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Analysis of Gasoline Octane Costs

Prepared for

Independent Statistics & Analysis
U.S. Energy Information Administration

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1. NOTICE

This report was prepared by Baker & O’Brien, Inc. (Baker & O’Brien) using its own models and analysis. The opinions and findings in this report are based upon Baker & O'Brien's experience, expertise, skill, research, analysis, and related work to date. Forecasts and projections contained in this report represent Baker & O'Brien's best judgment utilizing its skill and expertise and are inherently uncertain due to the potential impact of factors or future events that are unforeseeable at this time or beyond Baker & O'Brien's control. In the event that additional information should subsequently become available that is material to the conclusions presented herein, Baker & O'Brien reserves the right to supplement or amend this report. Nothing in this report should be construed as a recommendation for or against implementing any policies and regulations. Baker & O'Brien expressly disclaims all liability for the use, disclosure, reproduction, or distribution of this report by or to any third party.

2. Executive Summary

Since 2012, the average retail price differential between regular and premium gasoline in the United States increased from approximately 0.20 dollars per gallon ($/gal) – 0.30 $/gal to 0.53 $/gal in 2017. The differential has roughly doubled in PADDs 1, 2, 3, and 4 from the range of 0.20 $/gal - 0.30 $/gal to 0.50 $/gal - 0.55 $/gal, with a more modest increase in PADD 5, from approximately 0.25 $/gal to 0.35 $/gal. The U.S. Energy Information Administration (EIA) retained Baker & O'Brien, Inc. to analyze the factors and conditions leading to the increased differentials.

2.1 WHAT IS GASOLINE?

Gasoline is a complex mixture of hydrocarbons and other chemical compounds used as fuel for spark-ignition internal combustion engines, primarily in light duty transportation vehicles (LDV). Gasoline in the United States must meet over a dozen individual specifications, which may vary both regionally and seasonally. Different gasoline "classes" (i.e., conventional or reformulated) are formulated to meet particular regional specifications. Moreover, each "class" of gasoline has different octane levels (i.e., regular or premium), as well as specifications that vary seasonally (i.e., Reid Vapor Pressure).

2.2 GASOLINE PROPERTIES AND SPECIFICATIONS

The gasoline octane rating measures its ability to withstand pre-ignition during compression in an engine cylinder. Gasoline octane is a critical factor in engine design. Engine performance and efficiency increase with increasing compression ratio. Engines with higher compression ratios require gasolines with higher octane ratings. In the United States, the posted gasoline octane rating is the average of two different testing methods, the Research Octane Number (RON) and the Motor Octane Number (MON). The average is referred to as the Anti-Knock Index (AKI). Most U.S. LDV are designed for regular, 87 AKI gasoline. Approximately 10% of vehicles require or recommend premium gasoline (91 AKI or higher).

To burn, liquid gasoline must be vaporized and mixed with oxygen (air). Since gasoline is a blend of hundreds of molecules with different characteristics, gasoline boils (vaporizes) over a range of temperatures and must be blended in a way that vaporization will occur over the entire range of engine operating temperatures. Several specifications measure and control the vaporization performance of gasoline:

- Reid Vapor Pressure (RVP)
- Distillation
- Drivability Index (DI)
- Vapor-Liquid Ratio (V/L)

The EPA also sets limits on the sulfur and benzene content of finished gasoline. Other industry specifications limit the tendency and ability of the gasoline blend to foul, damage, or corrode gasoline storage facilities as well as components of the vehicles combustion and exhaust systems. These specifications include Gum, Oxidation Stability, Color, NACE Corrosion, and Phosphorous.

2.3 POTENTIAL CHANGES IN OCTANE REQUIREMENTS

The Energy Policy and Conservation Act enacted in 1975 required that the Department of Transportation (DOT) establish Corporate Average Fuel Economy (CAFE) standards setting the average new vehicle fuel economy that each manufacturer's fleet must achieve. Currently, CAFE standards require that average model year 2017 vehicles achieve approximately 40 miles per gallon (mpg), with model year 2025 vehicles projected to achieve approximate 51 mpg. These are calculated compliance fuel economy measures, so average on-road fuel economy would be lower. Automakers are considering technical solutions that include compression ratio increases and may require higher gasoline octane.

2.4 GASOLINE COMPONENTS

Petroleum refineries are the main source of finished gasoline and blendstocks for oxygenate blending (BOBs). Non-refinery blenders produce the balance using gasoline components also produced primarily in petroleum refineries. Other sources include natural gas processing plants, ethanol plants, and petrochemical plants. NGL production has almost doubled since 2010 and is equivalent to approximately 7% of 2016 finished gasoline consumption. Ethanol represents approximately 10 volume percent (vol%) of the finished gasoline consumed in the United States.

2.5 GASOLINE CONSUMPTION

U.S. gasoline consumption averaged 9.3 million barrels per day (b/d) in 2016, an all-time high. However, excluding ethanol, the consumption of petroleum-derived (i.e., excluding ethanol) gasoline is still below the 8.9 million b/d peak reached in 2006. Regular gasoline comprises 87% of all gasoline sold. Premium gasoline sales have increased slightly since 2012 to approximately 12% but remains well below historical peak levels of 18% seen in 2000. Thus, the total AKI demand for petroleum derived blending components also remains below the peak years of 2006 and 2007.

2.6 GASOLINE PRODUCTION

Between 2008 and 2016, U.S. gasoline production grew at an average rate of 1.6% per year, a rate faster than domestic consumption grew. The United States went from being a net importer to a net exporter of gasoline and gasoline components. In 2016, the total petroleum based gasoline production averaged 8.4 million b/d, the highest production over the past 16 years. This increase in gasoline production is a result of: 1) Changes at refineries; 2) Changes in crude oil quality; and 3) Increased ethanol usage.

The majority of refinery changes between 2010 and 2016 involved increasing crude throughput and increasing refinery distillate production. Crude distillation capacity increased 8%, while hydrocracking capacity increased by 26%. Hydrocrackers primarily produce distillates such as jet fuel and diesel, gasoline components, and feedstocks for other units. There were almost no capacity increases to units that primarily produce gasoline or high octane gasoline components. The U.S. refining crude slate quality changed significantly between 2012 and 2016. Refinery consumption of "light" shale crude and condensate more than doubled, reaching 20% of the total (from 10%). As the amount of light crude oil processed increased, production of low octane light straight-run naphtha also increased, refineries compensated for this by increasing reformer utilization and severity.

EIA data indicate that spare reformer capacity is still available in most PADDs implying that the U.S. refining industry has capacity to produce incremental octane. The cost of producing incremental octane was calculated using two approaches and was shown to be less than the market price of octane.

2.7 INTERNATIONAL GASOLINE MARKETS

Gasoline, gasoline components, and feedstocks (e.g. naphtha) used to make gasoline are global commodities that are frequently traded between regions and countries. The U.S. East Coast (PADD 1) and U.S. Gulf Coast (PADD 3) markets are particularly integrated with other markets in the Atlantic Basin. Large quantities of gasoline and gasoline components from Canada and Europe are imported into PADD 1. At the same time, even larger quantities are exported from PADD 3 primarily to Africa and Latin America.

2.8 PREMIUM TO REGULAR PRICE DIFFERENTIALS

Gasoline is distributed from refineries by a variety of methods and supply chain components owned and operated by a wide range of commercial interests. Owners include not only refining and marketing companies but also other independently owned and managed entities, such as transport companies, traders, marketers, and blenders that specialize in particular supply chain functions.

Finished gasoline is bought and sold at multiple points in the supply chain. The retail price that the consumer sees is usually set by the owner/operator of the individual retail outlet. Retail owners/operators purchase finished gasoline from bulk terminals on either a delivered tank wagon basis or at the rack price. Refiners, traders, and others also buy and sell finished gasoline and components in the spot market upstream of the bulk terminals. Spot market prices are more closely tied to refinery and blending costs than rack or retail prices.

The retail price differential between premium and regular has widened significantly over the past seven years, reaching over $0.50/gallon ($/gal) in September 2017. There is a significant regional variation with PADD 1 having the highest differential and PADD 5 the lowest.

The major U.S. petroleum product spot markets are the United States Gulf Coast (USGC) and New York Harbor (NYH). From 2010 through 2016, spot market premium to regular differentials in the USGC (PADD 3) and NYH (PADD 1) generally trended together. Prices in these two spot markets are indicative of refining costs and product availability in the Atlantic Basin. Smaller spot markets exist in Chicago (PADD 2) and the West Coast (PADD 5).

The NYH and USGC spot market data show a number of spikes in the premium to regular price differential beginning in 2011 and through 2015. It is most likely that these spikes were a result of changes in product cost and availability. The spot market differential spikes resulted in increased premium to regular differentials at the retail level. After each of these spot market spikes, the spot market differential declined more rapidly than at the wholesale and retail levels.

2.9 CONCLUSIONS

This study tested the premise that retail premium to gasoline differentials have risen due to increased refining costs or long-term structural shortages of the high octane gasoline components. The analysis did not support either of these conjectures. Instead it appears that asymmetric price transmission (known colloquially as the rocket and feathers hypothesis) is responsible. The rocket and feathers phenomenon, in which retail gasoline prices increase rapidly when costs increase but decrease much more slowly when costs decrease, has been observed previously in refined product prices. There is general agreement among studies that the phenomenon is common and that there is a statistically significant difference between the speed of upward movements and the speed of downward movements in gasoline prices relative to input costs (i.e. crude prices). Since the studies differ in the statistical methods they use, estimates of the length of time it takes for the gasoline-crude price spread to return to a normal level vary widely.

A possible explanation for the slower price decline rate is the existence of search and adjustment costs. For the most part, discovering the lowest price after a market change requires physically visiting different retail outlets. This implies a cost to finding the station with the best price and a tradeoff between search costs and price discovery. This tradeoff would cause consumers to stick with their normal outlet at first, then gradually discover locations with better prices and switch.

The search and adjustment cost theory implies lower price elasticity immediately after a market change. Each retail outlet can quickly raise pump prices to recover wholesale cost increases without losing sales to other stations. If a spike in wholesale prices is temporary, retail outlets will only slowly feel pressure to lower prices because the cost of search will, therefore, tend to keep consumers with their normal supplier. As consumers gradually acquire more information about prices in different locations, retailers will be forced by competition to lower prices but with a lag based on how quickly consumers gain additional information.

While the regular-premium price differential has been increasing since 2014, absolute gasoline prices fell dramatically starting in 2014, as crude prices plummeted from over $100/barrel (b) in June 2014 to approximately $50/b at the end of 2016. The drop in absolute prices coincides with an increase in premium gasoline consumption as a percentage of total gasoline sales. It appears that the marginal premium gasoline buyer is more sensitive to the absolute price of premium gasoline than to the price differential to regular gasoline. This implies that premium gasoline is a separate market from regular gasoline.

Higher search costs to discover premium prices relative to search costs for regular prices could also help explain why premium prices decline more slowly than regular prices. This would be the case if retail premium prices are less transparent to the consumer. In many instances, only the regular gasoline price is advertised on the street, so consumers must physically drive into the retail outlet to determine the premium price of gasoline. The theory that high search costs have an impact is supported by the data from Los Angeles. In this market, retailers must display prices, for all grades of gasoline, prominently on the street. Los Angeles showed essentially no change in the retail differential across the 2010 to 2016 period. PADD 5 on average showed the smallest increases in premium to regular differentials of all the PADDs.

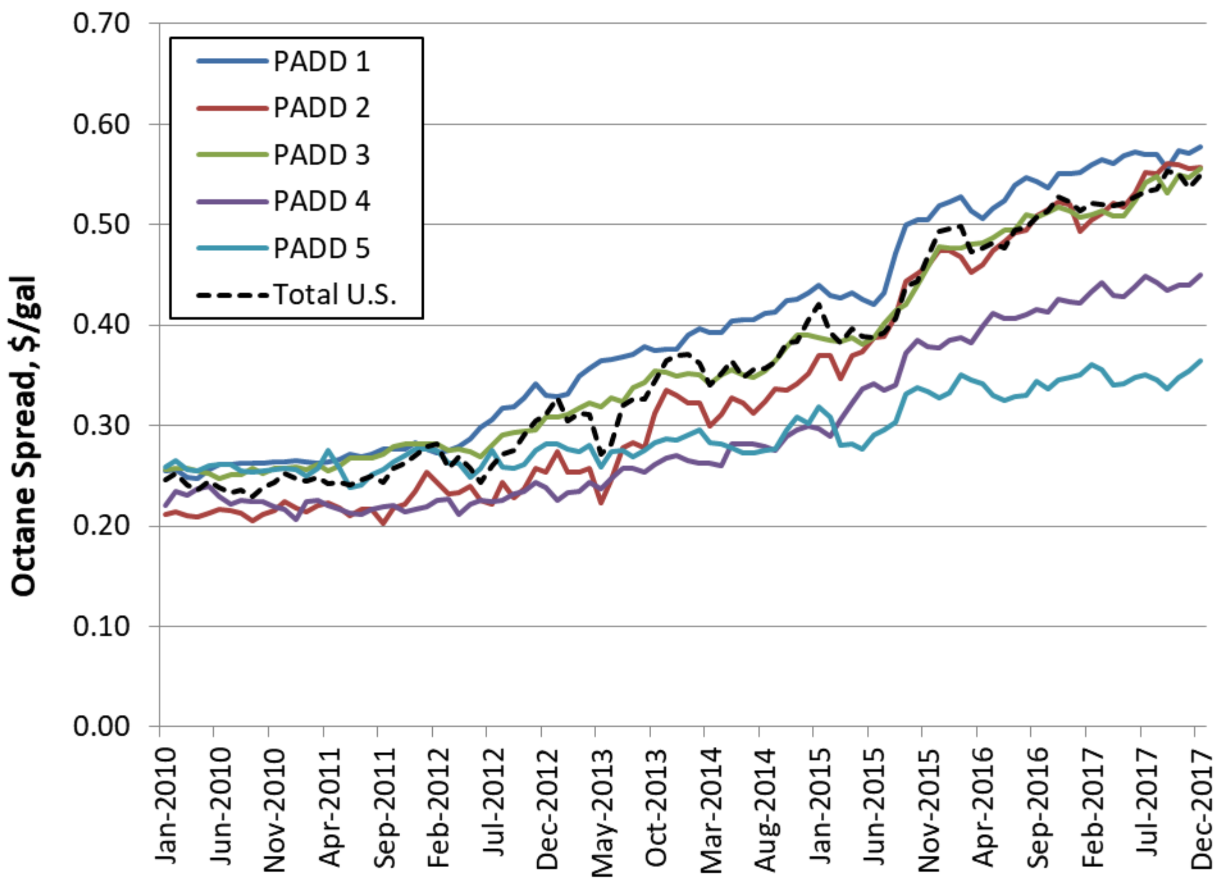
A detailed analysis of price asymmetry and search costs was outside the scope of this study.

3. INTRODUCTION

Beginning around 2012, the retail price difference between regular grade gasoline, typically an 87 Anti-Knock Index (AKI), and premium grade gasoline, typically 91 AKI to 93 AKI, has steadily increased in all Petroleum Administration for Defense Districts (PADDs) (Figure 1). For the total United States during 2017, the average retail price differential between regular and premium gasoline averaged 0.53 dollars per gallon ($/gal). In PADDs 1, 2, 3, and 4, the current differential is approximately double what it was in 2010 and 2011 (0.50 $/gal - 0.55 $/gal versus 0.20 $/gal - 0.30 $/gal). The differential has increased at a slower rate in PADD 5 (from approximately 0.25 $/gal to 0.35 $/gal).

FIGURE 1

PREMIUM TO REGULAR RETAIL PRICE DIFFERENTIAL



Source: U.S. Energy Information Administration

The United States (U.S.) Energy Information Administration (EIA) has retained Baker & O’Brien, Inc. (Baker & O’Brien) to analyze the factors and conditions that have resulted in increased differentials. The period studied was 2010 through 2016.

Baker & O’Brien made extensive use of its *PRISM*™ Refining Industry Analysis modeling system in the performance of this study. The *PRISM* model is based on publicly-available information and Baker & O'Brien's industry experience and knowledge. No proprietary or confidential refining company information is solicited or included in the *PRISM* modeling results. The results are estimates, and actual outcomes could vary.

Baker & O’Brien subcontracted to EMC-Energy Market Consultants (UK) Ltd., part of the FGE Group (FGE) and Hedges & Company (Hedges) for portions of the analysis presented in this report. Dr. W. David Montgomery also assisted Baker & O’Brien in the analysis and preparation of this report.

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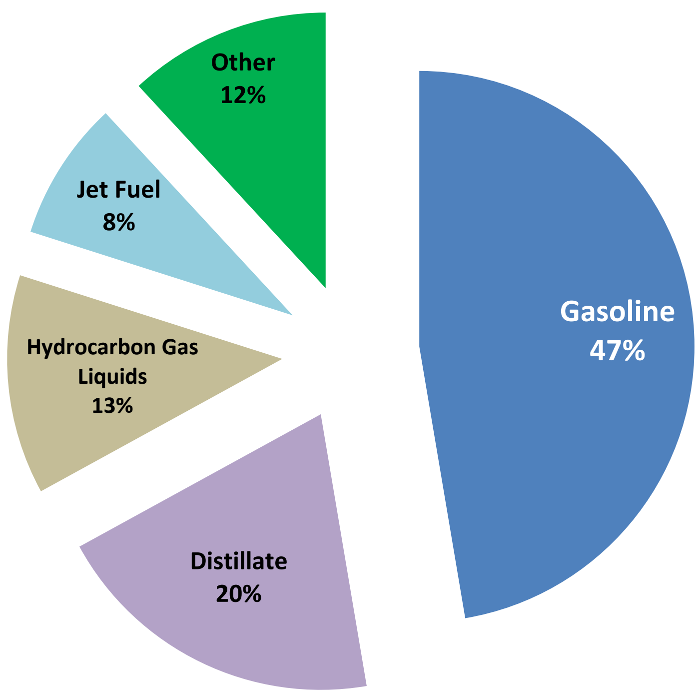
4. BACKGROUND

4.1 WHAT IS GASOLINE?

Gasoline is a complex mixture of chemical compounds used as fuel for spark-ignition internal combustion engines. In 2016, gasoline represented 47% of total U.S. finished petroleum-based fuel consumption (Figure 2). In the United States, gasoline is the predominate fuel for light duty transportation vehicles. It is also used for other modes of transportation (i.e., boating) and in small engines such as lawnmowers.

FIGURE 2

2016 U.S. PETROLEUM-BASED FUEL CONSUMPTION[1]



Sources: EIA, Baker & O'Brien Analysis

[1] Excludes ethanol and other bio-fuels.

4.2 GASOLINE PROPERTIES AND SPECIFICATIONS

Finished gasoline sold in the United States must meet over a dozen individual specifications. These specifications vary both regionally and seasonally. The term “class” is used in this report to describe gasoline that meets the specifications for a particular region (i.e., conventional gasoline or reformulated gasoline). Within each class, there are different grades which vary in octane rating (i.e., regular or premium). Some specifications are constant throughout the year for a class, while others (i.e., RVP) change seasonally. The term “finished gasoline” refers to gasoline that meets all specifications for retail sales. The terms “components” and “blendstocks” refer to products that may be used to produce finished gasoline. One special group of blendstocks is Blendstocks for Oxygenate Blending (BOBs). BOBs are blended so that they meet finished gasoline specifications when a predetermined quantity of ethanol (usually 10%) is added.

4.2.1 OCTANE RATING

Octane rating measures a fuel’s ability to withstand compression without pre-igniting. In a gasoline engine, a fuel-air mixture is compressed by the piston moving upward in each cylinder. As it is compressed, the fuel-air mixture temperature rises. After the spark plug fires, the expanding vapor and flame propagates through the cylinder, further increasing the temperature and pressure of the remaining uncombusted fuel-air mixture. A combination of heat and pressure can cause the mixture to ignite (in the cylinder) before the spark plug fires, or before the propagating flame reaches the mixture. This pre-ignition results in the characteristic knocking or pinging sound and can lead to engine damage. The compression ratio (the ratio of the maximum volume of a cylinder to its minimum volume) of an engine has increased with engine design to improve efficiency. However, as the compression ratio increases, the peak pressure and temperature increase, and consequently the tendency of gasoline to pre-ignite also increases. Therefore, engines with higher compression ratios may require gasolines with higher octane ratings. Engine manufacturers specify the Octane Number Requirement (ONR) of each engine based on engine design factors and in-use conditions.

Two different methods are used to measure octane ratings. The Research Octane Number (RON) method tests fuel at low engine loads by comparing it under variable compression ratios to mixtures of the reference fuels isooctane (100 RON) and normal heptane (0 RON). In most of the world, the RON is what is posted on the retail station pump. The second method, the Motor Octane Number (MON), is similar to RON testing but at a higher engine load. The arithmetic average of RON and MON (RON plus MON divided by two; (R+M)/2) is known as the Anti-Knock Index (AKI). The AKI is what is posted at retail station pumps in North America.

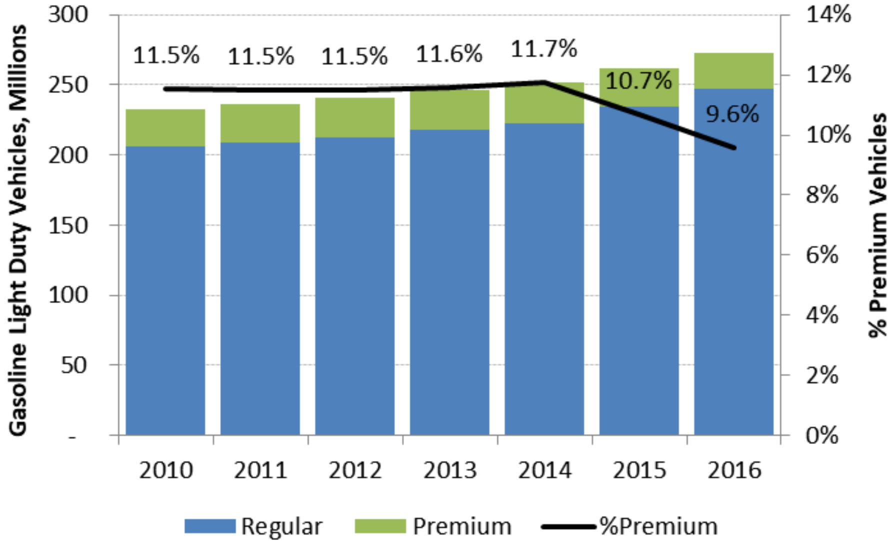
Most North American light-duty gasoline fueled vehicles (LDV) are designed to operate using regular gasoline with an AKI of 87.[2] For approximately 10% of these LDVs, the manufacturer's owner's manual requires or recommends premium gasoline (AKI of 91 or higher). Engine designs that require higher AKI gasoline can result in higher vehicle fuel economy, better performance, or both. EPA allows manufacturers to certify vehicle fuel economy using either 87 AKI or 91 AKI gasoline. Premium recommended vehicles are certified using 91 AKI gasoline, but do not require 91 AKI for daily driving.

Between 2010 and 2016, the total number of light duty vehicles in operation in the United States increased from 233 million to 273 million. Between 2010 and 2014, premium recommended or premium required vehicles (based on owner's manuals) comprised between 11.5% and 11.7% of the total fleet (Figure 3). In 2015 and 2016, the count of these "premium" vehicles declined and the percentage of the fleet decreased to 10.7% and 9.6%, respectively.

[2] In some regions of the United States, regular gasoline with AKI ratings of 85 or 86 is sold. In other regions, premium gasoline with AKI ratings of 92 or 93 is sold. AKI requirements in certain mountain regions are generally lower, based on previous studies that indicated knock tendencies in carbureted engines decreased at high altitudes.

FIGURE 3

U.S. LIGHT DUTY GASOLINE VEHICLES IN OPERATION



Source: Hedges & Company. Includes vehicles with gross weight up to 10,000 pounds.

Modern light-duty vehicles sold in the United States are equipped with knock sensors and computer controlled ignition systems that compensate for the use of gasoline with a sub-specification AKI rating. The use of sub-specification gasoline will likely result in loss of performance and fuel economy, but the driver may not experience any noticeable knock.[3]

4.2.2 VOLITILITY AND DISTILLATION SPECIFICATIONS

To burn, gasoline must be vaporized and mixed with oxygen (air). Since gasoline is a blend of hundreds of molecules with different characteristics, gasoline does not boil at one temperature but over a range. Gasoline must be blended in a way that vaporization will occur over the entire range of operating temperatures, beginning with cold starts. Several specifications are used to measure and control the vaporization performance of the blend.

[3] Baker & O'Brien does not recommend purchasing gasoline that does not meet the AKI requirements or recommendations of the manufacturer as stated in the owner's manual.

REID VAPOR PRESSURE (RVP)

Vapor pressure is the pressure exerted by the vapor in a liquid-vapor mixture at a specified temperature. Reid Vapor Pressure (RVP) measures vapor pressure of a gasoline blend at 100 degrees Fahrenheit (°F). If the RVP of a gasoline blend is too high, some components may escape when exposed to the atmosphere (e.g., when filling up the car at the gas station). If the RVP is too low, starting the engine at low temperatures may be a problem.

U.S. Environmental Protection Agency (EPA) regulations require the RVP of summer gasoline blends not to exceed 7.8 pounds per square inch, absolute (psia) in some regions, and 9.0 psia in others. Some state and local authorities implemented even lower RVP specifications of 7.0 psia during the summer season. Winter gasoline blends are phased in as the weather gets cooler. The first increase in RVP occurs on September 15 and, in some areas, the allowed RVP eventually increases to 15 psia.

DISTILLATION

The temperature range over which the gasoline mixture boils is known as the distillation profile. The gasoline's distillation profile directly impacts engine performance, from its cold start and warm up behavior, to its ability to provide power and acceleration, to its fuel economy on both short and long trips. Gasoline specifications limit the temperature ranges at which 10% (T10), 50% (T50), and 90% (T90) of the gasoline boils. These specifications vary by season and class, similar to RVP.

DRIVABILITY INDEX

The Drivability Index (DI) is another measure of how the gasoline will perform over the entire range of operating temperatures. The DI is a function of the distillation profile and ethanol content. The DI formula is:

DI = 1.5(T10) + 3.0(T50) + (T90) + 2.4(ethanol volume percent)[4]

DI specifications vary with gasoline class and season in the range of 850 to 1,275.

[4] T10, T50, and T90 must be in °F.

VAPOR-LIQUID RATIO

The vapor-liquid ratio (V/L) measures the temperature at which the vapor volume is 20 times the liquid volume. The V/L specification was intended to prevent gasoline from vaporizing in the fuel line (vapor-locking). The vapor-lock problem has largely been eliminated by the relocation of fuel pumps from the engine compartment to the fuel tank but the specification remains. Higher V/L values indicate greater protection against vapor lock. V/L specifications vary between 95°F and 140°F with the season.

4.2.3 SULFUR

As of January 1, 2017, EPA's Tier 3 regulations require most U.S. gasoline producers and importers to meet an annual 10 parts per million (ppm) average sulfur limit on all gasoline produced. For refiners, the 10 ppm limit applies at the point where gasoline leaves the refinery. Individual batches can have up to 80 ppm sulfur at the refinery and up to 95 ppm downstream of the refinery (See Section 4.3).

4.2.4 BENZENE

EPA rules limit the average benzene content of all gasoline produced by each refining company to 0.62 volume percent (vol.%). Refiners may use averaging, banking, and trading of benzene credits to meet the benzene limit. U.S. reformulated gasoline must also meet a 1.3 vol.% limit that applies to every gallon produced (See Section 4.3). California has its own gasoline benzene limits that are stricter than the federal standard.

4.2.5 MERCAPTANS

Mercaptans are foul-smelling sulfur compounds that can also damage fuel-system components and lead to excessive sulfur-dioxide emissions.

4.2.6 GUM AND OXIDATION STABILITY

The specifications for Gum and Oxidation Stability ensure that the gasoline will not form solid, insoluble deposits (gums) during storage, where gasoline may be exposed to the atmosphere for extended periods of time. Gums can form and cause fouling throughout the vehicle fuel system, from the tank to the engine.

4.2.7 COLOR, NACE CORROSION, PHOSPHOROUS

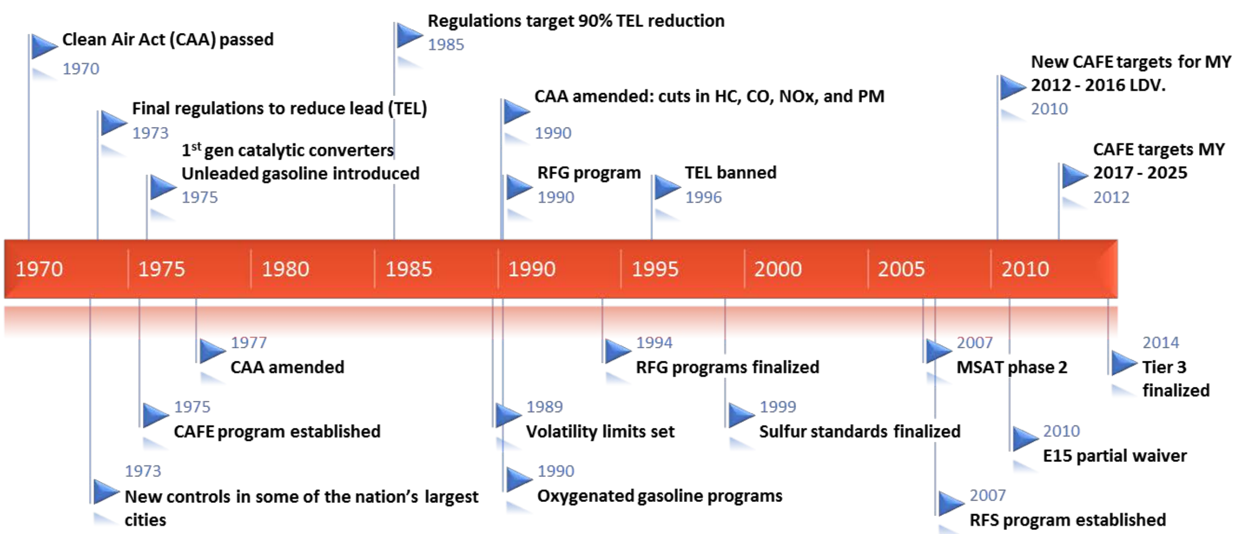
These specifications limit levels of contaminants that can foul, damage, or corrode components of the vehicle's combustion and exhaust system.

4.3 GOVERNMENT REGULATIONS

Passage of the Clean Air Act (CAA) in 1970 triggered increased federal government involvement in gasoline specifications. These have become increasingly stringent over time (Figure 4). As of 2017, major federal gasoline regulations reformulated gasoline include requirements, renewable fuel standards (RFS), and restrictions on sulfur, mobile source air toxics (MSAT), and RVP. In 1970, California already had a program in place to tighten gasoline specifications. The CAA allows the EPA to exempt California from federal regulations if California has standards that are stricter. As a result, California is not subject to the federal Reformulated Gasoline (RFG), sulfur, and MSAT regulations discussed in sections 4.3.2, 4.3.4, 4.3.5, and 4.3.6.

FIGURE 4

TIMELINE OF GASOLINE REGULATIONS



4.3.1 LEAD PHASE-OUT

Tetraethyl lead (TEL) was extensively used as an octane improver prior to passage of the CAA. In 1975, automobile manufacturers introduced first-generation catalytic converters on vehicle exhaust systems to reduce vehicle emissions. Unleaded gasoline is introduced at the same time, since lead was found to cause disintegration of these catalytic converters. Use of leaded gasoline in vehicles with catalytic converters was prohibited. The use of TEL steadily decreased over time, as the vehicle population turned and other methods including methyl-tertiary-butyl-ether (below) were used to maintain gasoline AKI. In 1996, EPA banned TEL from motor gasoline.

4.3.2 FEDERAL REFORMULATED GASOLINE

In response to the 1990 Clean Air Act Amendments, EPA required that the nine worst ozone non-attainment areas (classified as extreme or severe) be supplied with RFG. The original metropolitan areas included were Baltimore, Chicago, Hartford, Houston, Los Angeles, Milwaukee, New York City, Philadelphia, and San Diego. Other ozone non-attainment areas (classified as serious, moderate, or marginal) could "opt-in" to the RFG program upon request of that state's governor to EPA. As of January 1, 2018, portions of 17 states and the District of Columbia require RFG.[5]

There were various phases to the RFG program, including a series of computer models that predicted engine emissions based on the physical and chemical properties of the gasoline. The emissions categories predicted by the model included volatile organic compounds (VOCs), toxics, and nitrogen oxides (NOx). The program required RFG to meet specific reductions in each category relative to the average gasoline produced in 1990 (the “baseline gasoline”). Additionally, each refinery was required to use the models to prove that their non-RFG gasoline was no worse than the baseline period. The latest version, introduced in 1998, is known as the Complex Model.[6]

The program originally required that RFG contain oxygenates such as ethanol or methyl-tertiary-butyl-ether (MTBE). Oxygenates are molecules that contain oxygen. Combustion reactions, such as the reaction that occurs in a vehicle engine, require a fuel source (the gasoline), an

[5] Reformulated Gasoline. (August 7, 2018), Retrieved from https://www.epa.gov/gasoline-standards/reformulated-gasoline
[6] EIA, “Refiners Switch to Reformulated Gasoline Complex Model”, Jan 9, 1998, www.eia.doe.gov.

ignition source (the spark from a spark plug), and oxygen (supplied by the air). If insufficient oxygen is available to fully "complete" the combustion step, undesirable by-products such as VOCs and carbon monoxide (CO) are produced. Adding oxygenates to the gasoline increases the amount of available oxygen and has been shown to decrease VOC and CO emissions. RFG no longer requires oxygenates, although almost all RFG contains ethanol.

4.3.3 METHYL-TERTIARY-BUTYL-ETHER PHASE OUT

MTBE is a high octane, low RVP oxygenate that was first added to gasoline in 1979 when EPA granted a waiver for up to 7.0 vol.% MTBE in gasoline. A second waiver in 1988 increased the allowable volume to 15.0 vol.%. In the 1990s, MTBE was the predominate oxygenate used by refiners and blenders. In 2000, EPA drafted plans to phase out MTBE's use over four years. California banned its use in 2004, with a number of other states following suit. In 2006, the Energy Policy Act (passed in 2005) rescinded the oxygenated gasoline requirement in federal RFG, after which MTBE was completely removed from U.S. gasoline.

4.3.4 RENEWABLE FUELS STANDARD (RFS)

The Energy Policy Act of 2005 included a Renewable Fuels Standard (RFS). That law required 7.5 billion gallons of renewable fuel to be blended into gasoline by 2012. Shortly thereafter, the Energy Independence and Security Act of 2007 dramatically expanded the RFS by requiring that 36 billion gallons of renewable fuel be blended into gasoline by 2022. Most of the ethanol is blended to 10 vol.% of the finished gasoline (E10), but there is a smaller volume of gasoline containing up to 83% ethanol (E85). In 2012, EPA approved the use of 15% ethanol blends (E15) in model year 2001 and newer LDV. However, most car manufacturer warranties do not permit the use of E15, and E15 adoption remains very low. According to EIA, total sales of E15 and E85 comprise less than 0.4% of fuels used in gasoline-burning engines.[7]

With the low adoption of E85 and E15 gasoline, refiners are increasingly challenged to meet the mandated RFS blending volumes. Since the maximum ethanol content for most finished gasoline is 10%, refiners must sell more gasoline each year to meet the annual RFS targets. If

[7] EIA, *Today in Energy,* "Almost all U.S. Gasoline is blended with 10% ethanol," May 4, 2016.

the RFS mandated volume exceeds 10% of the expected gasoline production, it will be difficult for refiners to comply with the mandate. This is known as the ethanol "blend wall." In 2016, the RFS requirement equated to approximately 10.1% of gasoline production.

