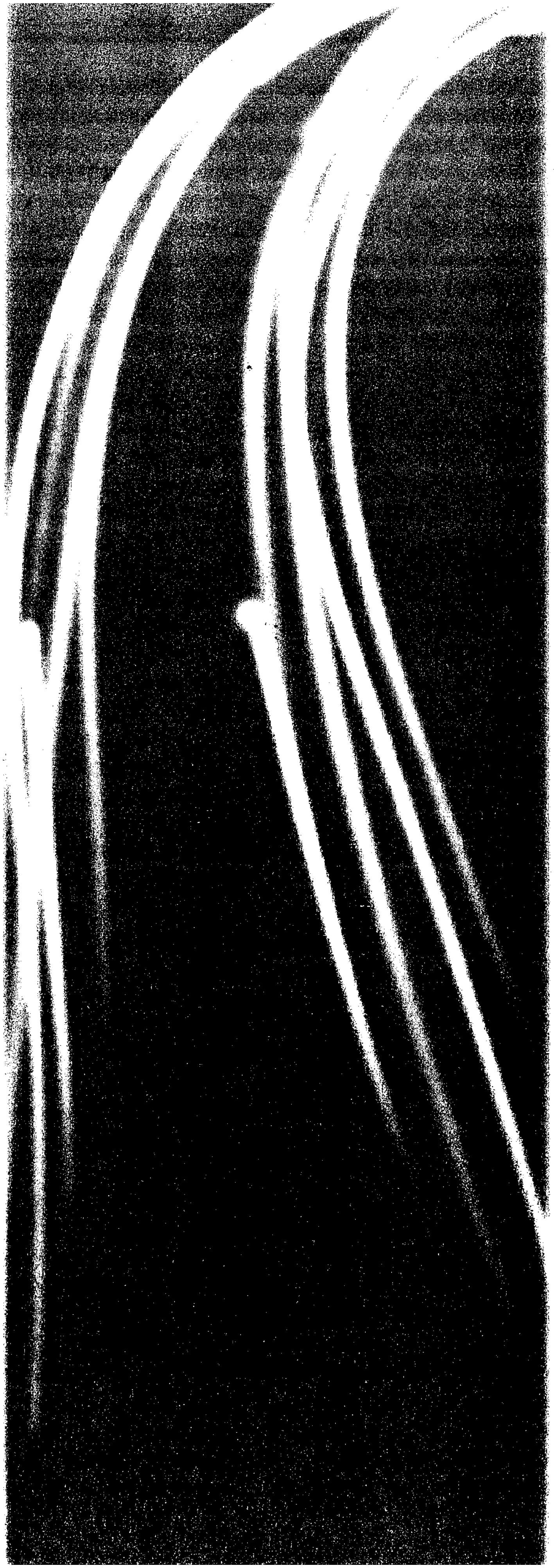

Fuel Economy and Engine Performance Issues

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CONTENTS

EXECUTIVE SUMMARY

- Oxygenates have been used in gasoline since the 1970s as fuel extenders or octane enhancers. During the 1980s, oxygenates came into wider use as some states implemented oxygenated gasoline programs for the control of carbon monoxide (CO) pollution. Denver, Colorado, implemented the first oxygenated gasoline program in 1988.

- The 1990 Clean Air Act Amendments required oxygenated gasoline programs in several areas of the country that failed to attain the National Ambient Air Quality Standards (NAAQS) for CO. Many new oxygenated gasoline programs were first implemented during the winter months of 1992–1993.

- Consumers in some areas of the country expressed concerns that oxygenated gasoline has led to large reductions in fuel economy or poor engine performance. This chapter examines existing studies and literature related to fuel economy and engine performance. Large fuel economy losses (as high as 20%) have been claimed by some consumers.

- With regard to fuel economy, the theoretical change in fuel economy as a result of the addition of oxygenates to gasoline is in the range of a 2% to 3% reduction in fuel economy. Existing research indicates that "real world" fuel economy changes correspond to changes in energy content. A 2% to 3% reduction in fuel economy equates to a less than 1 mile per gallon change in fuel economy for a car that averages 27 miles per gallon.

- Engine performance problems due solely to the presence of allowable levels of oxygenates in gasoline are not expected. Although engine performance problems may be linked to poor gasoline quality, the manufacturing and handling actions that cause poor quality can occur with either oxygenated or nonoxygenated gasoline. Many engine performance problems are due to factors other than gasoline and may be corrected by relatively simple consumer actions.

SCOPE OF THE CHAPTER

Consumers in some areas of the country have expressed concern that the use of oxygenated gasoline has led to large reductions in fuel economy or poor engine performance. The purpose of this chapter is to assess the effects of oxygenated gasoline on fuel economy and engine performance issues and to summarize all relevant literature.

This chapter discusses nonoxygenated and oxygenated gasoline from the standpoint of fuel economy and engine performance. The focus is on winter oxygenated gasoline (i.e., gasoline designed to meet the requirements of CO reduction programs). Issues that are not likely to be encountered during the winter months, such as summer volatility issues, are not discussed.

The following fuel-related sources of potential engine performance problems are discussed: enleanment, fuel quality, antiknock quality, fuel handling and storage practices, water absorption/phase separation, materials compatibility, and fuel mixtures. All of the fuel-related potential engine performance problems can occur with either oxygenated or nonoxygenated gasoline.

