public policy. Ethanol is produced primarily from corn in the US, and so increased ethanol production results in higher corn prices that in turn increase farm income or

[43] Malcolm Pirnie, "Evaluation of the Fate and Transport of Ethanol in the Environment", for the American Methanol Institute, November 1988 and Surbec-Art Environmental , LLC, "The Fate and transport of Ethanol-blended gasoline in the Environment", for the Governor's Ethanol Coalition, October 1999.

reducing the cost of Federal farm subsidy payments. In addition, there is a lower overall use of crude oil and an extension of finished petrol refining capacity. Ethanol is subsidized through an excise tax exemption on petrol; the level of the exemption makes ethanol price competitive with petrol.

There has been considerable discussion related to the energy efficiency of ethanol production from corn. A recent comprehensive analysis[44] demonstrates the energy balance for corn ethanol production is very favorable (1.2 to 1.4 times fossil energy input) and uses very little refined products. Only about 7% of the energy in corn ethanol is derived from petroleum resources while 93% comes from natural gas and coal.

Cost of Production of Unleaded Petrol:

The cost to increase octane using any of the alternatives is modest. Thomas and Kwong[45] have estimated that the cost of treating petrol with lead was 1.5 cents per gallon to 7.6 cents per gallon in 1999 depending on treatment rate. The recent cost of lead may be near 4.4 cents per gram and the cost of MMT might be 2.3 cents per gram [46]. However, the blending level of MMT as manganese is only 0.06 g/gal. The indicated cost of MMT blending is thus less than one cent. Thomas and Kwong estimate at $20 crude and higher, that the premium in cost of finished petrol will be no more than 5 cents per gallon when blending ethanol or MTBE.

The potential cost of manufacturing differences for the three main scenarios, MMT, purchased MTBE and purchased ethanol were computed with the following set of economic assumptions.

These economic values were adapted from U.S. refinery modeling data[47]. The cost of 92 RON petrol is used as the basis. If one RON number costs 1 cent per gallon, the cost of 94.4 RON petrol is estimated to be $0.826. The value of 90.8 gasoline was adjusted for octane and removal of the butane in the petrol. The economic value of the butane free base, $0.801, is used for all blending economic calculations.

Table 17
Economic Assumptions

	$/Barrel	$/Gallon	RON
Crude	$25.00	$0.595	
Petrol	$33.65	$0.801	92.0
SA base, butane free	$33.66	$0.801	90.8
SA purchase	$34.70	$0.826	94.4
MTBE	$42.89	$1.021	

[44] Graboski, M.S., "Fossil Energy Use in the Manufacture of Corn Ethanol", Colorado School of Mines, September 2002.
[45] Thomas, V., Kwong, A. "Ethanol as a Lead Replacement:Phasing Out Leaded Gasoline in Africa", Energy policy 29 pp 1133-1143, 2001.
[46] www.hpiconsultants.com/blending/out-MG2.htm
[47] Hadder, J., "Ethanol Demand in Gasoline Production", ORNL-6926, Oak Ridge National Laboratory, Nov 1998.

Ethanol	$52.50	$1.250	
Butane	$18.86	$0.449	
Lead	$0.945	$0.0225	
MMT	$0.42	$0.01	
Octane	$0.42	$0.010	Per 1 RON increase

The value of MTBE was assigned using the historical octane cost and its octane value, which is assumed to be 22 R+M/2 units higher than petrol. Ethanol is assumed to be available at $1.25 per US gallon[48]. Lead is valued at 1.5 cents per gram as TEL. MMT is assumed to cost 1 cent per gallon treated. Since each scenario requires a different blendstock, the cost of the blendstock is adjusted for octane and butane content to bring the petrol to the requisite octane at 9.0 psi RVP. In addition, the cost per gallon is adjusted to yield a constant amount on an energy basis of petrol with the appropriate research octane. Thus, in scenarios that produce more or less petrol, the cost of production is adjusted for the revenue associated with the excess or shortage of supply of complying petrol.