4.3.5 SULFUR REDUCTION

Sulfur is naturally present in gasoline and other petroleum products. Sulfur in gasoline impairs the effectiveness of emission control systems and contributes to air pollution. The Tier 2 gasoline sulfur program, finalized in 2000, reduced the gasoline sulfur content by up to 90%, enabling the use of new emission control technologies in cars and trucks. Requirements for use of low-sulfur gasoline became effective in model year 2004. The Tier 3 program finalized in 2014 sets new vehicle emissions standards and lowers the gasoline sulfur content to a maximum average of 10 ppm beginning in 2017 for most refiners and by 2020 for all refiners.

4.3.6 MOBILE SOURCE AIR TOXICS (MSAT)

MSAT Phase 1 became effective in 2002 and limited the amount of benzene in both RFG and conventional gasoline. MSAT Phase 1 was refinery specific and prohibited credit trading but allowed carry over of credits for one year. In February 2007, EPA finalized the MSAT Phase 2 rule. Phase 2 limited benzene in each refiner or blender's total gasoline pool[8] to an annual average of 0.62 vol.% beginning January 1, 2011, for most, and January 1, 2015, for small refiners. The program included averaging, banking, and trading provisions. With implementation of MSAT Phase 2, refiners were no longer required to meet the Complex Model toxics test for the Federal RFG program.

4.3.7 OTHER STATE AND LOCAL REGULATIONS

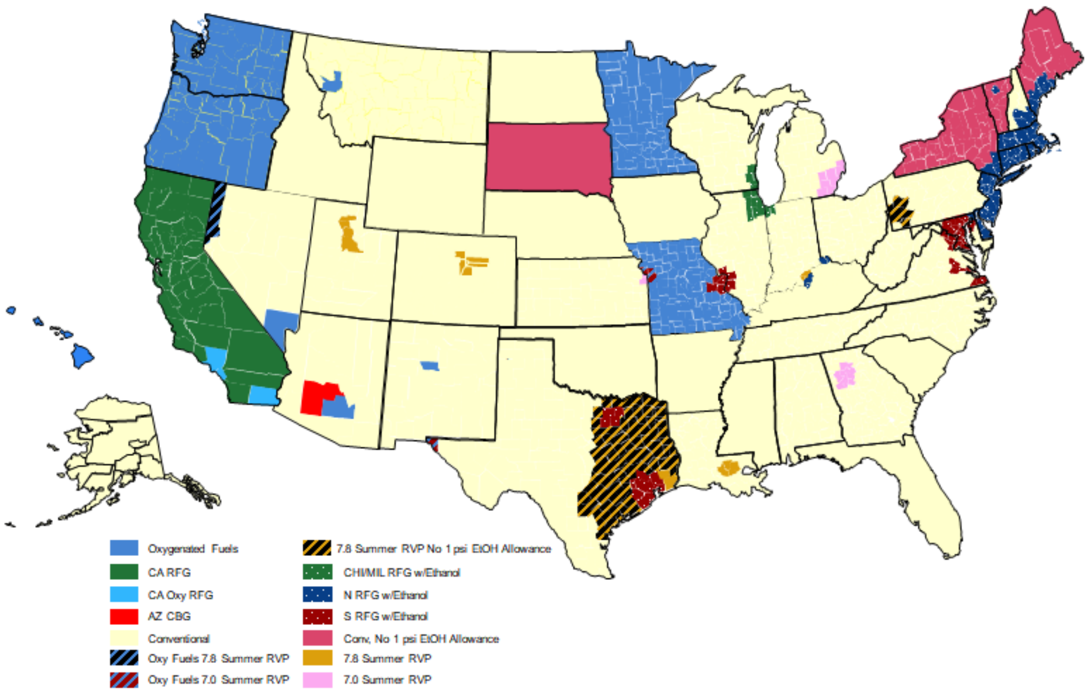
Some states set requirements for gasoline sold state-wide or in selected areas. This often includes reduced RVP. Winter season use of oxygenates was required in some regions. Since these fuels are unique to small areas they are often called "boutique fuels." Besides California, states with unique gasoline specifications include: Arizona, Colorado, Georgia, Hawaii, Indiana,

[8] Combined conventional, RFG, reformulated BOB, and conventional BOB.

Michigan, Minnesota, Missouri, New Mexico, Ohio, Oregon, Pennsylvania, Utah and Washingon (Figure 5). The uncolored “conventional” gasoline areas in the figure are generally subject to a set of specifications published in ASTM International standard D4814.

FIGURE 5

U.S. GASOLINE REQUIREMENTS AS OF JANUARY 2018[9]



4.4 POTENTIAL ENGINE DESIGN CHANGES

In 1975, Congress enacted the Energy Policy and Conservation Act. It included a requirement that the Department of Transportation (DOT) establish Corporate Average Fuel Economy (CAFE) standards setting the average new vehicle fuel economy that each manufacturer's fleet must achieve. DOT delegated responsibility for developing these standards to the National Highway Traffic Safety Administration (NHTSA). In April 2010, the Supreme Court ruled that

[9] Source: U.S. Gasoline Requirements. (January 2018), Retrieved from https://www.api.org/oil-and-natural-gas/wells-to-consumer/fuels-and-refining/gasoline/us-gasoline-requirements. Kentucky opted out of the RFG program effective July 1, 2018, therefore the Kentucky RFG areas shown in the map no longer require RFG.

DOT's authority to regulate CAFE did not preclude EPA from developing separate rules for carbon dioxide (CO2) emissions from motor vehicles. The Supreme Court suggested that DOT and EPA could coordinate their rule-making to achieve both the fuel economy and CO2 emissions objectives.

In April 2010, DOT and EPA published their first joint CAFE/CO2 rule covering model years 2012 through 2016. This was followed in 2012 with a rule covering model years 2017 through 2025. As a result of a "mid-term" review EPA has deemed that part of the 2012 rule is inappropriate and changes are currently pending.

To meet these standards, automakers are considering range of technical solutions including but not limited to:

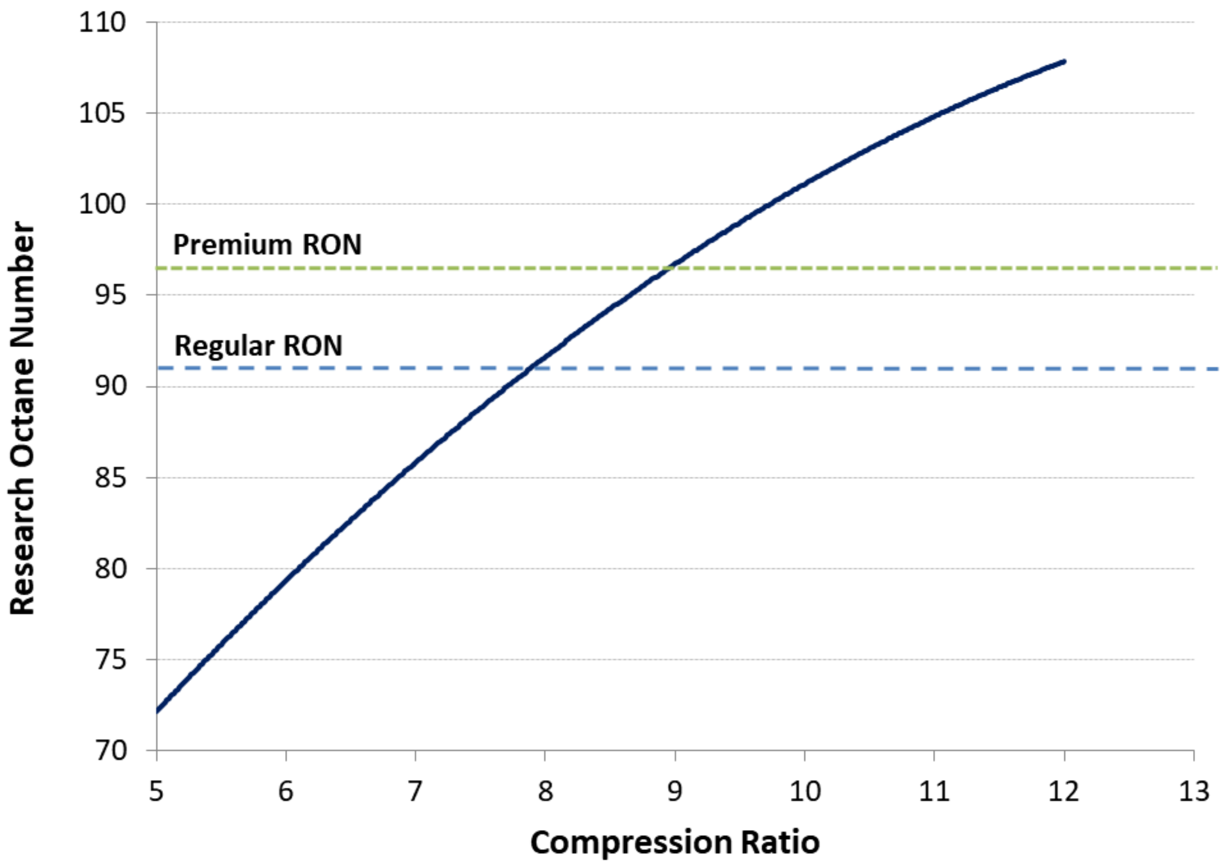
1. Higher compression ratios
2. Direct injection
3. Turbocharging and downsizing

4.4.1 HIGHER COMPRESSION ENGINES

Compression ratio is the maximum volume in an engine cylinder (when the piston is at bottom dead center) to the minimum volume within the cylinder (when the piston is at top dead center). The higher an engine's compression ratio, the more mechanical energy it converts from the combustion of a fixed amount of fuel and air. Compression raises the temperature within the cylinder and can cause pre-ignition or knock (see Section 4.2.1). Higher compression ratios require higher octane gasoline (Figure 6).

FIGURE 6

COMPRESSION RATIO VERSUS OCTANE REQUIREMENT



Source: Changes in Gasoline IV, Renewable Fuels Foundation, June 2009, p. 4

4.4.2 DIRECT INJECTION

Direct injection technology sprays fuel directly into a gasoline engine's combustion chambers instead of its intake ports. The Japanese-market Mitsubishi Galant was the first car to combine direct injection with computer-controlled injectors in 1996. Injecting fuel directly into the cylinder during the compression stroke reduces cylinder temperature due to the cooling effect of the vaporizing fuel. This reduces octane requirements at constant compression ratios. Direct injection requires higher cost engine components than conventional port fuel injection because the cylinder pressures are 1,500 psia to 3,000 psia rather than 60 psia to 115 psia in port fuel injection, and the injectors must withstand the pressure and heat of combustion.

4.4.3 TURBOCHARGERS

Turbochargers use some of the energy in the engine exhaust gas to compress the intake air. This increases the amount of oxygen in the cylinder, allowing more fuel to be burned in each cycle. Smaller, turbocharged engines can raise fuel economy while meeting or exceeding the power and torque of larger naturally aspirated engines. However, the increased compression can lead to engine knock. Use of higher-octane gasoline can offset the increased risk of engine knock caused by increasing engine compression.

4.5 GASOLINE COMPONENTS

Petroleum refineries are the main source of finished gasoline, BOBs, and other gasoline components. Other sources include natural gas processing plants, ethanol plants, standalone component production facilities, and petrochemical plants.

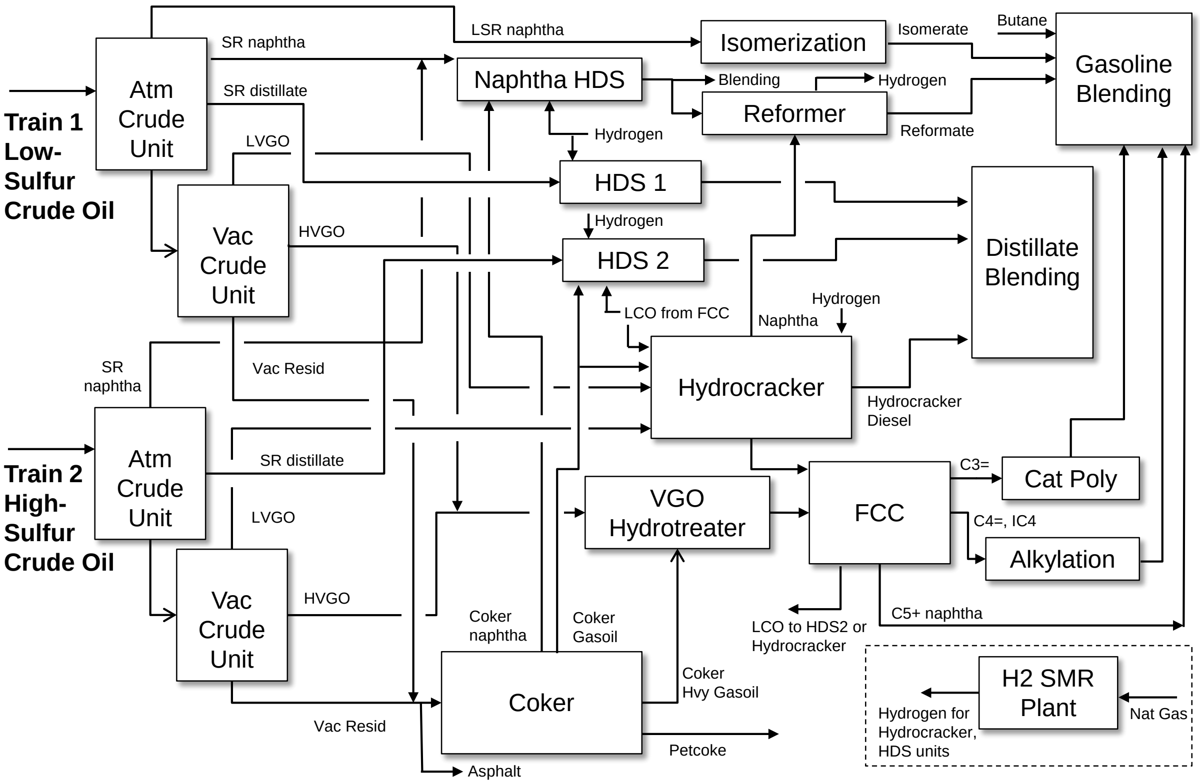
4.5.1 COMPONENTS PRODUCED IN PETROLEUM REFINERIES

All refineries are different. They have different unit configurations and capacities, physical locations, and economic drivers. Although no single example can capture all of the possible combinations and permutations of processing units that comprise a petroleum refinery, a simplified example schematic of a high conversion refinery[10] is shown in Figure 7.

[10] Note: In the example refinery shown in Figure 7, kerosene and diesel are shown as a combined straight run (SR) distillate stream and AGO is not shown.

FIGURE 7

EXAMPLE REFINERY CONFIGURATION



Crude oil processing in petroleum refineries begins with distillation units that fractionate crude oil into product streams (Table 1). The crude distillation products are mixtures of hydrocarbons that boil over specific temperature ranges. Depending on the quality of the crude oil, the crude distillation products contain varying amounts of contaminants. In modern refineries, most of these distillation products require additional processing in conversion units.

TABLE 1

CRUDE OIL DISTILLATION PRODUCTS

Distillation Product	Typical Boiling Range, °F	Typical Disposition
Light hydrocarbons	85 and less	Refinery fuel, propane, liquefied petroleum gas (LPG) sales and gasoline blending
Light straight run (LSR) naphtha	85 to 185	Isomerization unit, petrochemical feedstock, or gasoline blending
Heavy (SR) naphtha	185 to 350	Reformer unit, petrochemical feedstock, or gasoline blending
Kerosene	350 to 500	Treating unit, sales as jet fuel or kerosene, or other fuel blending
Diesel	500 to 640	Hydrotreating unit, diesel or heating oil blending
Atmospheric gas oil (AGO)	640 to 680	Hydrotreating, fluid catalytic cracking unit (FCC) or hydrocracking unit
Light vacuum gas oil (LVGO)	680 to 800	
Heavy vacuum gas oil (HVGO)	800 to 1050	
Vacuum resid	1050 and greater	Coker, resid hydrocracking or solvent deasphalting unit, asphalt or fuel oil blending

The lightest distillation products include normal butane (nC4), isobutane (iC4), propane (C3), and fuel gas. The only one of these that is typically blended into gasoline is nC4, which has a high RVP that limits the amount that can be blended, particularly during the lower RVP summer season. Therefore, summer gasoline blends typically contain less nC4 than winter blends. Excess nC4 may be sold or stored in the summer for blending during the winter. LPG is typically recovered and sold. Lighter components are routed to refinery fuel gas systems.

Atmospheric gas oil (AGO), light vacuum gas oil (LVGO), and heavy vacuum gas oil (HVGO) contain large hydrocarbon molecules and have limited uses as finished products. Some refineries produce lubricants from these distillation products but in most refineries, they are "cracked" into smaller molecules that can be blended into finished products like gasoline, jet fuel, and diesel. Fluid catalytic cracking (FCC) and hydrocracking units are used for this purpose.

FCC units produce a range of products from light hydrocarbons to diesel and a heavy residual product. The light hydrocarbons are similar to those listed above except that they also include propylene (C3=) and butylenes (C4=). C3= is often sold as a petrochemical feedstock to plants that make polypropylene or other polymers. C4= is sometimes sold as a petrochemical feedstock, but more frequently it is processed in refinery alkylation or catalytic polymerization (cat poly) units to produce gasoline components. C3= is sometimes fed to alkylation and cat poly units. In the cat poly process, two C3= or C4= molecules are combined to make one gasoline molecule. In the alkylation process, one C3= or C4= molecule is combined with one iC4 molecule to make one gasoline molecule. One of the gasoline molecules produced in the alkylation process is isooctane. Isooctane has a MON, RON, and AKI of 100 (see Section 4.2.1).

FCC naphtha(s) are blended to gasoline (desulfurization may be required). The desulfurization process typically results in a loss of RON anywhere between one to five octane numbers, necessitating increased blending with high octane blendstocks. FCC diesel or light cycle oil (LCO) can be hydrotreated and then blended into finished diesel or it can be hydrocracked to increase gasoline production. Hydrocracking units produce naphtha(s) that can be blended directly into gasoline or sent to other units for further upgrading before blending. Hydrocracking units also produce LPG that can be sold, iC4, and nC4. Depending on the design and operating conditions, hydrocracking units can also produce kerosene for jet fuel blending, diesel fuel, and FCC feed.

Many U.S. refineries also include process units to convert vacuum residual (resid) into higher value products. Common technologies for this include solvent deasphalting, resid hydrocracking, and coking. The example refinery shown above includes a coking unit.

Coking units produce products that can be blended into gasoline and diesel, although additional processing is required. They also produce a heavy gas oil stream than can be fed to the FCC or hydrocracker.

The example refinery (Figure 7) also includes a reformer and isomerization unit. These units rearrange atoms within naphtha molecules to produce molecules with higher octane ratings. Reformers remove hydrogen atoms and rearrange the hydrocarbon molecules, to form “aromatic” molecules including benzene, toluene, and xylenes. These aromatics have high octane ratings when used in gasoline and are also have uses as petrochemical feedstocks.

As previously mentioned, EPA regulations limit the amount of benzene in gasoline (Section 4.2.4). Refiners use several different strategies to limit the benzene produced in reformers or remove it from the product. Isomerization units increase octane ratings of LSR but also increase its RVP, limiting the use of isomerization units in increasing the octane ratings of finished gasoline.

In FCC and hydrocracking units, most of the products have lower densities than the feed. Therefore the total volume of products exceeds the volume of the feed. This is known as volume gain. In reforming, alkylation, and cat poly units, there is a volume loss (total product volume is less than total feed volume). Since nearly all refinery feedstocks and products in the United States are sold on a volume (not mass) basis, the volume gain or loss can have a significant impact on the overall profitability of a refinery or individual operating unit. Additionally, since most refinery unit feedstocks and product prices are highly dependent on the crude oil price, the magnitude of the volume gain (or loss) impact can change based on crude oil prices.

Table 2 summarizes the gasoline blending components that are produced in petroleum refineries. The highest octane blending components are alkylate, reformate, and nC4.[11] Both alkylate and reformate have relatively low RVPs, making them excellent blending components. nC4's high RVP limits its use, particularly in the summer.

[11] A small amount of iC4 blending may occur, but iC4's higher vapor pressure limits the volume, and iC4 typically has much higher value as feedstock into an alkylation unit.

TABLE 2

REFINERY PRODUCED GASOLINE COMPONENTS

Component	Process Unit Source	AKI (R+M)/2	RVP psia	Sulfur ppm	Limiting GasolineSpec
Normal Butane	Distillation	90 to 92	70 to 74	2 to 6	**RVP,** V/L
Light Straight Run Naphtha	Crude Distillation	60 to 66	10 to 13	10 to 500+	**Octane, RVP,** V/L
Heavy Naphtha (non-hydrotreated)	Crude Distillation, Coker, Hydrocracker	58 to 64	1 to 1.5	40 to 500+	**Octane,** Sulfur
Reformate	Reformer	87 to 95	2 to 3	2 to 6	DI, T50, **Benzene**
FCC Gasoline (non-hydrotreated)	FCC	82 to 87	1 to 2	10 to 500+	Sulfur (if untreated)
Alkylate	Alkylation Unit	90 to 96	4 to 5	5 to 15	None
Isomerate	Isomerization Unit	78 to 83	7.8 to 8.5	1 to 10	**RVP**

Blending Quality:	
	Highly Favorable
	Favorable
	Neutral
	Unfavorable
	Highly Unfavorable

4.5.2 NON-REFINERY GASOLINE COMPONENTS

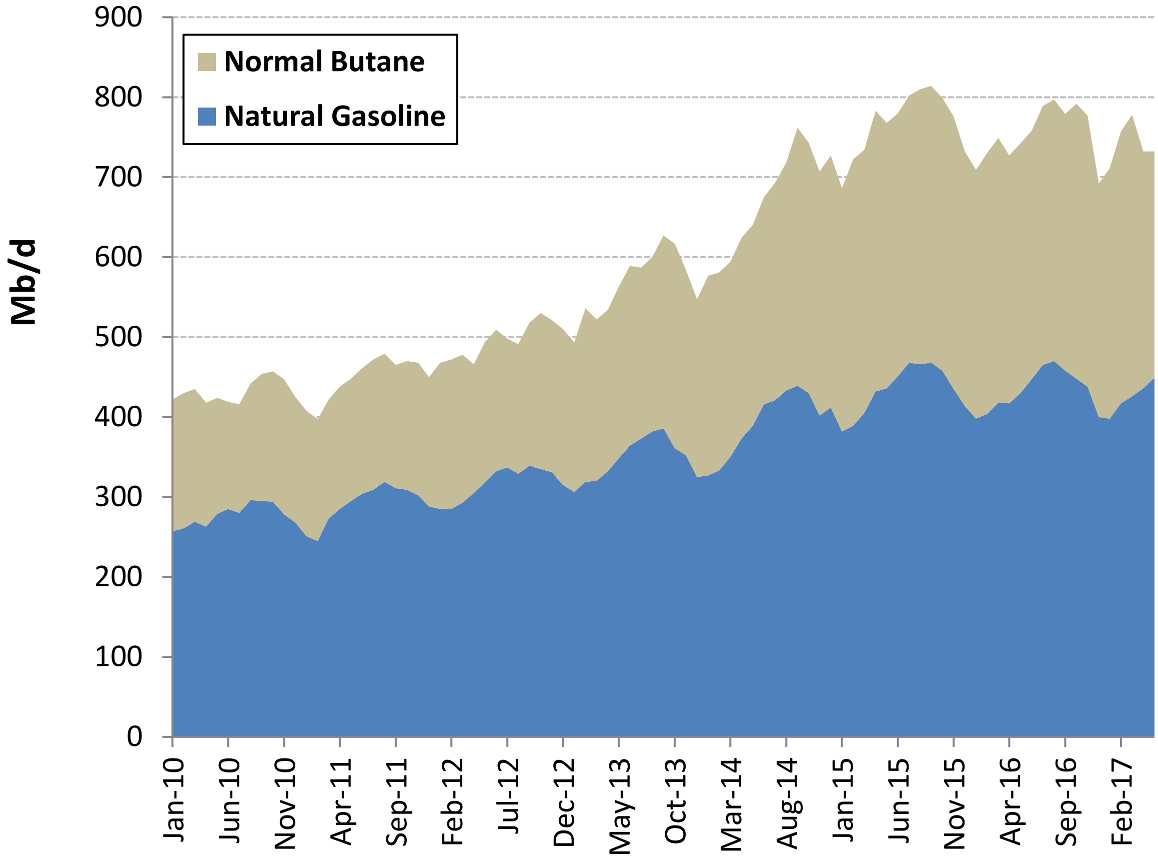
Non-refinery sources of gasoline components include natural-gas liquids (NGL) plants, standalone alkylation and MTBE plants, petrochemical plant by-products, and ethanol plants. With the exception of ethanol, these sources represent a relatively small volume of the overall gasoline pool. The RVP, AKI, and sulfur levels of these components vary widely, limiting the amount that can be blended.

NATURAL-GAS LIQUIDS (NGL)

Natural gas extracted from the ground often contains LPG, iC4, nC4, and natural gasoline (also known as pentanes plus or C5 plus) that are recovered from the "wet" natural gas in processing plants. Natural gasoline is similar to refinery produced light straight run (LSR). It is a low octane, relatively high RVP blendstock (Table 2). Butane (nC4) has high octane ratings, but its high RVP limits the amount that can be blended into gasoline. Production of nC4 and natural gasoline from U.S. NGL plants has grown over this decade due to increased natural gas production from shale formations (Figure 8). Total NGL plant nC4 and natural gasoline production are equal to about 7% of the 2016 finished gasoline consumption.

FIGURE 8

U.S. NGL PLANT PRODUCTION



Source: U.S. Energy Information Administration, Monthly Natural Gas Liquids Report.

STAND-ALONE ALKYLATION AND MTBE PLANTS

Currently all alkylation units are located in petroleum refineries, but at least one major refiner (Marathon Petroleum) is considering an investment to build a stand-alone alkylation complex located in the Appalachian region to utilize the natural gas liquids produced from the Marcellus shale formation. In the 1990s, there were several stand-alone MTBE plants. Since MTBE was phased out in the United States, remaining MTBE production is used for export to countries that still use it in gasoline.

PETROCHEMICAL BY-PRODUCTS

Some petrochemical plants produce by-products that are blended into gasoline. These include pyrolysis gasoline from olefins plants and raffinate from aromatics plants. They represent a very small fraction of the total gasoline pool.

ETHANOL

The use of ethanol in U.S. gasoline is mandated by the RFS (Section 4.3.4 above). Almost all ethanol is produced from a fermentation process using starch or sugar crops as the feedstock. The RFS also mandates that specific quantities of ethanol be produced from "cellulosic" feedstocks, but technologies to meet these requirements have not developed in accordance with the legislated schedule.

Ethanol has a high AKI (~99.5) that is beneficial in gasoline blending. It also raises the RVP of the finished gasoline, and is highly miscible in water, both of which are undesirable (Table 3). Ethanol contains about 30% less energy per gallon than petroleum-based gasoline,[12] which reduces fuel economy. Beginning in 1992, conventional E10 summertime blends were granted a waiver to exceed the normal summer RVP standards by 1 psia. RFG and higher level ethanol blends, such as E15, have not received this waiver.

[12] The energy content of petroleum-based gasoline is typically around 114,000 Btu/gallon, *Changes in Gasoline IV, Renewable Fuels Foundation*, June 2009.

TABLE 3

ETHANOL PROPERTIES[13]

Property	Value
Research Octane Number (RON)	120-135
Motor Octane Number (MON)	100-106
Vapor Pressure Increase to gasoline RVP : 10% - 20% of Blend	+ 1.0 psi
Miscibility in Water	High
Energy Content, Btu/gallon	77,300

Blending Quality:

Highly Favorable
Favorable
Neutral
Unfavorable
Highly Unfavorable

Ethanol has an affinity for water and can cause corrosion in pipelines, so finished E10 gasolines cannot be shipped in pipelines to wholesale terminals. Therefore, ethanol is typically blended with BOBs (Section 4.2) at wholesale terminals as the gasoline is loaded into tank trucks for delivery to retail sales locations. The BOBs produced at refineries are blended so that the finished gasoline (with ethanol) sold at the pump will meet the required specifications. Most refiners and blenders account for ethanol's high AKI and RVP by producing BOBs with lower AKIs and lower RVPs than specified for finished gasoline.

Considering ethanol's positive impact on AKI and negative impacts on RVP and energy content, every 100 gallons of ethanol added to the total gasoline pool at constant RVP and energy consumption does the following:

[13] Ethanol Properties retrieved from http://www.iea.amf.org/content/fuel_information/ethanol/e10/ethanol_properties

1. Reduces petroleum-based gasoline consumption by 70 gallons (18 gallons of butane and 52 gallons of other components)
2. Increases total finished gasoline consumption by 30 gallons
3. Raises the AKI of the resulting blend by 1.2- 3.2 AKI?

The AKI increase may allow refiners to lower reformer throughput or severity.

4.6 PETROCHEMICAL MARKETS FOR GASOLINE COMPONENTS

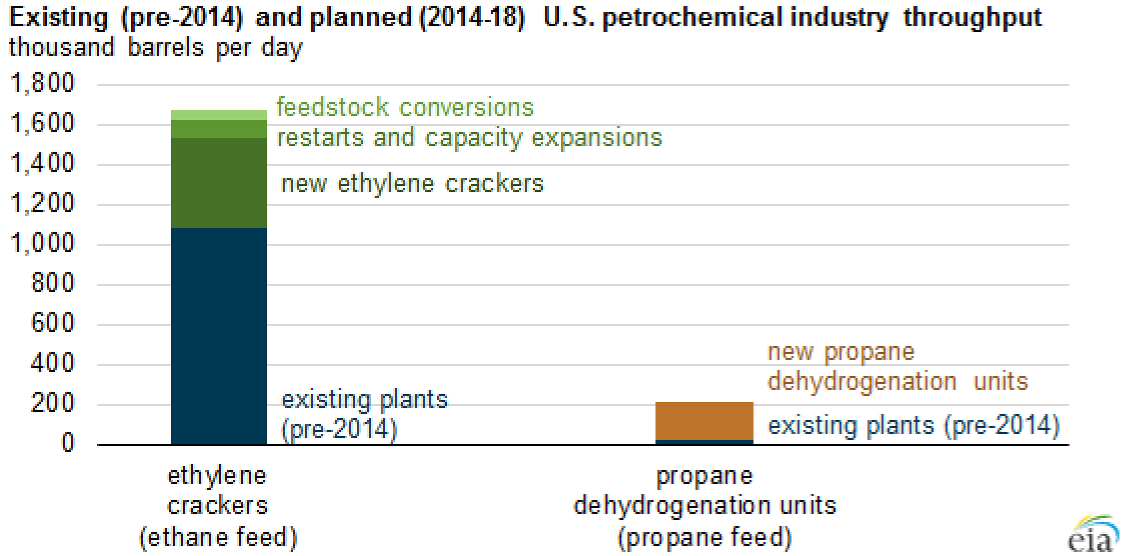
Petrochemical plants consume refinery and NGL plant products, and produce intermediate and finished petrochemical products. Thus petrochemical facilities "compete" with refineries for certain feedstocks and intermediate products, some of which are highly desirable gasoline blendstocks. The primary intermediate petrochemical products are aromatics and olefins. Aromatics (benzene, toluene, and xylene [BTX]) are used to make a wide variety of consumer products, from dyes and detergents to synthetic fibers. BTX is recovered from reformate (see Section 4.5.1). Toluene and xylene have excellent gasoline blending characteristics (high octane, low RVP) and the petrochemical and gasoline markets compete for these products.

Olefins, (ethylene, C3=, and C4=) are used to make plastics, synthetic rubber, and fibers. C3= and C4= are potential feedstocks to alkylation and polymerization units that produce high-octane blending components. The petrochemical markets compete with the gasoline market for these products.

Ethane produced in NGL plants is an important olefin plant feedstock, particularly in the United States. In the United States, the surge in natural gas production has led to an increase in ethane supply. Many U.S. ethylene producers are taking advantage of the abundance of low-cost ethane to expand their ethylene production capacity (Figure 9).

FIGURE 9

U.S. ETHYLENE CRACKER EXPANSIONS

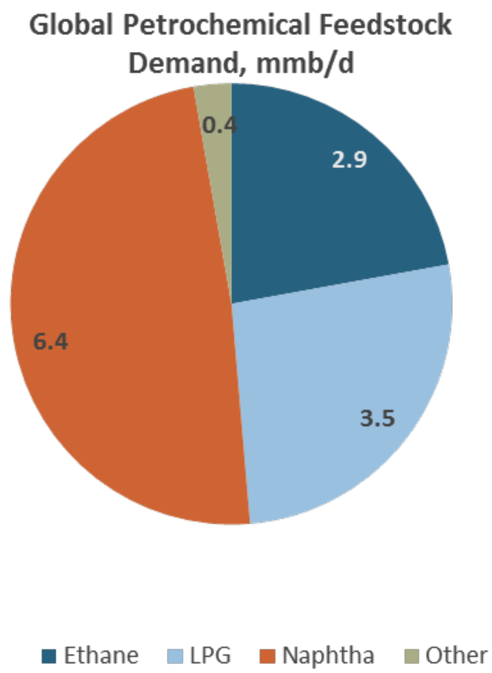


Source: U.S. Energy Information Administration, Today in Energy, January 29, 2015.

Some olefin plants use nC4, natural gasoline, naphtha, and vacuum gas oil as feedstocks for the production of olefins. All of these products are used in refineries to produce gasoline (Section 4.5.1) and the two industries compete for these feedstocks. In the rest of the world, naphtha is the dominant olefin plant feedstock, representing over 50% of the global market [including the United States] (Figure 10). U.S. refiners on the coasts have the option of exporting some of their naphtha production instead of using it to produce gasoline. This is an economic decision that will vary by refinery and will depend on prevalent market conditions.

FIGURE 10

PETROCHEMICAL FEEDSTOCKS



Source: FGE

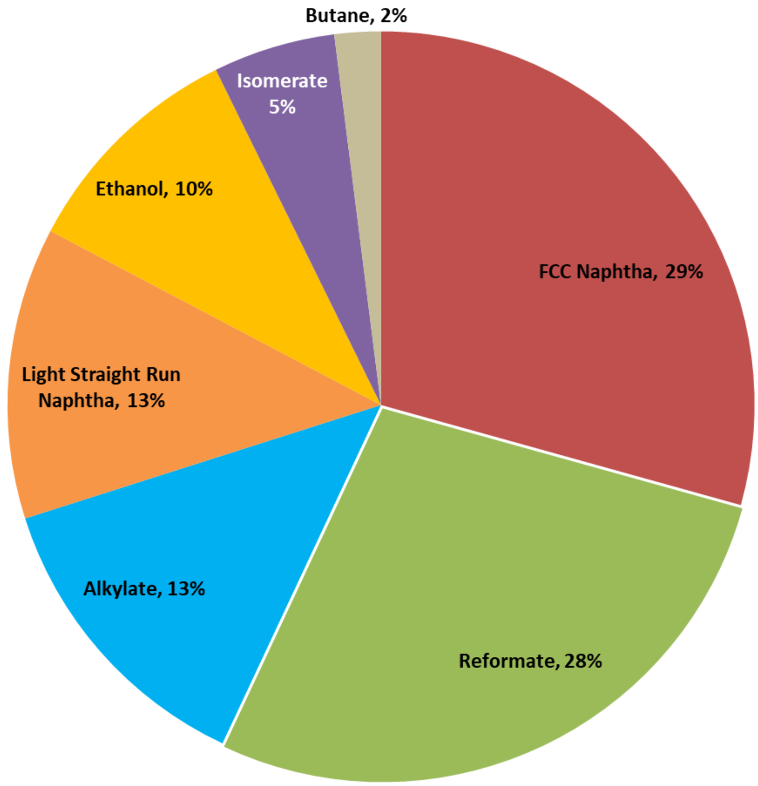
4.7 SUMMARY

Finished gasoline in the United States is primarily comprised of components produced in petroleum refinery conversion units. The combination of FCC naphtha and reformate make up over 50% of the gasoline pool (Figure 11). Some feedstocks to refinery conversion units and some gasoline components have alternative uses in the petrochemical industry.