Engine performance problems due solely to the presence of oxygenates in gasoline are not expected because oxygenated gasoline and nonoxygenated gasolines are blended to conform to the same American Society for Testing and Materials (ASTM) standard. Many engine performance problems are linked to factors such as operating conditions, normal vehicle wear, deterioration due to aging, or poor maintenance practices.

With regard to fuel economy, the theoretical change in fuel energy as a result of the addition of oxygenates to gasoline is in the range of a 2–3% reduction when compared to nonoxygenated gasoline. This corresponds to less than 1 mile per gallon (i.e., approximately 0.5 to 0.8 miles per gallon) for a car that averages 27 miles per gallon. As discussed in greater detail below, the large body of research indicates that actual measurements of changes in fuel economy agree with the theoretical changes in fuel energy. However, some older vehicles experience slightly improved fuel economy with oxygenated gasoline because of the resulting enleanment of the air-fuel mixture. Any fuel economy loss actually experienced is the result of the slight decrease in energy content of the fuel.

The primary reference for this chapter is EPA's "Technical Overview of the Effects of Reformulated Gasoline on Automotive and Non-Automotive Engine Performance."[1]

FUEL ECONOMY

Since the introduction of the oxygenated gasoline (CO) and RFG (ozone) programs, the EPA has received questions from the public regarding various aspects of the programs.

[1]EPA420-R-95-001 (April 1995).

The majority of the questions have been related to reduced vehicle performance and fuel economy. Some motorists indicated large fuel economy losses in excess of 20%. Such complaints were not consistent with the experiences of most motorists in regions of the country using similar oxygenated gasoline formulations. The complaints were also inconsistent with the results of many automotive testing programs which indicate that oxygenated gasoline does not negatively impact vehicle driveability and will not produce more than a slight reduction in fuel economy.

Measurement Variability

A large amount of variability is inherent in fuel economy measurements. Sources of this variability include differences in personal driving habits, weather conditions (temperature, wind effects and precipitation), traffic patterns (e.g., rush hour versus midday or weekends and highway driving versus city driving), the temperature effect on fuel volumes when fueling, and changes in tire pressure.

Ambient Temperature Effects

Wintertime driving results in large decreases in fuel economy when compared to other times of the year. These large decreases are due to increased stop and go driving, more friction between vehicle mechanical parts, idling to heat up the vehicle prior to a trip, increased rolling resistance due to poor road conditions, a greater power load on the engine, and longer periods spent in cold engine operating modes at richer fuel/air mixtures. A combination of these variables can produce a profound effect on mileage. For example, the difference between city versus highway driving, excluding the wintertime temperature effects of increased wind resistance and tire rolling resistance, can cause a variation in fuel economy in the range of 5 to 10 miles per gallon. These cumulative effects can account for as much as a 35 to 40% difference in expected fuel economy and far outweigh the effect of the small change in gasoline energy density that is described below.

Seasonal Fuel Composition

Wintertime gasoline has a lower density and therefore less energy per gallon than summertime gasoline, regardless of whether it is oxygenated. Lower energy results in lower fuel economy.

One of the most important characteristics of gasoline is its rate of evaporation. The property of a liquid that defines its evaporation characteristics is called "volatility." A gasoline with low volatility will evaporate comparatively slowly and will cause engine start up and warm up problems. These problems are caused by either insufficient fuel reaching the combustion chamber or insufficient mixing of the air-fuel charge. Evaporation that is too rapid (high volatility) will cause warm engine operating problems, primarily because the liquid gasoline turns to a gas prior to reaching the carburetor or fuel injectors, thereby blocking fuel flow. Such a condition is called "vapor lock." Fuel manufacturers vary the proportions of gasoline components to produce volatilities within appropriate ranges. The wintertime mixture is made up of less dense, lower molecular weight hydrocarbons in order to provide higher volatility for cold weather engine operation.

Historic data on geographic and seasonal variations in temperature are used by manufacturers to produce fuels with volatilities that are appropriate for the temperatures in their marketing area. The ASTM specifications for gasoline include a schedule for volatility classes based on climate and region.

Theoretical Basis for Fuel Economy Changes Due to Oxygenates
Fuel economy theoretically decreases when oxygenates are used due to the lower energy content of the oxygenate which is added. The energy content of MTBE is approximately 93,500 British Thermal Units per gallon[2] (Btu/gal) while that of gasoline is approximately 109,000 Btu/gal.[3] Therefore, for equal amounts of MTBE and gasoline, MTBE contains approximately 14 percent less energy than gasoline.[4] The following table indicates the theoretical loss in energy for the addition of various oxygenates at levels required for the RFG program (2.0 weight percent oxygen), the oxygenated gasoline program (2.7 weight percent oxygen), and, in the case of ethanol, for levels (3.5 weight percent oxygen) traditionally used in both regulated and non-regulated areas.

As can be seen in Table 3-1, the theoretically expected decrease in fuel energy as a result of oxygenate use is in the 2% to 3% range when compared to gasoline. This corresponds to 0.5 to 0.8 miles per gallon for a car that averages 27 miles per gallon. As can be seen from the works cited below, research in this area indicates that any fuel economy loss experienced as a result of oxygenate use agrees with the theoretical prediction for fuel energy loss. Thus, it is reasonable to conclude that any fuel economy loss experienced with oxygenate use is solely a function of the change in fuel composition and the resulting slight decrease in energy content of the fuel.

