Hoekstra Trading LLC

George.hoekstra@hoekstratrading.com

+1 630 330-8159

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The Octane Value of Ethanol

CONTENTS

1. SUMMARY

Refinery octane production constraints have increased gasoline production costs and prices in the U.S. One way to overcome the constraints is to blend more ethanol into gasoline. Using data from best-available industry sources, Hoekstra Trading estimated U.S. industry-level costs for producing incremental octane by two alternative routes:

1. increasing the ethanol concentration in gasoline (producing more "ethanol octane")
2. increasing refinery-produced octane (producing more "refinery octane")

The estimated costs, in compatible year 2025 units, are:

1. cost of ethanol octane = 1.4 ¢/AKI-gal
2. cost of refinery octane = 6.3 ¢/AKI-gal

The 6.3 ¢/AKI-gal cost of refinery octane is 4.5 times higher than the 1.4 ¢/AKI-gal cost of ethanol octane which implies a large economic incentive to increase the ethanol content of gasoline.

To analyze the economics of ethanol/refinery gasoline substitution, it is necessary to define the quantity of octane in units of octane-gallons, and the cost of octane in units of $/octane-gallon (octane is denoted AKI in this report which stands for Anti-Knock Index which is the octane measure used in U.S. commerce). One AKI-gallon is the quantity of octane that will raise the octane of one gallon of gasoline by one AKI. We measure the blending octane value of ethanol in units of AKI-gal/gal. That is the quantity of octane delivered to a blend by one gallon of ethanol. We then compute the cost of ethanol octane in units of $/AKI-gal as the price of ethanol divided by the blending octane value of ethanol.

The blending octane value of ethanol is derived here from data published in a Society of Automotive Engineers (SAE) technical paper by an industry group that includes Ford Motor Company, GE Energy, BP, and AVL Powertrain Engineering (Reference 1) to be 124 AKI-gal/gal. With the 2025 price of ethanol at $1.71/gal, the cost of ethanol octane is calculated to be $1.71/124 equals 1.4 ¢/AKI-gal.

We measure the blending octane value of refinery gasoline in the same units as for ethanol (AKI-gal/gal), and the cost of refinery gasoline octane in the same units as for ethanol ($/AKI-gal). But quantifying the cost of refinery gasoline octane requires a different kind of analysis. That's because refinery gasoline is not a single compound like ethanol, it is a chemical soup made up of 450 different compounds. Increasing refinery octane involves modifying the chemical composition of the soup by additional refining to increase its octane, which comes at an incremental cost.

The incremental cost of refinery gasoline octane is derived here from a study published by MathPro, a company with deep expertise in gasoline and refinery process technology, economics and optimization (Reference 2), to be 6.3 ¢/AKI-gal.

To analyze the economics of substituting ethanol for refinery gasoline, we consider the differences in the energy content and the octane content of the two components. In this analysis, we derive the cost for a constant energy substitution, which implies a constant number of vehicle miles travelled in the U.S. A constant energy gasoline pool means ethanol is substituted for refinery gasoline in a 1-to-0.67 ethanol/refinery gasoline volume ratio. As ethanol substitution increases at this volume ratio, the pool volume and pool octane both increase. The cost of substitution consists of a volume substitution cost that depends on the relative prices of the two components, and a (negative) octane substitution cost that depends on their relative blending octane values. These two costs are derived here for the condition that the total energy content of the blended gasoline pool remains constant as the ethanol content increases.

The results show that, for today's 10% ethanol (E10) gasoline, the (negative) cost of octane substitution far outweighs the (positive) cost of volume substitution, that is to say, the value of the higher octane of ethanol far outweighs its higher energy-equivalent cost. The energy-equivalent substitution to a level of 10 volume% ethanol implies that ethanol is adding a net of 39 cents/gal worth of octane to the U.S. E10 gasoline pool. To say this another way, if ethanol was removed from the U.S. gasoline pool, replacing its current octane contribution with refinery octane would increase refining cost and the wholesale cost of gasoline by 39 cents per gallon or $54 billion/year.

The value of ethanol’s octane contribution can be realized in different ways. One way is to reduce refinery octane-gallon production and capture part of ethanol’s higher octane value in the form of lower refining cost. Another way is to sell more octane-gallons into the market. How the ethanol octane value is realized does not change the value of substitution, only how it is realized and distributed between the refinery and the market.