FIGURE 11

U.S. AVERAGE FINISHED GASOLINE COMPOSITION

SECOND QUARTER 2017[14]



Source: Baker & O'Brien *PRISM* database

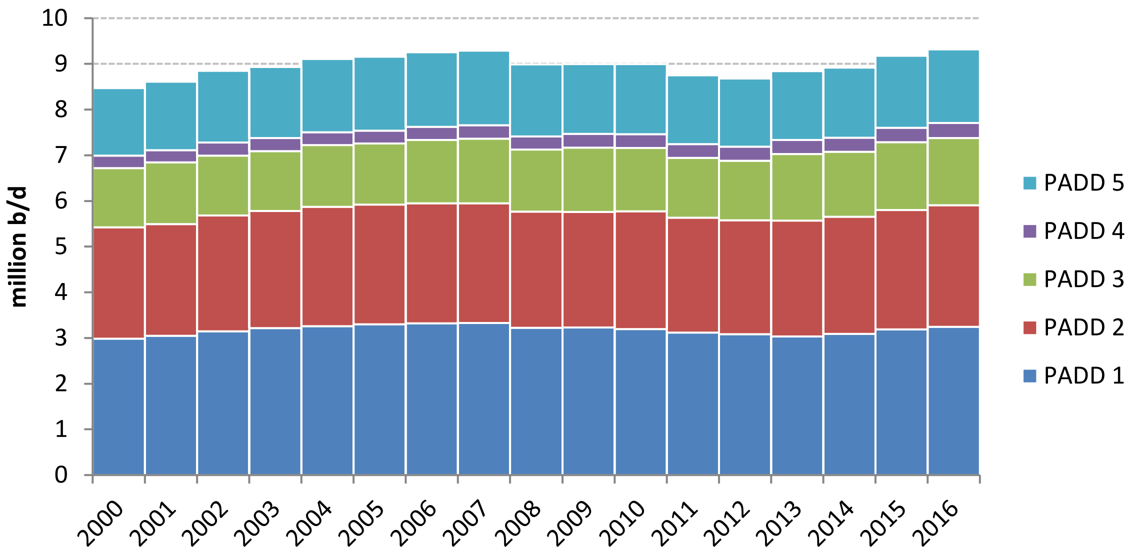
[14] The majority of what is labeled LSR in the chart is refinery produced, but this category also includes natural gasoline.

5. Gasoline Consumption

U.S. finished gasoline consumption has steadily increased since 2012, reaching approximately 9.3 million barrels[15] per day (b/d), or over 390 million gallons per day, in 2016 (Figure 12) and surpassing the previous high consumption mark set in 2007. PADD 1 is the largest consumer, accounting for approximately 35% of demand in 2016, followed by PADD 2 with 29%.

FIGURE 12

FINISHED GASOLINE (INCLUDING ETHANOL) CONSUMPTION BY PADD



Source: U.S. Energy Information Administration, Product Supplied.

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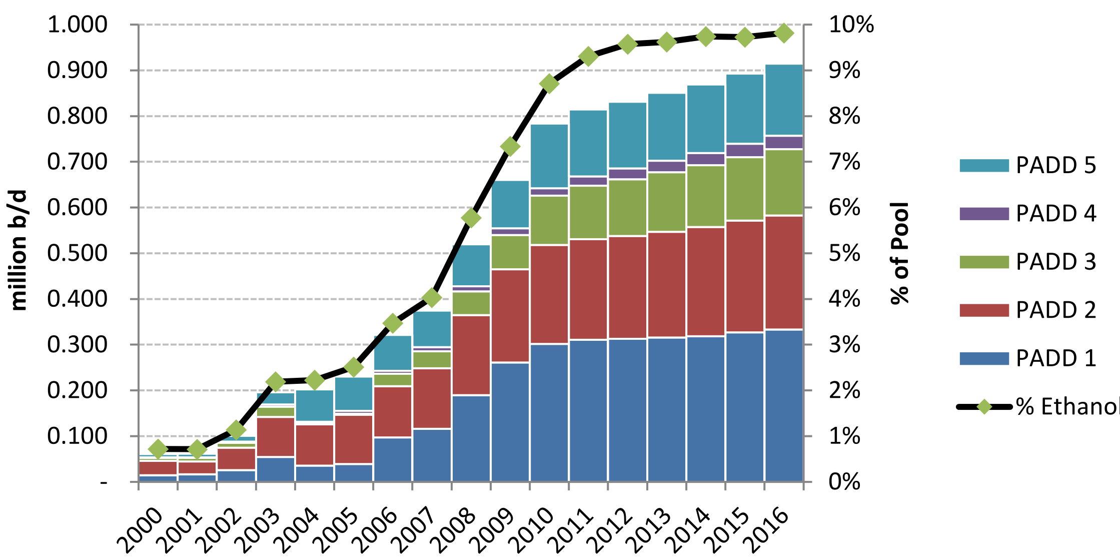
[15] A barrel is 42 gallons.

The volume of ethanol in finished gasoline increased dramatically from 2000 through 2010. Since 2010, ethanol consumption has continued to increase but at a slower rate and stood at approximately 915,000 b/d (Figure 13), just below 10% of total finished gasoline consumption. More than 60% of this ethanol was consumed in PADDs 1 and 2.

FIGURE 13

ETHANOL INCLUDED IN GASOLINE CONSUMPTION BY PADD[16]



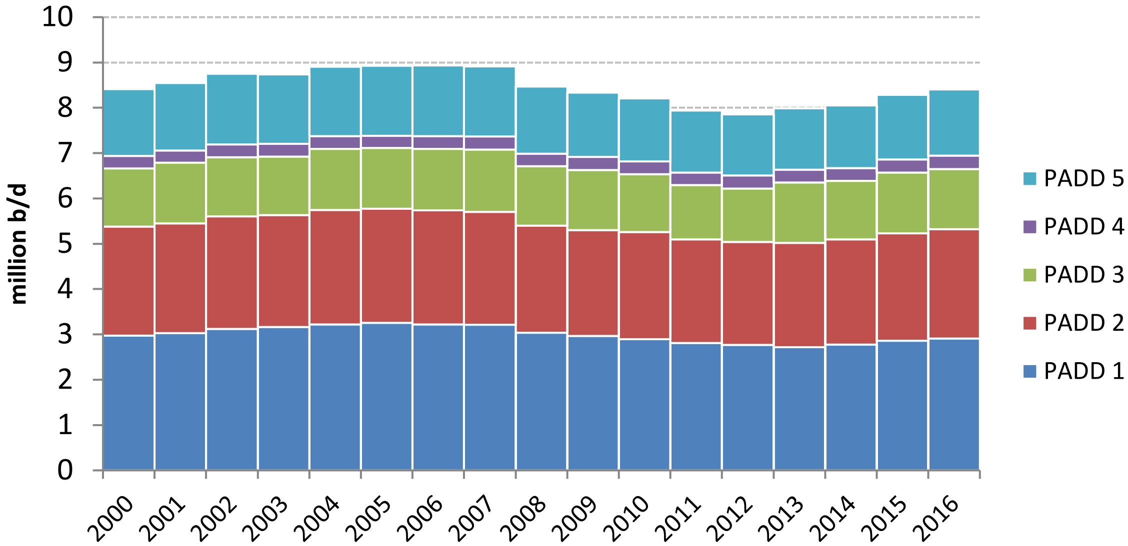
Source: U.S. Energy Information Administration, Supply and Disposition Balance; Baker & O'Brien Analysis

[16] Ethanol blending by PADD is not provided prior to 2004 for the majority of the PADDs. Therefore, the U.S. average ethanol blend percentage has been applied to all PADDs, excluding PADD 2, from 2000-2004.

Excluding ethanol, the consumption of petroleum-based gasoline and BOBs is still below the 8.9 million b/d peak reached in 2006 (Figure 14).

FIGURE 14

PETROLEUM-BASED GASOLINE CONSUMPTION BY PADD

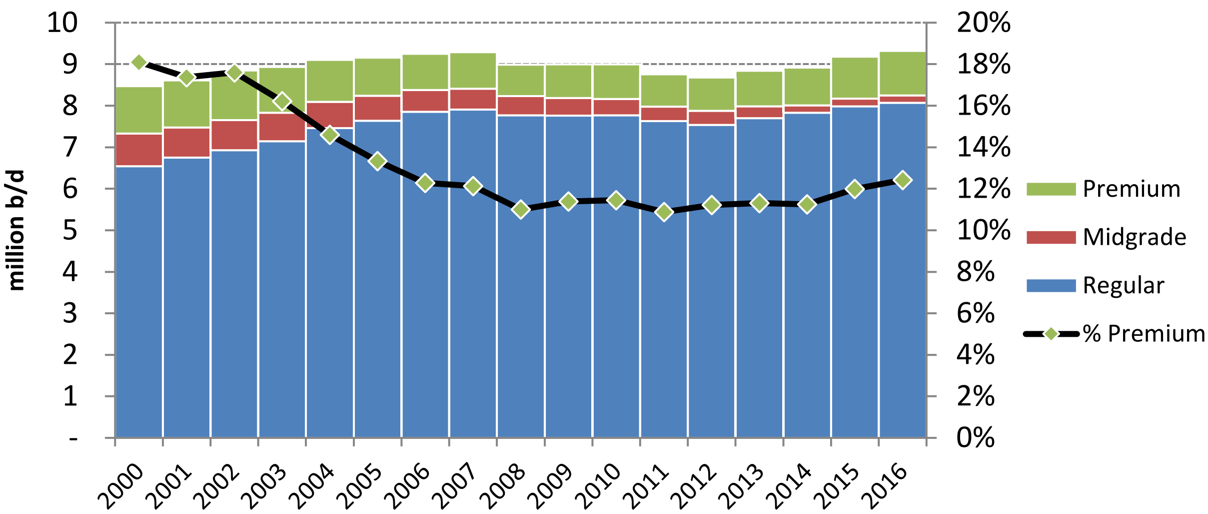


Sources: U.S. Energy Information Administration, Supply and Disposition Balance; Baker & O'Brien analysis

Finished gasoline consumption by grade is dominated by regular, with 8.1 million b/d in 2016, nearly 87% of total consumption (Figure 15). Premium accounted for approximately 1.1 million b/d in 2016 or 11% of consumption. Consumption growth has primarily been in regular gasoline, increasing by 1.3% per year on average between 2000 and 2017. Midgrade gasoline consumption has seen a dramatic decline, from a high of 786,000 b/d in 2000 to 177,000 b/d in 2016, or 8.9% per year. Premium gasoline consumption declined between 2000 and 2008 but increased between 2012 and 2016. However, the premium gasoline consumption of 1.07 million b/d in 2016 is still lower than the peak levels observed between 2000 and 2003.

FIGURE 15

FINISHED GASOLINE (INCLUDING ETHANOL) CONSUMPTION BY GRADE[17]



Sources: U.S. Energy Information Administration, Monthly Report of Prime Supplier Sales of Petroleum Products Sold for Local Consumption; Baker & O'Brien Analysis

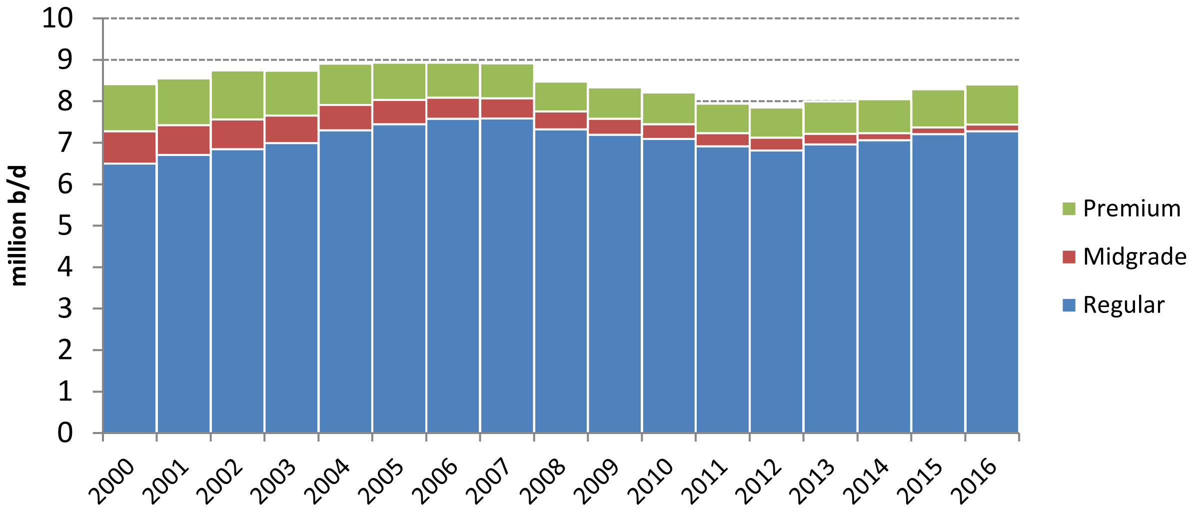
Excluding ethanol, petroleum-based regular gasoline and BOB consumption grew between 2000 and 2007, declined through 2012, and then grew again through 2016 (Figure 16). The overall compound average growth rate for regular gasoline and BOB since 2000 is 0.7% per

[17] EIA defines regular as an AKI of 85 to less than 88, midgrade 88 to less than 91, and premium 91 and higher. Ethanol blending into the different grades of gasoline is assumed to be equal (e.g., 10% ethanol is blended into regular and premium grades).

year, with 2016 consumption still lower than the peak achieved in 2007. Midgrade gasoline and BOB consumption has declined every year since 2000, with an average decline rate of 9.4% per year. Petroleum-based premium gasoline and BOB experienced some growth from 2012 to 2016 after steadily declining from 2000 through 2008.

FIGURE 16

PETROLEUM-BASED GASOLINE CONSUMPTION BY GRADE

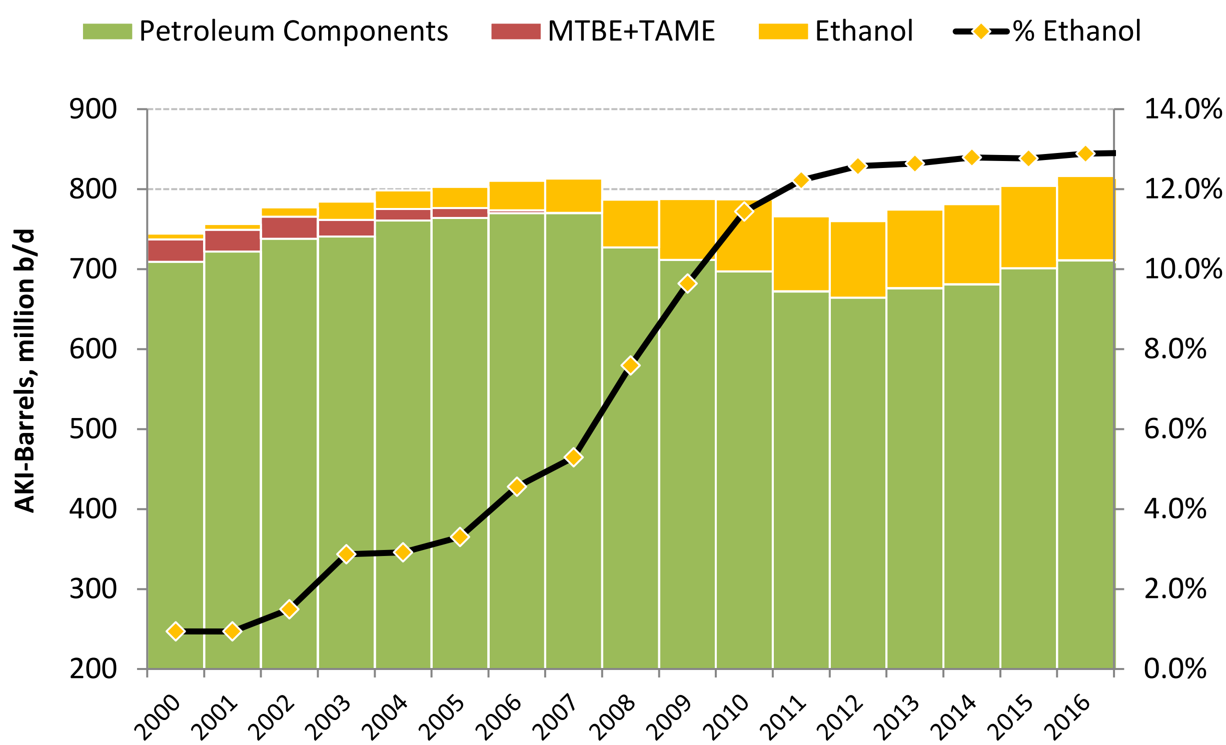


Sources: U.S. Energy Information Administration, Monthly Report of Prime Supplier Sales of Petroleum Products Sold for Local Consumption; Baker & O'Brien Analysis

Another way to look at gasoline consumption is to multiply the AKI of the gasoline consumed by the volume, resulting in a quantity of "AKI-barrels." AKI-barrel consumption initially peaked in 2007, dropped through 2012, then began increasing again. In 2016, AKI-barrel consumption exceeded the 2007 peak, but with ethanol supplying a much larger share. In 2016, the consumption of petroleum based AKI-barrels produced in refineries remained less than the peak years of 2006 and 2007 (Figure 17).

FIGURE 17

U.S. FINISHED GASOLINE OCTANE CONSUMPTION[18]



Sources: U.S. Energy Information Administration, Monthly Report of Prime Supplier Sales of Petroleum Products Sold for Local Consumption; Baker & O'Brien Analysis

[18] AKI Assumptions: Regular = 87, Mid-grade = 89, Premium = 92. Ethanol = 114.95

In 2016 ethanol contributed 13% of the total AKI-barrel supply , even though it contributed only 10% of the volume (Table 4).

TABLE 4

2016 GASOLINE AKI-BARREL BALANCE

	Volume, barrels			AKI-barrels	
	barrels	% of Total	AKI	AKI-barrels	% of Total
Ethanol (10% blend)	100	10%	115	11,500	13
Components (CBOB)	900	90%	84	75,600	87
Total Blend	**1000**	**100%**	**87.1**	**87,100**	**100**

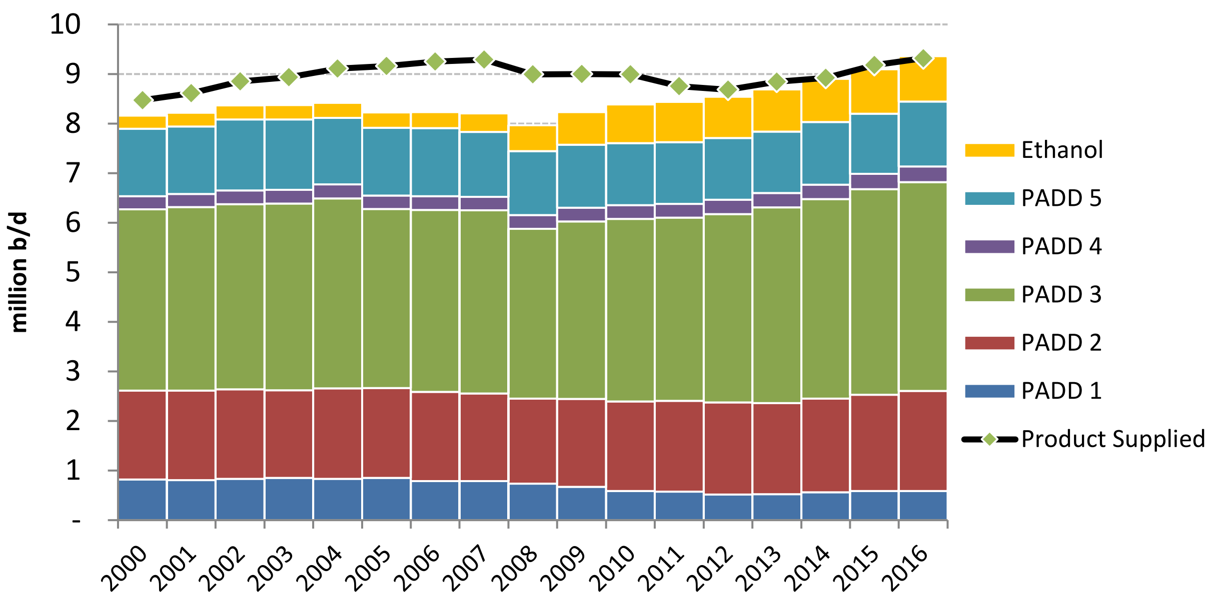
6. Gasoline Production

Gasoline production increased between 2000 and 2004, declined through 2008, then increased every subsequent year. Between 2008 and 2016, U.S. gasoline production grew at an average rate of 1.6% per year, a rate faster than domestic consumption grew. The United States went from being a net importer to a net exporter of gasoline and gasoline components. The increased production was primarily in PADDs 2 and 3. In 2016, the total petroleum-based gasoline production averaged 8.4 million b/d, the highest production over the last 16 years (Figure 18). This increase in gasoline production is a result of various factors including:

1. Changes at refineries (capacity additions, configuration improvements, and utilization increases)
2. Changes in crude oil quality
3. Increased ethanol usage

FIGURE 18

U.S. GASOLINE PRODUCTION VERSUS PRODUCT SUPPLIED



Sources: U.S. Energy Information Administration, Product Supplied; U.S. Energy Information Administration, Monthly Refinery Report Baker & O'Brien Analysis. EIA's "Product Supplied" is used as an estimation of domestic consumption

6.1 REFINING CHANGES

Based on their individual perceptions of economic conditions, refiners invest in projects to expand capacity and optimize their configuration. Between 2010 and 2016, atmospheric distillation capacity increased by approximately 8% (Table 4), with most of the capacity increase coming from the Marathon Garyville and Motiva Port Arthur expansions. Those two projects were early in the time period and designed to process heavy, sour crude oil. More recent expansion has been targeted at processing light, sweet crude oil from the shale formations (Section 6.2).

In PADD 2, there were three major projects designed to increase heavy crude processing through installation of delayed cokers and modifications or replacement of crude units. These were at WRB's Wood River, Illinois, refinery (December 2011), Marathon Petroleum's Detroit, Michigan, refinery (November 2012), and BP's Whiting, Indiana (October 2013) facility. Additional hydrotreating capacity was also included in the projects. Although the crude capacity increases associated with these projects were not great, they resulted in a significant change in crude processing capability and light product (gasoline, jet fuel, and diesel) make.

Beyond the crude oil and coker capacity increases, there were several large hydrocracker projects in the 2010 through 2016 period including new units at Valero's Port Arthur and St. Charles refineries (60,000 b/d each). Hydrocracking capacity increased 26% over the period. Hydrocrackers produce gasoline components, jet fuel, diesel, and feedstocks for other units (Section 4.5.1). Most of the 2010-2016 hydrocracker projects focused on increasing diesel production and taking advantage of low natural gas and hydrogen costs.[19]

Process units that produce high octane gasoline components include alkylation, catalytic polymerization, catalytic reforming, and to a lesser extent, C5/C6 isomerization. The aggregate capacity change in these types of process units has been small.

[19] Hydrocrackers consume natural gas and hydrogen that is produced from natural gas.

TABLE 5
U.S. CAPACITY CHANGES

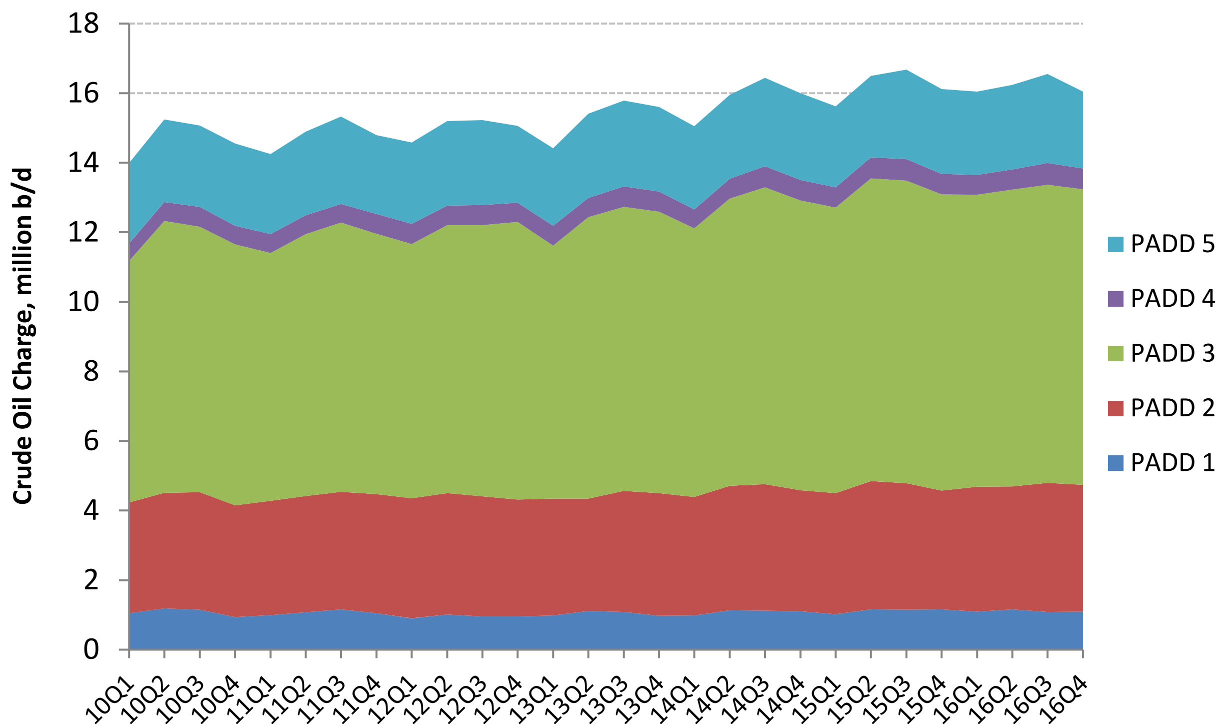
Process Unit	2010 Capacity, Mb/d	2016 Capacity, Mb/d	Difference, Mb/d
Atmospheric Crude Oil Distillation	17,333	18,723	1,390
FCC Unit	5,649	5,622	(27)
Alkylation	1,157	1,189	32
Catalytic Polymerization	61	59	(2)
Catalytic Reforming	3,588	3,665	77
C5/C6 Isomerization	492	531	39
Hydrocracking	1,763	2,222	459

Source: Baker & O'Brien *PRISM* database

While crude oil distillation capacity increased 8% from 2010 to 2016, refinery crude oil throughput increased just over 10% (Figure 19). The growth in crude oil throughput occurred primarily in PADDs 2, 3, and 4. PADD 3 saw the greatest increase at approximately 1 million b/d from 2010 to 2016, largely a result of the Motiva and the Marathon projects. PADD 2 also saw a significant increase in throughput (approximately 500,000 b/d) mainly due to increased capacity utilization. As crude oil throughput increased, gasoline and distillate production increased 11% and 17%, respectively, leading to increased net exports of finished petroleum products.

FIGURE 19

CRUDE OIL CHARGE BY PADD

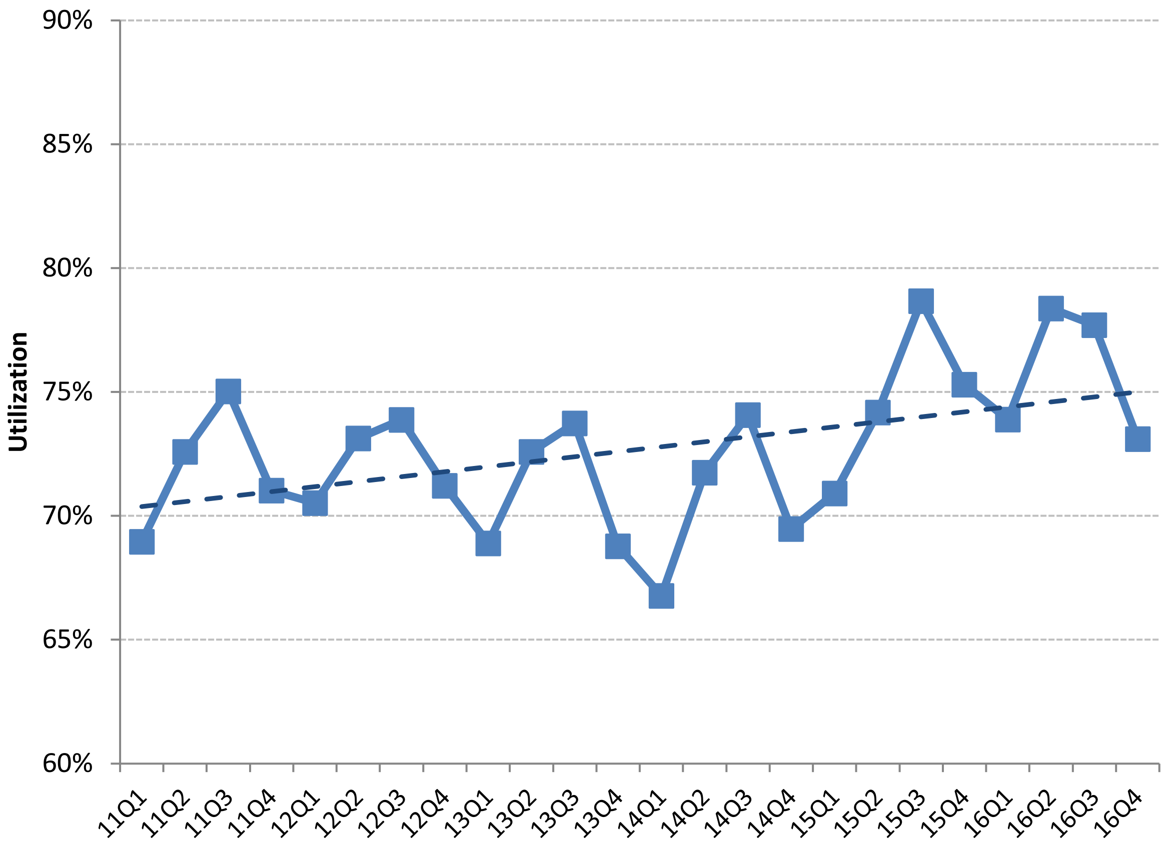


Source: Baker & O'Brien *PRISM* database

EIA compiles and reports domestic refinery catalytic reformer throughput but not alkylate production. Baker & O'Brien's *PRISM* modeling of the domestic refining industry leads us to conclude that alkylation unit throughput is being maximized across the country. On the other hand, the EIA data indicate that reformer units are not fully utilized (Figure 20). The seasonal variation is due to seasonal changes in gasoline demand and seasonal RVP changes that impact the amount of butane added to the blends. Capacity utilization has increased but remains at relatively low levels. While there is some variation in utilization across the PADDs (± 5% utilization), none of the individual PADDs show annual utilization exceeding 80%. Assuming the data collected by EIA is correct, the U.S. refining industry has spare capacity to produce higher octane gasoline.

FIGURE 20

REFORMER UTILIZATION (ALL PADDS)



Source: U.S. Energy Information Administration, Monthly Refinery Report.

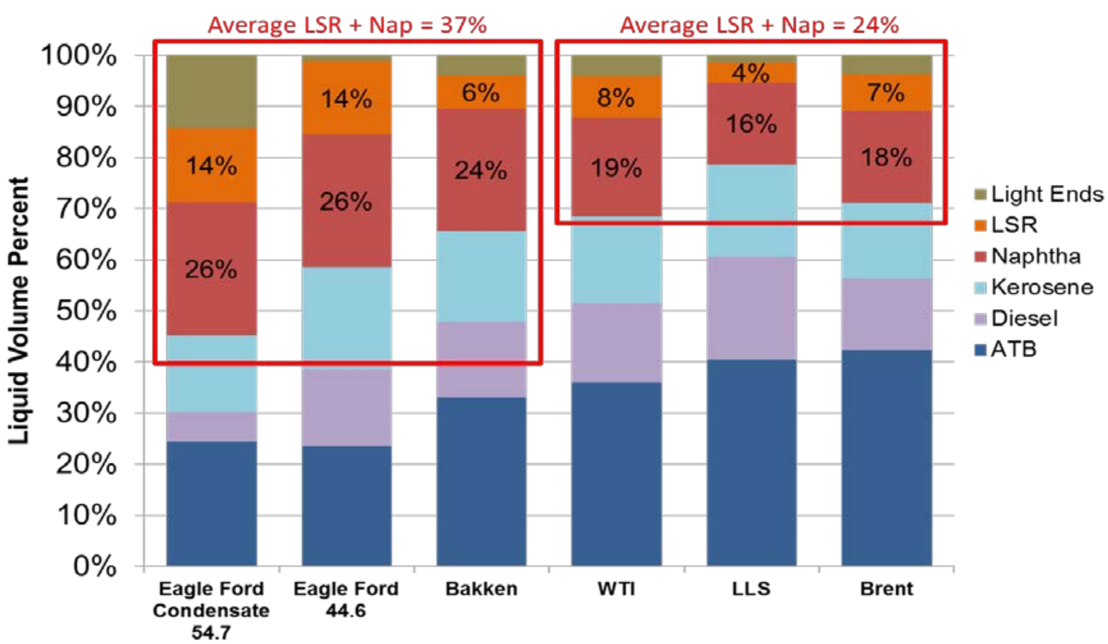
6.2 CRUDE OIL QUALITY

Crude oil quality varies widely, from light (low density) [20] sweet (low sulfur content) to heavy (high density) sour (high sulfur), with many grades in between. Individual refineries are generally designed to operate optimally with specific types of crude oil and changes in crude oil quality impact refinery gasoline production.

Domestic production increased by approximately 3.5 million b/d between 2011 and 2016, with the incremental production primarily light and sweet crude oil from the Eagle Ford and Bakken regions with a high LSR content (Figure 21 and Figure 22). This has directly impacted domestic refinery component production and the "recipe" of the domestic gasoline pool. As previously discussed, LSR is a low octane blending component with a relatively high RVP (Table 2). It is not an ideal gasoline blending component.

FIGURE 21

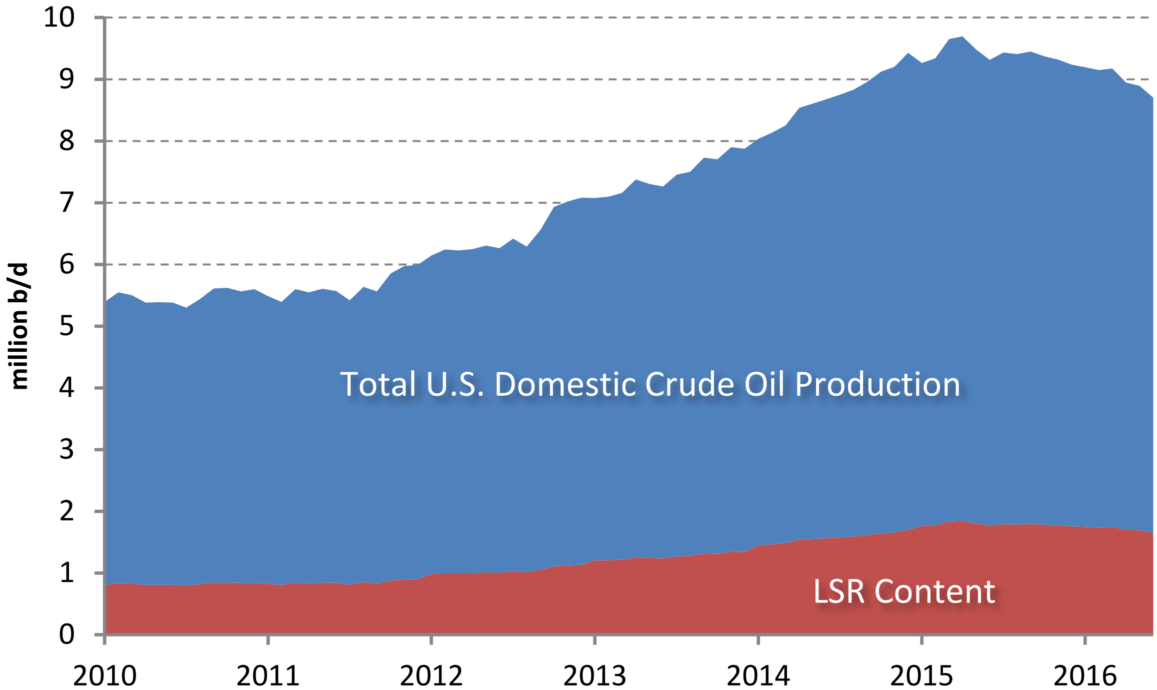
SAMPLE YIELDS FROM CRUDE OILS



[20] In this report, crude oil density is discussed in terms of API gravity. On the API gravity scale, a low number represents heavy (high density) crude oil and a high number represents light (low density) crude oil.