Table 3-1. Theoretically expected effect of oxygenates on fuel energy.

Oxy-genate	Weight percent oxygen	Volume percent oxygenate	Volume percent gasoline	Energy content of oxygenate Btu/gal	Energy from oxygenate Btu/gal	Energy from Gasoline Btu/gal	Energy of 1 gal of Blend Btu/gal	%Reduction Compared to Gasoline
MTBE	2.0	11.0	89.0	93,500	10,285	97,010	107,295	1.6
Ethanol	2.0	5.7	94.3	76,000	4,332	102,787	107,119	1.7
ETBE	2.0	12.6	87.4	97,700	12,310	95,266	107,576	1.3
MTBE	2.7	15.0	85.0	93,500	14,025	92,650	106,675	2.1
Ethanol	2.7	7.7	92.3	76,000	5,852	100,607	106,459	2.3
ETBE	2.7	17.0	83.0	97,700	16,609	90,470	107,079	1.8
Ethanol	3.5	10.0	90.0	76,000	7,600	98,100	105,700	3.0

Studies Related to Fuel Economy Effects
The EPA, industry, and the scientific community have conducted numerous studies examining the effects of oxygenates on motor vehicles. Listed below are some of the fuel economy test results from the many known test programs. The name of each study, which appears in *italics*, is followed by a summary of the findings.

[2]"Alcohols and Ethers," American Petroleum Institute, API Publication 4261, 1988, p.2.

[3]Starkman, E.S., H.K. Newhall, and R.D. Sutton, "Comparative Performance of Alcohol and Hydrocarbon Fuels," Society of Automotive Engineers Paper Number SP-254, p. 5.

[4]The precise energy content of any gasoline blend varies somewhat. These calculations are for a typical blend.

"On-Road Study of the Effects of Reformulated Gasoline on Motor Vehicle Fuel Economy in Southeastern Wisconsin " U.S. Environmental Protection Agency and the Wisconsin Department of Natural Resources, March 31, 1995. The Wisconsin Department of Natural Resources and the U.S. Environmental Protection Agency conducted an on-road study of the fuel economy effects of RFG in March, 1995. The intent of the study was to respond to consumer concerns that RFG was responsible for large reductions in motor vehicle fuel economy–much larger than the 2% to 3% reduction predicted by previous studies or by the theoretical energy content of the fuel formulations. In this study, fuel economy was measured from a group of Milwaukee area vehicles representing various model years and fuel delivery systems, and using four types of gasolines, one conventional gasoline and three oxygenated RFGs (MTBE, ETBE, and ethanol). Eight vehicles were driven over a fixed, 100-mile route with urban, suburban and rural segments. Their fuel usage was determined by weighing the fuel at the beginning and end of the route. The study utilized vehicles with highly variable technologies and included carbureted vehicles, port fuel-injected vehicles, and throttle body fuel-injected vehicles. The study vehicles included older and newer technology vehicles as well as a pickup truck in order to represent as large an array of on-road vehicles as possible.

In general, the results of this practical on-the-road study were consistent with the predictions (based on both laboratory and on-road studies, as well as the energy content of the fuels tested) that were set out in the RFG regulations. The average change in fuel economy when RFG was compared to conventional gasoline was a 2.8% reduction in miles per gallon when using RFG.

40 CFR Part 80 Regulation of Fuels and Fuel Additives: Standards for Reformulated and Conventional Gasolines, February 16, 1994. EPA combined the results of 19 studies with over 4000 vehicle/fuel tests. The analysis confirmed that fuel economy impacts are solely a function of fuel energy content. The analysis concluded that fuel economy is reduced by 2% to 3% during the winter season and 1% to 2% during the summer season.

"Fuel Composition Effects on Automotive Fuel Economy - Auto/Oil Air Quality Improvement Research Program." Albert M. Hochhauser et al., AQIRP, SAE Paper #930138. Excerpt: "The Auto/Oil Air Quality Improvement Research Program (AQIRP) is a cooperative research program initiated by three domestic automobile companies and 14 petroleum companies. This paper discusses the fuel economy measurements from two fleets of vehicles running on fuels whose composition varied in a number of parameters. The vehicle fleets used in this study are identified as the "Current Fleet" (20 vehicles, 1989 model year) and the "Older Fleet" (14 vehicles, model years 1983 to 1985)."

Summary of findings on fuel economy: "Reducing aromatics from 45% to 20% lowered fuel economy by 2.8% in the Current Fleet and by 3.2% in the Older Fleet."

"Adding 2.7 wt% oxygen lowered fuel economy by 2.3% in the Current Fleet and by 1.6% in the Older Fleet."

"Reducing T_{90} from 360 °F to 280 °F lowered fuel economy by about 1.5% in both fleets."

"Reducing olefins from 20% to 5% lowered fuel economy by 0.2% in the Current Fleet and by 0.6% in the Older Fleet."

"Performance Features of 15% MTBE/Gasoline Blends," Walter H. Douthit, et al., Sun Refining and Marketing Company, SAE Paper #881667. An average 1.8% to 3.4% loss in fuel economy was observed in a nine-vehicle test program comparing a 15 wt% MTBE blend to a nonoxygenated fuel.