At some higher fuel ethanol level, the increased use of fuel ethanol would increase the price of ethanol to a point where the net cost of substitution is zero. Determining that octane cost optimum is a good ultimate goal but is beyond the scope of this report. This report also does not address the implications of ethanol/refinery gasoline substitution for gasoline properties other than octane.

Recommended next steps in this work would be to quantify:

1. How the cost of substitution has varied over time
2. How the cost of substitution varies with changes in the variables that determine it
3. How increased fuel ethanol demand affects the ethanol price
4. How decreased refinery gasoline demand affects refinery gasoline price
5. The ethanol blend level that would minimize the per-gallon cost of octane supply
6. The optimal distribution of octane value between reduced refining cost and increased market value

2. OCTANE FUNDAMENTALS

2.1. WHAT IS OCTANE?

Octane is a measure of a gasoline’s resistance to pre-ignition during compression in an engine cylinder which can cause a knocking sound.

Retail gasoline is classified by its octane rating: regular gasoline has an octane rating of 87 and premium gasoline has an octane rating of 91 to 93. In the U.S., the posted octane rating is the average of the octane measured two different ways, the Research Octane Number (RON) and the Motor Octane Number (MON). That average is called the Anti-Knock Index (AKI), which is the octane number we see posted on the pump.

AKI Octane is the primary indicator of gasoline quality in the U.S., and as most drivers know, higher octane means a higher price per gallon.

2.2. OCTANE BLENDING

Octane blending involves mixing six primary components to meet the target octane specification on the blended gasoline while simultaneously meeting a list of other gasoline specifications. The six components are butane, alkylate, reformate, isomerate, fluid catalytic cracking (FCC) gasoline and ethanol.

The first five of these are petroleum-derived components and are mostly made and blended at refineries to produce refined gasoline intermediates called Blendstocks for Oxygenate Blending (BOB)s which have octane values about 3 AKI below the targeted finished gasoline octane.

Ethanol is blended into BOBs downstream at blending plants or racks near the point of use where trucks are filled to deliver the final blended product to filling stations. Blending with 10% ethanol boosts the octane of BOB by about 3 AKI to meet the finished gasoline octane target.

2.3. OCTANE DEMAND AND PRICE

U.S. demand for premium gasoline has been increasing steadily, from under 9% of total gasoline sales in 2008 to 15% in 2024.

The trend is tied to the fact that more cars, SUVs and trucks are fitted with high-compression engines and/or turbochargers, which improve fuel economy without sacrificing performance — but which also require higher-octane fuels. Also, many car manufacturers require or recommend premium gasoline, and some drivers buy premium for other reasons despite its higher price.

While octane demand has been increasing, a number of factors have been reducing octane supply, spurring a relentless run-up in the retail "price" of octane, which is measured by the difference between the pump prices of premium gasoline and regular gasoline, Figure 1:

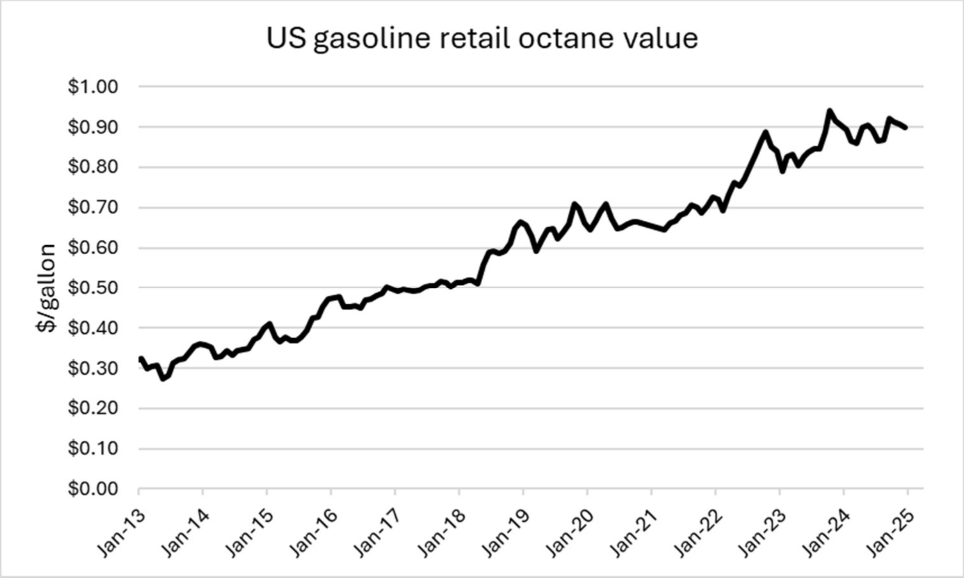

Figure 1 Average annual U.S. retail price differential between premium and regular gasoline Source: Energy Information Administration

The current retail premium minus regular price differential of 90 ¢/gal can be divided by 93-87 = 6 AKI to express the retail octane value as 15 ¢/AKI-gal.

Result 1: U.S. retail value of octane = 15 ¢/AKI-gal.

This means we pay 15 ¢/gal more per single unit increase in AKI octane quality.

2.4. OCTANE SUPPLY

2.4.1. Long term octane supply trends

Figure 2 shows the long-term history of U.S. octane supply divided into three eras.

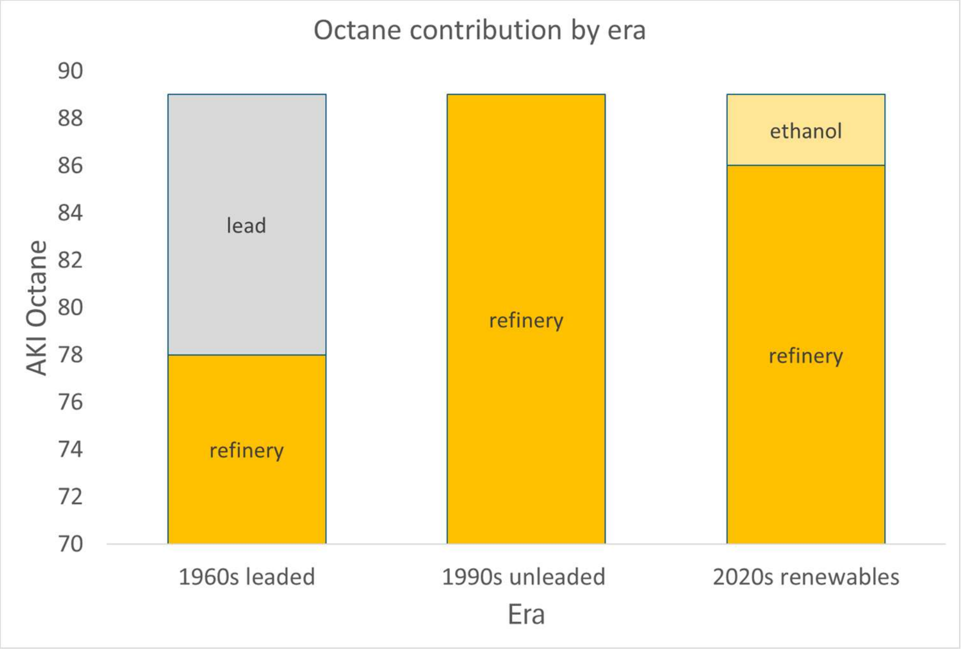

Figure 2 Octane contribution to U.S. gasoline pool Source: Hoekstra Trading LLC

In the *leaded era*, which lasted until the mid-1970's, the U.S. refinery-produced gasoline pool averaged 78 octane and the octane additive tetra-ethyl lead was used to add 11 octane units to make an 89 octane finished gasoline pool.

With lead phase out, the *unleaded era began*. By 1988, tetra-ethyl lead was gone and refineries were delivering *all* the 89 octane units demanded by the market directly from the refinery. That was accomplished by major advances in refining technology and by capital investment in especially 3 processes – fluid catalytic cracking, catalytic reforming and hydroprocessing.

In the 1990's, the need to reduce urban air pollution (particulates, smog and ozone) led to further reduction in harmful vehicle emissions. For gasoline, this meant production of low sulfur, low volatility refined gasoline, accompanied by use of several oxygen-containing octane additives called oxygenates including ethanol.