FIGURE 22

U.S. CRUDE OIL PRODUCTION

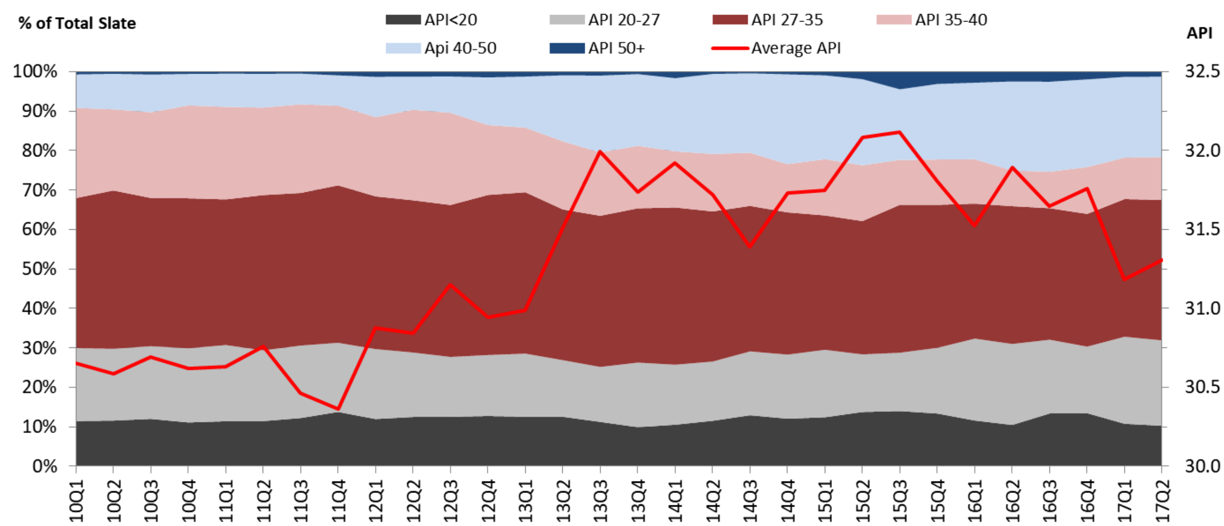


Source: U.S. Energy Information Administration, Petroleum Supply Annual

Domestic refiners increased their shale crude oil inputs and reduced imports of light and medium gravity sweet crude oil. This resulted in a significant shift in the overall composition of the domestic refinery feed slate. Shale and light domestic crude oils, typically in the 40 API - 50 API range, increased from 10% to 20% of the U.S refinery slate, displacing imported crude oils in the 27 API - 40 API range, such as Brent and various low-sulfur West African crude oils (Figure 23).

FIGURE 23

U.S. REFINERY CRUDE OIL MIX

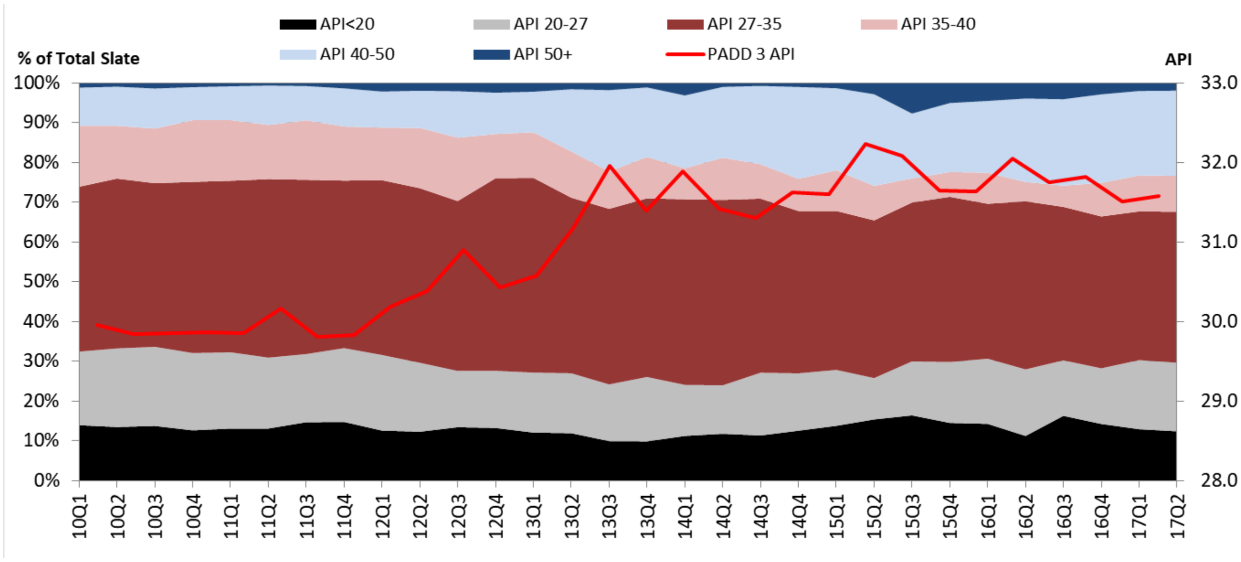


Source: Baker & O'Brien *PRISM* database

The two districts with the largest crude oil refining capacity, PADDs 2 and 3, had the largest percentage increases in 40 API - 50 API crude oil processing (Figures 24 and 25). As light crude oil processing increased in PADD 3, the average gravity of crude oil processed in the PADD increased by more than 1.5 API.

FIGURE 24

PADD 3 REFINERY CRUDE OIL MIX

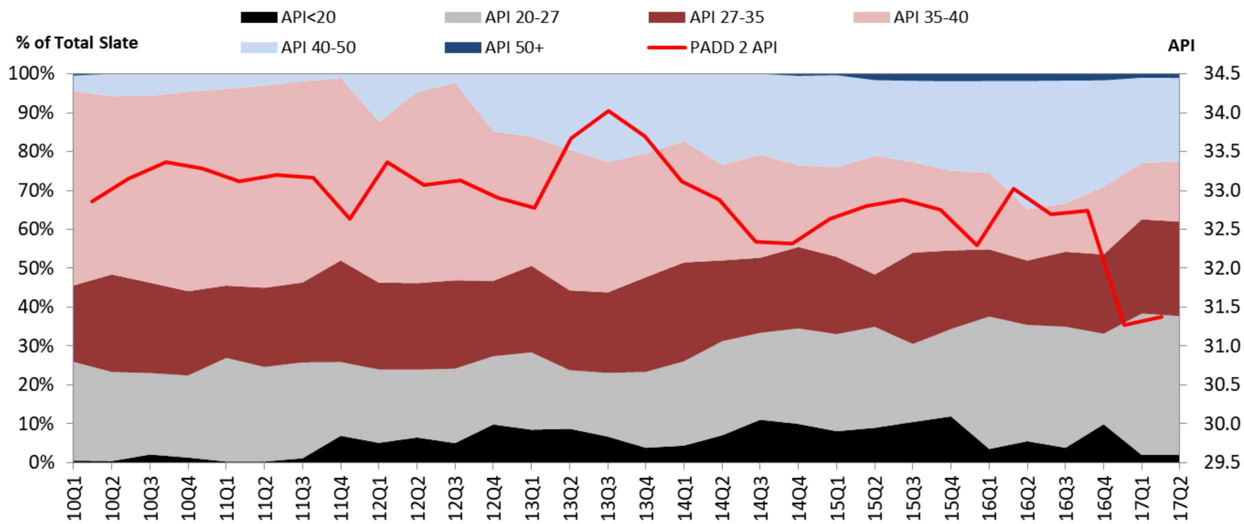


Source: Baker & O'Brien *PRISM* database

PADD 2 had simultaneous increases in light and heavy (20 API-27 API) crude oil processing, largely due to investments at BP Whiting, Marathon Detroit, and WRB Wood River. The increase in heavy crude oils more than offset the impact of light crude increases on the average crude oil gravity for the PADD, which decreased by over 1.5 API.

FIGURE 25

PADD 2 REFINERY CRUDE OIL MIX



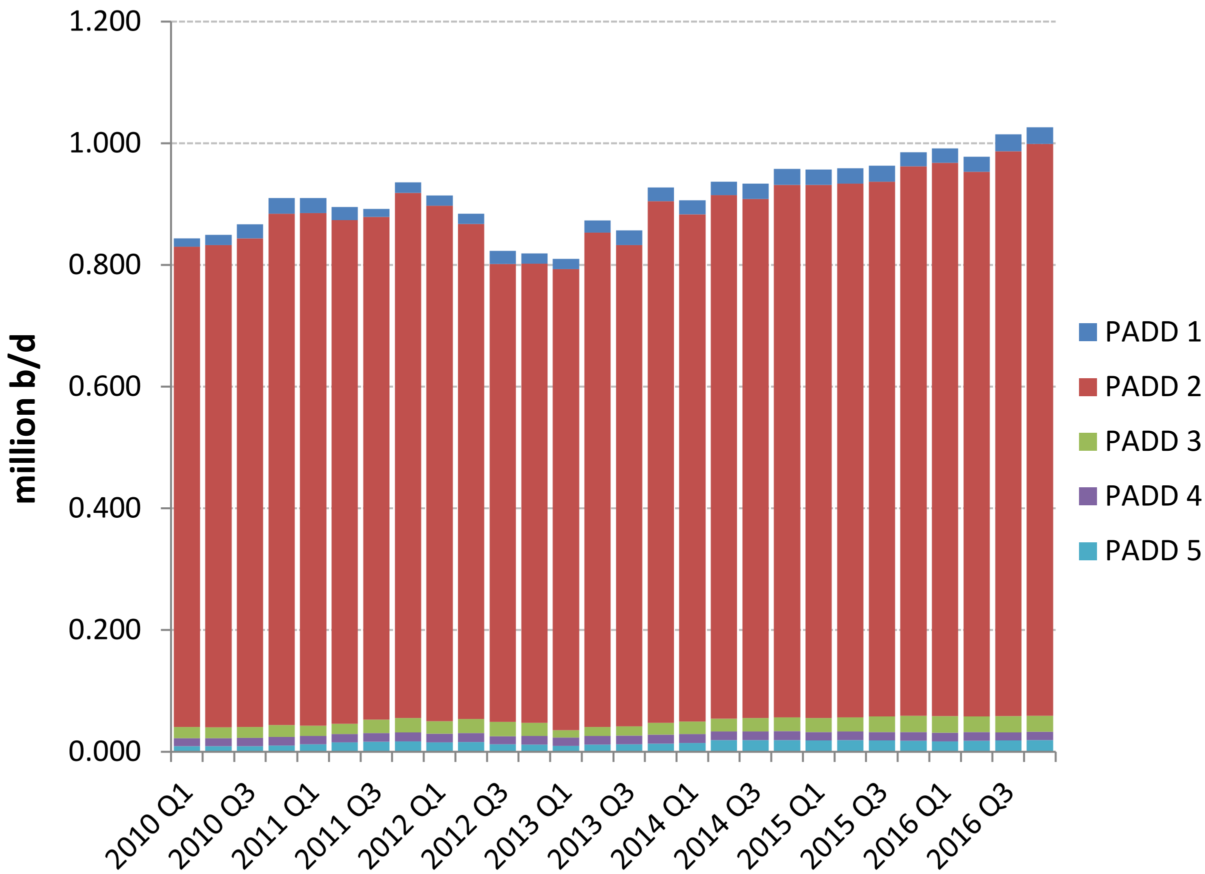
Sources: Baker & O'Brien *PRISM* database

6.3 ETHANOL

The volume of ethanol blended into gasoline increased dramatically from 2000 through 2010, but the rate of increase has slowed in this decade (Section 5 Figures 12 and 13). It increased by 14% from 2010 to 2016 and stood at 914,000 b/d in 2016.

FIGURE 26

U.S. ETHANOL PRODUCTION



Source: U.S. Energy Information Administration, Monthly Oxygenates Telephone Report.

Ethanol's blending properties and impact on the quality and quantity of the finished gasoline pool are discussed in Section 4.5.2.

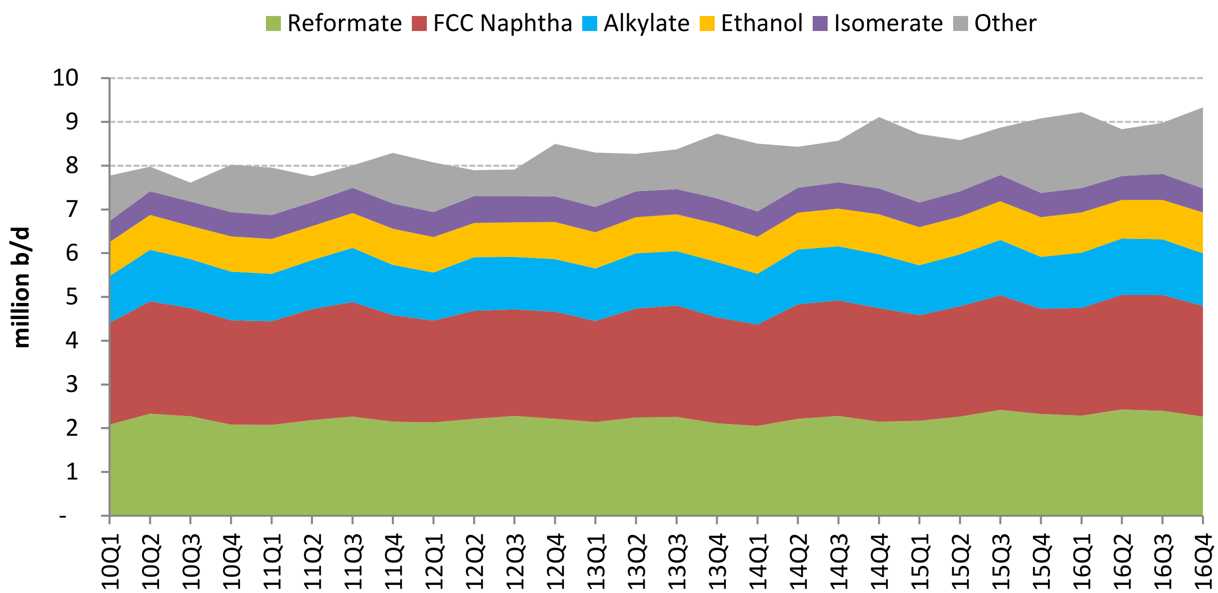
6.4 FINISHED GASOLINE COMPOSITION

The increase in light crude oil processing impacted the refinery produced gasoline components (Figures 27 and 28). The "Other" category in Figures 27 and 28 includes butane, LSR, naphtha, and natural gasoline. The seasonal variability is due to the RVP specification changes (Section

4.2.2). In the winter, refiners can blend more high-RVP components such as butane and LSR. During 2016, the average quantity of these components in the gasoline pool was over 650,000 b/d greater than the 2010 average, an increase of over 85%.

FIGURE 27

U.S. FINISHED GASOLINE COMPOSITION

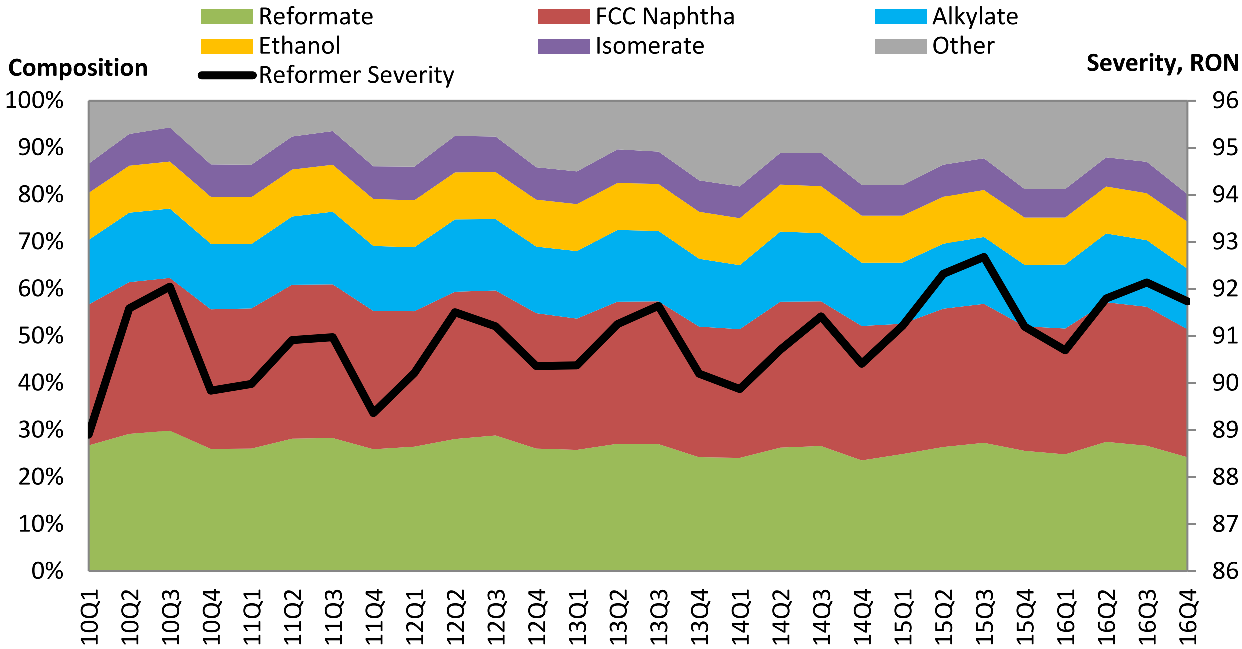


Source: Baker & O'Brien *PRISM* database

Refiners have off-set the additional low-octane LSR and naphtha through increased ethanol blending, as well as increased Reformer severity (Figure 28) and throughput. Additionally, spare refinery reformer capacity appears to be available to manage current and future octane requirements (Section 6.1, Figure 20).

FIGURE 28

U.S. FINISHED GASOLINE COMPOSITION AND REFORMER SEVERITY



Source: Baker & O'Brien *PRISM* database

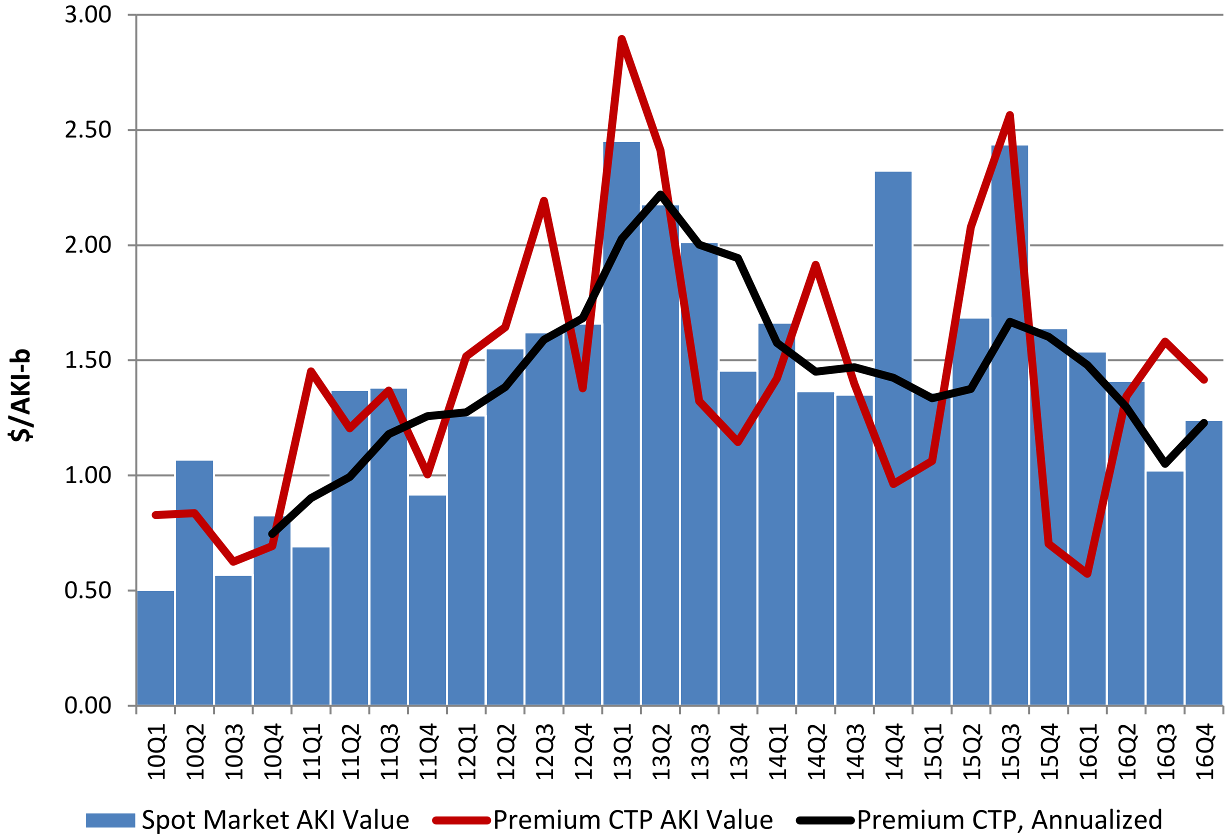
6.5 COST OF INCREMENTAL OCTANE

Octane costs and values are often described in terms of dollars per octane-barrel ($/AKI-b).[21] To measure the cost of producing incremental octane, we calculate the cost of producing an incremental barrel of premium gasoline (CTP) by raising reformer severity (Figure 29, red and black lines). The market value of octane is calculated by dividing the price differential between premium and regular gasoline by the difference in octane rating (Figure 29, blue bars).

[21] The concept of octane-barrels is discussed in Section 5.

FIGURE 29

COST OF INCREMENTAL OCTANE, U.S. GULF COAST



Source: Platts, OPIS, and Baker & O'Brien Analysis

The USGC spot market is very active, connected to other markets in the Atlantic Basin, and octane market values react quickly to changes in production costs and supply interruptions (Section 7.3). The spot market value of the octane closely tracks the incremental octane cost through the 2010 to 2016 period.

Octane costs appear to have reached a peak in in 2012/2013 and slowly decreased back down to early 2011 levels by 2016. The falling costs, starting in 2013, is a result of declining naphtha (reformer feedstock) prices relative to gasoline largely due to the change in the U.S. refinery crude slate and subsequent increased naphtha supply (Section 6.2).

The increasing differentials between premium and regular gasoline seen at the retail levels are not solely due to sustained high costs of producing incremental octane and premium gasoline.

Although octane CTP spiked several times between 2012 and 2016, costs have been trending down since 2013.

In summary:

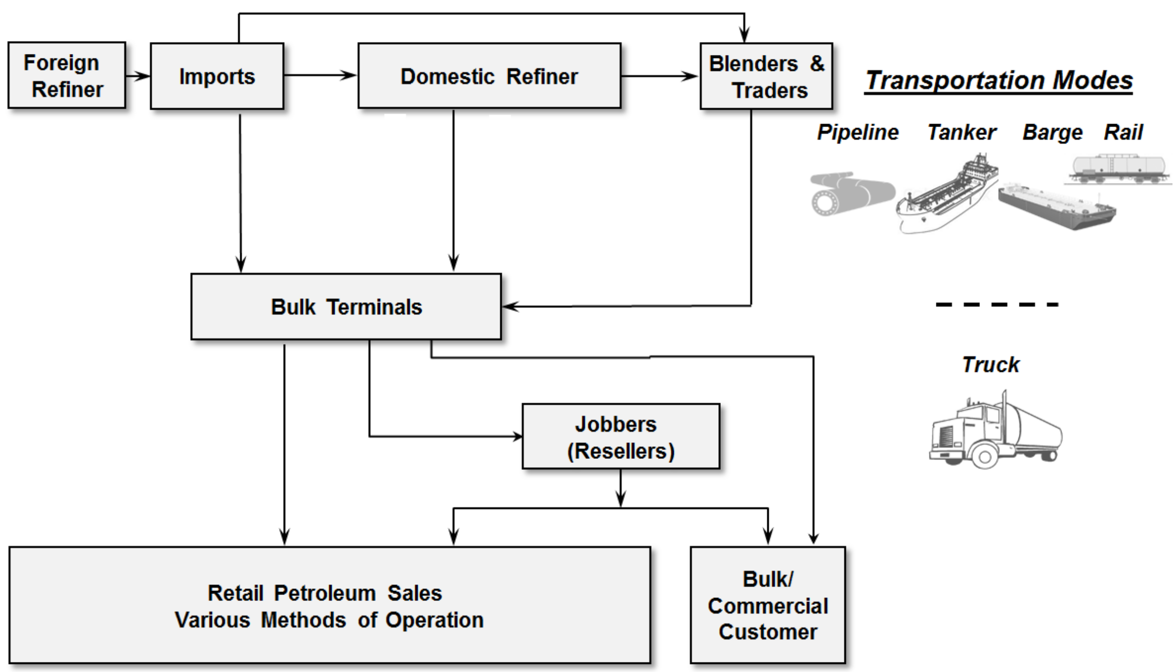
1. Reformer economics are one of the primary determinants of the incremental cost of octane (Section 6.1),
2. Changes to refinery crude slates have increased supplies of low octane LSR and reformer feedstocks (naphtha) (Section 6.2), and decreased their cost,
3. Spare refinery reformer capacity for converting the additional naphtha into high octane components has and continues to exist (Section 6.1, Figure 20),
4. Through a combination of higher reformer throughput and modest increases in reformer severity (Figure 28), refiners have been able to convert the additional naphtha into high octane components,
5. Evidence of this can be found in the fact that the difference between premium and regular gasoline at the spot level, or the first point of sale, has not increased, but in fact has declined since 2013.

7. Premium to Regular Price Differentials

Gasoline is distributed from refineries by pipelines, marine tankers, barges, railcars, and tank trucks. A wide range of commercial interests own and/or operate the different supply chain components. Owners include not only refining and marketing companies but also other independently owned and managed entities, such as transport companies, traders, marketers, and blenders that specialize in particular supply chain functions.

FIGURE 30

OVERVIEW OF GASOLINE SUPPLY CHAIN



Finished gasoline is bought and sold at multiple points in the supply chain. The retail price that the consumer sees is usually set by the owner/operator of the individual retail outlet. These are typically small or medium size businesses that own one or more outlets. These retail outlets include both branded and unbranded operations. In branded operations, the owner/operator of the location has a marketing agreement with the company owning the brand (often a refining company), but the owner/operator sets the retail price. The company sets the retail gasoline price only in locations owned and operated by a refining company.

Retail owner/operators purchase finished gasoline from bulk terminals on either a delivered tank wagon basis or at the rack price. In the latter case, the retail owner/operator is responsible for transporting the gasoline to the retail location. There are separate rack prices for branded and unbranded gasoline.

Refiners, traders, and others also buy and sell finished gasoline and components in the “spot market” upstream of the bulk terminals. These transactions are typical for quantities of 1 million gallons or more. Spot market prices are more closely tied to refinery and blending costs than rack or retail prices.

The remainder of this section of the report will discuss the historical price differential between premium and regular gasoline at retail, rack, and spot markets.

7.1 RETAIL

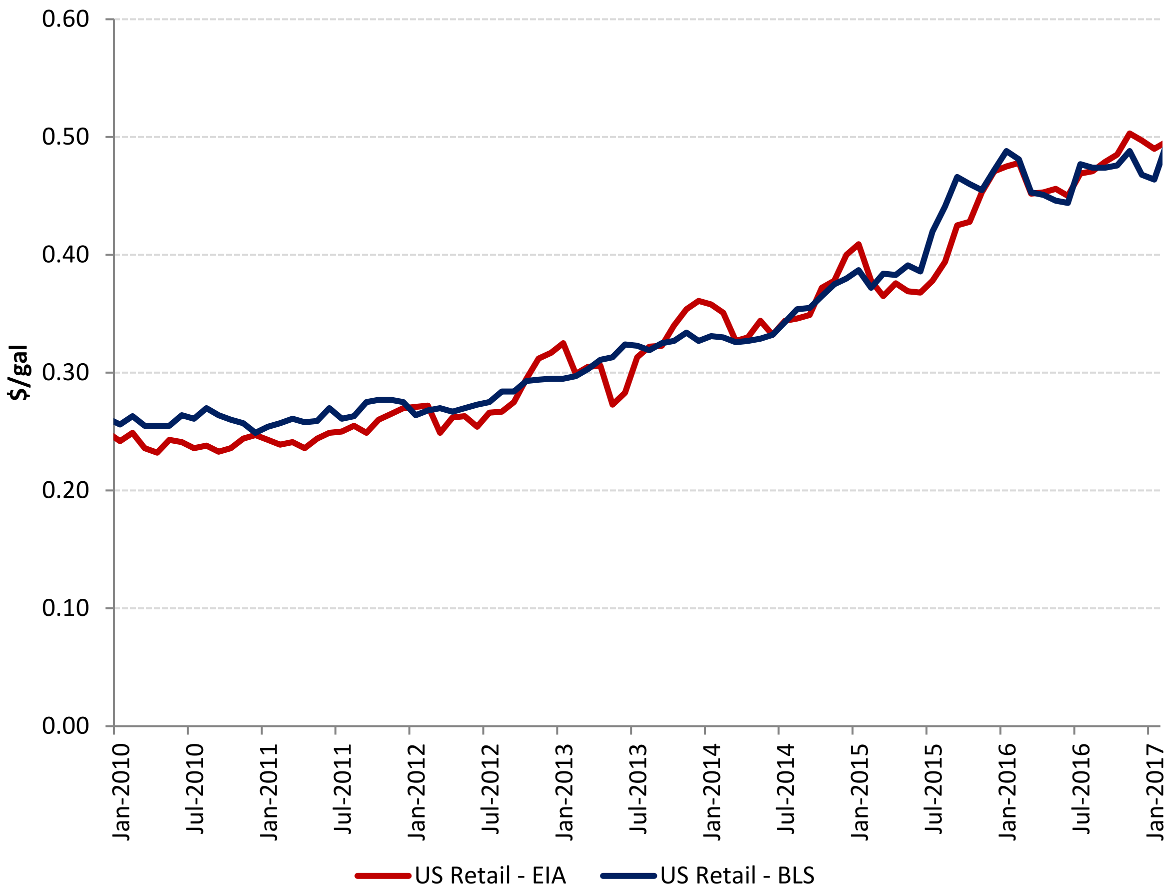
Retail price data are available through several public data sources such as EIA and the Bureau of Labor Statistics (BLS), as well as a variety of private and trade organizations. Retail price data are collected by EIA through a telephone survey of a sample of approximately 800 retail gasoline outlets every Monday.[22] Retail price data are also collected by the BLS since the gasoline price index makes up one of the components of the Consumer Price Index (CPI). Data for the gasoline index are collected by BLS economic assistants over 1,000 selected outlets in 87 metropolitan statistical areas across the country.

The EIA and BLS price surveys show very similar premium to regular gasoline price differentials (PRdiff) (Figure 31). Both series show that the PRdiff has widened significantly over the past seven years, reaching nearly 0.50 $/gal at the end of 2016.

[22] The reported price includes all taxes and is the pump price paid by a consumer as of 8:00 a.m. Monday. The price data are used to calculate weighted average price estimates at the city, state, regional, and national levels using sales and delivery volume data from other EIA surveys and population estimates from the Bureau of Census.

FIGURE 31

U.S. RETAIL PREMIUM TO REGULAR GASOLINE DIFFERENTIAL

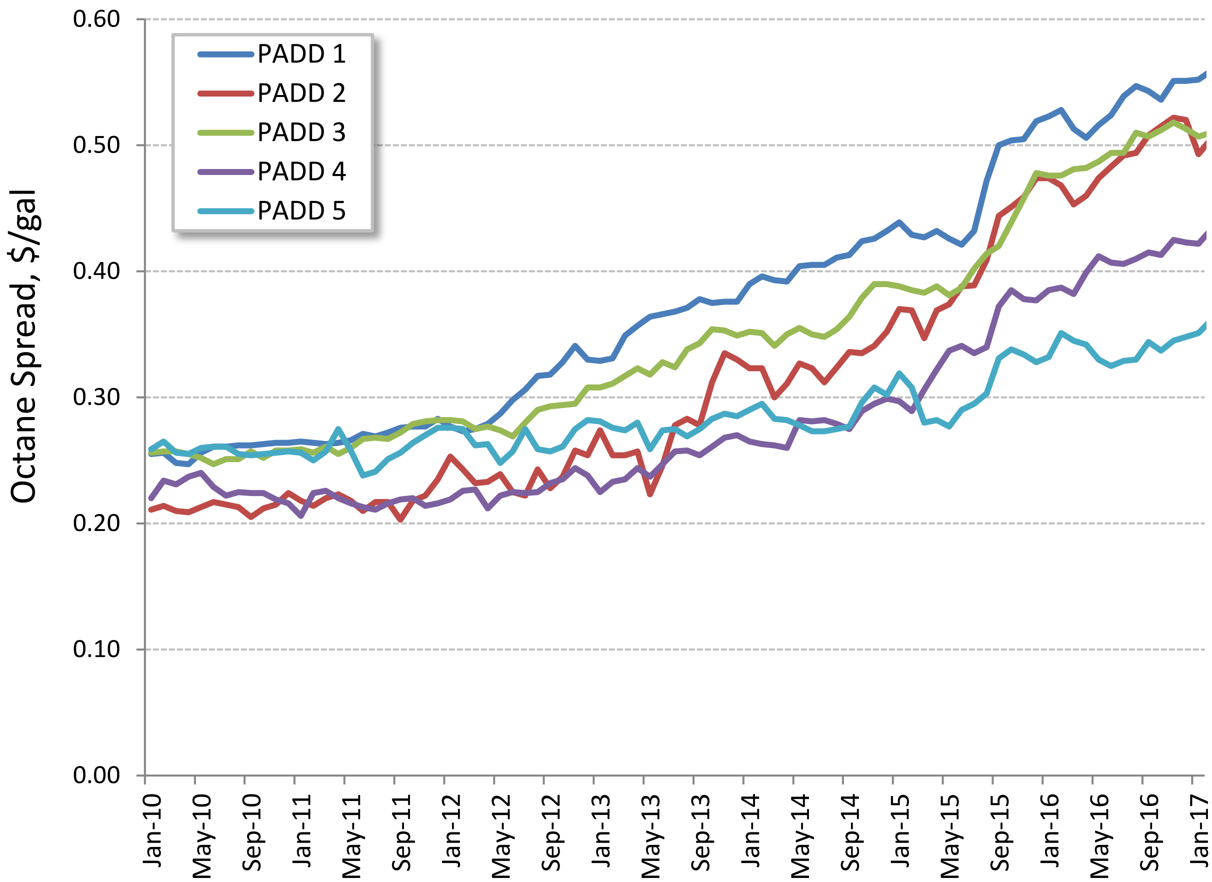


Sources: U.S. Energy Information Administration, Motor Gasoline Price Survey; Bureau of Labor Statistics

While the premium to regular price differential has increased in all regions, there is significant geographical variation in the differential, with PADD 1 having the highest differential and PADD 5 the lowest (Figure 32).