"Are the Reductions in Vehicle Carbon Monoxide Exhaust Emissions Proportional to the Fuel Oxygen Content?" J.A. Gething, et al., Chevron Research Company, SAE Paper #890216. An average 1.8% decrease in fuel economy was observed in an 18-vehicle test program testing a nonoxygenated fuel and comparing it to a 2.0 wt% MTBE fuel and a 3.5 wt% ethanol fuel.

"Fuel Economy Effects -- Controlled Fleet Study," Memo from Frank Gerry, BP Oil Company, to Jim Williams, American Petroleum Institute, February 24, 1995." British Petroleum Company conducted an extensive on-road fuel economy test program testing eight 1992 model cars on nonoxygenated fuel and a 10% ethanol blended fuel. Each car accumulated 20,000 miles of test data. The results of this study show a fuel economy loss due to the use of the ethanol blend of 3.3% for the summer season, 2.4% for the winter season, and 2.8% overall.

"The Effect of Gasoline Composition and Characteristics on Fuel Economy," Downstream Alternatives, Inc. Information Document #930901, September 1993. This paper is a summary of current studies and an overview of the many factors that may affect fuel economy. The factors discussed are engine design, consumer practices, climate, and fuel composition. The paper emphasizes the effects of oxygenates on fuel economy. The paper cites theoretical calculations and observed fuel economy results from several sources. The conclusion is that a 2.7 wt% oxygen level fuel will cause, on average, a 1.6% to 2.3% decrease in fuel economy.

"Vehicle Fuel Economy -- The CleanFleet Alternative Fuels Project," John E. Orban, Michael J. Murphy, M. Claire Matthews, Battelle, SAE Paper #950396. Dynamometer tests were conducted on 36 vehicles comparing California Phase 2 reformulated gasoline to industry average unleaded gasoline (RF-A). Tests results revealed a 2.7% decrease to a 0.9% increase in fuel economy.

"Evaporative and Exhaust Emissions from Cars Fueled with Gasoline Containing Ethanol or Methyl Tert-Butyl Ether," R.L. Furey and J.B. King, SAE Paper #800261. Motor vehicle test fuels using 10 volume percent ethanol or 15 volume percent MTBE experienced a decrease in fuel economy ranging from 0.9% to 3.7%. These results were consistent with the generally lower energy content of oxygenated fuels. The ethanol test fuel had a 3.4% lower energy content and the MTBE test fuel had a 2.8% lower energy content than the nonoxygenated base fuel.

"Exhaust and Evaporative Emissions from Alcohol and Ether Fuel Blends," T.M. Naman and J.R. Allsup, U.S. DOE, SAE Paper #800858. Steady-state tests were conducted on a chassis dynamometer at 35- and 45-mph on 7 volume percent MTBE and 10 volume percent ethanol blends using a fleet of eight 1978 model-year automobiles. The fuel economy results ranged from a 3.3% decrease to a 0.2% increase. An on-road study using a 1978 Oldsmobile Delta 88 was also conducted on the same 10 volume percent ethanol blend resulting in an average 2.7% decrease in fuel economy.

"Assessment of Unregulated Emissions from Gasoline Oxygenated Blends," Craig Harvey, U.S. EPA, SAE Paper #902131. Five vehicles of various technology types were tested on four fuels. The general conclusion is that fuel economy is lower when oxygenates are present in gasoline. No fuel economy specifics were cited.

"Effects of MTBE on Gasoline Engine Cold Weather Operation," J. Viljanen, J. Kokko, and M. Lundberg, Neste Oy Finland, SAE Paper #890052 Eight vehicles were tested in cold weather conditions. The average fuel consumption of these test vehicles was 0.8% higher on gasoline using 8 volume percent MTBE than on a nonoxygenated base fuel.

"Alcohols and Ethers: A Technical Assessment of Their Application as Fuels and Fuel Components," API Publication 4261, second edition, July 1988. This is a comprehensive survey of the effects of oxygenates on fuel economy, measured volumetrically, for 256 test vehicles ranging from model year 1973 to 1980. Overall, fuel economy was reduced by 1.7%. As a group, the forty-one 1973 and 1974 model year vehicles showed a 3.7% to 4.1% lower fuel economy due to the use of oxygenates. One hundred ninety-seven vehicles of model years 1975 to 1979 showed a 0.6% to 1.7% fuel economy loss.

"Air Pollution Control Division Report to the Colorado Air Quality Control Commission," August 1995. A report on the eighth year of operation of the Colorado Oxygenated Gasoline Program, a wintertime CO control program in the Denver area. Fuel economy measurements from mass emissions testing were used to determine the fuel economy effects from gasoline oxygenated with MTBE and ethanol. Taking the market share of MTBE and ethanol blended gasoline into account, and the breakdown of the motor vehicle fleet by vehicle technology group, average fuel economy was reduced by approximately 1.0%.

ENGINE PERFORMANCE ISSUES

Fuel-related sources of engine performance problems include excessively high or low volatility, water absorption, improper storage and handling, enleanment, reduced motor octane, and materials compatibility. Performance problems can occur for a variety of reasons, and tracing performance problems to a specific cause is difficult, and often impossible. Potential engine performance problems resulting from fuel-related sources include rough engine operation, overheating, damaged pistons, vapor lock, starting difficulty, plugged fuel filters, fouled spark plugs, fuel leaks, hesitation during acceleration, flooding, stalling, and engine fires.

