Gasoline Blending

An EPRINC Primer

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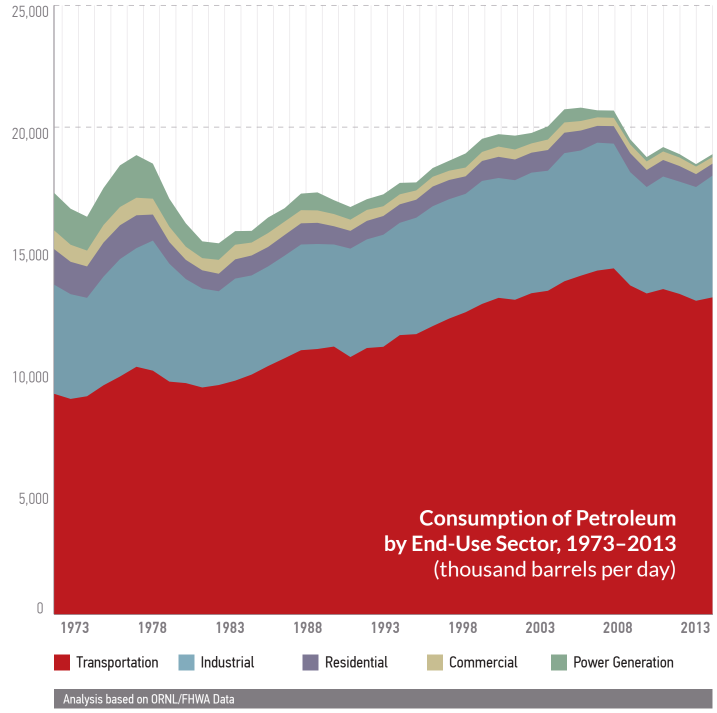
INTRODUCTION

In the US, transportation fuels account for a growing percentage of total petroleum use. In 1973, transportation fuels accounted for 52.3% of total petroleum consumption; in 2013, its share was almost 70%. In the collective category of light vehicles (automobiles, light trucks, and motorcycles), gasoline is the fuel for over 97% of them. Gasoline remains the predominant transportation fuel in the US.

While gasoline is derived from crude oil, for most of its history and in its current formulation it was always a blend of oil-derived components. Blending biofuels into the gasoline pool is a recent development. Today gasoline sold in the US market must meet the operational requirements of modern combustion engines, stringent environmental standards, and biofuel blending mandates; these three themes govern gasoline blending.



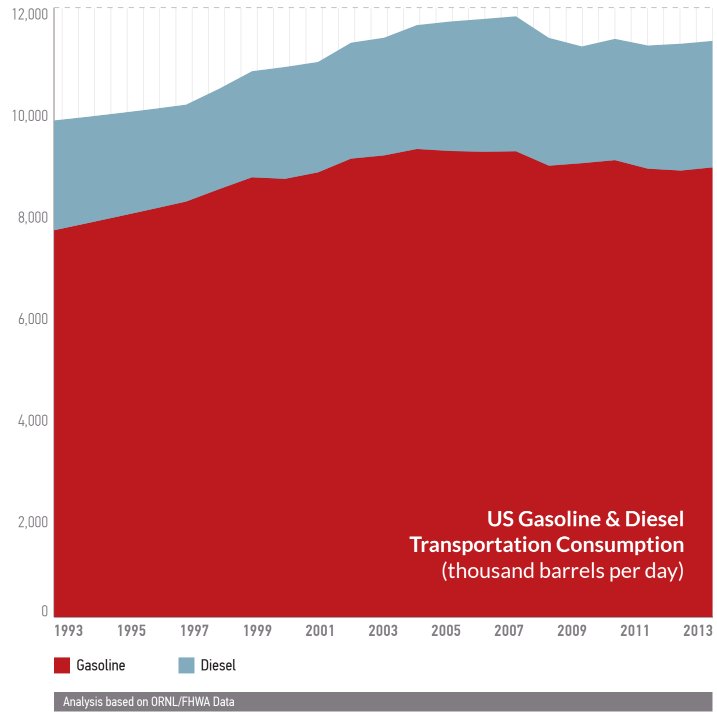
[1] EPRINC issued the Primer on Gasoline Blending in 2009. It has been updated to reflect the growing use of biofuels in the U.S. gasoline pool in recent years.