The cost of production is summarized in Table 18. The first portion of the table provides the input and production rates. The costs are then calculated in the second part of the table. The "butane opportunity cost" is revenue associated with blending butane into petrol. If it must be sold as butane and not petrol, it is worth the value of butane and not petrol. The value assigned to purchased or sold gasoline adjusts the supply to equal energy compared to the leaded case. It thus includes extra petrol that must be purchased by refiners due to the lower mileage obtained with MMT fuels and the greater production associated with MTBE and ethanol blending.

For $25 per barrel crude, the premium compared to lead ranges from 0.4 cents per gallon to 3.95 cents per gallon. The MMT option provides the lowest cost. However, the cost benefit to MMT is directly related to the 1 cent per gallon assumption. If the supplier were to charge 4.5 cents per gallon, the oxygenate choices would be superior on a cost of production basis.

The price of MTBE floats with the crude oil price. In the US, the price of ethanol also floats with crude price. If the price of ethanol is held constant at $1.25, the MTBE and 9-psi ethanol cases have equal cost of production at $34.20 crude. If the volatility waiver is allowed for ethanol, MTBE and ethanol-based fuels would have equal costs of production at about $29.15 crude price.

The U.S. based cost for ethanol production may be higher than that for an indigenous South African industry. To produce equal cost gasoline compared to MTBE, ethanol

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[48] Shapouri, H, Gallagher, P., Graboski, M.S., "Ethanol Plant Operation Analysis", Dry Mill Ethanol Plant Conference, Normal Illinois, May 3, 2001. The reported average variable cost of production of 18 corn dry mills was 95 cents per gallon. The typical installed cost of a dry mill is $1.50 per annual gallon. Allowing 10 year payback at 20%, the capital charge is 30 cents per gallon resulting in $1.25 ethanol. If ethanol were valued at octane, it would cost $1.06 per gallon.

might be valued at about $1.00 to $1.10 depending on whether the petrol with ethanol had a 9 or 10 psi RVP.

The calculations confirm that the likely maximum cost difference among all replacement scenarios is several cents per gallon.

In examining the cost of production economics, it is useful to compare the increased cost of the use of oxygenates compared to MMT with maintenance. If the vehicle achieves 25 mpg for 100,000 miles, the total fuel use is 4,000 gallons. If the use of ethanol results in a 3.5 cents per gallon increase, the cost associated with fuel is $140. Any increased maintenance cost associated with MMT could easily cost more than the fuel premium.

Capital Cost for Unleaded Petrol:

Refiners suggest that the total cost of refinery upgrades for meeting lead removal and lowering sulfur in diesel are about $1.25 billion.

A typical 15,000 to 20,000 barrel per day butane dehydrogenation plant to produce MTBE from natural gas liquids has a capital cost near $250 MM. Such a facility would require 6,200 bbl/d of methanol and 20,000 bbl/day of mixed butanes. The sources of these feedstocks are uncertain.

12,000 barrels per day of ethanol represents about 185MM gallons per year of denatured alcohol. At $1.50 per annual gallon project cost for dry milling, ethanol can be produced from corn (maize) for about $276 MM. If molasses, sugar or cassava is used, the capital cost will be different. Molasses and sugar facilities will be lower in cost since milling is not necessary. In addition, there is no cost for drying feed grain byproducts. Because of its high starch content and low oil content, processing of cassava might be less costly as well.