Starting in 2005, a series of federal and state renewable fuels standards took effect which require the blending of 10% ethanol. That initiated the *renewable fuels era*. Ethanol emerged as the (renewable) oxygenate of choice for gasoline. As currently blended, ethanol contributes 3 octane units with refineries contributing 86 octane units to create the 89 octane finished gasoline pool.

The octane boost from oxygenates and ethanol allowed production of lower-octane refinery gasolines called Blendstocks for Oxygenate Blending (BOB) which reduced the load on refineries to deliver the octane demanded by the market.

2.4.2. Recent octane supply trends

In recent years, increased demand for petrochemicals has boosted competition for the same refinery gasoline molecules that contribute most to the octane of gasoline — namely, aromatics and olefins for use as petrochemical feedstocks.[1]

Shale oil production from fracking has increased supply of low-octane natural gasoline from gas processing plants, which finds a home in refineries able to upgrade its octane for use in gasoline.

Many refineries that used to run heavier crudes are running more domestic lighter/sweeter crude slates that give high yields of low octane gasoline, spurring the need for more octane upgrading. The low octane gasoline is hard to blend into finished U.S.-spec gasoline without costly refining.

The above trends have tightened the octane market, but not enough to explain the persistent long term uptrend seen in Figure 1. However, the reduction of gasoline sulfur to 10-ppm has affected octane values in that way. The Tier 3 gasoline sulfur standard, enacted in 2014, with phase in starting in 2017 and full implementation in 2020, has caused steadily increasing destruction of octane produced in U.S. refineries. This octane destruction has grown persistently, especially since 2020, placing increasing strain on the octane production capabilities of the U.S. refining system and is now a major bottleneck in the U.S. gasoline supply picture, contributing to higher refinery octane production costs (Reference 3).

2.5. OCTANE PRODUCTION PROCESSES

Refinery-produced gasoline is a chemical soup containing about 450 different chemical compounds that were originally present in the crude oil. The composition of the soup is manipulated in the refinery via chemical reactions to meet gasoline property specifications.

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[1] Aromatics and olefins are categories of hydrocarbon molecules present in refined gasoline that have high octane contributions to gasoline and are also used as feedstocks for petrochemical production.

Refineries can increase octane production by increasing reaction severity in the catalytic reforming process. Catalytic reforming changes the chemistry of low-octane (and consequently low-value) naphtha[2] distilled from crude oil (as well as cracked naphthas from other refinery process units) to convert the low-octane naphtha into high-octane, high value reformate.

While catalytic reforming boosts octane, it also causes loss of gasoline volume to light hydrocarbon gasses. That tradeoff, between higher octane and lower gasoline volume, is what defines most refineries' incremental cost of octane production. This incremental cost varies across refineries and with changes in crude oil and fuel prices.

Refineries can also increase octane production by making more alkylate, which is produced in a refinery's alkylation unit or by making more isomerate, which is produced in a refinery's isomerization unit. Alkylate and isomerate are good high octane gasoline blendstocks but make up less than 10% each of the refinery gasoline pool and usually come at higher cost than reformate for producing incremental octane.

Refineries can also increase octane production by buying sulfur credits (Reference 3).

Beyond these steps, refineries can increase octane production by investing capital in new processes and/or the processes that limit their octane production today.

Octane production can also be increased by blending high octane additives like ethanol into refinery-produced gasoline.

3. ECONOMICS OF OCTANE SUPPLY

3.1. OCTANE-GALLONS

For doing octane economics, we will measure the *quantity of octane* in units of octane-gallons.[3] One octane-gallon is the quantity of octane that will raise the octane of one gallon of gasoline by one octane number.

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[2] Naphtha is a generic term describing light hydrocarbons in the gasoline boiling range that could potentially be used in, or refined for use in marketable gasoline.