OPERATIONAL REQUIREMENTS—OCTANE

With the rapid adoption of automobiles at the beginning of the twentieth century, gasoline consumption increased rapidly. Initially, gasoline-powered automobiles had engines with low compression. Consequently, light naphtha, or straight-run gasoline was adequate. But automobile manufacturers quickly sought ways to accommodate increasing demand for vehicle power. More power could be obtained by increasing the number of cylinders in an engine; another way was to increase the compression of engines. With increased compression, straight-run gasoline would prematurely combust (commonly referred to as "knocking" or "pinging"), thereby delivering less power and with time damaging the engine to the point of making them inoperable. To mitigate and eliminate knocking, straight-run gasoline required something to delay or prolong combustion. The solution was to blend in "octanes."

The term "octane" is derived from those distilled crude oil components that have eight carbon molecules (hence "oct"). A metric of a gasoline's capability to not ping is its octane-rating. The higher the rating, the higher the gasoline's anti-knocking properties. Gasoline octane-rating improvements moved in tandem with increasing performance requirements of automobiles through 1970.The first widely used anti-knock compound was tetraethyl lead, a form of lead colloquially also known as "ethyl." It was introduced during World War I and had the added benefit of reducing wear on key engine valves.

There are three other refining conversion processes that increase the octane-rating of gasoline: catalytic cracking, alkylation, and isomerization. Catalytic cracking was first put into production in 1937, targeting residue and heavy distillates and converting them into high-octane gasoline components. Alkylation was developed initially in 1940 for World War II military aviation purposes, transforming butane-related components produced during distillation into alkylate, another high-octane additive. However, alkylation is a costly process, and therefore has a small installed base compared to other refinery processes.



OPERATIONAL REQUIREMENTS—RVP (REID VAPOR PRESSURE) AND SEASONAL BLENDING

While the octane of a particular grade is constant throughout the year, the RVP specification changes as cooler weather sets in. (Of course, all gasoline produced for sale in the U.S. must meet all local environmental specifications and include nationally set standards for blending in biofuels.)

RVP is the vapor pressure of the gasoline blend when the temperature is 100 degrees F. Normal atmospheric pressure varies, but is usually around 14.7 lbs per square inch (psi). Atmospheric pressure is caused by the weight of the air over our heads. If a liquid has a vapor pressure of greater than local atmospheric pressure, that liquid boils. For example, when you heat a pot of water, the vapor pressure increases until it reaches atmospheric pressure. At that point, the water begins to boil.

In the summer, when temperatures can exceed 100 degrees F in many locations, it is important that the RVP of gasoline remain well below 14.7. Otherwise, it can pressure up gas tanks and gas cans, and it can boil in open containers. Gas that is boiled off ends up in the atmosphere, and contributes to air pollution. Therefore, the EPA has declared that summer gasoline blends may not exceed 7.8 psi in some locations, and 9.0 psi in others[2]. A few counties have requirements as low as 7.0 psi as part of a program to comply with EPA requirements to bring a locality into compliance with national ambient air standards. This is why refineries produce a more expensive fuel blend during the summer as it is helpful in cutting down on smog during hot months. Stations nationwide will start selling a less-expensive winter fuel usually by mid September, which on average means that winter gasoline is less expensive than summer gasoline.

A typical summer gasoline blend might consist of 40% FCC gas, 25% straight run gas, 15% alkylate, 18% reformate, and 2% butane. The RVP of the gasoline blend depends on how much of each component is in the blend, and what the RVP is of each component. Butane is a relatively inexpensive ingredient in gasoline, but it has the highest vapor pressure at around 52 psi. In a gasoline blend, each component contributes a fraction to the overall RVP. In the case of butane, if there is 10% butane in the blend, it will contribute around 5.2 psi (10% of 52 psi) to the overall blend. (In reality, it is slightly more complicated than this, because some components interact with each other which can affect the expected RVP). This means that in the summer, the butane fraction must be very low in the gasoline, or the overall RVP of the blend will be too high. That is the primary difference between winter and summer gasoline blends.

Winter gasoline blends are phased in as the weather gets cooler. September 15th is the date when an increase in RVP is permitted, and in some areas the allowed RVP eventually increases to 15 psi. This has two implications for gasoline prices every fall. First, as noted, butane is a cheaper blending component than most of the other ingredients. That makes fall and winter gasoline cheaper to produce. But butane is also abundant, so that means that gasoline supplies effectively increase as the RVP requirement increases. These factors normally combine each year to reduce gasoline prices in the fall. The RVP is stepped back down to summer levels starting in the spring, and this usually causes prices to increase.