FIGURE 32

U.S. RETAIL PREMIUM TO REGULAR GASOLINE DIFFERENTIAL BY PADD



Source: U.S. Energy Information Administration, Motor Gasoline Price Survey;

7.2 RACK

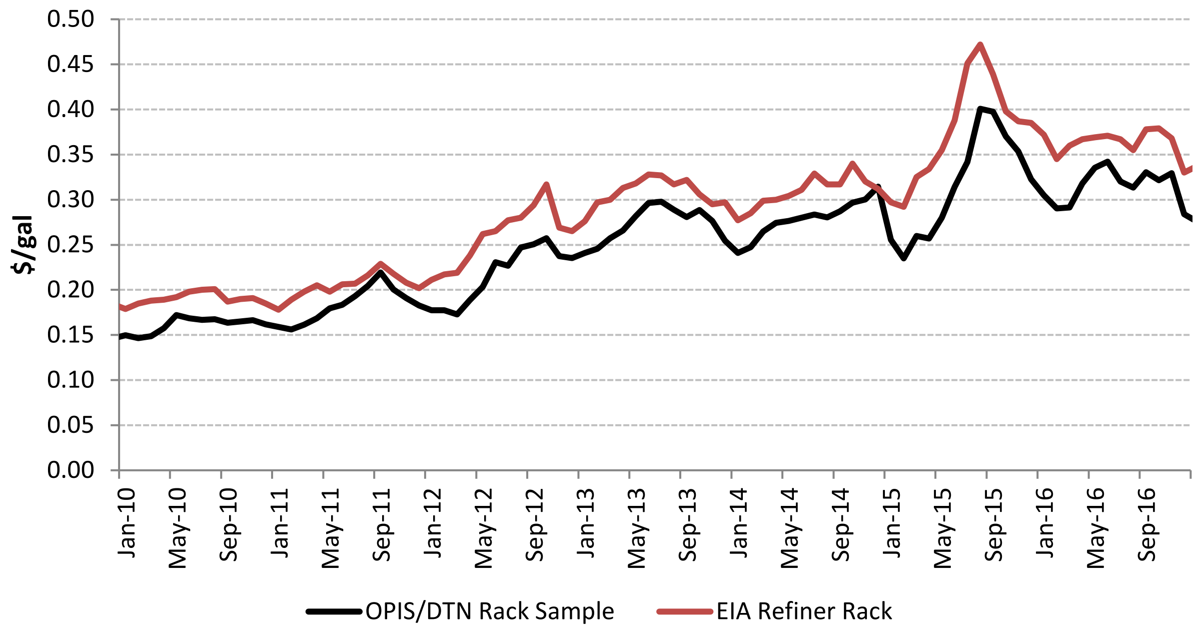
Rack prices include the delivered fuel cost, all other costs, and a profit for the owner/operator Rack sales prices are collected by EIA and commercial data providers such as OPIS, DTN, and Platts. The EIA data are volume weighted and only considers refiner rack sales and does not include other companies that participate in rack sales.[23] OPIS, DTN, and Platts provide more differentiation on reformulated versus conventional gasoline, but are not volume weighted.

[23] Collected on Form EIA-782A "Refiners'/Gas Plant Operators' Monthly Petroleum Product Sales Report." Within that report, rack level sales are reported including wholesale truckload sales or smaller batches of gasoline where the title transfers at the terminal.

Despite the differences in methodology, OPIS/DTN and EIA rack PRdiffs follow the same trend of widening from 0.15 $/gal – 0.20 $/gal to 0.40 $/gal – 0.45 $/gal between 2010 and late 2015, with some moderation into 2016 (Figure 33).

FIGURE 33

U.S. RACK PREMIUM–REGULAR GASOLINE DIFFERENTIAL[24]



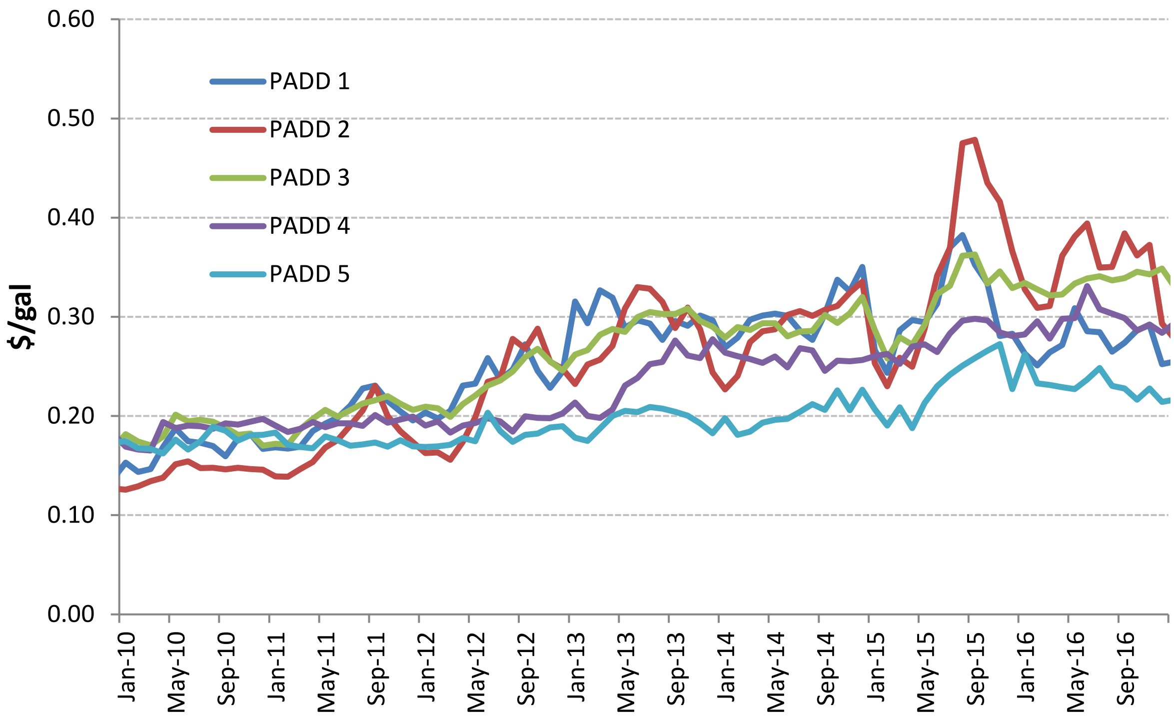
Source: U.S. Energy Information Administration, Refinery Gasoline Prices by Grade and Sales Type

While the rack PRdiff has increased in every PADD, regional variation exists. The average rack PRdiff started in a range of approximately 0.15 $/gal – 0.20 $/gal in early 2010 in all PADDs. Through 2016 the PRdiff increased more rapidly in PADDs 1, 2, and 3. PRdiff increases in PADDs 4 and 5 were smaller. The average PRdiff in PADD 5 only increased to approximately 0.25 $/gal while PADDs 1-3 reached highs near 0.40 $/gal – 0.50 $/gal (Figure 34).

[24] The OPIS/DTN data series includes approximately 100 locations and is an of all gasoline classes (i.e., reformulated and conventional) and includes both finished gasoline and BOB prices.

FIGURE 34

RACK PREMIUM–REGULAR GASOLINE PRICE DIFFERENTIALS BY PADD



Sources: OPIS, DTN, and Baker & O'Brien Analysis

7.3 SPOT

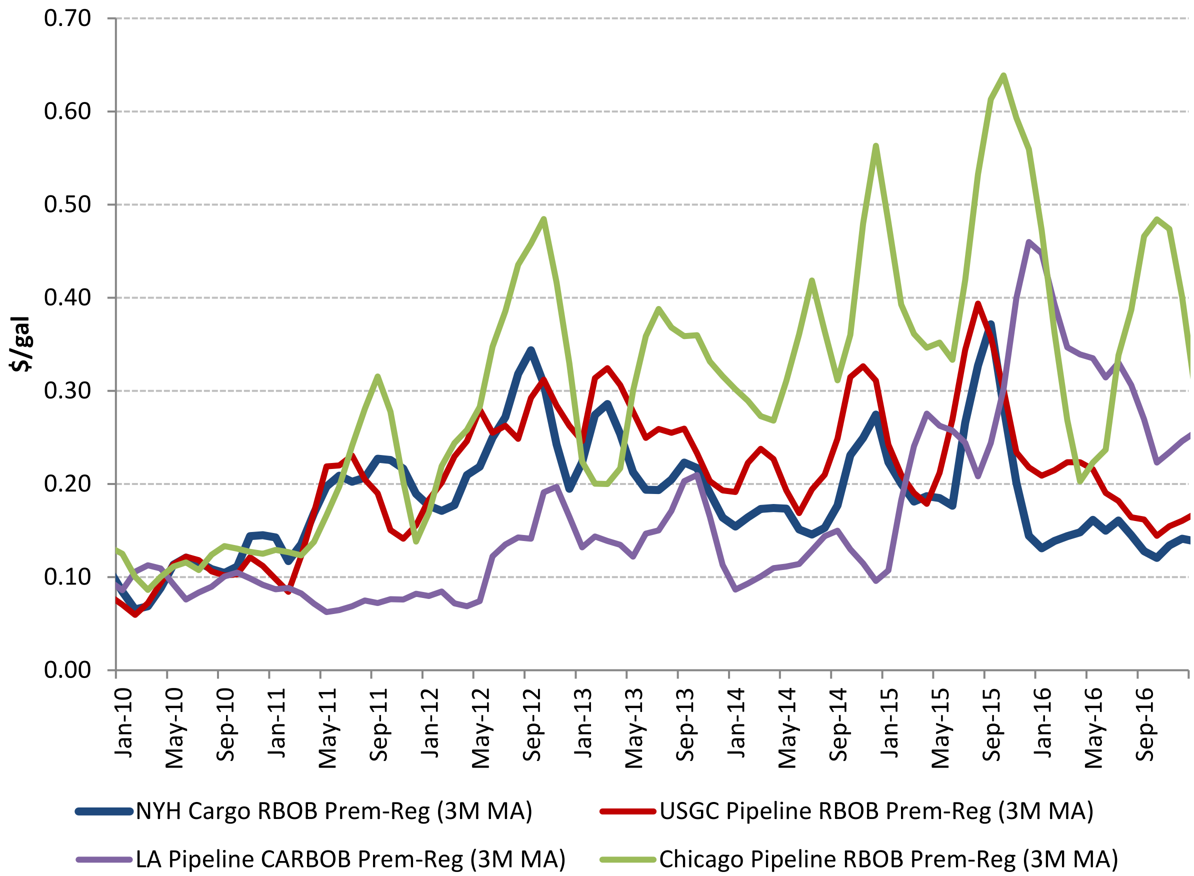
The spot market refers to high volume (25,000 barrels to 300,000 barrels) one-time transactions dictating delivery of petroleum products or crude oil in the near future. These markets are in regions with clusters of refineries and/or terminals. They react quickly to changes in refining costs and capacity. The major U.S petroleum product spot markets are the USGC and NYH. Prices for individual transactions are usually not disclosed publicly. Several companies survey traders in these markets and publish daily assessments of market prices. Spot market prices are also published for Chicago, "Group 3," Los Angeles, San Francisco, Seattle, and the Pacific Northwest. There are fewer spot transactions in these markets and additional caution should be exercised when drawing conclusions from the quoted prices.

For the period 2010 through 2016, spot market PRdiff in the USGC (PADD 3) and NYH (PADD 1) have generally trended together. The PRdiff in Chicago (PADD 2) and Los Angeles (PADD 5) started the decade in line with the USGC and NYH but have diverged (Figure 35). On a three-month moving average basis, the USGC and NYH reformulated blendstock for oxygenate blending (RBOB) markets increased to an average differential of 0.20 $/gal – 0.25 $/gal before declining in 2016. However, the Chicago PRdiff continued to climb through 2017, while the Los Angeles market didn't begin climbing until 2015, well after the increases in the other markets.

FIGURE 35

PREMIUM–REGULAR PRICE DIFFERENTIALS

SELECTED U.S. SPOT MARKETS

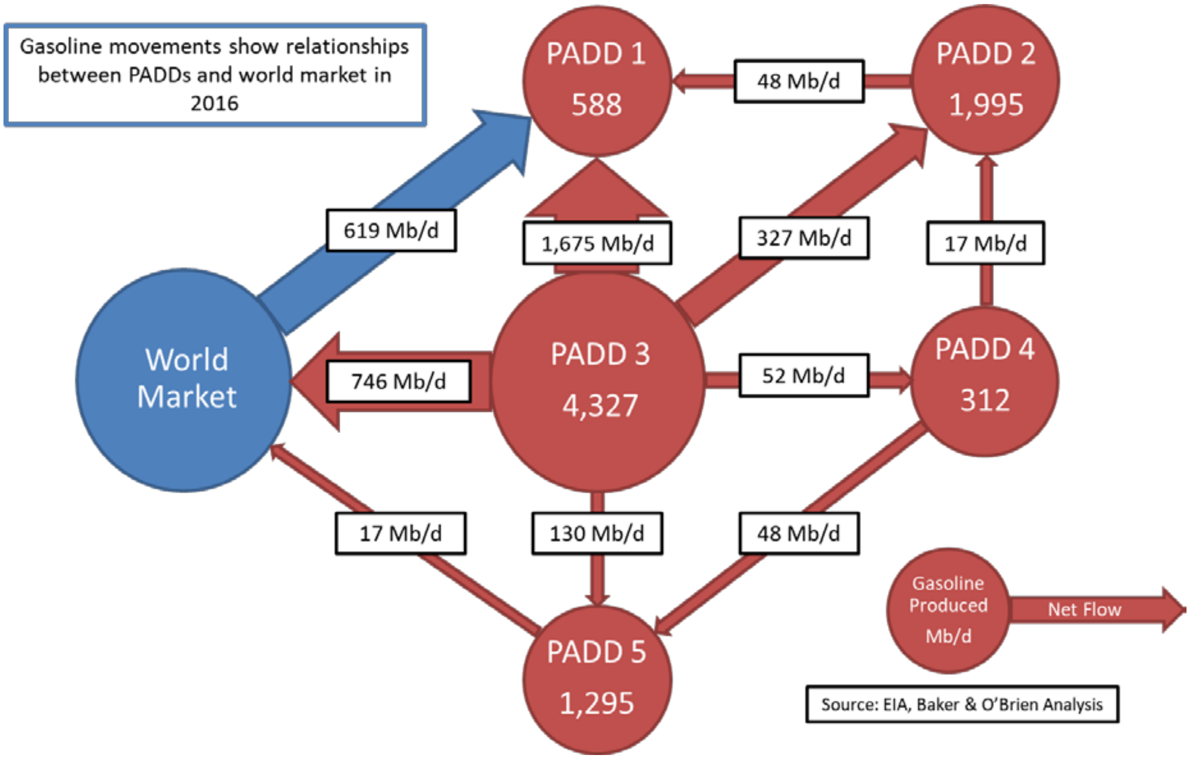


Sources: Platts,OPIS, and Baker & O'Brien analysis

The linkage (or absence of) between pricing in the spot markets can be attributed to similarities or differences in refining costs and the ability to quickly transport product between markets. PADD 3 supplies more gasoline to PADD 1 than is produced in PADD 1 refineries. PADD 3 is also the largest external supplier of gasoline to PADDs 2 and 4 (Figure 36).

FIGURE 36

NET GASOLINE FLOWS[25]



Large pipelines move refined products from PADD 3 to PADD 1 and directly connect the USGC and NYH spot markets. Gasoline also moves by barge and ship to PADD 1 and the NYH spot market. The NYH and USGC spot markets also interact with international markets for petroleum products. This is primarily with refineries and markets throughout the Atlantic Basin. With all of the interconnections, it is not surprising that prices in these two spot markets tend to follow similar patterns.

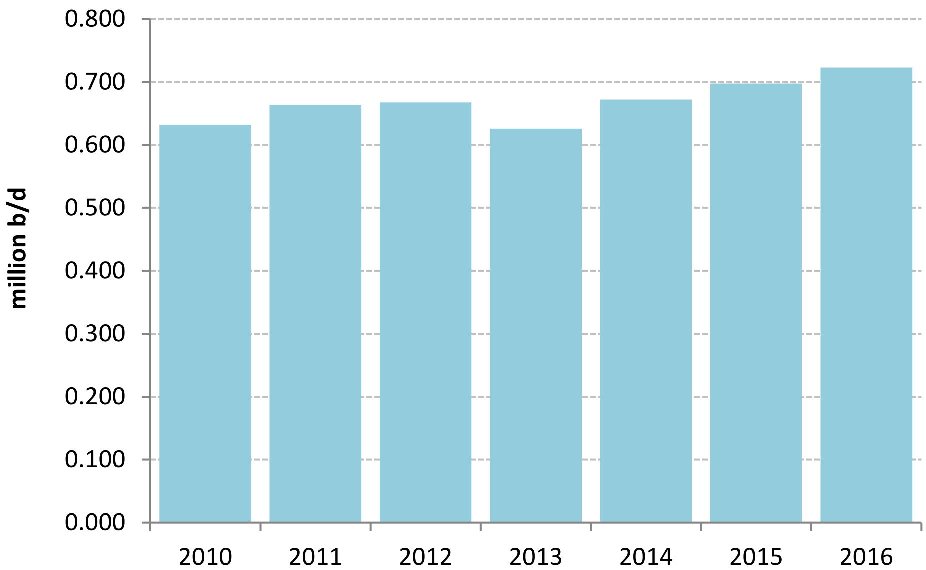
Pipelines and barges also connect PADD 2 and the Chicago spot market to PADD 3 and the USGC spot market. However, there have been changes in these markets over the 2010 to 2016 period. The WRB, Marathon, and BP heavy oil projects (Section 6.1) and other smaller

[25] The raw EIA data on PADD to PADD transfers shows 375,000 b/d moving from PADD 1 to PADD 2. These are pipeline volumes that originate in PADD 3 and transit through PADD 1 on their way to Tennessee in PADD 2. They are shown as a PADD 3 to PADD 2 movement in this figure.

projects increased light oil products[26] production in PADD 2 and particularly in the Chicago market (Figure 37). During this time period, two major pipelines that shipped gasoline from the USGC to the Chicago area reversed flow and now ship NGLs from PADD 2 to the USGC.

FIGURE 37

AGGREGATE LIGHT OIL PRODUCTS FROM WOOD RIVER, DETROIT, AND WHITING



Source: Baker & O'Brien *PRISM* estimate

PADD 5 is somewhat of an "island" with limited pipeline and logistical connections to the major refining centers in the rest of the country. PADD 5 is also "long" gasoline and must export excess product to foreign markets. Thus, PADD 5's exhibits mostly independent pricing behavior and has limited inter-relationships with the rest of the country. Structural shortages in PADD 5 would be filled by water-borne deliveries from the Asian refiners or Gulf Coast refiners (which have the extra shipping costs of going through the Panama Canal). These structural shortages can also result in extended periods of high pricing, as transportation costs and delivery times from external markets are relatively high.

[26] Combined gasoline, BOB, jet/kerosene, and diesel fuel.

7.4 REGIONAL SUPPLY CHAIN ANALYSIS

The following series of charts show retail (or "consumer") gasoline prices and how the PRdiff builds across the supply chain in four key markets. As previously mentioned, the USGC spot market PRdiff tends to reflect current refinery economics for producing incremental premium gasoline. The NYH spot market is well connected to the Atlantic basin would be expected to also track refinery economics, but since a significant portion of the product in that market in produced on the USGC and in Europe, supply disruptions can cause spikes. Premium gasoline trading in other spot markets reflects smaller volumes and it is less certain that the spot differential tracks refining costs in those regions. In the bar charts, the spot market PRdiff is represented by the blue bar.

The wholesale and retail PRdiffs reflect both the costs to produce premium and regular gasoline and the supplier's abilities to mark-up each of the grades. The PRdiff at the wholesale rack normally is greater than the spot market PRdiff, indicating that wholesale marketers earn a greater profit margin on premium gasoline than they do on regular. The red bars in charts that follow are the amount of this extra margin. When the red bar drops below zero, it indicates that the wholesale profit margin on premium is less than the margin on regular. It does not mean that wholesalers are losing money on premium sales.

The green bars show the extra profit margin that retailers earn on premium relative to their profit margin on regular. The sum of the three stacked bars is the PRdiff that the consumer sees at the pump. The black line on each chart shows the percentage of the total PRdiff that is attributed to marketing (the wholesale rack plus retailer PRdiffs, the "consumer PRdiff") as opposed to refining costs.

To summarize, the spot USGC PRdiffs reflect refiner cost to produce difference between the gasoline grades. The rack PRdiff and wholesale PRdiffs reflect those costs and additional mark-up marketers receive for premium versus regular gasoline.

7.4.1 CENTRAL ATLANTIC (PADD 1B)

From September 2010 to May 2011, the average retail price of both regular and premium gasoline in the Central Atlantic region (including New York) rose by roughly 1.30 $/gal driven largely by world oil prices.

FIGURE 38

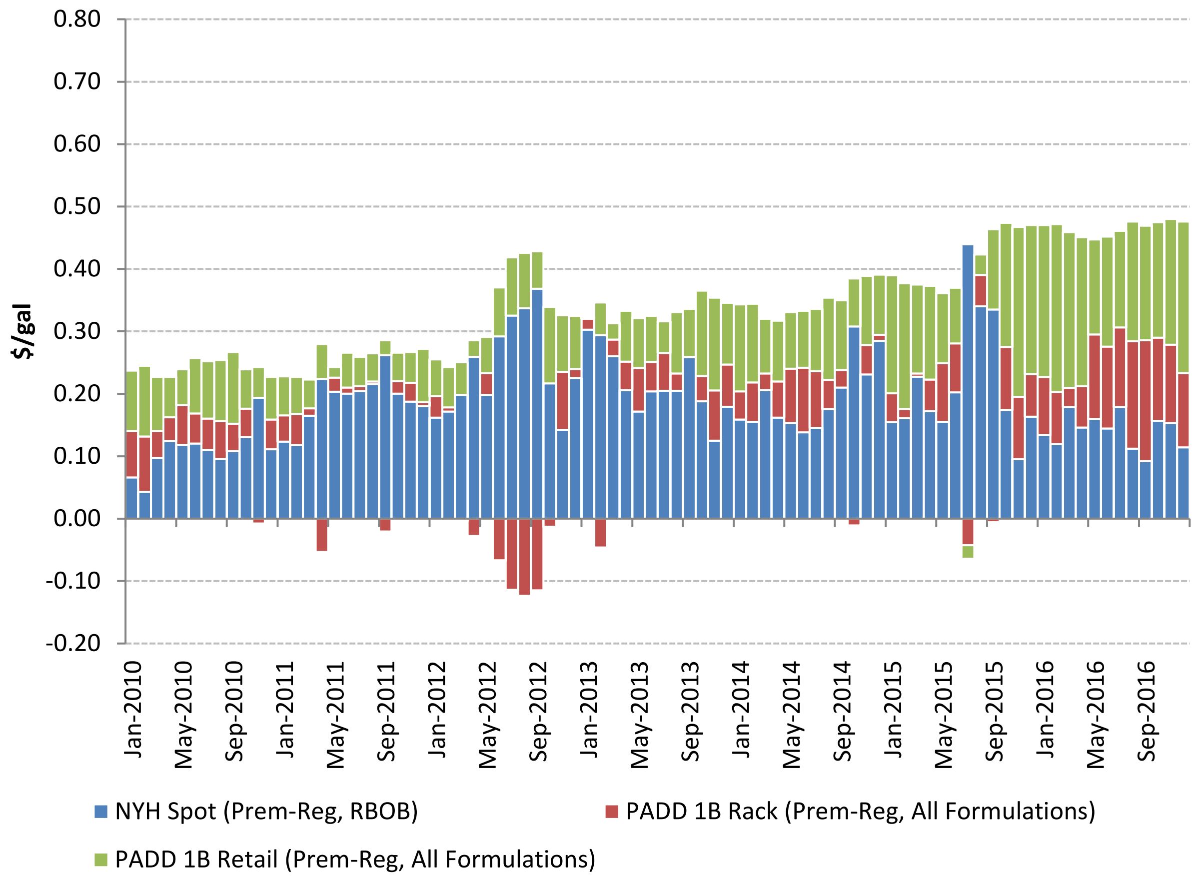
CENTRAL ATLANTIC RETAIL GASOLINE PRICES

Source: U.S. Energy Information Administration, Motor Gasoline Price Survey

The difference between the gasoline prices is deconstructed in Figure 39. During this period, the NYH spot market PRdiff increased from about 0.10 $/gal to approximately 0.20 $/gal, but most of this increase was not immediately passed through to consumers. The increase in retail prices from 2010 to 2011 coincides with a drop in total gasoline consumption, but premium sales as a percentage of total sales remained relatively constant (Section 5 Figure 15).

FIGURE 39

CENTRAL ATLANTIC PREMIUM-TO-REGULAR DIFFERENTIALS



Sources: U.S. Energy Information Administration, Motor Gasoline Price Survey; Platts; OPIS; DTN; and Baker & O'Brien Analysis

Through the remainder of 2011 and into 2012, the spot PRdiff hovered around 0.20 $/gal and the consumer PRdiff increased slightly. Starting in April 2012, the spot PRdiff moved up over a period of six months to nearly 0.37 $/gal in September 2012. Since that time, the spot PRdiff has trended down, with a couple of interrupting spikes. The average spot PRdiff in 2016 was 0.14 $/gal.

In September 2012, when the spot PRdiff reached 0.37 $/gal, the consumer PRdiff was just 0.31 $/gal. As the spot PRdiff declined, the consumer PRdiff remained in the 0.30 $/gal to 0.35 $/gal range through September 2014. Marketers were retaining a larger share of the total PRdiff. Total gasoline consumption increased from 2012 through 2014, with premium

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maintaining a fairly constant percentage of the total (Section 5 Figure 15). The increase in the PRdiff did not affect premium's market share.

Beginning in June 2014, gasoline prices (and oil prices generally) began a steep decline. Retail gasoline prices in the Central Atlantic region bottomed out in February 2016. As prices fell, regular gasoline prices fell faster than premium, the consumer PRdiff grew, and the share of the consumer PRdiff attributable to marketing increased. In 2015 and 2016, gasoline consumption increased. Premium gasoline consumption increased both in volume and as a percentage of total gasoline sales. It appears that the decline in absolute gasoline prices impacted premium consumption more than the price difference between premium and regular.

7.4.2 USGC

Given the interconnectivity of the USGC and Central Atlantic markets (Section 7.3), it is not surprising that the USGC story is very similar to what happened in the Central Atlantic. From September 2010 to May 2011, the average retail price of both regular and premium gasoline in the region rose by roughly 1.30 $/gal, but the consumer PRdiff remained in the 0.25 $/gal to 0.30 $/gal range. The portion of the PRdiff attributable to marketing dropped to 17% in May 2011.

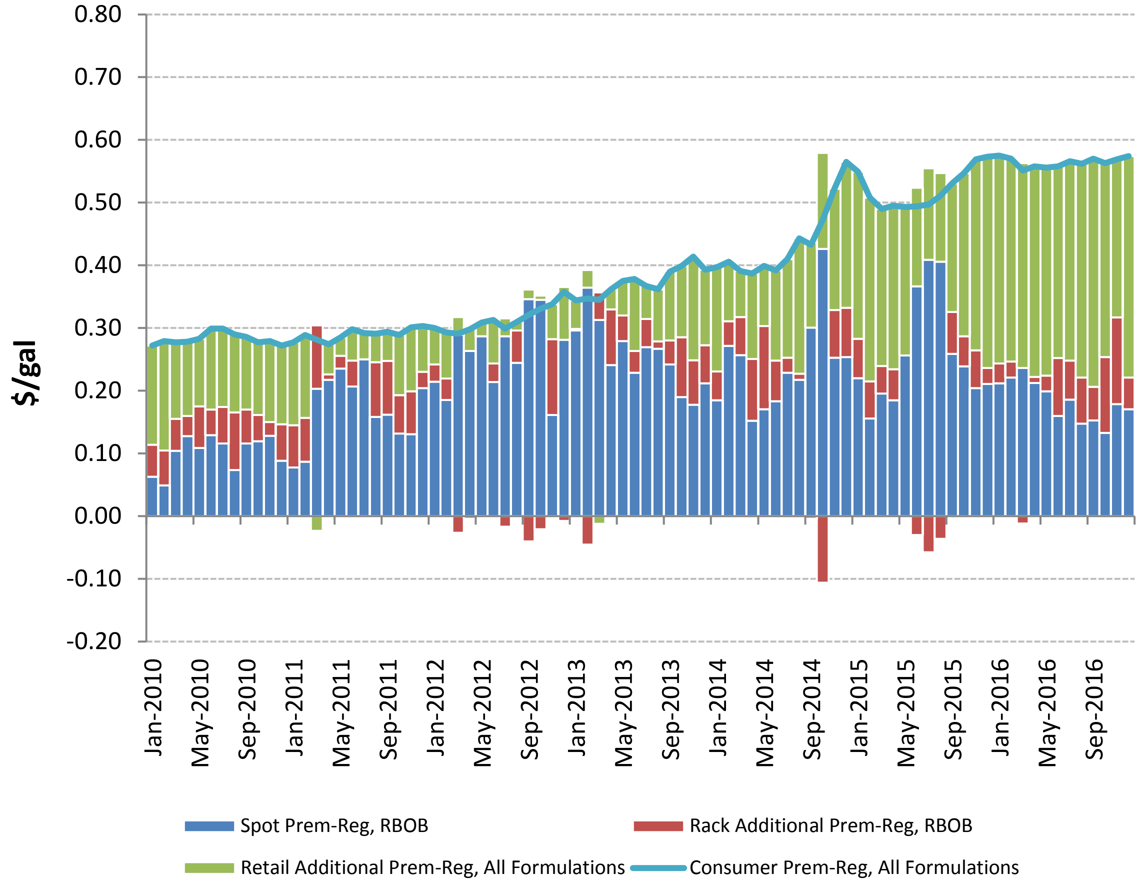
FIGURE 40

HOUSTON RETAIL GASOLINE PRICES

Source: U.S. Energy Information Administration, Motor Gasoline Price Survey

FIGURE 41

HOUSTON PREMIUM-TO-REGULAR DIFFERENTIALS



Sources: U.S. Energy Information Administration, Motor Gasoline Price Survey; Platts; OPIS; DTN; and Baker & O'Brien Analysis

In September 2014 and October 2014, the spot PRdiff briefly spiked to almost 0.43 $/gal. Marketers passed through some, but not all, of this increase to consumers. The consumer PRdiff was just over 0.47 $/gal in October 2014. During this period, retail gasoline prices were falling rapidly. Premium prices dropped more slowly than regular. Retail prices continued to fall, reaching a bottom of 1.50 $/gal for regular in February 2016. With retail premium prices declining more slowly than regular, the consumer PRdiff reached 0.57 $/gal in February 2016. Marketers accounted for 61% of the consumer PRdiff.

The spot PRdiff continued to decline and remained at less than 0.20 $/gal for most of 2016, while the consumer PRdiff stayed in the 0.55 $/gal to 0.60 $/gal range. Premium gasoline consumption increased both in volume and as a percentage of total gasoline sales. It again appears that premium consumption was impacted more by the decline in absolute prices than the differential between premium and regular.

7.4.3 CHICAGO

The pattern for retail prices in Chicago is similar to the Central Atlantic and USGC but with an upward basis.

FIGURE 42

CHICAGO RETAIL GASOLINE PRICES

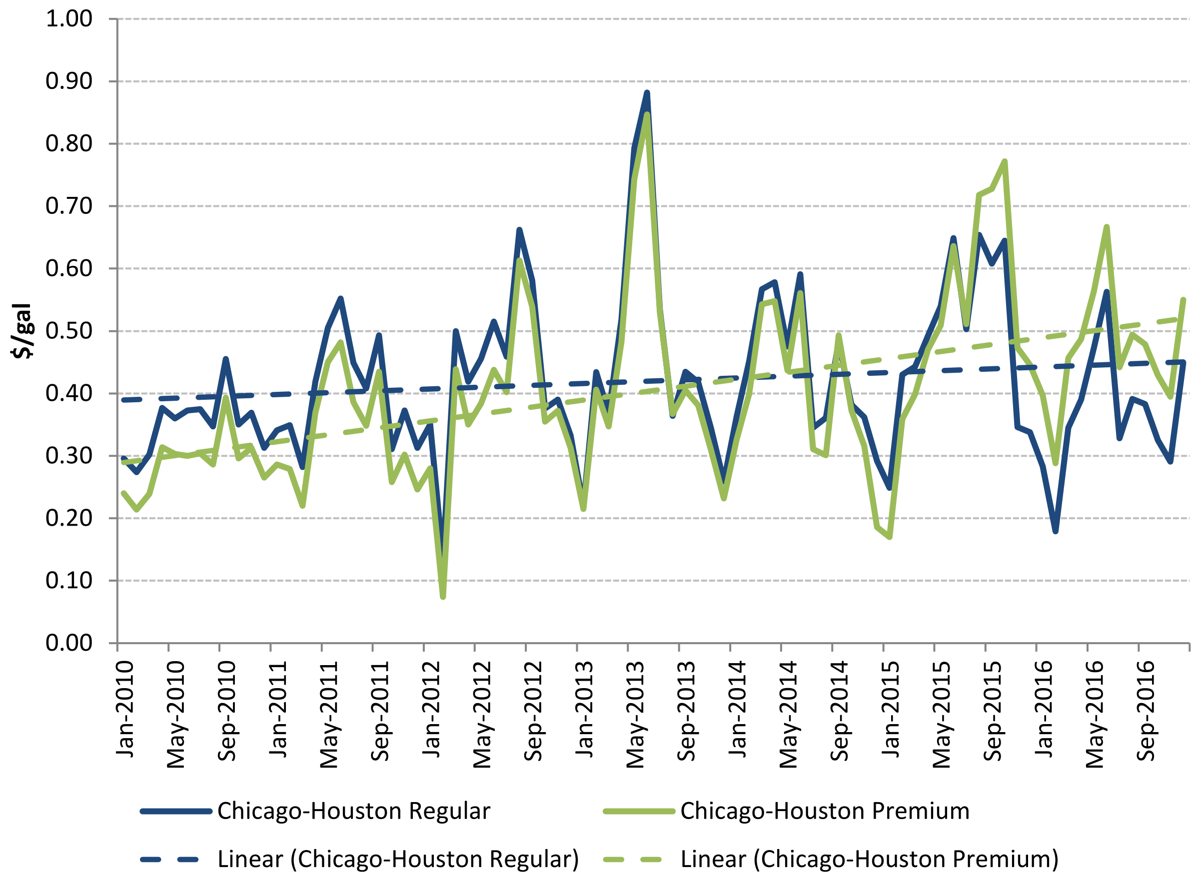
Source: U.S. Energy Information Administration, Motor Gasoline Price Survey

The Chicago market is connected with the USGC by two major pipelines, Explorer and Texas Eastern (Section 7.3). From 2010 through 2016, Chicago regular gasoline retail prices remained 0.40 $/gal to 0.45 $/gal over Houston prices. There has been a gradual increase in this differential. The Houston to Chicago retail premium price differential was approximately

0.30 $/gal in 2010 (below the location differential for regular). It gradually increased across the period to 2016, faster than the regular differential, and by end of 2016 was over 0.50 $/gal.