Most engine performance problems are, however, the result of non-fuel factors related to vehicle age or mileage, operating conditions, or maintenance history. In general, the normal changes in engine tune up parameters that occur over time, the wear caused by hard use, severe weather conditions, and improper maintenance, are much more significant than the contribution of an oxygenated fuel, if any, to the occurrence of performance problems. Most performance problems can be mitigated by operator preventative or corrective actions.

Oxygenated gasolines are very similar to many nonoxygenated gasolines in terms of composition and physical and chemical properties. In those cases where performance problems are related to fuel characteristics, no performance problems have been found that happen solely with oxygenated fuels and not with nonoxygenated (conventional) fuels. Certain small engine manufacturers have found that problems can occur if oxygenate blends are not blended to appropriate ASTM specifications, especially for volatility characteristics. The information available from automotive and non-automotive engine manufacturers suggests that performance problems directly attributable to oxygenate use are unlikely when ASTM gasoline standards are complied with.

All automobile manufacturers allow or recommend oxygenated gasolines up to the legally allowed oxygenate limits[5]. Most non-automotive engine manufacturers' owner's manuals also include oxygenated fuels in their list of acceptable or recommended fuels and will not void their warranties if gasolines containing oxygenates within the allowed limits are used. However, some manufacturers acknowledge that because only limited testing with oxygenated gasolines on non-automotive engines has been completed, they are not completely certain of the effects, if any, of oxygenated gasolines on their engine components or performance.

Mixtures of gasolines containing different oxygenates and mixtures of oxygenated and nonoxygenated gasolines are likely to occur in consumers' fuel tanks. However, such mixtures should not impact engine performance any differently than nonoxygenated fuels or mixtures of fuels containing the same oxygenate. Overblends, that is, gasolines containing oxygenates at greater than the legally allowed limits, could adversely affect engine performance, depending on the volume of oxygenate used. However, for a number of technical and economic reasons, such blends are unlikely to be encountered in the marketplace.

Enleanment

Nonoxygenated gasolines are mixtures of many hydrocarbon compounds that consist solely of hydrogen and carbon. Oxygenates consist of hydrogen, carbon and oxygen. The addition of oxygen to a hydrocarbon-only fuel results in a change in the proportion of fuel to air that is required to provide complete combustion of the fuel to water and carbon dioxide. The exact air-to-fuel ratio needed for complete combustion of gasoline is called its “stoichiometric air-fuel ratio,” and is about 14.7 pounds of air to one pound of fuel (14.7:1) for nonoxygenated gasoline. For oxygenated gasolines, less air is required because oxygen is contained in the fuel and because some of the hydrocarbons have been displaced. For example, oxygenated gasolines containing the 2.7 weight percent oxygen, required in CO nonattainment areas in the wintertime, require 14.2 to 14.3 pounds of air per pound of fuel. The effect of this type of fuel change on an engine is called “enleanment.”

The air-fuel ratio requirement is an important factor in the design of engines and fuel metering controls. Most automobiles made after 1981 use some form of “closed loop” fuel system that continuously monitors and adjusts the amount of fuel delivered to the engine to maintain the stoichiometric air-fuel ratio. These vehicles have adjustment ranges that accommodate oxygenated fuels and, when operating in the “closed loop” mode, do not experience any effects from the oxygenated fuel. During cold start and at full throttle, these systems operate in an “open loop” mode that provides a rich fuel mixture that is

[5]Although EPA regulations allow methanol blend gasoline, and most vehicle manufacturers allow its use within specified limits, it is not currently in the marketplace. Another oxygenate, MTBE, is sometimes confused with methanol.

necessary for those conditions. In the rich mixture, "open loop" mode, vehicles do experience enleanment effects from the oxygenated fuel.

Automobile driveability characteristics are not normally affected by switching between oxygenated and nonoxygenated gasolines, whether or not a vehicle is using a "closed loop" fuel control system. In a situation where a vehicle is not properly adjusted and is operating in a "too lean" condition, switching to a fuel with increased oxygen would increase the risk of a driveability problem. The symptom most likely to appear in this situation is a hesitation during acceleration. Vehicles that are in an adequate state of tune should not experience such problems.

In older vehicles (built before 1981) and in small engines like those used in lawnmowers, snowmobiles, and marine applications, "open loop" fuel metering systems are used, which do not automatically compensate for changes in fuel oxygen content. They provide the same ratio of air to fuel for both oxygenated and nonoxygenated gasolines. As a result, the air-fuel mixture is slightly enleaned when oxygenated fuel is used and some change in engine operation is possible. In general, the dynamic operating range of most engine air-fuel ratios is large relative to the small change caused by enleanment and the change should be imperceptible to the operator.

Many engines, particularly small air-cooled engines such as those used in snowmobiles and in other high performance or high load applications, use fuel-rich mixtures to cool the engine under some operating conditions. Heat is absorbed by the additional fuel as it evaporates, thus cooling the engine combustion chamber and valves. In these engines, particularly if they are "open loop," the enleanment effect of oxygenates can increase engine operating temperatures.

In small engines, temperature increase is the primary fuel-related performance effect due to enleanment. The enleanment effect due to oxygenates, in engines with "open loop" systems, is similar in magnitude to the enleanment effect due to operating the engine at low ambient temperatures where the higher air density enleans the air-fuel mixture. Some small engine manufacturers recommend enriching the air-fuel mixture when using oxygenated gasolines, just as they recommend enriching the mixture to compensate for the enleanment effect of low temperatures. The adjustment needed to offset the enleanment effect due to oxygenates is roughly comparable to the enrichment needed to offset a 5 to 15 °F drop in ambient temperature[6].