[2] EPA regulations permit gasoline ethanol blends of 9-10% to exceed this standard by 1.0 lb. psi of applicable RVP, subject to state and local environmental conditions.

ENVIRONMENTAL STANDARDS

The EPA (US Environmental Protection Agency) is the organization that regulates emissions and other environmental aspects relating to gasoline. The EPA first received its authority through the 1970 Clean Air Act (CAA); subsequent additional amendments have been added to the CAA to expand its mandate. It is with the 1970 CAA that the tandem of gasoline octane-rating improvements and increasing performance requirements of automobiles ended. The CAA stipulated the necessity of the reduction of emissions such as carbon monoxide and ozone, and the elimination of the use of lead, aromatics, and other similar octane-enhancing additives. In their place, engines began being built with evaporative control systems and catalytic converters, and oxygenates were required in place of aromatics.

All vehicles sold in the United States (at least since the 1980s) are required to have a fuel evaporative control system (called an EVAP system in automotive jargon) which collects expanding fuel vapor from the fuel tank in a charcoal-lined canister while the engine is stopped and then releases the collected vapors (through a "purge valve") into the engine intake for burning when the engine is running (usually only after it has reached normal operating temperature.) The fuel evaporative control system is also required to include a special filling cap which seals the fueling inlet to prevent vapors from escaping directly from the tank through it. Modern vehicles with OBD-II emissions control systems will turn on the MIL (Malfunction Indicator Light, a.k.a. "check engine" light) if it is detected that the gas cap is missing or loose and so not sealing. (The general purpose of this light is to indicate when any of the emissions controls are not working properly.)

Oxygenate blending adds oxygen to the fuel through the addition of oxygen-bearing compounds such as MTBE, ETBE and ethanol, and so reduces the amount of carbon monoxide and unburned fuel in the exhaust gas, thus reducing smog. In many areas throughout the U.S. oxygenate blending is mandated by EPA regulations to reduce smog and other airborne pollutants. For example, in Southern California, fuel must contain 2% oxygen by weight, resulting in a mixture of 5.6% ethanol in gasoline.

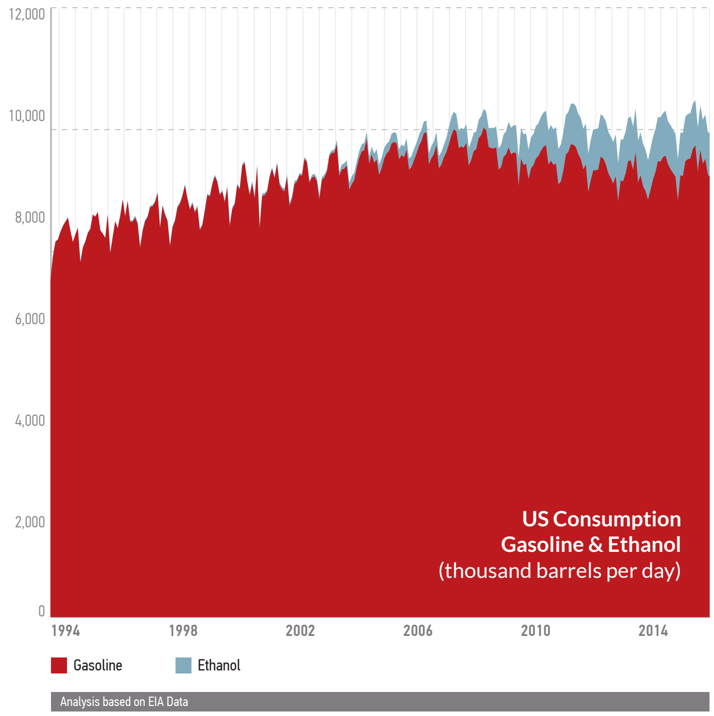
With the CAA-targeted elimination of aromatics and lead, other components were required to maintain octane-rating in gasoline. Also, reduction was required of carbon monoxide and unburned fuel in the exhaust gas in order to reduce smog. MTBE, ETBE, and ethanol initially proved serviceable as replacements. The resulting fuel is often known as RFG[3] (reformulated gasoline) or oxygenated gasoline.