FIGURE 43

CHICAGO-HOUSTON RETAIL GASOLINE PRICES

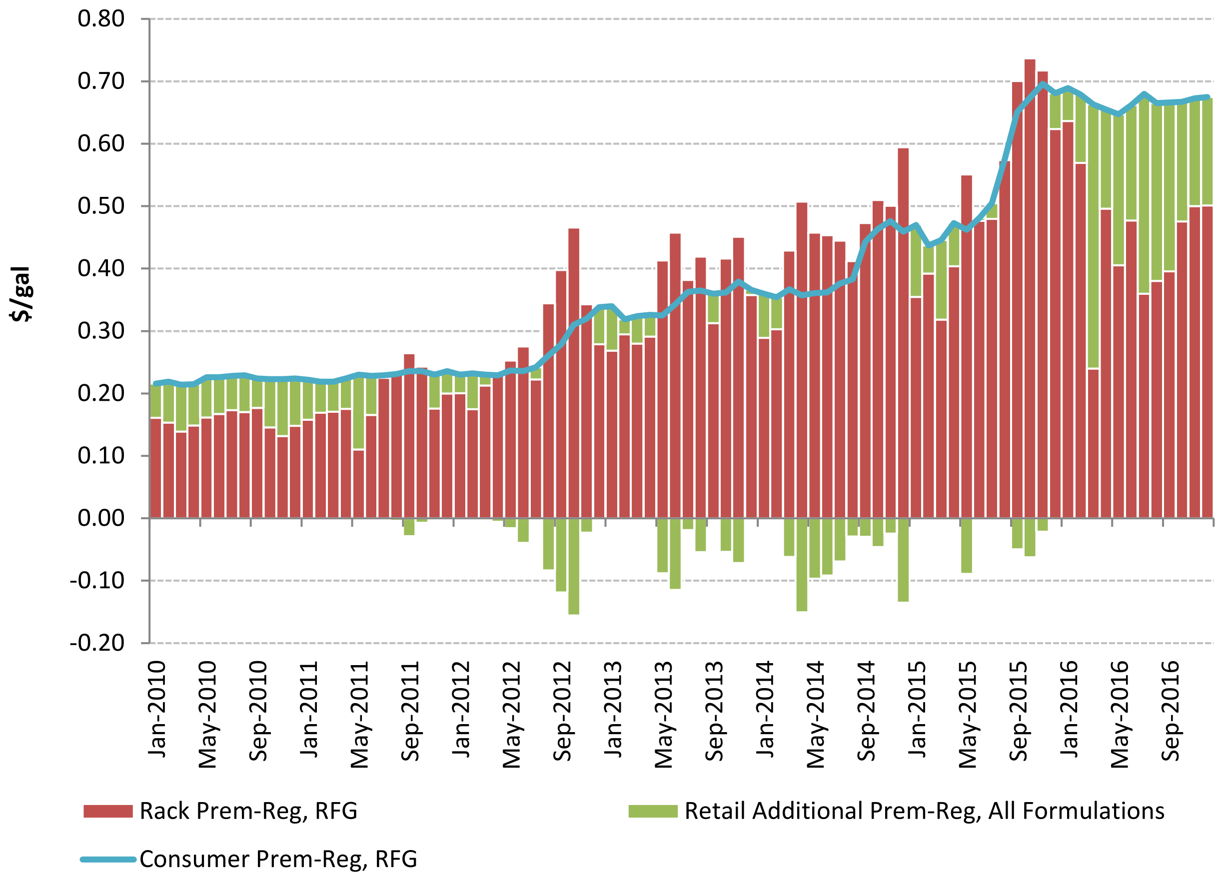


Source: U.S. Energy Information Administration, Motor Gasoline Price Survey

There is a spot petroleum products market in Chicago, but the volumes traded are smaller than the USGC or NYH markets. It is not clear that conclusions can be drawn about the spot PRdiff in this market (Section 7.3). The consumer PRdiff was in the 0.21 $/gal to 0.24 $/gal range from 2010 through July 2012. That July there was a small fire at a coker in the BP Whiting refinery that coincided with a turnaround at the Marathon Robinson refinery. This was followed in September by a two-month shutdown of the Marathon Detroit refinery to complete their heavy oil project. It is possible, that these events caused the rack PRdiff to spike (Figure 44). The consumer PRdiff rose rapidly during this period to over 0.30 $/gal and then remained in the 0.30 $/gal to 0.35 $/gal range until 2014.

FIGURE 44

CHICAGO PREMIUM-REGULAR DIFFERENTIALS



Sources: U.S. Energy Information Administration, Motor Gasoline Price Survey; OPIS; DTN; and Baker & O'Brien Analysis

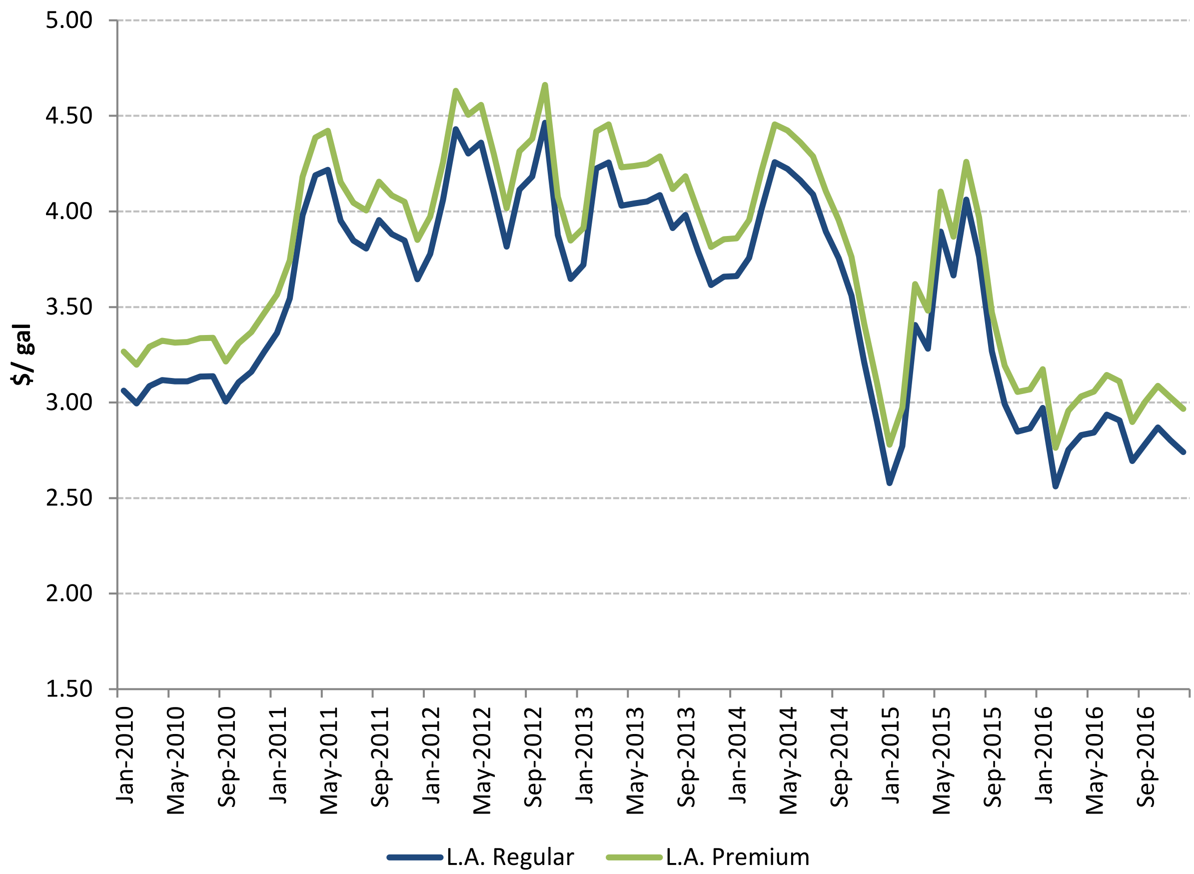
As in the Central Atlantic and USGC, starting in 2014, gasoline prices declined rapidly but premium prices fell slower than regular. Despite the increase in the consumer PRdiff, premium gasoline sales grew on an absolute and percentage of total sales basis. In 2016, the consumer PRdiff leveled out at 0.65 $/gal to 0.70 $/gal.

7.4.4 LOS ANGELES

The West Coast, especially California, is often described as an island when it comes to energy pricing dynamics. It has limited connectivity to the other domestic markets (Section 7.3) and unique product specifications in California. Los Angeles gasoline prices generally follow the trends in the other markets, based on world oil prices, but the absolute price is higher than the other markets. The impact of the February 2015 explosion and fire at the ExxonMobil Torrance refinery had a clear impact on gasoline prices in this market.

FIGURE 45

LOS ANGELES RETAIL GASOLINE PRICES

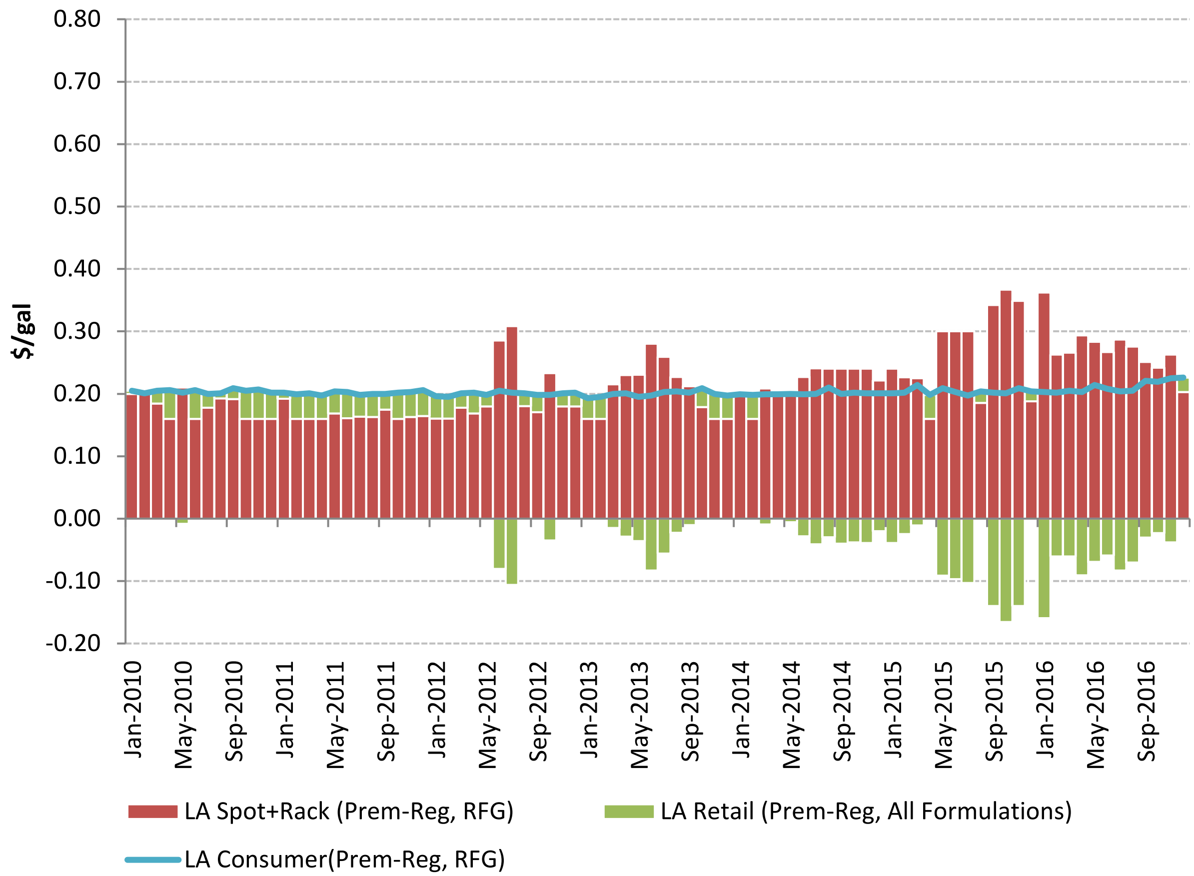


Source: U.S. Energy Information Administration, Motor Gasoline Price Survey

Unlike the other markets discussed above, the Los Angeles market has not seen the dramatic increases in the consumer PRdiff.

FIGURE 46

LOS ANGELES PREMIUM-REGULAR PRICE DIFFERENTIALS



Sources: U.S. Energy Information Administration, Motor Gasoline Price Survey; OPIS; DTN; and Baker & O'Brien Analysis

Los Angeles showed essentially no change in the retail differential across the 2010 to 2016 period. PADD 5 on average showed the smallest increases in premium to regular differentials of all the PADDs. A unique facet of the California retail market is that retailers must display prices for all grades of gasoline prominently on the street. [27] Consequently, drivers would be able to "price shop" for premium prices before selecting a station. This may increase the

[27] California Business & Professional Code, Division 5, Chapters 14 and 15, and California Code of Regulations, Title 4, Division 9, Chapters 6, 7, and 8.

competition for premium gasoline sales between wholesalers, and reduce their “pricing power” for premium gasoline.

8. International Gasoline Markets

Gasoline, gasoline components, and feedstocks used to make gasoline (i.e., naphtha) are global commodities frequently traded between regions and countries. International gasoline markets were reviewed to determine whether the increasing PRdiff seen in the United States is a global phenomenon or if there were any major changes to the supply costs, demand, or gasoline flows in international markets that could impact U.S. gasoline costs.

8.1 Octane Grades and Price Differentials

In most of the world, retail gasoline octane quality is specified in terms of RON instead of the AKI used in North America (Section 4.2.1). The primary octane specification in North America is 87 AKI (U.S. regular gasoline). In the rest of the world, the primary specification is (or is moving to) 95 RON. Gasoline with a 95 RON typically will have a 90 AKI to 91 AKI,[28] meeting the EIA definition of premium. In most U.S. markets, the premium gasoline supplied is in the range of 91 AKI to 93 AKI. In European (EU) and some other markets, limited volumes of 98 or higher RON gasoline are sold. EU premium 98 RON gasoline is similar in octane quality to a 93 AKI U.S. premium gasoline.

In markets such as Japan and Europe, most automobiles require 95 RON gasoline and very few require anything greater than 95 RON. This is a significantly different situation than the United States. In the United States, roughly 90% of the LDV fleet requires regular gasoline (87 AKI), and the remainder requires premium (91AKI or greater; Section 4.2.1). In the United States, consumption of premium gasoline is driven both by vehicle requirements and consumer preference. In the rest of the world, consumption of high octane gasoline (greater than 95 RON) is almost exclusively the result of consumer preference.

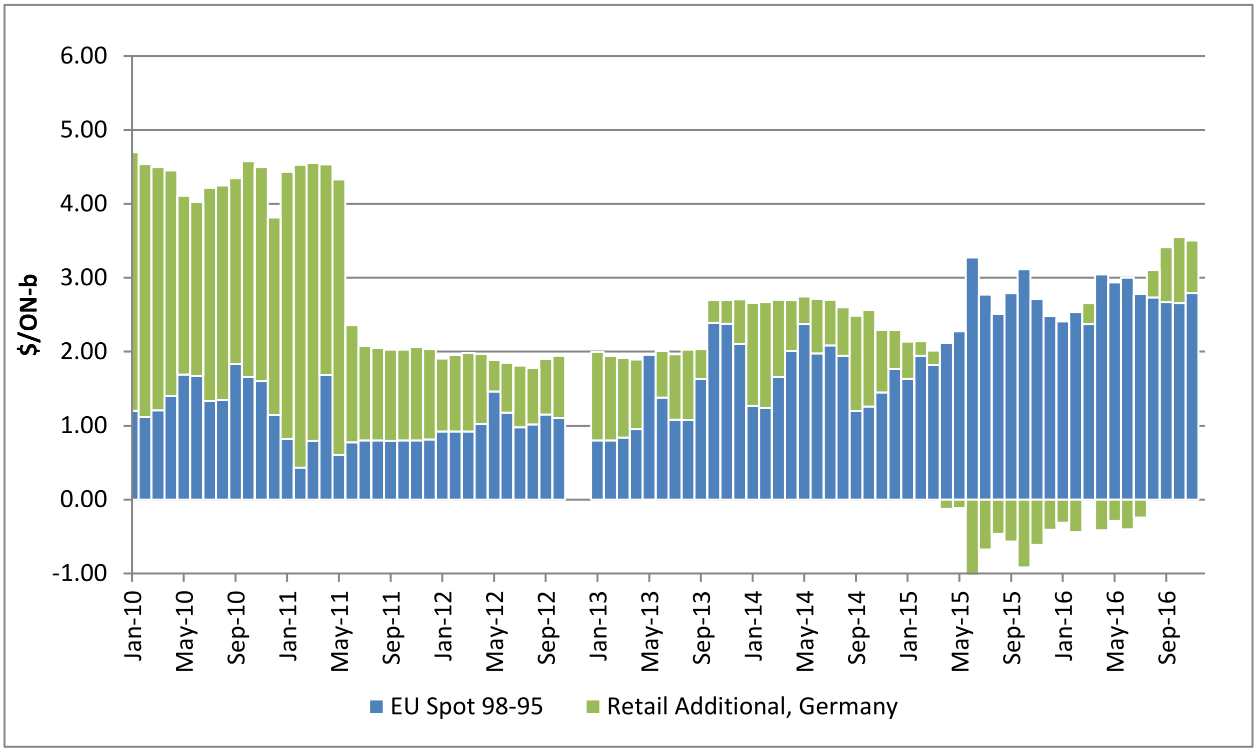
In many countries, retail prices are controlled by governments and not useful for comparing retail octane pricing. In other markets, obtaining reliable retail pricing data for the small volume of gasoline that exceeds 95 RON is difficult. FGE did identify reliable retail pricing data for 95

[28] RON ratings are typically 4 to 5 numbers higher than AKI ratings for the same finished gasoline.

and 98 RON gasoline for Germany. In recent history, the price differential between these grades at retail is close to and sometimes below the spot market differential in Northwestern Europe (Figure 47). This is clearly different than what has been observed on the USGC and U.S. East Coast (USEC) (Section 7.4). European retail markets appear to have a limited ability to sustain premium prices markedly higher than the spot value, possibly because 98 RON gasoline is a consumer preference instead of a vehicle requirement.

FIGURE 47

EU PREMIUM-REGULAR PRICE DIFFERENTIALS

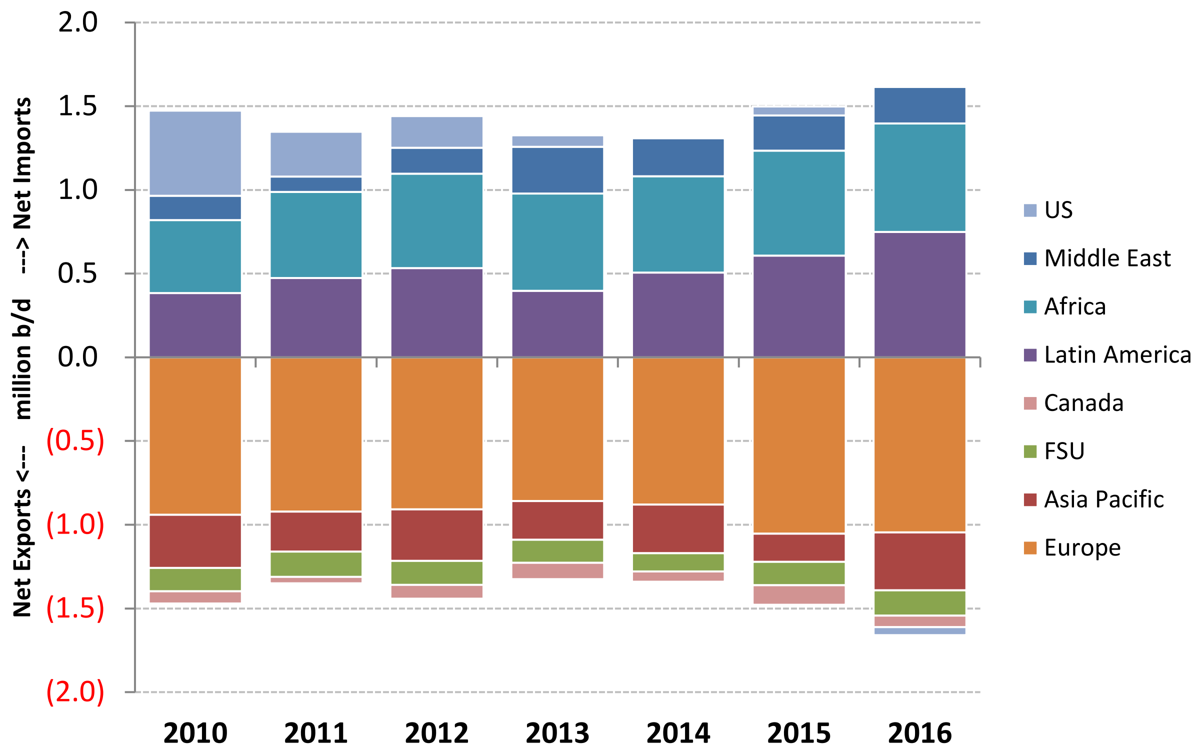


8.2 GASOLINE AND COMPONENT TRADE FLOWS

The United States is the world's largest gasoline consumer and has historically been a net importer of gasoline and gasoline components. However, with the steady growth of ethanol blending and refinery throughput, U.S. imports fell while exports rose. In 2016, the United States became a net exporter of gasoline. Today the largest importers of gasoline are Africa and Latin America. Europe continues to be the world's largest gasoline exporter (Figure 48).

FIGURE 48

REGIONAL GASOLINE BALANCE



Sources: FGE, Baker & O'Brien Analysis

The USEC (PADD 1) and Gulf Coast (PADD 3) markets are particularly integrated with other markets in the Atlantic Basin. Large quantities of gasoline and gasoline components from Canada (approximately 150,000 b/d) and Europe (approximately 330,000 b/d) are imported into PADD 1. At the same time, even larger quantities are exported from PADD 3 (Section 7.3, Figure 36), primarily to Africa and Latin America. Because of this dynamic, PADD 1 and PADD 3 spot market prices tend to react to supply and demand changes across the entire Atlantic Basin.

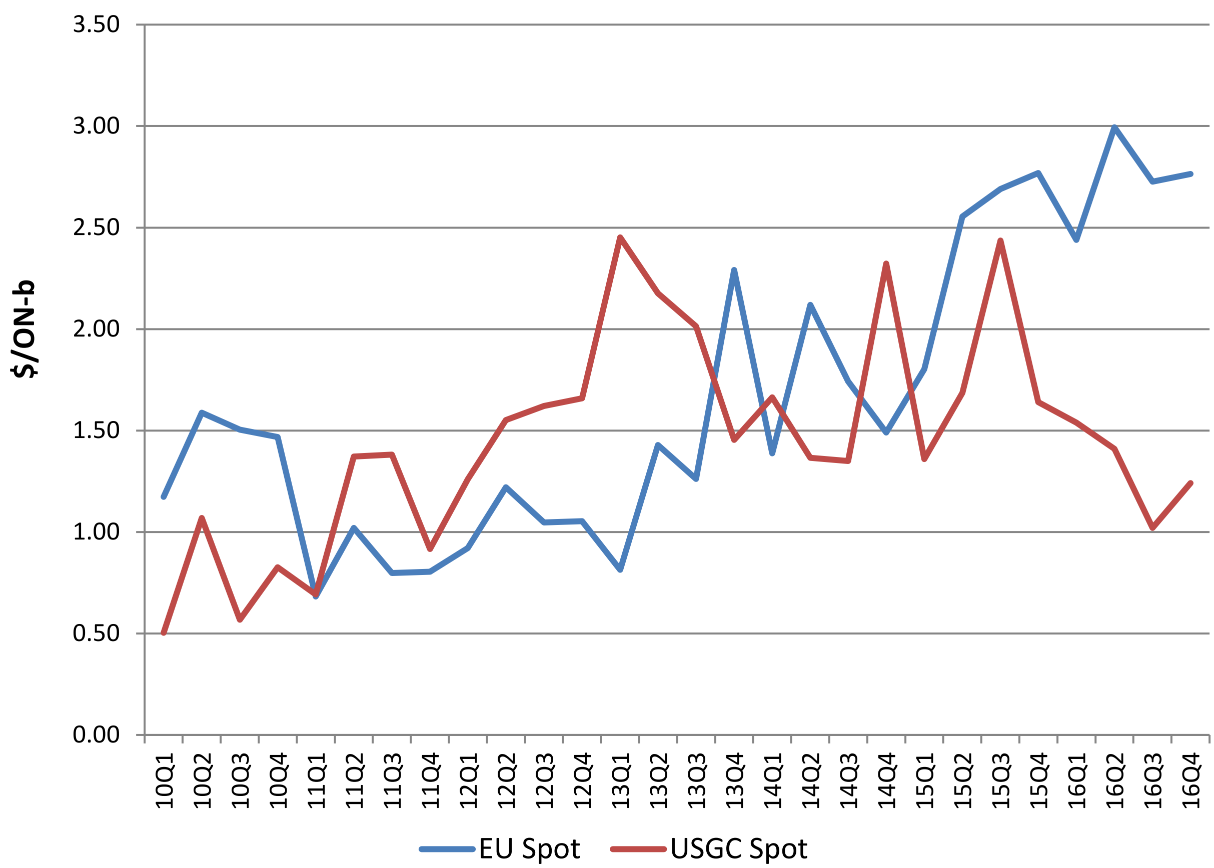
8.3 OCTANE COSTS

Spot market prices in major trading hubs (e.g., Singapore and Northwestern Europe) would be expected to reflect incremental refining costs just as they do on the USGC (Section 6.5). Singapore is the major gasoline market for the Asia Pacific region and posts spot prices for 92, 95, and 98 RON gasoline. In the Asia Pacific region, about 52% of gasoline sold is between 91 and 94 RON and 24% of gasoline sold is 94 RON or higher (roughly equivalent to 90 or higher AKI). The overall RON of the Asia Pacific gasoline pool is increasing as governments move away from lower RON gasoline to 95 RON.

The USGC[29] and Northwest Europe (NWE) spot markets are closely connected (Section 7.3). As previously discussed, spot market octane values on the USGC track local refining costs (Section 6.5). From 2010-2016, NWE spot octane values have generally tracked the USGC market with a couple of noticeable lags in 2011-2013 and again in late 2015-2016 (Figure 49).

FIGURE 49

REGIONAL SPOT OCTANE VALUES



[29] Spot Octane costs in the USGC and NYH markets are roughly the same (Figure 35).

Sources: FGE, Baker & O'Brien Analysis

The analysis indicates that the U.S. cost to produce octane is the primary determinant of the spot PRdiff in the United States, and international markets do not appear to have a marked impact on the spot PRdiff. Each of the U.S., European, and Asia-Pacific markets has unique supply-demand dynamics. Europe is "long" gasoline and exports significant volumes of gasoline to PADD 1, but European refiners tend to have higher operating costs and may not have the ability to set octane prices in U.S. markets. Moreover, almost all EU premium gasoline demand is due to consumer preference and not vehicle requirements. Asian refiners, meanwhile, have limited access to the NYH gasoline hub in PADD 1. Thus, the small volume reaching the U.S. market has limited or no impact.

A detailed review of international gasoline markets is presented in Appendix B.

9. Conclusions

Since 2012, the average retail price differential between regular and premium gasoline in the United States increased from approximately 0.20 $/gal – 0.30 $/gal to 0.53 $/gal in 2017. In this report, many factors that influence the pump prices of gasoline and the price differentials between different gasoline grades (PRdiff) were examined. Gasoline is a complex chemical mixture with stringent quality specifications and is subject to extensive regulation (Section 4). Reductions in allowable sulfur levels in gasoline in the United States and other markets have and will continue to reduce the octane rating of some gasoline components (4.5.1). This reduction in sulfur and octane supply increases the cost of gasoline production but is not a major factor in the observed increase in PRdiff.

U.S. gasoline markets, particularly those east of the Rockies, are interconnected with international markets (Section 7.3). Gasoline is a widely traded commodity bought and sold in open, transparent markets around the world. Excluding North America and Europe, gasoline demand has been increasing (Appendix B). Latin American demand, in particular, surged during the 2012 to 2016 period, as have U.S. exports to that region. Octane specifications have been increasing and sulfur specifications are being reduced in many international markets (Appendix B). These changes may have and may continue to have an impact on U.S. gasoline prices but are not a major factor in the increases in U.S. PRdiff.

After five years of decline, U.S. gasoline consumption increased 1.4% annually from 2012 through 2016, reaching an all-time high in 2016 (Section 5, Figure 17). However, 2016 demand only marginally surpassed the 2007 peak. From 2012 to 2016, premium gasoline consumption increased approximately 1.7% annually but remained well below levels seen, between 2000 and 2003 (Section 5, Figure 16). AKI-barrel consumption saw a similar annual increase during the 2012 through 2016 period but only just returned to peak levels reached in 2007 (Section 5, Figure 17). Because of increased ethanol blending, petroleum-based AKI-barrel consumption is still below the 2007 peak. Major changes in U.S. gasoline demand have not occurred and are likely not a significant factor in the increasing PRdiff.

Premium gasoline sales are primarily driven by vehicle engine requirements. As vehicle manufacturers modify engine designs to meet future CAFE standards (Section 3), engine compression can be expected to continue to increase. Increasing compression ratios should directionally lead to increased AKI demand from the gasoline pool (Section 4.4.1, Figure 6). However, this does not appear to be the case yet, as the share of “premium-only” vehicles appears to have plateaued at 12% of the LDV fleet since 2012 and started declining in 2015 (Section 4.2.1, Figure 3). Vehicle engine design changes through 2016 have not had a material impact on premium gasoline demand, the overall octane balance, or the PRdiff.

From 2010 through 2016, domestic gasoline production increased 1.6% annually, exceeding domestic demand growth, and the United States became a net gasoline exporter in 2016 (Section 6). From 2010 through 2016, U.S. refinery crude oil throughput increased 10% due to a combination of capacity and utilization increases. During this period, the quality of the crude oil processed also changed (Section 6.2). Light, sweet crude processing more than doubled, and the proportion of naphtha, natural gasoline, and other lighter, low-octane components in the final gasoline pool increased by over 80% (Section 6.4, Figure 27).

Reforming units have traditionally acted as the swing octane supply in refineries. As octane requirements increased from both the increasing gasoline production and the need to blend the additional low-octane components in the gasoline pool, reformer utilization (Section 6.1, Figure 20) and severity (the RON of produced reformate; Section 6.4, Figure 28) both increased. Despite this, ample reformer capacity remains, with 2016 utilization ranging between 73% - 80%. Due to the abundant supply of naphtha, refiner costs to produce premium gasoline from regular gasoline and reformate have declined since 2014, closely matching the spot market PRdiff (Section 6.5, Figure 30).

The NYH and USGC spot market data (Section 7.4.1 and Section 7.4.2) show a number of spikes in the premium to regular price differential beginning in 2011 through 2015. These spot markets react quickly to supply changes, not only in the United States, but the entire Atlantic Basin (Section 7.3). Therefore, it is most likely that these spikes were a result of changes in product cost and availability. The spot market differential spikes resulted in increased premium to regular differentials at the retail level. After each of these spikes, the differential in the spot market declined more rapidly than at the retail level.

The phenomenon of retail gasoline prices rising rapidly, when costs increase and then falling back much more slowly when costs decline, has been observed previously and has been named the rocket and feathers hypothesis. Research[30] into this hypothesis has focused on the crude versus retail gasoline price spread, but the price spreads between grades at various points in the supply chain have not been studied. There is general agreement among studies that the phenomenon is common and that there is a statistically significant difference between the speed of upward movements and the speed of downward movements in retail gasoline prices. Since the studies differ in the statistical methods they use, estimates of the length of time it takes for the gasoline-crude price spread to return to a normal level vary widely.

It is clear that, during periods of low crude oil price volatility; there is a substantial and detectable lag. A sampling of price data between January 1991 and September 1995 indicates that it took about five weeks for the gasoline price to decline by 50% of the change in the crude price and about five months for the price changes to converge.[31] These findings about the consistent appearance of the rocket and feathers hypothesis provide no explanation of what causes it, although they are very useful as a basis for short-term forecasting of gasoline prices after a price spike.

A possible explanation is based on the existence of search and adjustment costs. Although some real-time reports of regular gasoline retail prices are available online, for the most part, discovering the lowest price after a market change requires physically visiting different retail outlets. This implies a cost to finding the outlet with the best price and a tradeoff between search costs and price discovery. This tradeoff would make consumers willing to stick with their normal outlet at first, then gradually discover locations with better prices and switch.

The search and adjustment cost theory implies lower price elasticity immediately after a market change, as each retail outlet can at first raise pump prices by its full wholesale cost increase without losing sales to other outlets. If the spike in wholesale prices is temporary, retail outlets will only slowly feel pressure to lower prices because the cost of search tends to keep

[30] Asymmetries in the Oil-Gasoline Price Relationship, Matteo Manera, September 29, 2015 EIA Presentation, and Behavior and Determinants of Petroleum Product Prices, Louis H. Ederington, Chitru S. Fernando, Thomas K. Lee, Scott C. Linn, and Seth A. Hoelscher, September 29, 2015 EIA Presentation.

[31] Oil price volatility and the asymmetric response of gasoline prices to oil price increases and decreases, Stanislav Radchenko, August 2004, Figure 8.

consumers with their normal supplier. As consumers gradually acquire more information about prices in different locations, retailers will be forced by competition to keep lowering prices but only with a lag based on how quickly consumers gain additional information.

While the regular to premium price differential has been increasing since 2014, absolute gasoline prices fell dramatically starting in 2014, as crude prices plummeted from over $100/b in June 2014 to approximately $50/b at the end of 2016. The drop in absolute prices coincides with an increase in premium consumption as a percentage of total gasoline sales (Section 5, Figure 9). It appears that the marginal premium buyer is more sensitive to absolute price of premium than to the price differential to regular gasoline. This implies that premium is a separate market from regular.

Higher search costs to discover premium prices relative to search costs for regular prices could also help explain why premium prices decline more slowly than regular prices. This would be the case if retail premium prices are less transparent to the consumer. In many instances, only the regular gasoline price is advertised on the street, so consumers must physically drive into the retail outlet to determine the premium price. The theory that high search costs have an impact is supported by the data from Los Angeles. In this market, retailers must display prices for all grades of gasoline prominently on the street.[32] Los Angeles showed essentially no change in the retail differential across the 2010 to 2016 period. PADD 5, on average, showed the smallest increases in premium to regular differentials of all the PADDs.

Price asymmetry and search costs are possible explanations for increasing premium-regular differentials, but a detailed analysis of these factors was outside the scope of this study.

A review of the European market indicates that this is not a global occurrence but appears to be somewhat unique to the major U.S. markets.

[32] California Business & Professional Code, Division 5, Chapters 14 and 15, and California Code of Regulations, Title 4, Division 9, Chapters 6, 7, and 8.