Table 18
Cost of Production of Petrol for Various Scenarios Adjusted for Fuel Supply Data, Barrels per Day

	Lead	MMT	MTBE	EtOH	EtOH(10)
Petrol Component					
Butane	5,666	5,203	5,468	3,612	6,241
EtOH	-	-	-	12,050	12,050
MTBE	-	-	18,200	-	-
MMT	-	18	-	-	-
Base Petrol	159,885	159,885	159,886	159,885	159,885
Total Product Supply	165,551	165,088	183,554	175,547	178,176
Barrels leaded equivalent	165,551	164,680	179,292	171,180	173,166
Butane to sales	-	463	198	2,054	(575)
Relative Energy	1.000	0.995	1.083	1.034	1.046
Relative Volume	1.000	0.997	1.109	1.060	1.076
		Cost Data $/day			
Base Gasoline	5,381,153	5,381,153	5,381,187	5,381,153	5,381,153

Additive	156,446	69,337	780,668	632,625	632,625
Butane	106,837	98,107	103,103	68,107	117,679
Butane opportunity cost	-	7,338	3,138	32,552	(9,113)
Purchased or sold gasoline	-	116,633	(476,856)	(195,339)	(264,282)
Total Cost	5,644,436	5,672,567	5,791,240	5,919,099	5,858,063
COP, $/gallon	0.8118	0.8158	0.8329	0.8513	0.8425
Premium, cents per gallon	-	0.40	2.11	3.95	3.07

Discussion:

During the next three years, refiners will be planning and implementing lead phase-out. Because of lead-time requirements for logistical planning and refinery modifications, it is imperative that any government policy decisions related lead phase-out be developed and promulgated in the near timeframe.

Regulatory policy will dictate petrol quality, emissions characteristics, environmental and health issues and supply.

The single specification for Research Octane in each area may lead to a need to supply more octane than the fleet actually requires.

An analysis should be made of the fleet octane requirement to determine whether sale of multiple unleaded grades would contribute to a cost effective approach to producing unleaded gasoline. Public education would be necessary for this approach to be successful.

Refiners will opt for a solution that minimizes their cost of production of petrol. For refiners, the minimum cost option may be replacement of lead with MMT. The government sets the price of petrol, thus refiners have an incentive to minimize their cost of production to maximize profits. At the same time, refiners may request help with the cost of refinery modifications. One option open to refiners is to increase aromatics production to meet RON requirements. USE of MMT and aromatics may produce negative health and welfare impacts.

When setting policy, all scenarios do not result in the same impact on health and welfare.

Use of indigenous resources has different economic implications than those involving imports. MMT and MTBE are readily available on the world market and South Africa should have no problem obtaining ample supplies at a reasonable price.

South Africa has a potential supply of coal and natural gas based octane boosters as well as the agricultural resources to produce a substantial amount of ethanol. Use of coal and agricultural resources provides high paying jobs and new markets and in general should positively impact rural areas.

The “life cycle” economics and environmental impacts of fuels needs to be considered.

Good regulatory policy should evaluate the life cycle cost of all of the alternatives because the public will ultimately pay both for petrol and externalities associated with its use. Of major importance are social costs associated with the various alternatives, especially health costs.

The greenhouse gas implications of the various scenarios may also be important. South Africa may elect to integrate international greenhouse gas targets with its fuel policy. Such an approach could provide international financial support.

Policy related to greenhouse gas mitigation could provide a source of non-domestic funding for renewable fuel supply.

Conclusions:

South African refinery supply capacity may come close to actual demand by 2006. Demand creep is bringing supply and demand in the South African Refining sector more into balance.

Based upon the quantity of lead blended into petrol in South Africa, the RON of clear petrol produced in South Africa is approximately 90. The pool RON requirement based upon SABS 1598 will be about 94.4 in 2006. To effectively use refining capacity, the specifications for petrol RON should be carefully examined in relation to the requirement for the South African fleet.

Refiners can probably meet the 2006 unleaded requirement using a number of approaches; these include adding isomerization capacity and blending MMT and/or aromatics, and blending oxygenates including MTBE and ethanol.

Refiners could invest and modify their refineries to satisfy all or part of the octane requirement with a combination of isomerization and aromatics. The gasoline aromatic content would increase by about 6% to 40% if aromatics were used to replace lead. Increasing aromatics will result in increased hydrocarbon and carbon monoxide emissions, increased levels of PM2.5, ozone and elevated levels of benzene and polycyclic aromatic hydrocarbons in the ambient air.