But MTBE had an unintended consequence: its seepage from underground tanks contaminated water supplies. The 2005 Energy Policy Act required the elimination of MTBE with no mandated substitute. By default, ethanol's use was expanded as an oxygenate.

However unlike gasoline blended with MTBE, gasoline blended with ethanol cannot be sent through pipeline systems because of ethanol's high solubility

[3] RFG is required in cities with high smog levels and is optional elsewhere. RFG is currently used in 17 states and the District of Columbia. About 30 percent of gasoline sold in the U.S. is reformulated.Reformulated Blendstock for Oxygenate Blending (RBOB) and a close alternative, Conventional Gasoline Blending Components (CBOB) are the two base gasoline stocks that get mixed with ethanol at the terminal racks. RBOB is more expensive to produce—more energy and more effort are required to pull some of the additional hydrocarbons out of the fuel.

with water. Therefore, ethanol-oxygenated gasoline cannot be manufactured at a refinery, but instead needs to be blended at terminals close to filling stations, the final delivery point. To this end, gasoline blending underwent a major logistical reconfiguration, and RBOB (reformulated blendstock for oxygenate blending) was formulated and began production for pipeline deliveries to terminals.



BIOFUEL MANDATES

Soon after ethanol began to be widely used as an oxygenate, concerns about U.S. dependence on imported oil led to the passage of the Energy Policy Act of 2005 and the Energy Independence and Security Act (EISA) of 2007. These laws established a mandate for increased blending of renewable fuel into the domestic gasoline pool. Although the mandate includes requirements for biodiesel and cellulosic biofuel, ethanol from corn remains the main blending component for gasoline[4]. The mandate required specific and higher volumes of ethanol blending into domestic gasoline supplies under the assumption that U.S. gasoline demand would continue to grow at high rates. This assumption proved incorrect. In 2014, U.S. drivers consumed about 8.9 million barrels/day of gasoline, 4% less than the U.S. record high consumed in 2007.

The EISA contains a volumetric mandate under the renewable fuel standard (RFS). Refiners are required to blend specific quantities of renewable fuels each year into the gasoline pool. These volumetric targets began at 26,000 bbl/d in 2006 and rise to 2.35 million bbl/d in 2022, or approximately 22% of the gasoline pool depending upon the growth in U.S. gasoline consumption. Administering the program is complex, and every year EPA is required to estimate gasoline (and diesel consumption) ahead of time and then set percentage targets for renewable fuels for refiners to blend into gasoline. However, EPA has not issued the volumetric requirement on a timely basis in recent years as the introduction of higher volumes of biofuels into transportation fuels has

[4] The RFS program regulates the volume and blending of biofuels in gasoline and diesel, and is met with a combination of conventional (ethanol) and so-called advanced (cellulosic) renewable fuels. Cellulosic fuels continue to face a wide range of economic and technical constraints and have had limited availability. The RFS program has an extremely complex compliance program, with considerable regulatory risk which is beyond the scope of this paper. For a full discussion of the operation of the RFS program, consequences to supply and transportation fuel prices under different scenarios, see The Renewable Fuel Standard – Issues for 2014 and Beyond. Congressional Budget Office, June 2014. https://www.cbo.gov/publication/45477.

come against technical and cost constraints. A major problem with the program is that meeting the volumetric targets is becoming increasingly difficult (and costly) because of consumer resistance and technological constraints in placing ethanol into the gasoline pool at percentages higher than 10 percent, also known as the blendwall. A large percentage of the automobile fleet cannot accept fuel with more than 10% ethanol without damaging engines and U.S. law generally has prohibited such higher blends.

The RFS program is administered by requiring all refiners and other obligated parties (such as importers) to document that they have blended ethanol into gasoline by acquiring RINs (renewable identification numbers). Ethanol producers generate RINs when product is produced and are then acquired from ethanol producers by obligated parties when blended into gasoline. In recent years, the ethanol fuel mandate or RFS permitted ethanol blending below 10% of the gasoline pool. Refiners and other obligated parties could, however, blend above their mandated requirement and then retain those extra RINs for sale to obligated parties who had not met their volumetric mandates.