APPENDICES

APPENDIX A

GASOLINE SPECIFICATION REQUIREMENTS

Average Knock Index

Sulfur, wt.%

RVP, psia

Benzene, vol.%

Color

NACE Corrosion

Mercaptan Sulfur, wt.%

Existing Gum, mg/100 ml

Gravity, °API

Oxidation Stability, minutes

Phosphorous, g/gal

Driveability Index

Distillation Temperature (10 vol.%, 50 vol.%, 90 vol.%, and Endpoint), °F

Vapor/Liquid Ratio

APPENDIX B

INTERNATIONAL ANALYSIS

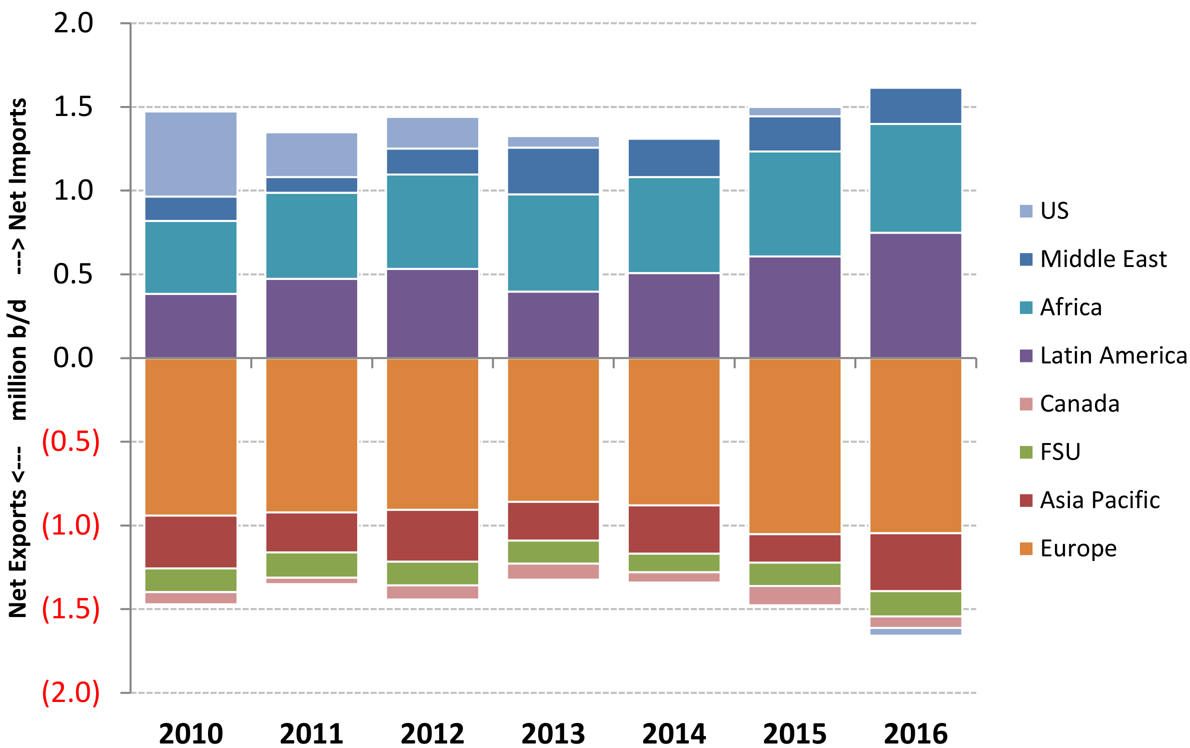
Gasoline, gasoline components, and feedstocks used to make gasoline (i.e., naphtha) are global commodities that are frequently traded between regions and countries. The U.S. East Coast (PADD 1) and Gulf Coast (PADD 3) markets are particularly integrated with other markets in the Atlantic Basin. Large quantities of gasoline and gasoline components from Canada and Europe are imported into PADD 1. At the same time, even larger quantities are exported from PADD 3 primarily to Africa and Latin America (Section 8.2 Figure 36). Due to this dynamic, PADD 1 and PADD 3 spot market prices tend to react to supply and demand changes across the entire Atlantic Basin.

In most of the world, retail gasoline octane quality is specified in terms of RON instead of the AKI used in North America (Section 4.2.1). The predominate octane specification in North America is 87 AKI (U.S. regular gasoline). In the rest of the world, the predominate specification is (or is moving to) 95 RON. Gasoline with a 95 RON typically will have a 90 to 91 AKI, meeting the EIA definition of premium. In most U.S. markets, the premium gasoline supplied is in the range of 91 AKI to 93 AKI. In European and some other markets, limited volumes of 98 RON gasoline are sold. These are similar in octane quality to a 93 AKI U.S. premium gasoline.

CHANGES IN GLOBAL GASOLINE MOVEMENTS

At over 9 million b/d, the United States is the world's largest gasoline consumer and was historically a net importer of gasoline. However, with the steady growth of ethanol blending and refinery throughput, U.S. imports fell while exports rose. In 2016, the United States became a net exporter of gasoline. Today the largest importers of gasoline are Africa and Latin America. Europe continues to be the world's largest gasoline exporter (Figure 50 and Figure 51).

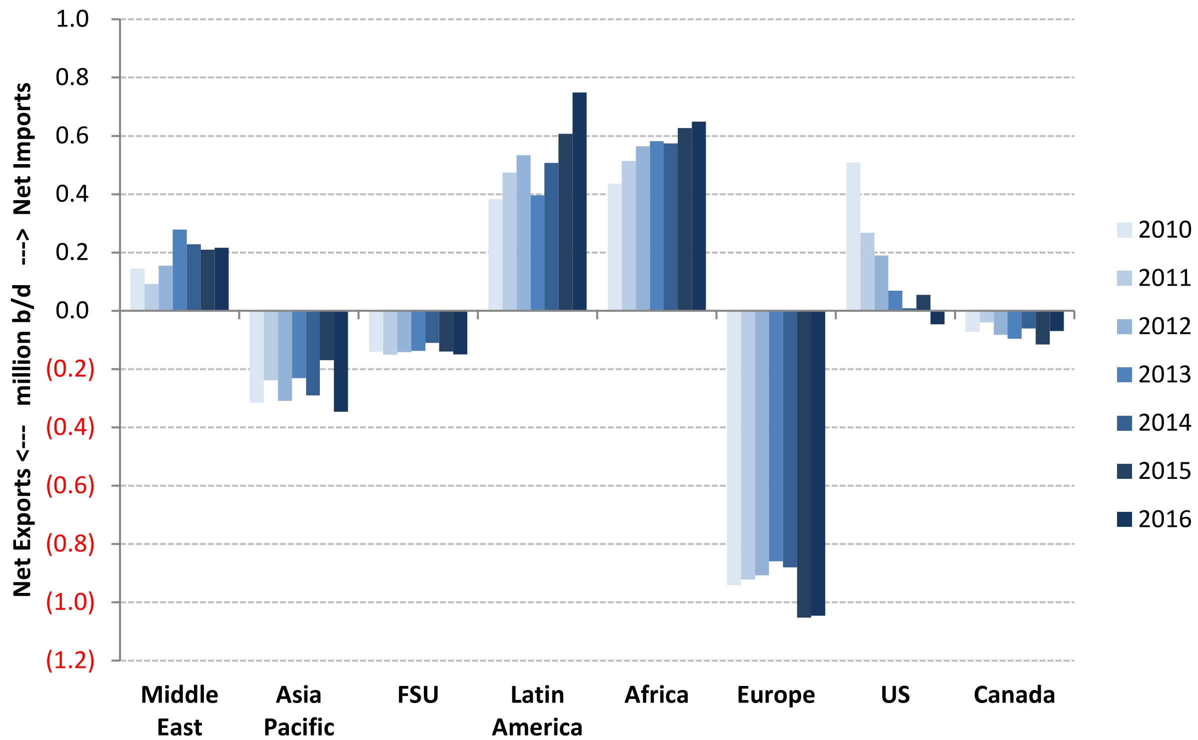
FIGURE 50
REGIONAL GASOLINE BALANCE



Sources: FGE, Baker & O'Brien Analysis

FIGURE 51

GASOLINE IMPORTS/EXPORTS BY REGION

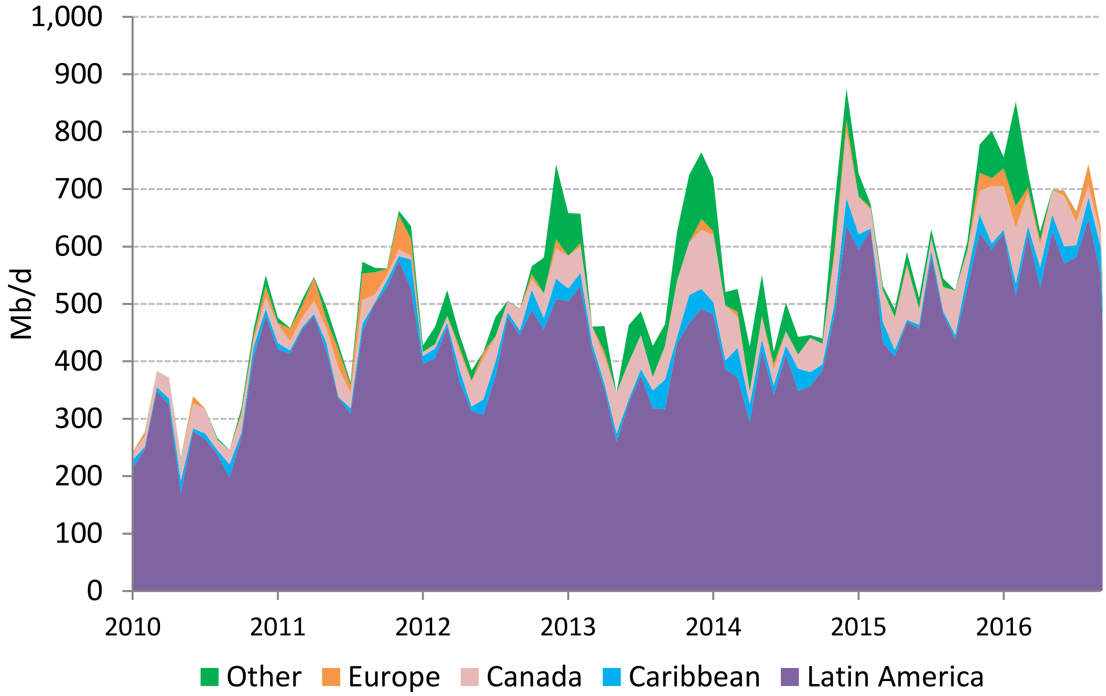


Source: FGE

Latin America represents the largest destination for U.S. gasoline exports (Figure 52). Most regular grades in these markets match the U.S. 87 AKI requirement. Brazil and Argentina blend larger amounts of ethanol (up to 27% and 12%, respectively), reducing the octane requirements of any imported BOBs.

FIGURE 52

U.S. GASOLINE EXPORT DESTINATIONS BY VOLUME



Source: U.S. Energy Information Administration, Exports

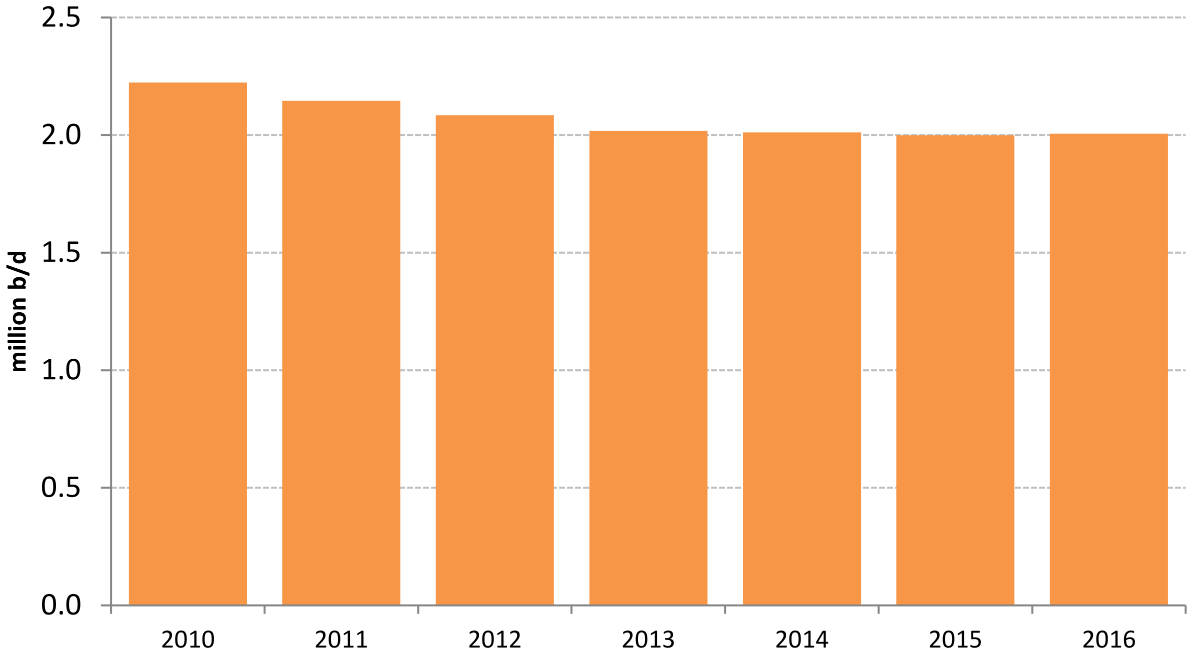
EUROPE

The tax-incentivized dieselization trend has significantly contributed to a fundamental change in Europe's road fuel demand structure. The shift from gasoline to diesel began some 25 years ago and led to a major demand decline for gasoline as well as a shortage of diesel production in the European Union (EU). Gasoline demand continues to decline while diesel demand is on the rise. In addition, alternative fuel vehicles continue to grow in Europe. In 2016, alternative fuel vehicles accounted for 4.2%[33] of the total EU's vehicle population. European gasoline consumption has declined since 2010 by 217,000 b/d to approximately 2 million b/d in 2016 (Figure 53).

[33] Fuels Europe Statistical Report 2017.

FIGURE 53

EU GASOLINE CONSUMPTION



Source: FGE

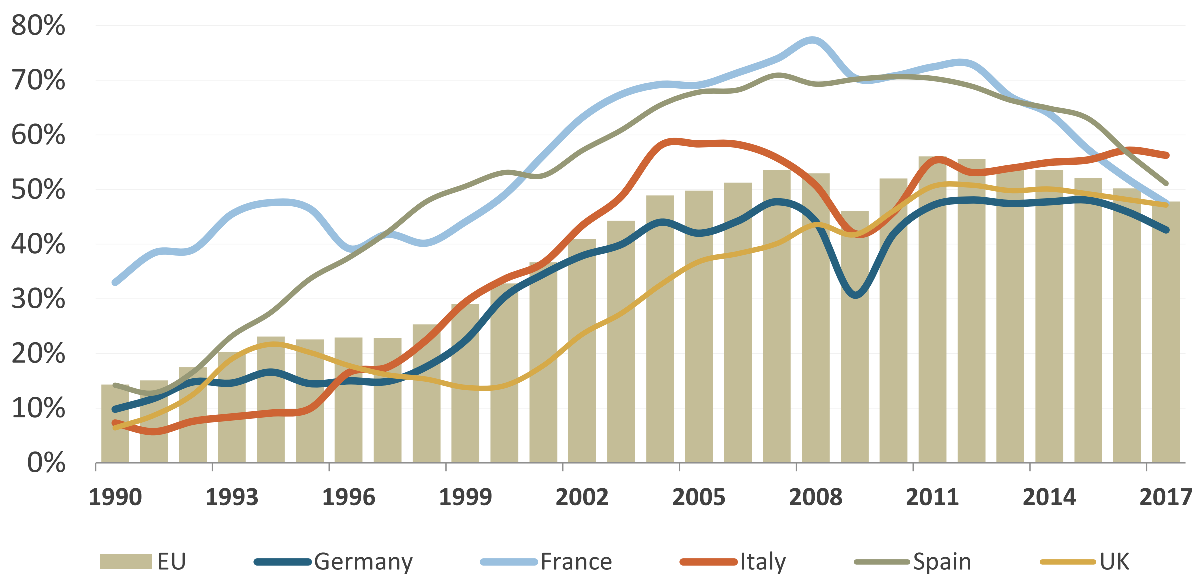
The gap between gasoline and diesel taxes in Europe is quite unique in the world and is the main reason why diesel engines have taken off in Europe and not worldwide. Ravaged post-war Europe needed tax revenues. Gasoline was used by those people who were able to afford a car; hence, governments started to tax gasoline. Diesel was used by trucks and lightly taxed or, in some countries, not at all. During the 1990s, fuel efficiency benefits of diesel vehicles were used by European countries to further enhance tax incentives for diesel versus gasoline powered vehicles. The gap in tax levels for diesel and gasoline paid by motorists can be significant and varies by country. "*Although the gap has decreased over time, in 2014, the sales-weighted average gap was more than €0.14/liter. In some member states, such as the Netherlands, the difference is even €0.28/l. Only the UK has a policy in place to ensure that diesel and petrol are taxed at the same level.*"[34] Because today the majority of the passenger

[34] Europe's Tax Deals for Diesel, October 2015, Transport & Environment, Carlos Calvo Ambel.

vehicle fleet in Europe uses diesel engines, Europe is traditionally short diesel while long gasoline. The dieselization of the car fleet in Europe increased between 1990 and 2011, with some stabilization and decline through 2016. Diesel vehicles accounted for over 50% of EU new car sales in 2016 (Figure 54).

FIGURE 54

DIESEL SHARE OF NEW CAR SALES



Source: FGE

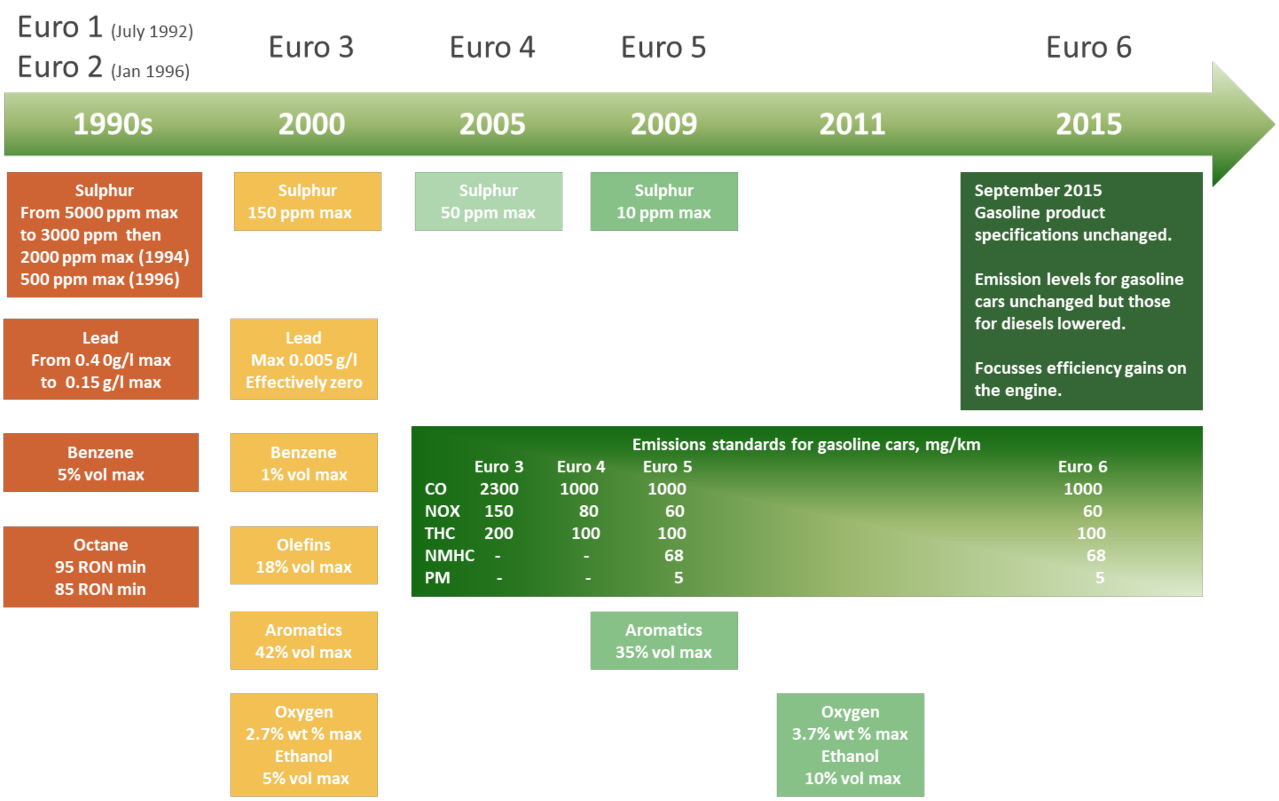
Recent concerns with environmental emissions from diesel engines have led to a rethinking in the use of diesel powered passenger vehicles in Europe. In recent years, sales of new diesel powered cars have been falling in Europe's key markets as customers react to a backlash against the powertrain following Volkswagen Group's emissions-cheating scandal. For example, the market share of diesel vehicles in France fell below 50% in 2017 for the first time since 2000, after reaching a record penetration level of 73% in 2012.[35]

[35] Automotive News Europe, October 1, 2017, Diesel Sales Fall in Key Europe Markets, Peter Sigal.

Gasoline specifications in Europe have also gone through a series of changes over the years (Figure 55) but, at a minimum, gasoline is required to have 95 RON and 85 MON (equivalent to AKI 90 in the United States, meeting the EIA definition of premium.)

FIGURE 55

EUROPEAN GASOLINE KEY FUEL PROPERTIES



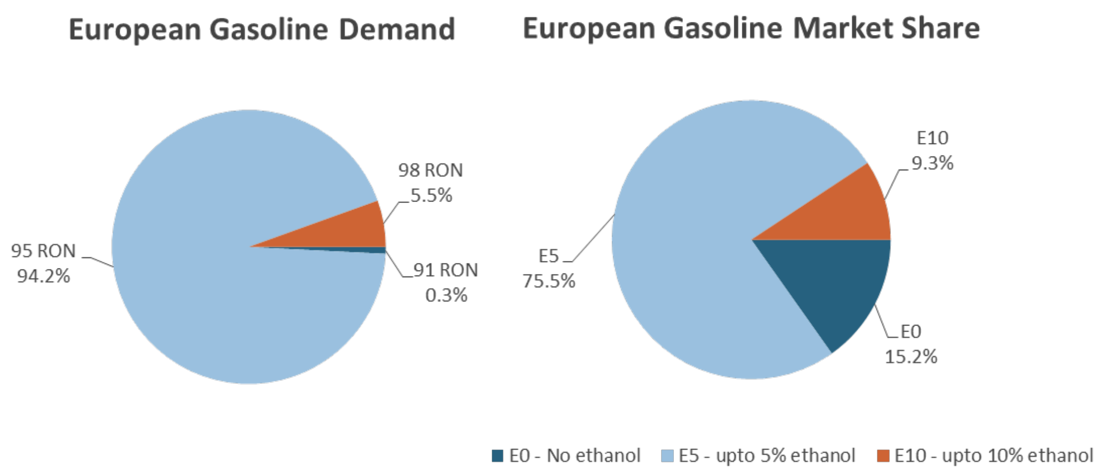
Source: FGE

European octane demand is overwhelmingly 95 RON / 85 MON, at over 94.2% share (Figure 56). 98 RON accounts for 5.5% share of demand. 91 RON / 81 MON has 0.3% share but is predominantly only consumed in Denmark. Notably, no current production car requires 98 RON gasoline; it is purely a marketing option with demand driven by consumer sentiment.

In addition, ethanol blending in gasoline is far more limited in Europe than it is in the United States (Figure 56). The EU has a 2020 target for 10% of total road transport fuels to be biofuels; however, this is under re-consideration in light of various environmental and social concerns associated with biofuels, such as, rising food prices and deforestation.

FIGURE 56

EUROPEAN GASOLINE CONSUMPTION BY GRADE AND ETHANOL CONTENT

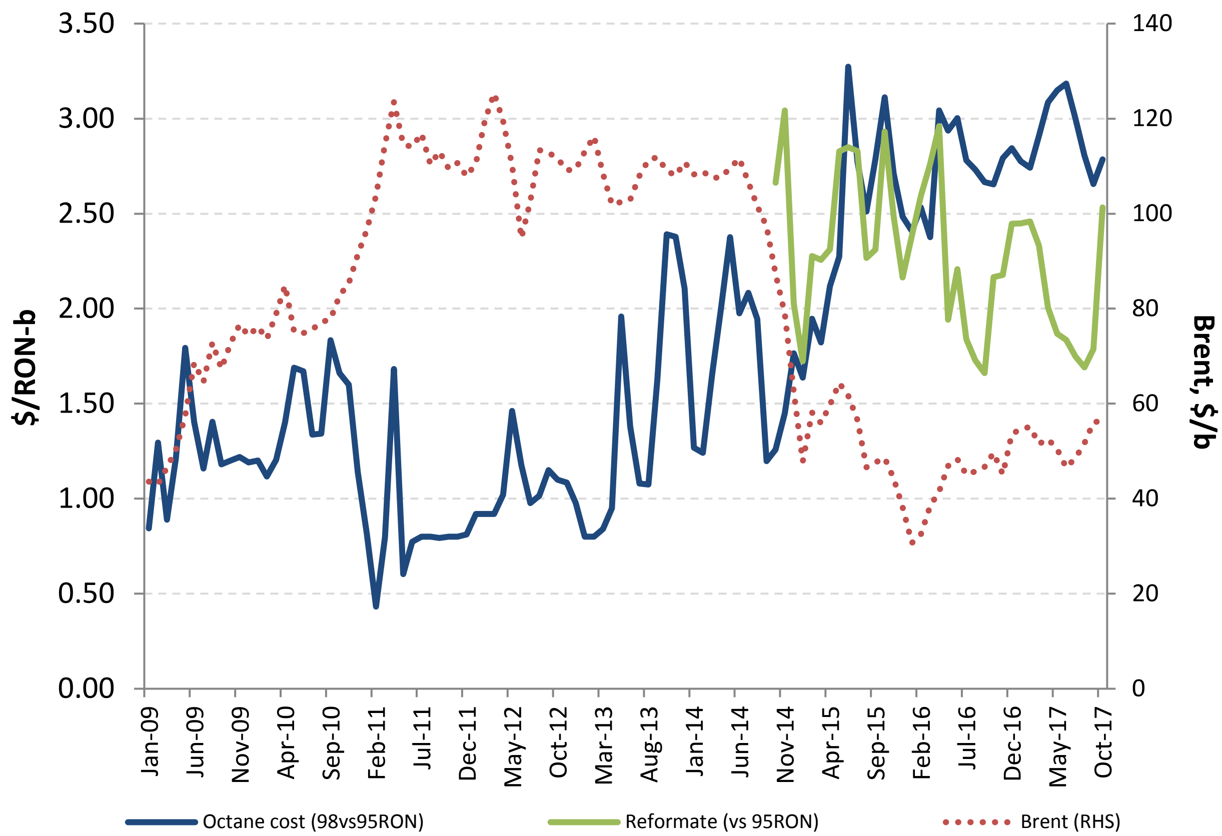


Source: FGE

Comparing 95 RON and 98 RON spot pricing in Europe shows that the value of octane has increased since 2009, similar to the United States, while the price of crude oil has fallen. Octane values have increased from about 1 $/RON-b to 2.75 $/ RON-b as of 2017 (Figure 57, blue line represents octane cost while the red dashed line represents the crude cost). Unlike the U.S (Section 6.5, Figure 29), octane costs have not dropped back down to 2011 levels. Although Europe does supply gasoline to PADD 1 in the United States, the U.S. spot octane costs reflect the economics of the U.S. Gulf Coast (PADD 3) refineries, and not European differentials.

FIGURE 57

EUROPEAN OCTANE PRICING



Source: FGE

ASIA

Gasoline consumption in Asia is estimated to exceed 7 million b/d 2017, with China and India accounting for 52% of the region's gasoline demand (Figure 58). Japan, Indonesia, and Australia round up the top five consumers in the region and together, with China and India, account for 78% of regional consumption.

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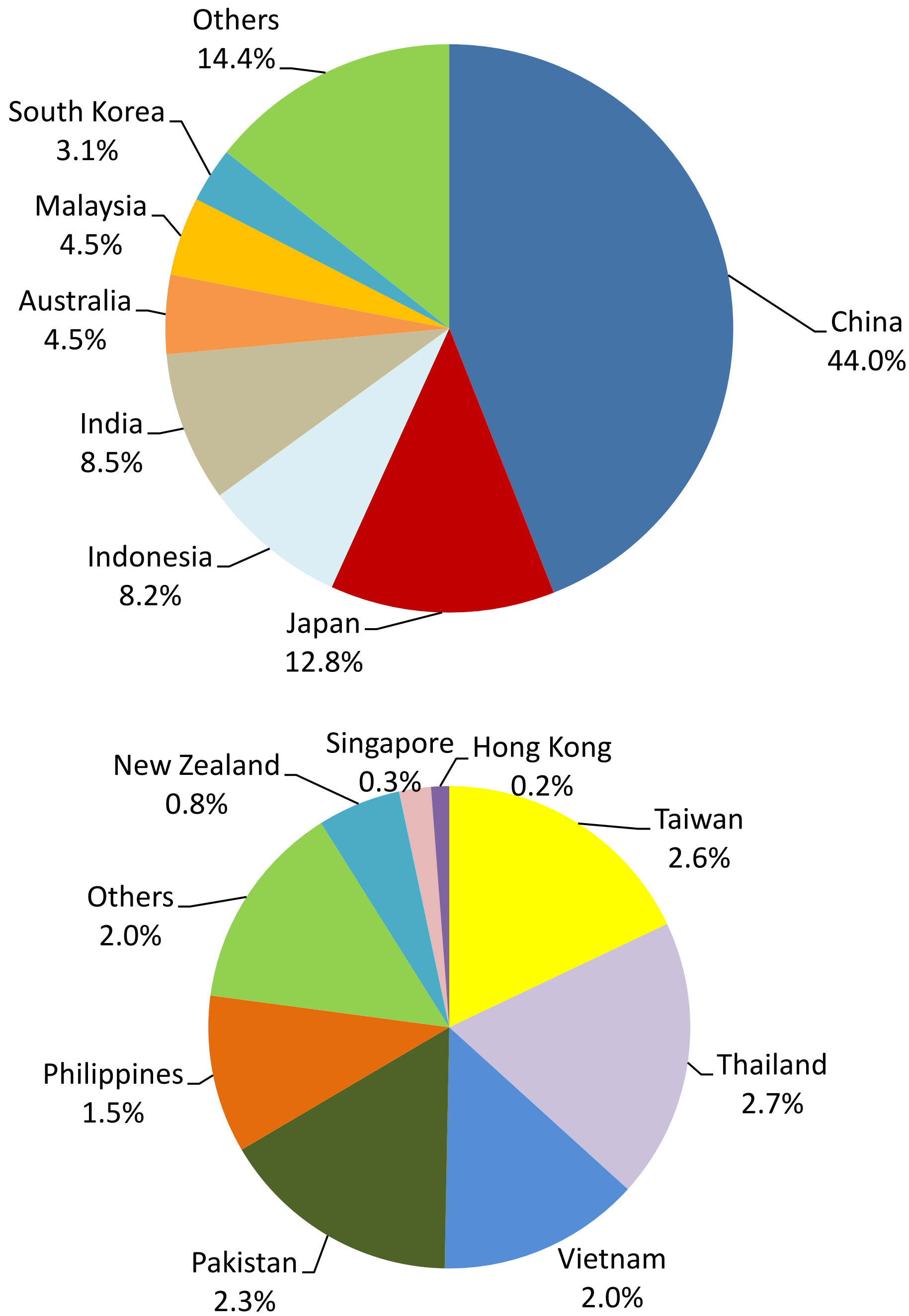
FIGURE 58

2017 ASIA PACIFIC GASOLINE CONSUMPTION BY COUNTRY



Source: FGE

Gasoline consumption in Asia grew robustly between 2010 and 2016, from 4.9 million b/d to 6.8 million b/d, or 5.5% per year (Figure 59). The strongest gasoline growth on a percentage basis

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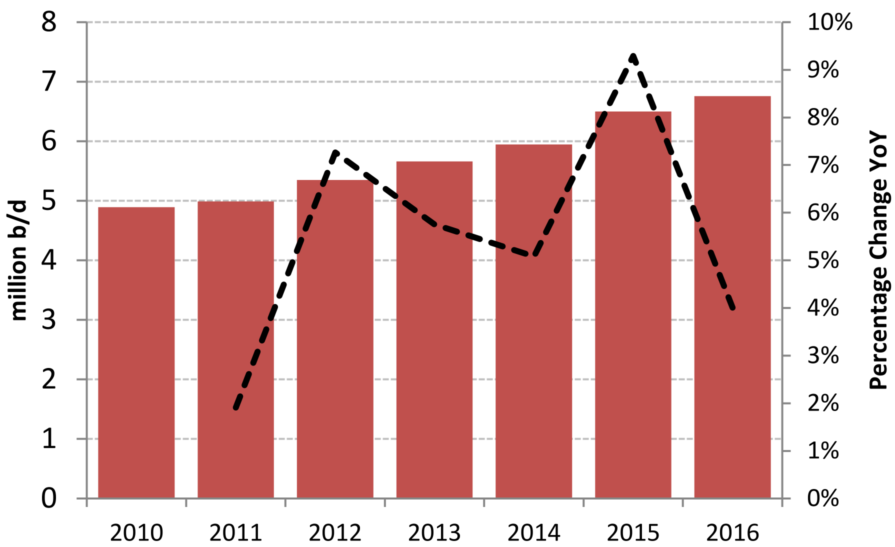
was experienced in Pakistan, China, and India, while the lowest consumption growth was in the mature economies of Japan, Australia, and New Zealand.

FIGURE 59

ASIA PACIFIC GASOLINE CONSUMPTION

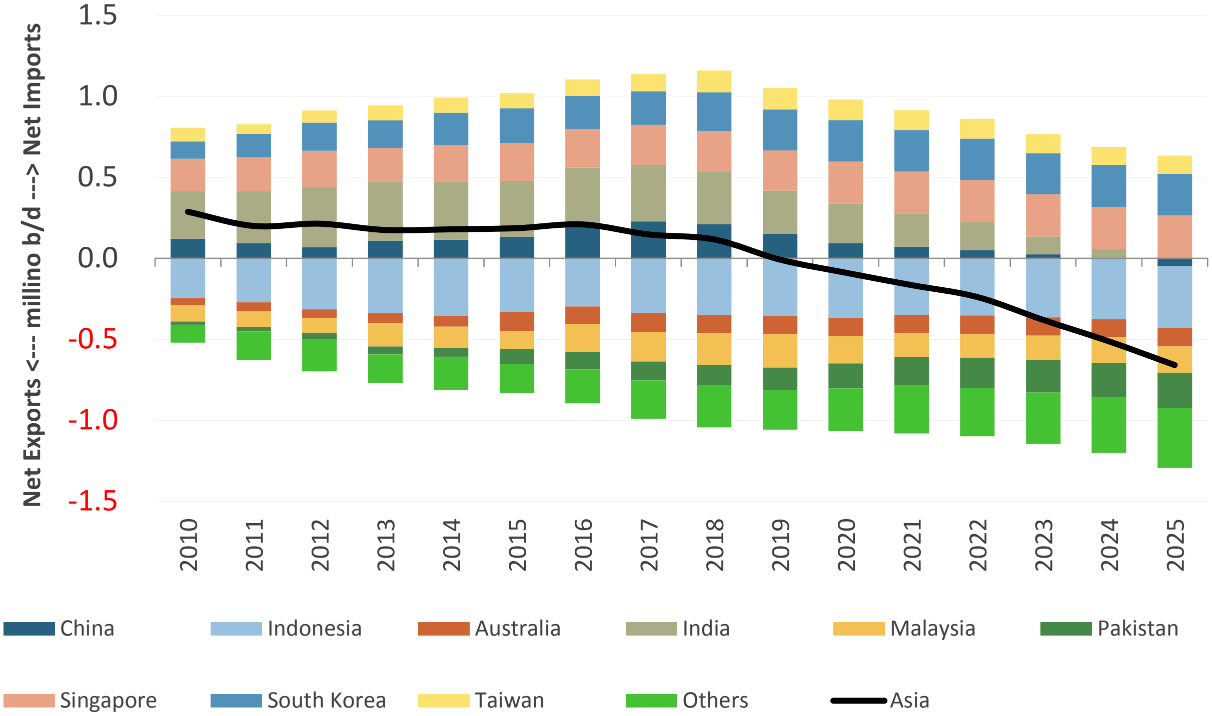


Source: FGE

Asia has been structurally long in gasoline, with a surplus moving in a narrow 200,000 b/d range from 2010 to 2016. Countries such as China, India, Singapore, South Korea, and Taiwan are long while Indonesia, Australia, Malaysia, Pakistan, and others are short. While China's gasoline supplies have shored recently, balances of several key Southeast Asian countries are getting increasingly tighter. Asian gasoline surplus should continue to fall in the next two years, and the region is expected to transition to a new importer on or before 2020.