Fuel Quality

Rough engine operation includes stalling, stumbling, rough idle, engine misfire, or engine knocking. It can occur for a variety of reasons, many of which are not fuel-related. Substandard fuel can, however, contribute to rough engine operation. The fuel characteristics responsible for such problems include excessively high or low volatility, insufficient octane, contaminants, and gum formation.

[6] Any adjustments for enleanment should be performed carefully; overcompensating for enleanment can create additional engine performance problems and increase emissions. Consumers should consult the manufacturer or a qualified service technician to obtain further information about engine adjustments.

Volatility. Gasoline volatility is controlled during refining to meet the requirements for the climate and region where it is sold. If its volatility is not appropriate, may cause either cold engine or warm engine start up problems.

Octane. As with any gasoline, insufficient fuel octane can result in knock or dieseling. Such problems may be corrected by switching to a higher-octane fuel. Continued rough operation on premium fuel may be an indicator of mechanical or other problems with the engine.

Contaminants. Plugged fuel filters occur when contaminants block the filter surface, reducing fuel flow through the filter. Some gasoline constituents, such as ethanol, behave like solvents and remove or dissolve components built up in the fuel tank or fuel lines. Once these components are loosened, they are transported to the fuel filter and if excessive, may cause filter plugging. Gasoline may also pick up contaminants from storage tanks and delivery trucks. For automobiles, this type of fuel filter plugging is expected to be a concern only in older cars (pre-1975 vintage). The lacquer build-up in the fuel systems of those cars is probably caused by gasoline with poor oxidation stability. The amount of build-up is related to vehicle age. Newer non-automotive equipment may experience fuel filter plugging though this is related more to extended storage periods where gasoline can deteriorate and lead to more deposits. The only remedy to a plugged fuel filter is replacement. Both automobile manufacturers and non-automotive equipment manufacturers usually offer a prescribed service schedule which includes periodic replacement of the filter.

Gum formation. Stored gasolines will oxidize over time and produce gums. The rate of gum formation varies with the types of hydrocarbons, the amount of oxidation inhibitor present, and time. Gum formation from poor quality gasoline can plug fuel filters and form engine deposits. In addition to poor gasoline quality, gum formation can occur due to adverse storage conditions, as discussed later in this report.

Antiknock Quality

The octane value posted on retail gasoline pumps is the average of the "Research" (RON or R) and "Motor" (MON or M) octane numbers, or "(R+M)/2". In the past, oxygenates have been used to increase gasoline octane, since oxygenates have higher octanes than many gasoline components. Oxygenates boost research octane to a greater extent than motor octane, however, and as a result, it is possible for an oxygenated fuel, with the same <u>posted</u> octane rating as a nonoxygenated fuel, to have a slightly lower <u>motor</u> octane level. Some engines respond more strongly to motor octane than research octane. At high speeds or under heavy load conditions, for instance when pulling a trailer up a hill, motor octane is the best indicator of antiknock performance. For these engines, a small reduction in motor octane could result in a slightly higher incidence of engine performance problems, such as engine knock, dieseling, or increased temperature. Over time, severe engine knock can lead to damaged pistons or other engine damage.

Although ASTM does not specify a minimum standard, it recommends that gasolines with a (R+M)/2 octane of 87 have a minimum motor octane of 82. Some refiners have their own internal minimum value which their gasoline must meet. Switching to a higher octane fuel will usually reduce or eliminate the symptoms caused by insufficient octane. If the symptoms persist, the engine is most likely suffering from problems unrelated to the fuel and should be examined by a qualified repair technician.

Improper Fuel Handling and Storage Practices

Improper fuel handling and storage practices can create a number of operational problems and can occur at all levels: fuel distributors, retailers, consumers. Gum formation and phase separation are two fuel-related phenomena that can be caused by improper handling and storage procedures and that can lead to operational problems.

Any gasoline stored for long periods of time or at high temperatures can deteriorate, contributing to gum formation, which can lead to plugged fuel filters and engine deposits, and the formation of deposits in engines and fuel systems. If gasoline is not to be used for long periods of time (greater than 1-2 months), it should be drained from the fuel tank or stabilized with a fuel stabilizer.

Ethanol-blended gasolines are particularly sensitive to poor handling and storage practices because of the possibility of phase separation. Basic precautions must be followed when introducing ethanol-containing fuels in a fuel distribution system for the first time. Water must be removed from fuel tanks and fuel lines to prevent water absorption and possible subsequent phase separation. Anytime a new fuel ingredient is introduced, its compatibility with the storage and delivery system materials must be verified to prevent deterioration of system components. Filters and screens must be in place to ensure that any foreign material is removed before it reaches consumers' fuel tanks. Failure to do so can result in fuel contamination with fuel system component materials or deposits, which can in turn impair vehicle performance by clogging fuel filters. Both the American Petroleum Institute and the Renewable Fuels Association have guidelines for station operators to follow to prevent problems related to fuel handling and contamination.