Some refinery investment will be required if MMT is used because MMT cannot raise the petrol octane to the same degree as lead. It is important to note that MMT causes a reduction of 2% in mileage resulting in the need to expand refining capacity and/or purchase gasoline. MMT use will likely increase hydrocarbon and air toxic emissions including manganese compounds. The impact of long-term low-level exposure to manganese compounds through inhalation is not known.

Ethers and alcohols can be used to meet the petrol octane requirements. The principal ether that may be used is MTBE while ethanol is the main alcohol. To satisfy the octane requirement, it appears that South Africa would have to import MTBE. Ethanol is currently produced from coal, natural gas and sugar in South Africa. Most of the ethanol is used for petrochemicals and solvents. There appears to be sufficient indigenous resources to produce domestic fuel grade ethanol to upgrade octane for all South African petrol. An advantage of either MTBE or ethanol is that petrol supply is expanded. Ethers may pollute ground water. Alcohols may cause increased evaporative emissions. Both produce elevated aldehydes in the exhaust compared to clear petrol.

The estimated increased cost of production when replacing lead priced at 1.5 cents per gram with MMT valued at 1 cent per gallon, MTBE at $43 per barrel and ethanol at $1.25 per gallon is 0.4, 2.11 and 3.95 cents per gallon with $25 per barrel crude respectively. All fuels would have an RVP of 9 psi. If the ethanol-based petrol RVP was 10 psi, the cost increase associated with ethanol would be about 3.07 cents per gallon.

The impacts of all scenarios are not the same. The lifecycle cost, not refiners cost, should be used to set policy since vehicle maintenance, external health care costs paid, benefits of domestic supply on rural mining and agricultural areas and the impact of incentives need to be evaluated.

Appendix 1: Useful Websites

Country profile
http://www.cia.gov/cia/publications/factbook/geos/sf.html

Oil industry overview
http://www.bp.com/location_rep/south_africa/sa_oil.asp

Pipeline data
http://www.simulutions.com/images/Project%20Profile%20Sheet%20-%20Petronet%20Website.pdf

Information for Africa
http://www.mbendi.co.za/indy/chem/af/sa/p0005.htm

Databases
http://www.haver.com/
http://208.184.43.197/cc/?section=energy2

World supply and disposition
http://www.eia.doe.gov/emeu/iea/table31.html

DOE International Energy Annual 2000 has supply and demand data.
http://www.eia.doe.gov/emeu/international/safrica.html

http://www.eia.doe.gov/iea/

1999 SA energy balance
http://www.eia.doe.gov/emeu/world/country/cntry_SF.html

Mossgas home page
http://www.mossgas.com/frmain.htm

Department of Minerals And Energy
http://www.dme.gov.za/

Transportation statistics
http://www.transport.gov.za/library/docs/stats/2001/statistics-f.html

Ministry Of Health
http://196.36.153.56/doh/

National Association of Automobile Manufacturers of South Africa
http://www.naamsa.co.za/

World ethanol production
http://www.distill.com/world_ethanol_production.htm

Sasol ethanol
http://www.chemicals-technology.com/projects/secunda/

Sugar to ethanol economics
http://www.mct.gov.br/clima/ingles/comunic_old/alcohol4.htm

GTL economics and review
http://www.chemlink.com.au/gtl.htm

Bureau of Standards
http://www.sabs.co.za/

Energy reserves SA
http://www.epa.gov/coalbed/pdf/001saf.pdf
http://www.eia.doe.gov/emeu/cabs/tbl3c.html

Useful links
http://www.eri.uct.ac.za/ERI%20WEBSITE_page11.htm

South African renewable supplies
http://www.worldenergy.org/wec-geis/edc/countries/SouthAfrica.asp

Auto industry and pollution control manufacturer's industry websites
http://www.meca.org

http://www.autoalliance.org/