Fuel providers could also comply with the mandate for blending more ethanol volumes into the gasoline pool through sales of specialty blends, so called E15 or E85. In October 2010, the EPA granted a waiver to allow up to 15% of ethanol blended with gasoline to be sold for cars and light pickup trucks with a model year of 2007 or later. January 2011, the waiver was expanded to authorize the use of E15 to include model year 2001 through 2006 passenger vehicles. E15 has had only limited acceptance by consumers over concerns over misfueling, its potential to harm engine performance, disagreements over its effect on engine and fuel systems, and warnings by some auto manufacturers that warranties will be cancelled if blends above 10% are used.

E85 is another alternative to raise the volume of biofuel into the U.S. gasoline supply, but its application has been limited as there are not enough flex-fuel vehicles (only about 4% of the vehicle fleet), E85 service stations, and consumer demand for E85, and because E85 infrastructure and marketing is uneconomic. Consumer resistance to E85 is substantial as the fuel is more costly than premium gasoline when adjusted for energy content and mileage performance. Both E15 and E85 do not provide a cost effective compliance strategy for meeting volumetric targets under the RFS and therefore EPA, using its authority under EISA, has reduced required blending volumes into the gasoline pool.

When relative prices of all the components used for the production of gasoline shift, refiners move quickly to produce and blend a new mix of components to achieve a lower cost gasoline that can meet both engine performance and environmental requirements. The federal biofuel mandate constrains refiners from making cost-effective adjustments and adds considerable uncertainty and cost escalation in the production of gasoline. In those circumstances when EPA sets volumetric biofuel requirements above the 10% blendwall, refiners and other obligated parties that fail to meet the volumetric blending requirements must pay a costly fine to the government or must purchase RINs from refiners and blenders who have excess RINs acquired in an earlier period from blending at rates above the required mandate.

As the entire gasoline pool faces a requirement of 10% or greater ethanol blending, the availability of excess RINs will be limited as they expire 18 months after acquired and such excess blending opportunities are fast disappearing. As the RFS mandate requires blending increasing volumes of ethanol above 10% of the gasoline pool, fuel providers will face a rapidly rising compliance cost requirement. The high cost of compliance creates a cost incentive for refiners to undertake measures to keep their sales in the domestic market at a volume that will not impose rising costs (i.e., crossing the 10% blendwall).

Several alternatives are available to refiners and obligated parties. Among these are, shifting production of fuels outside the mandate (e.g., jet fuel), exporting higher volumes of refined products, or reducing production (refinery runs) of transportation fuels for the domestic market. All of these outcomes add costs to refinery operations and will bring about rising domestic gasoline and diesel fuel prices. The amount of the fuel price increase will depend upon the volumetric targets set by EPA, particularly if that target is set above the blendwall. Although feed stock costs (crude oil) continue to play the primary role in setting gasoline prices, EPA's, through its administrative authority to specify requirements for biofuel use in U.S. transportation fuels, will now also play an important role in determining gasoline prices in the domestic market.

US Transportation Energy Consumption by Mode and Fuel Type (thousand barrels per day)

	1993					2013				
	Gasoline	Diesel	Jet	Residual fuel oil	Total	Gasoline	Diesel	Jet	Residual fuel oil	Total
HIGHWAY	7,393.6	1,573.5			**8,973.0**	8,359.4	2,706.8			**11,114.7**
Light vehicles	7,042.0	133.7			7,175.7	8,041.6	192.1			8,268.3
Cars	4,835.9	58.7			4,894.6	3,820.3	18.9			3,839.2
Light trucks	2,193.3	74.9			2,268.2	4,188.3	173.3			4,396.2
Motorcycles	12.9				12.9	33.0				33.0
Buses	20.2	66.6			86.8	4.7	80.5			85.2
Medium/heavy trucks	331.4	1,373.2			1,708.1	313.2	2,434.2			2,761.2
OFF HIGHWAY	71.2	268.1			**339.3**	73.6	268.1			**341.7**
NON-HIGHWAY	150.5	323.0	946.2	409.0	**1,828.7**	119.8	391.2	997.6	299.3	**1,807.8**
Air	19.7		946.2		965.9	14.8		997.6		1,012.3
Water	130.8	133.3		409.0	673.2	105.1	143.9		299.3	548.2
Rail		189.6			189.6		247.3			247.3
TOTAL HIGHWAY & NON-HIGHWAY	7,615.3	2,164.6	946.2	409.0	**11,140.9**	8,479.2	3,098.0	997.6	299.3	**12,922.4**

Analysis based on ORNL and FHWA Company Data