Water Absorption/Phase Separation

Separation of a single phase gasoline into a "gasoline phase" and a "water phase" can occur when too much water is introduced into the fuel tank. The actual occurrence of phase separation is rare. However, the water absorption that can eventually lead to phase separation is less rare and is most commonly caused by improper fuel storage practices at the fuel distribution or retail level, or due to the accidental introduction of water during vehicle refueling. Water has a higher density than gasoline, so if the water separates, it will form a layer below the gasoline. Because water does not burn, and because most engines obtain their fuel from at, or near, the bottom of their fuel tank, most engines will not run once the phases separate. Some small engines, however, that require that oil be mixed with the gasoline, may create a special situation. In such cases, if phase separation occurs, the alcohol/water phase may separate with the oil, thus removing the oil from the gasoline. If the engine is able to run on the remaining gasoline, damage could result from insufficient lubrication. Again, because the engine draws fuel from the bottom of the tank, it is unlikely to run on the alcohol/water mixture.

Nonoxygenated gasolines can absorb only very small amounts of water before phase separation occurs. Gasolines containing ethers such as MTBE or ETBE can absorb slightly more water before phase separation occurs. In such circumstances, the ethers remain mostly blended into the gasoline. The situation is more complicated for ethanol-containing fuels, however. Such fuels can absorb significantly more water without phase separation occurring than either nonoxygenated or ether-containing gasolines. Ethanol-containing fuels can actually dry out fuel tanks by absorbing the water and allowing it to be drawn harmlessly into the engine with the gasoline. If, however, too much water is introduced into an ethanol-containing gasoline, the water and most of the ethanol (typically 60-70%) will separate from the gasoline and the remaining ethanol. The amount of water that can be absorbed by ethanol-blended gasolines without phase separation, varies from 0.3 to 0.5 volume percent, depending on temperature, aromatics and ethanol content[7]. If phase separation does occur, the ethanol/water mixture would be drawn into the engine. In general, no gasoline engine can run on this mixture (except those also designed to run on high ethanol content blends).

Some manufacturers have expressed concern that ethanol-blended gasolines might absorb water vapor from the atmosphere, leading to phase separation. Such problems are of greatest concern for engines with open-vented fuel tanks that are operated in humid environments, such as marine engines. However, evidence for this phenomenon occurring is limited at best. States with extensive ethanol programs, such as Minnesota, have not reported problems with phase separation due to absorption of water from the atmosphere. Limited testing with ethanol blends suggests that the rate of water absorption from the atmosphere is very slow; it requires several months for open-vented marine fuel tanks to accumulate sufficient water to make phase separation possible, and another source of water is needed before separation will actually occur. Of far greater concern is the accidental introduction of water, by splash or spray, during fueling or the presence of water in the fuel tank prior to the addition of ethanol-blended gasolines.

Ether-blended gasolines are no more susceptible to phase separation than nonoxygenated gasolines. Consumers storing equipment for extended periods can select an ether blend if they are concerned about phase separation. Consumers can prevent phase separation by maintaining full fuel tanks when not in use and by purging the fuel tank of water condensation prior to introducing fuels, particularly ethanol-containing fuels. If phase separation does occur, the separated fuel should be removed from the tank and disposed of properly, in accordance with federal, state, or local requirements.

Materials Compatibility

Some materials used in fuel systems tend to degrade over time, such as the elastomeric materials used to make hoses and valves. Other fuel system components are made of metals and plastics and must also be compatible with the wide range of fuels. Elastomer degradation can occur for many reasons, such as repeated heating and cooling cycles, normal oxidation by the atmosphere, and corrosion by road salt and other substances. Fuel composition can also affect deterioration rates. For example, aromatics (a natural component of gasoline) can cause some parts to swell. In addition, degradation of some older elastomeric fuel distribution components may be accelerated by exposure to oxygenates, particularly methanol and ethanol.[8]

There are two distinct types of materials compatibility problems. <u>Acute failures</u> occur when a substance causes a part to fail within a very short period of time. <u>Accelerated deterioration</u> occurs when a substance causes a part to fail noticeably faster than would have been the case had the part not been exposed to that substance. Accelerated

[7]Fuel Ethanol Technical Bulletin: Archer Daniels Midland, September 1993.

[8]Of the alcohols, methanol blends may have the largest effect on elastomeric deterioration but methanol blends are not utilized to any significant degree in gasoline markets today.

deterioration can result from corrosion, chemical reactions between the fuel and the affected material, or permeation of the fuel through the material.

New elastomers called fluoroelastomers have been used in automotive and non-automotive engines since the mid-1980s. These newer materials are specifically designed to handle all modern gasolines, including high-aromatic, ethanol-containing, and ether-containing gasolines within these substances' legally permissible levels, without experiencing either of the materials compatibility concerns described above. Fluoroelastomers are far more resistant to permeation and corrosion than were earlier elastomers.[9]

Except for the oxygenates, the components found in oxygenated gasoline are normal constituents of gasoline that have been thoroughly tested for materials compatibility. The oxygenates used in gasoline have also been tested for materials compatibility, and no acute failures have been noted. Engine and elastomer manufacturers have indicated that even in older vehicles, any materials compatibility or deterioration problems that may be encountered would not result in immediate, acute failures of elastomeric components but rather would result in an increase in deterioration rates in-use. However, areas covered by the Oxygenated Gasoline program have not reported higher rates of materials degradation or failure than areas receiving conventional gasolines. Furthermore, gasolines with high levels of aromatics accelerate material degradation to a similar degree as oxygenated fuels. However, no increase in the rate of materials failures has been reported over the past several decades despite substantial increases in aromatics levels in order to maintain desired octane levels.