FIGURE 60

ASIA PACIFIC GASOLINE BALANCE BY COUNTRY

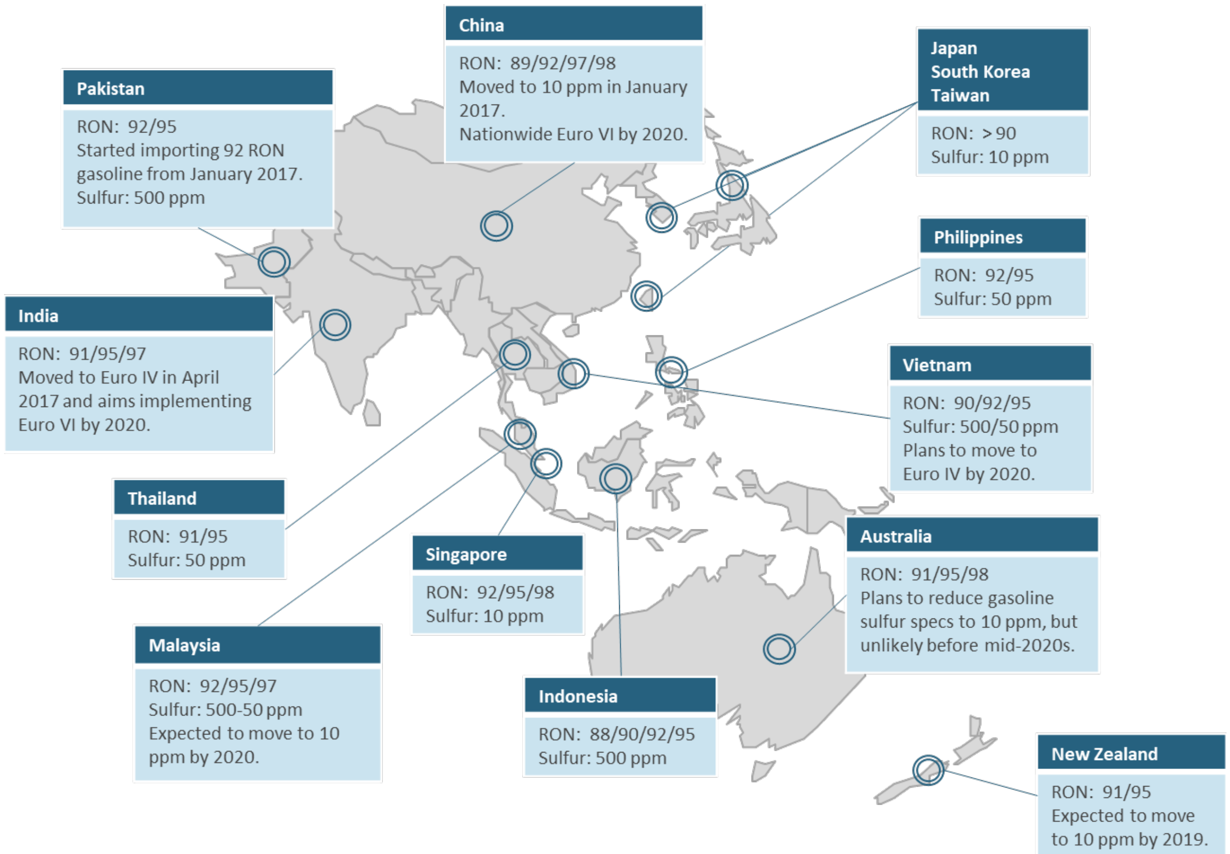


Source: FGE

Gasoline specifications have become increasingly more restrictive in the Asia Pacific region as the countries move toward cleaner gasoline. Specifications such as minimum octane levels, sulfur contents, and benzene content have tightened since 2003. Several countries are expected to continue reducing sulfur content over the next three years as they move towards Euro IV specifications (Figure 61). These markets may no longer be as extensively used as a "home" for low-quality or undesirable blending components. Moreover, the desulfurization process typically results in a loss of RON anywhere between one to five octane numbers, necessitating increased blending with high octane blendstocks.

FIGURE 61

ASIA PACIFIC RON AND SULFUR REQUIREMENTS

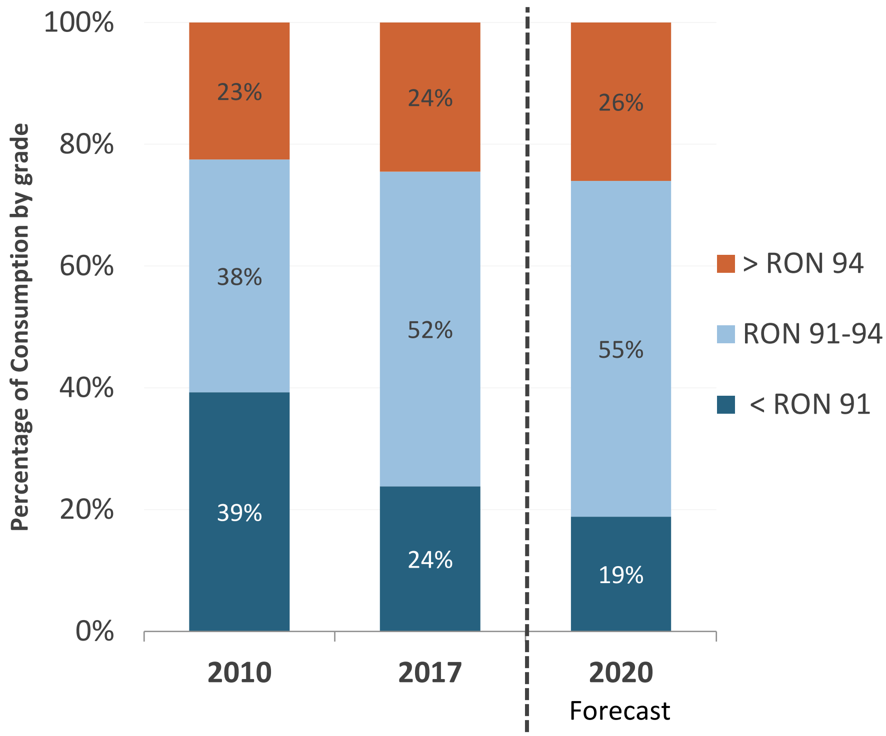


Source: FGE

RON 91 grade and above accounts for roughly 52% of total gasoline consumption in 2017, versus 38% in 2010, as countries such as China, Indonesia, Pakistan, and Bangladesh moved away from lower RON gasoline in recent years (Figure 62). In addition, several countries including China, Philippines, Singapore, Taiwan, Thailand, Pakistan, Sri Lanka, and Bangladesh moved to lower sulfur specifications.

FIGURE 62

ASIA PACIFIC GASOLINE CONSUMPTION BY RON



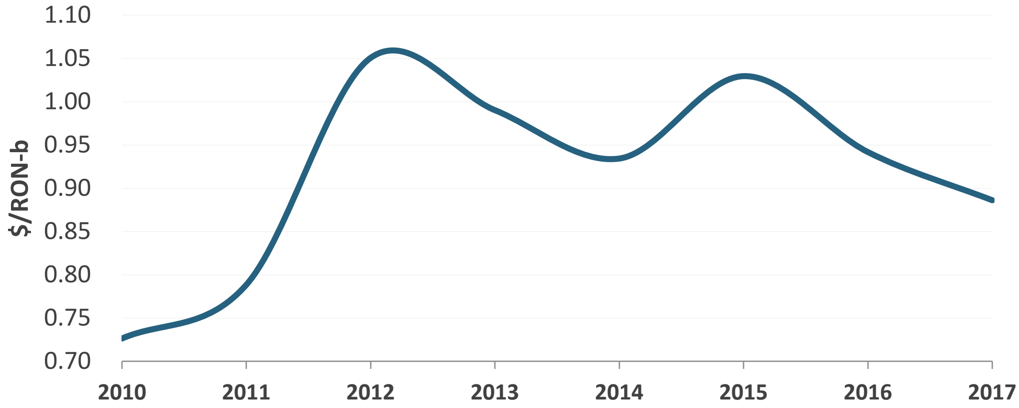
Source: FGE

Octane costs per barrel saw a small surge in the Singapore spot market[36] between 2010 and 2012 as some key Asian markets shifted away from lower RON gasoline. Eventually, the cost came down to reach a low of 0.88 $/b/ON this year as refiners added considerable capacity to their reforming and isomerization units in recent years (Figure 63). China was a game changer as substantial deep processing units came online along with MTBE and alkylation units. The increase in consumption for higher RON gasoline was largely met by higher supplies as Asian refiners boosted their ability to produce higher RON gasoline. This kept octane price premiums range bound.

[36] The Singapore spot market is the major market for the Asia Pacific region.

FIGURE 63

SINGAPORE OCTANE COST PER BARREL



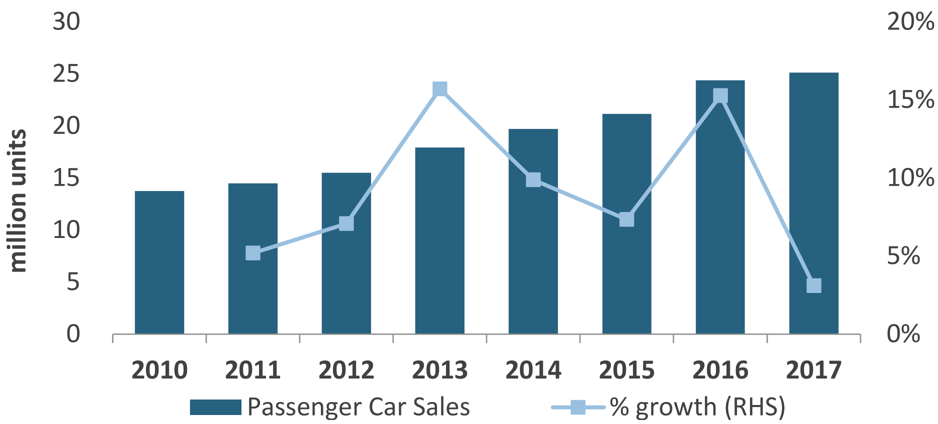
Source: FGE. Note: Price spread between FOB Singapore RON 95 gasoline and RON 92 gasoline

CHINA

In line with economic growth, China's gasoline consumption has been increasing robustly in recent history, at times over 10% year-over-year (YoY). The robust consumption growth was largely due to a rapidly increasing car fleet, establishing China as one of the world's largest vehicle markets (Figure 64).

FIGURE 64

PASSENGER CAR SALES IN CHINA



Source: FGE

After reaching approximately 14% in 2015, China's gasoline consumption growth has moderated somewhat and is projected to grow by less than 5% in 2017. Increased promotion of electric vehicles, partial withdrawal of tax incentives on light cars, and the growing popularity of alternative forms of transport such as high-speed rail and air travel has impacted China's gasoline consumption.

China formally implemented the National Standard IV (NS-IV-equivalent to Euro-IV) fuel specification in 2014. Subsequently, the NS-V specification was officially rolled out nationwide in 2017; several more-developed cities had already adopted the new standard earlier, with Beijing the first to do so in May 2012.

As the country imposed more stringent sulfur standards in accordance to NS-V, octane specifications for gasoline were lowered to the lowest octane grade and changed to 89 RON from 90 RON while the regular grade was lowered to 92 RON from 93 RON. This emphasizes China's commitment to cutting sulfur emissions but compromises the octane rating. This reduction in gasoline octane specification is attributed to continued high demand growth for gasoline coupled with Chinese refineries configured to maximize diesel compared to gasoline leading to gasoline supply issues. The 92 RON grade is most widely available, although consumption of the higher octane grades is increasing.

China plans to move to a nation-wide NS-VI standard (Euro-VI equivalent) by mid-2020. The country typically implements fuel specification changes in stages across the country, with the stricter NS-VI standard already introduced in Beijing since January 2017.

INDONESIA

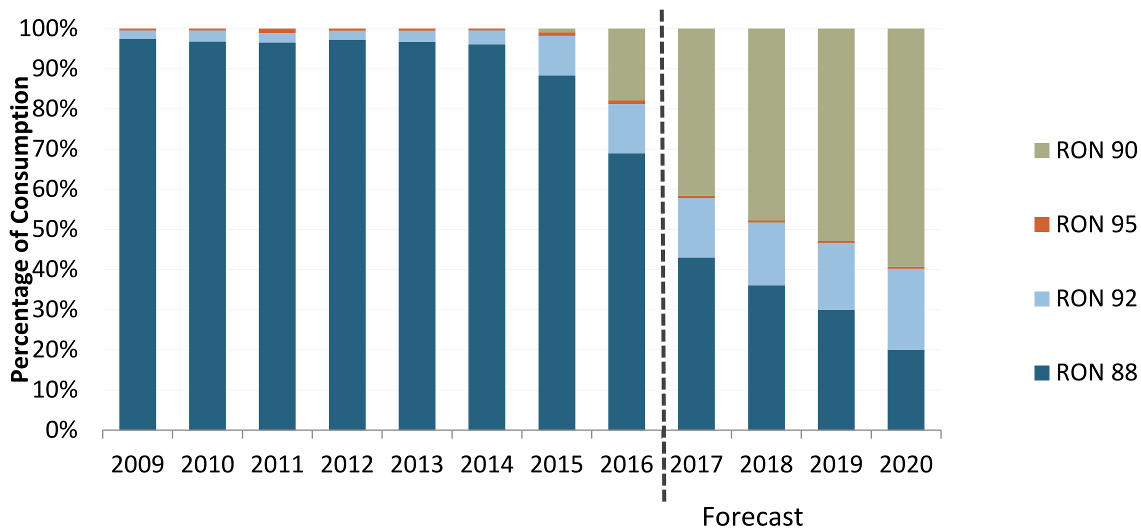
Indonesia's gasoline consumption grew at an average rate of 9.0% per year between 2008 and 2013, largely as subsidized gasoline prices spurred the growth of discretionary driving. After the subsidy reduction and eventual removal in January 2015, annual consumption growth receded to the 1%-2%.

Two-wheelers make up roughly half of the country's total gasoline consumption. Motorcycle sales saw an 8.8% YoY decline in 2016 and have continued declining into 2017. However, car sales grew by 7.1% YoY in the same two year period.

Indonesia traditionally sells three grades of gasoline: 88 RON (Premium), 92 RON (Pertamax) and 95 RON (Pertamax Plus). In July 2015, Pertamina launched a new 90 RON grade (Pertalite). Consumption has grown strongly since introduction, at the expense of the 88 RON grade (Figure 65).

FIGURE 65

INDONESIAN GASOLINE CONSUMPTION BY GRADE



Source: FGE

Indonesia remains the last major importer of low octane gasoline in Asia. As long as the refineries remain configured for low octane gasoline production, Indonesia likely won't legislate to move to a higher octane on the retail side.

INDIA

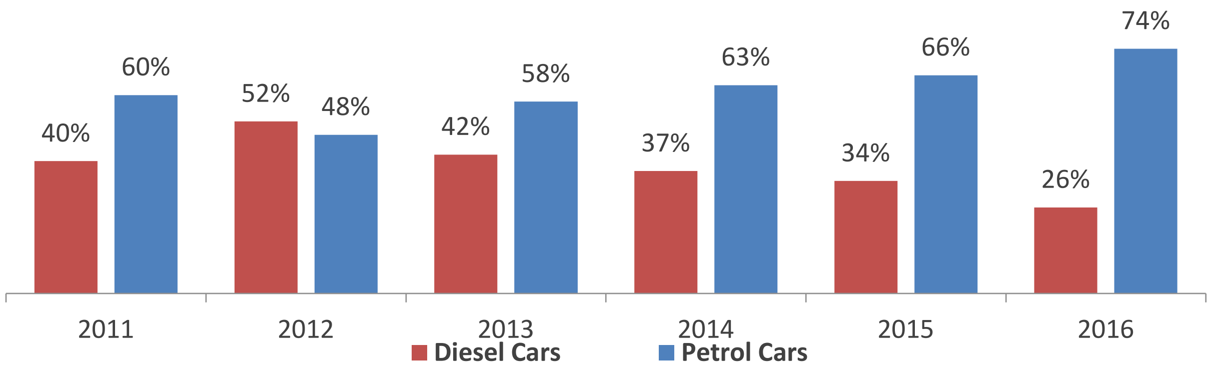
India's gasoline consumption has grown significantly since 2010, from 326,000 b/d to 551,000 b/d in 2016. Rapid expansion in vehicle ownership and increasing affluence of the middle class population underpinned a strong 8% consumption growth between 2000 and 2010.

Gasoline retail prices were deregulated in 2011, which led to a shift in the car purchase trend. Consumers started buying more diesel-cars, as diesel was still subsidized. The move dampened gasoline consumption growth between 2011 and 2014. However, the trend reversed in 2014 when India deregulated diesel prices. The differential between gasoline and diesel dropped from 1.40 US$/gal in 2012 to as low as 0.79 US$/gal in 2014.

The share of gasoline cars in the overall passenger vehicle sales grew from 48% in 2012 to about 74% by 2016, resulting in an increase of gasoline consumption over the past few years (Figure 66). Lower oil prices provided additional impetus to consumption growth as discretionary driving surged in the price sensitive market.

FIGURE 66

INDIA SHARE OF PASSENGER VEHICLE SHARES



Source: FGE

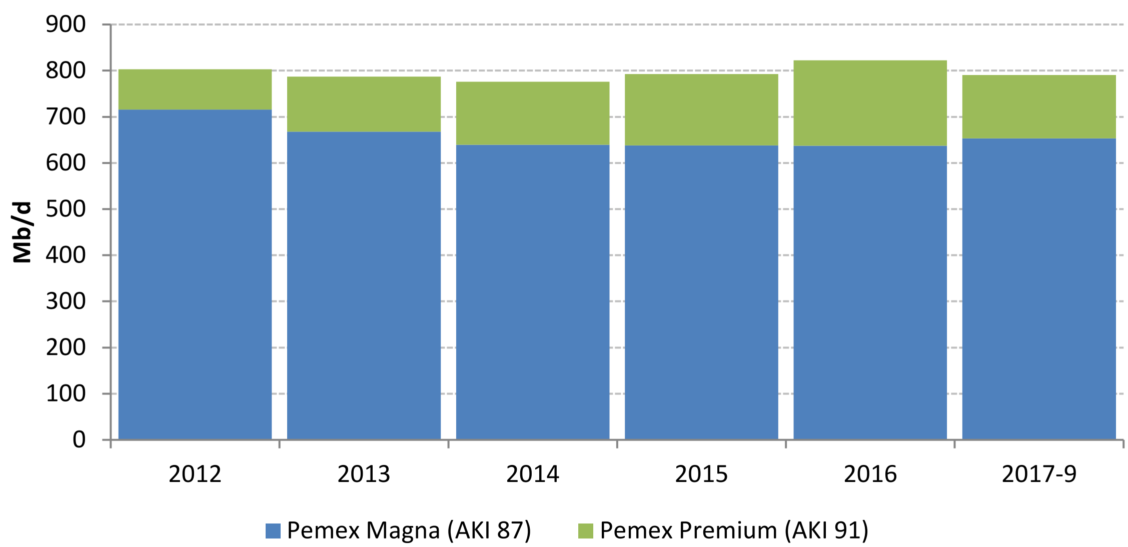
Although the growth in passenger car sales took the spotlight, the two-wheeler segment will remain the main growth driver in the medium term. Roughly 60% of India's gasoline consumption is from the two-wheeler segment. India's demonetization move in the first quarter of 2017 dampened sales of two-wheelers, contracting gasoline consumption. Since then, the effects of demonetization have waned, and we have seen vehicle sales rebounding. Sales of two-wheelers are estimated to grow by 12.9% YoY to touch 20 million units in 2017.

India moved to BS IV (equivalent to Euro IV) nationwide in April 2017 and is planning to skip Euro V and move directly to Euro VI by April 2020. The emphasis has always been on sulfur reduction in transport fuels. There was limited movement in RON ratings; the country mandated 91 RON gasoline in 2005, making a move from lower 88 RON. 91 RON remains the widely retailed grade since then, although both supply and consumption for premium octane gasoline is trending up on consumer preference.

MEXICO

Gasoline consumption in Mexico has been relatively stable since 2012 at approximately 800,000 b/d (Figure 67). Gasoline consumption declined slightly between 2012 and 2014 from 803,000 b/d to 776,000 b/d, before rebounding in 2015 and 2016.

FIGURE 67
MEXICO GASOLINE SALES



Source: Pemex

Gasoline in Mexico comes in two grades: Pemex Magna and Pemex Premium. Magna and Premium are similar to regular and premium in the United States with an AKI of 87 and 91, respectively (Figure 68). As in the United States, some specifications vary regionally in Mexico. Ethanol blending is allowed in gasoline in areas other than Mexico City, Guadalajara, and Monterrey. The maximum allowable content was raised by Mexico’s energy regulator, Comision

Reguladora de Energia, in 2017 from 5.8% to as much as 10%. In some regions, MTBE, ETBE, and TAME[37] are allowed.

FIGURE 68

SELECTED U.S. AND MEXICO GASOLINE QUALITY SPECIFICATIONS[38]

	U.S. Gulf Coast	Mexico[(1)]
Seasonal RVP Specs	Yes	Yes
Max Winter RVP PSI	13.5	7.8-11.5
Regular Octane (R+M)/2	87	87
Premium Octane (R+M)/2	93	91
Renewables Required	Yes	No
MTBE Blended	No	Yes
Sulfur, Per Gallon Max - PPM	80	80
Sulfur, Average Max	10	30
Aromatics, Vol % Max	50	25-32

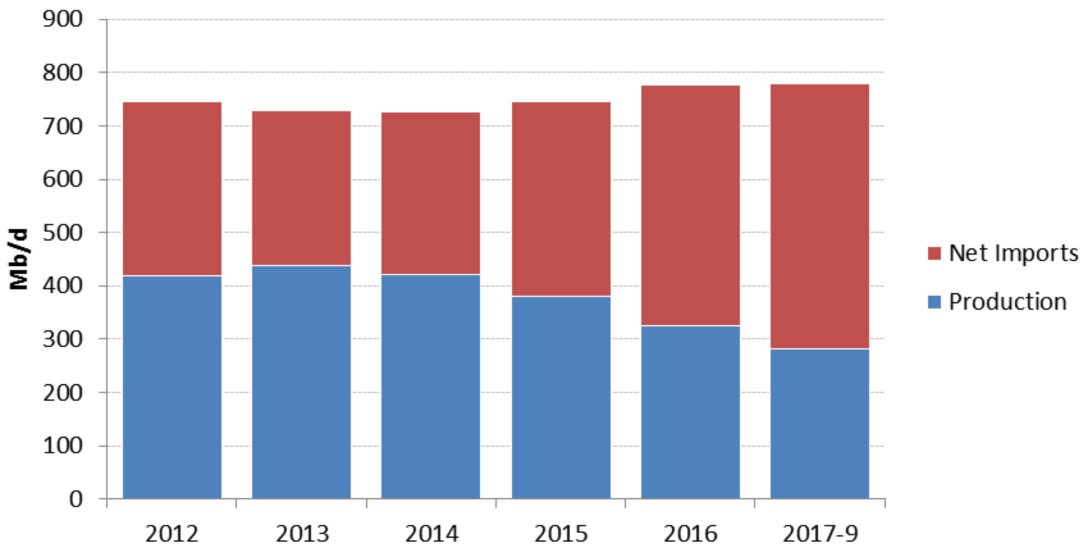
Sources: U.S. EPA, Mexico NOM-016-CRE-2016, Baker & O'Brien research. (1) The range on some specifications is due to regional variation within Mexico.

Mexico has six refineries but is structurally short gasoline[39] requiring increasing levels of imports (Figure 69). Net imports increased from 326,000 b/d in 2012 to nearly 640,000 b/d in 2016, with the majority (~66%) of the imports coming from the United States.

[37] Ethyl tert-butyl ether and tert-amyl methyl ether, respectively.
[38] RVP and aromatics specifications vary regionally in Mexico.
[39] Mexico refineries suffer from historical low capital investment leading to frequent outages and low refinery utilization.

FIGURE 69

MEXICO GASOLINE TRADE BALANCE

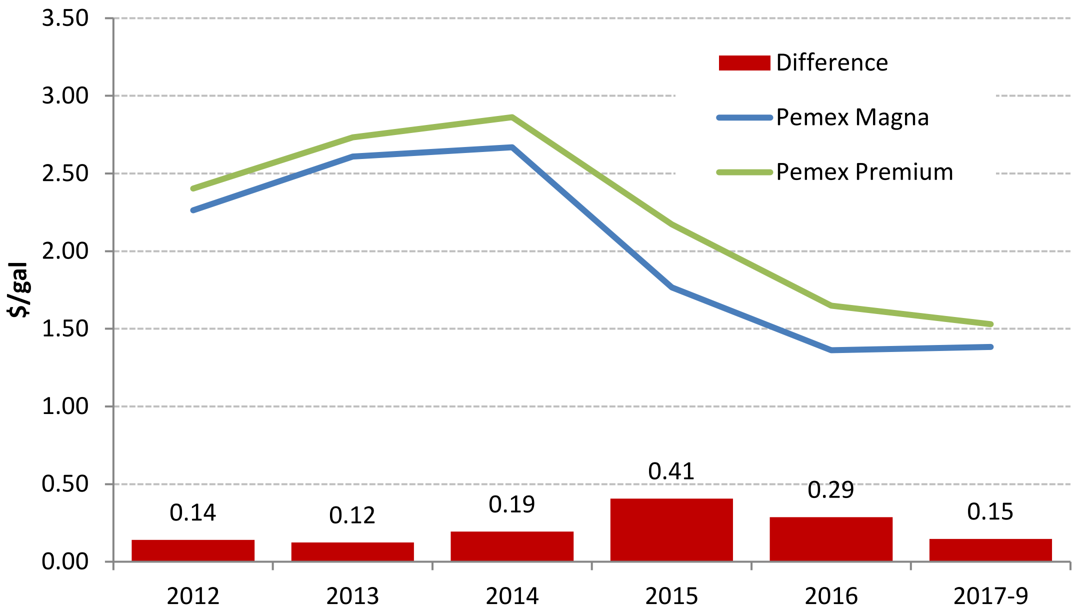


Source: Pemex

The energy industry in Mexico is currently going through deregulation and petroleum prices are moving toward a market pricing structure throughout 2017. Pemex publishes the value of domestic sales of refined petroleum products which exclude the Special Tax on Production and Services, VAT and distributor commission, enabling analysis of country level realized gasoline prices for Magna and Premium grades. The differential between Magna and Premium grades widened from 0.14 $/gal in 2012 to 0.41 $/gal in 2015 before declining in 2016 and 2017 (Figure 70).

FIGURE 70

MEXICO GASOLINE PRICES EXCLUDING TAX AND DISTRIBUTOR FEES



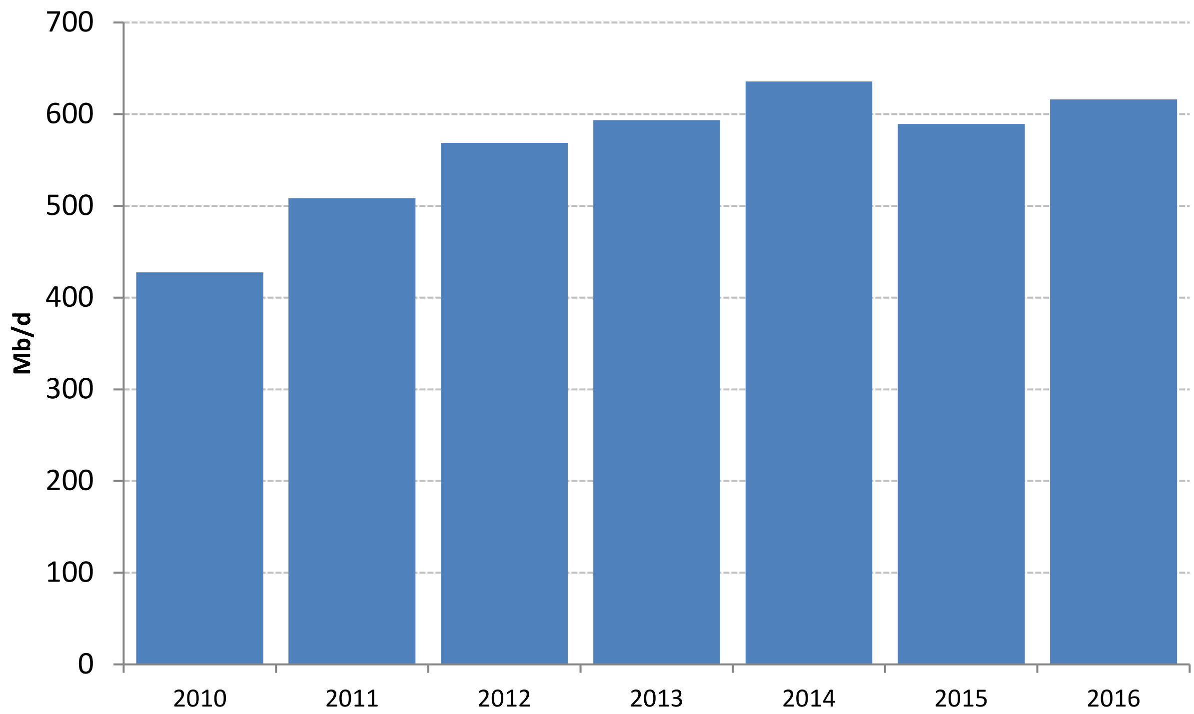
Sources: Pemex, Federal Reserve Bank of St. Louis

BRAZIL

Gasoline consumption in Brazil, including ethanol blending, increased from 428,000 b/d in 2010 to 636,000 b/d in 2014 (Figure 71). Consumption faltered in 2015 as Brazil's economy declined between 2014 and 2015 but rebounded in 2016.

FIGURE 71

BRAZIL GASOLINE SALES BY DISTRIBUTORS, OIL EQUIVALENT BARRELS[40]



Source: Agencia National do Petroleo (ANP)

Brazil is the second largest producer and consumer of ethanol in the world after the United States, and flex-fuel vehicles account for 60% of the total domestic fleet.[41] Brazil introduced an ethanol-use mandate in 1977, and the blend percentage has increased steadily over time. As of 2016, the mandate stood at 27%, but blends can vary between 18% and 27.5%.[42] The flex-fuel vehicle fleet can run on gasoline, ethanol (Hydrous), or a mixture of the two (gasoline and anhydrous ethanol).

[40] Large volumes of ethanol are included in Brazilian finished gasoline. ANP adjusts the actual volumes for the lower energy content of ethanol (Section 4.5.2) and reports the equivalent petroleum based gasoline consumption.

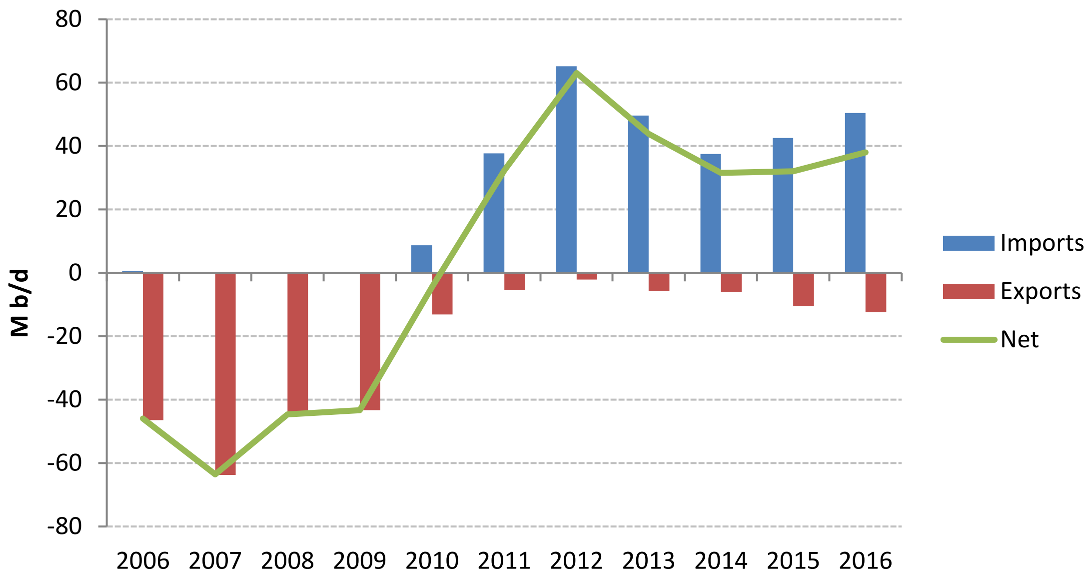
[41] https://www.eia.gov/beta/international/analysis.cfm?iso=BRA.

[42] https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_8-12-2016.pdf.

Brazil became a net importer of gasoline in 2011 (Figure 72). In 2012, net imports of gasoline were over 60,000 b/d.[43] Since then net imports have moderated averaging approximately 40,000 b/d.

FIGURE 72

NET IMPORTS OF GASOLINE IN BRAZIL



Source: ANP

Petrobras markets four types of gasoline: Regular, Petrobras Grid, Premium, and Petrobras Podium. Regular gasoline has an AKI of 87 and up to 50 ppm sulfur. Petrobras Grid gasoline has an AKI of 87 and max sulfur of 50 ppm but has friction-reducing additives. Premium gasoline has an AKI of 91 and up to 50 ppm sulfur. Petrobras Podium has an AKI of 97 and up to 30 ppm sulfur.

In the 1990s, Brazil liberalized its energy market and subsidies were removed through 2001.

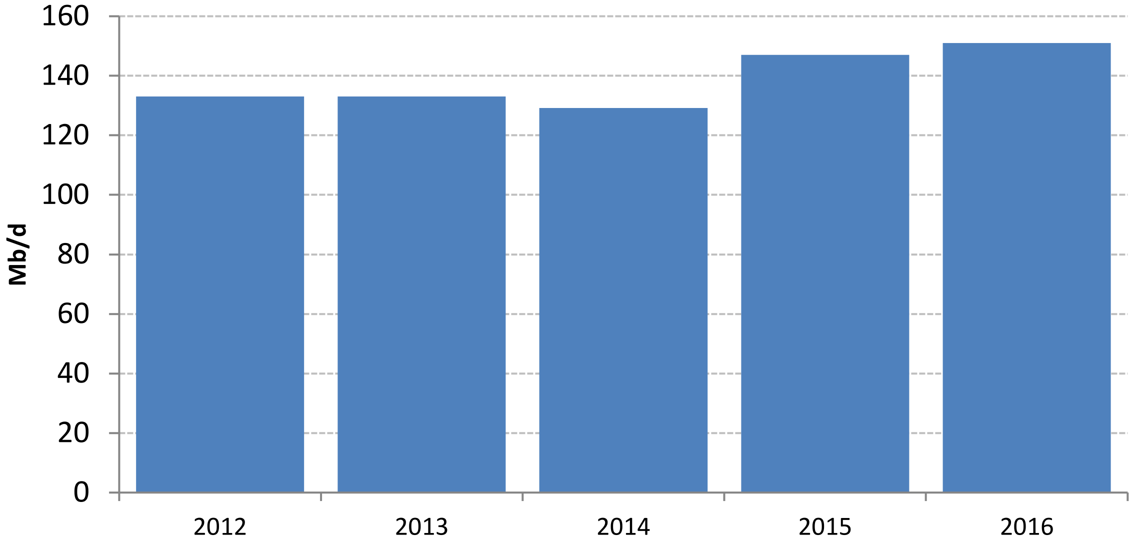
[43] This is largely due to increasing gasoline demand and a lack of capital investment in existing Brazilian refineries for expansions. Instead, Brazil focused on crude oil production investments rather than refining investments.

ARGENTINA

Gasoline consumption in Argentina increased from 133,000 b/d in 2012 to 151,000 b/d in 2016 (Figure 73). Consumption faltered in 2014 but rebounded in 2015.

FIGURE 73

ARGENTINA GASOLINE CONSUMPTION



Sources: U.S. Energy Information Administration, International Energy Statistics; USDA

In 2006, the Argentine Congress passed a law which mandated the use of biofuels starting in 2010. Ethanol blending grew between 2009 and 2017 from 0.1% to 11.6% by volume and the current mandate is for 12% ethanol by volume.[44] The biofuels industry in Argentina is supportive of higher blends, similar to Brazil and Paraguay, but the government has not implemented blends at higher levels.

[44]https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Buenos%20Aires_Argentina_7-17-2017.pdf.