Permeation of fuel through elastomers can accelerate deterioration. In general, ethanol blends have higher permeation rates through elastomers than ether blends, which have slightly higher permeation rates than nonoxygenated gasoline. The higher permeation rates of oxygenate-containing gasolines are well within safety limits and are not expected to create performance, deterioration, or safety problems. No such problems have arisen during the 15 to 20 years of oxygenate use in the U.S. Furthermore, engines built since the mid-1980's generally use fluoroelastomers, which have far lower permeation and deterioration rates than earlier materials regardless of the oxygenate type and concentration found in the fuel (within legally permitted limits).

As part of normal vehicle maintenance, engine owners should inspect their engine and fuel distribution system for leaks and replace older or leaking components. Owners of pre-1986 engines (both automotive or non-automotive) with degraded elastomers and other engine parts should consider installing modern replacement parts, which are engineered to assure compatibility with all modern gasolines, including oxygenated gasolines.

Ether-based oxygenated gasolines are generally believed to be compatible with the fuel system materials. One automobile manufacturer has investigated the cause of fuel leaks in some of its 1984 - 1989 models and believes that exposure to gasolines containing MTBE was a factor in the deterioration of a plastic (nylon 6,6) component in the fuel injectors of those vehicles. The manufacturer is conducting a voluntary service campaign to replace fuel injectors and fuel hoses. The replacement plastic fuel injector components

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[9] Manufacturers' data suggest that fluoroelastomers and Viton are the preferred materials for use with alcohols, ethers, and high concentrations of aromatics. "Changes in Gasoline II," Downstream Alternatives, Inc., July 1992.

are made from another formulation of nylon 6,6. Other manufacturers using similar plastics have not reported similar problems.

Ethanol-based oxygenated gasolines also generally present no significant difficulty for fuel systems in vehicles manufactured after the early 1980's, again because of the use of fluoroelastomeric components. Ethanol blends could present some problems in older fuel systems and some small engine fuel systems, however, blends of up to 10% ethanol should not present significant materials compatibility problems. Because these oxygenates have been in use throughout the country for years, most older vehicles have been using them and will not experience an abrupt change in fuel composition.

Some concerns have been raised about the effect of oxygenated fuels on vehicle external surfaces such as paint and metals. Auto manufacturers' materials testing results have not indicated adverse affects on automobile non-engine external or cosmetic parts such as highly polished aluminum and painted surfaces.

Fuel Mixtures

EPA is not aware of, and does not expect, performance or driveability problems in vehicles that are operating on mixtures of gasolines that contain different oxygenates. Consumers have operated with mixtures of different oxygenates over the past fifteen years, the result of refueling at different service stations, without experiencing performance or other problems.

The adverse engine performance effects discussed earlier were either a function solely of the oxygen content of the fuel (as in the case of enleanment) or related to the specific types of oxygenates (as in the case of materials deterioration, water absorption/phase separation, and motor octane levels). None of these effects has any impact on whether mixtures of multiple oxygenates will produce any effects.

Nonoxygenated gasoline may not be sold in areas covered by an oxygenated gasoline program. Consumers, however, are not limited to purchasing gasoline only where they live. They can and do purchase gasoline in both covered and non-covered areas, thereby commingling the fuels. No unique problems have been observed from mixtures of oxygenated gasoline and nonoxygenated gasoline.

Gasoline containing higher levels of oxygenates than legally allowed (over blends) could cause or contribute to vehicle performance problems. While gasoline containing more than 15% MTBE or 10% ethanol (the upper limits currently permitted in gasoline) could cause or contribute to the problems discussed here or to other problems, it is highly unlikely that overblending will occur. First, and foremost, gasoline containing oxygenate in excess of the waivered limits are illegal and should not be available in the marketplace. EPA and the states have a range of enforcement programs designed to ensure that gasolines sold commercially meet the legal requirements, and private industry also monitors fuel quality nationwide. Second, oxygenates tend to be more expensive than gasoline, so it would not be economically sound for a fuel producer to overblend. Finally, blending processes at either the refinery or at the terminal have become far more sophisticated and less susceptible to error over the past decade, thereby minimizing overblending (although the risk of accidental overblending can never be eliminated completely).

CONCLUSIONS

Oxygenates have been used in gasoline for many years. Since the 1970s, ethanol has been added to gasoline. During the 1980s, other oxygenates, primarily MTBE, came into widespread use. Oxygenated gasoline blends are manufactured to meet the same ASTM specifications as nonoxygenated gasolines and are therefore very similar in composition. The fuel parameters of oxygenated gasoline are well within the parameters of gasolines that have been in widespread use.

Engine performance problems due solely to the presence of oxygenates in gasoline are not expected because of the chemical similarity of oxygenated and nonoxygenated gasolines and because of the demonstrated ability of in-use engines to accommodate the relatively minor differences.

Consumer concerns about large reductions in fuel economy are not supported by numerous laboratory and on-road studies. Existing research indicates that the largest fuel economy loss that could be attributed to the presence of oxygenates is 3%. Consumer estimates frequently fail to account for several critical factors that would explain their calculation error or provide the reason for lower fuel economy.