[3] Octane is a gasoline *quality*. To do economics, we must be able to work with *quantities*. We measure *quantity of octane* in units of octane-gallons. That is the *quantity of a quality,* which can be confusing. Consider the economics of wine quality. Wine quality is rated on a scale invented by Robert Parker in the 1980s. The Parker quality rating is assigned to a wine, on a scale from 50 to 100, by wine experts. Suppose the data shows people are paying $12 per bottle more for 93 vs. 87 Parker wine. Then the *price of wine quality* is 12/(93-87) = 12/6 = *$2/Parker-bottle*. The Parker-bottle is a quantity of wine quality. With this number, you could calculate it

So, for example, if you have 3 gallons of gasoline and change its composition such that its AKI octane increases by 1 AKI, you have produced 3 additional AKI-gallons of octane. Or, if you have one gallon of gasoline and change its composition such that its AKI octane increases by 3 AKI, you have also produced 3 additional AKI-gallons of octane.

3.2. BLENDING OCTANE NUMBERS

In practice, octane blending calculations are done using *blending octane numbers* for the components. Blending octane numbers represent the octane quality of a component with a number that allows the octane of blends to be calculated using a simple linear volumetric blending equation.

WARNING - math to follow: For example, if you make a blend of 10% ethanol (v_{eth}= 0.1) having a 124 blending octane number ($ON_{eth} = 124$) with 90% gasoline having an 85 blending octane number (ON_{gas}= 85) you would calculate the octane number of that 10% ethanol blend (ON_{blend}) to be 88.9 as follows:

$$ON_{blend} = (1 - v_{eth}) * ON_{gas} + v_{eth} * ON_{eth}$$

Equation 1

$$ON_{blend} = (1 - 0.1) * 85 + 0.1 * 124 = 88.9$$

Equation 1 is applied for blending RON octane values, MON octane values and/or AKI octane values of gasoline blending components throughout the industry.

Linear volumetric blending is a simplification of the true octane blending characteristics of gasoline components and octane additives. But it is intuitive, easy to use, and works well when using blending octane numbers that are applicable over the range of interest.

3.3. COST OF ETHANOL OCTANE

3.3.1. Data basis

The cost of ethanol octane is derived here from data published in a Society of Automotive Engineers (SAE) technical paper by an industry group that includes Ford Motor Company, GE Energy, BP, and AVL Powertrain Engineering (Reference 1). They measured octane numbers of 26 different gasoline-ethanol blends. The blends were structured in a matrix spanning the range 0 to 75% ethanol blended into gasolines with octanes from 82 to 97 RON. This data, to my knowledge, is the best available basis for defining the true octane contribution of ethanol over the range of interest.

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will cost you $24/case more to buy an 88 versus an 87 Parker wine as follows: $2/Parker bottle * 12 bottles/case = $24/Parker-case.

Knowing the octane contribution per gallon of ethanol, the cost of ethanol octane production is easily calculated given the market price of ethanol.

3.3.2. Deriving the blending octane number of ethanol

To determine the blending octane number of ethanol, I used the octane blending data and octane blending methods reported in Reference 1. Table 1 and Figure 3 show the experimental data for the 26 blends of ethanol in 5 different gasolines:

Table 1 Octane of blended gasolines, Source: SAE technical paper 2012-01-1274 (Reference 1)

Measured octanes of gasoline-ethanol blends				
Gasoline ID	Volume fraction ethanol	RON	MON	AKI
82 RON 79 AKI	0	81.7	76.5	79.1
	10	88.3	81.0	84.6
	20	93.8	85.0	89.4
	30	98.1	87.2	92.6
	50	103.5	89.0	96.2
	75	106.8	90.1	98.4
88 RON 85 AKI	0	88.2	81.7	84.9
	10	93.1	85.3	89.2
	20	97.3	87.3	92.3
	30	100.8	88.4	94.6
	50	104.7	89.9	97.3
	75	107.7	90.5	99.1
92 RON 88 AKI	0	92.2	84.7	88.4
	10	96.1	86.7	91.4
	20	99.7	88.3	94.0
	30	102.2	89.0	95.6
	50	105.6	90.7	98.1
	75	108.1	91.1	99.6
95 RON 91 AKI	0	95.4	86.4	90.9
	10	98.9	87.7	93.3
	20	101.3	89.2	95.2
	30	103.5	89.8	96.7
	50	106.0	90.8	98.4
	75	108.0	91.2	99.6
97 RON 93 AKI	0	97.4	87.9	92.7
	20	102.7	89.9	96.3

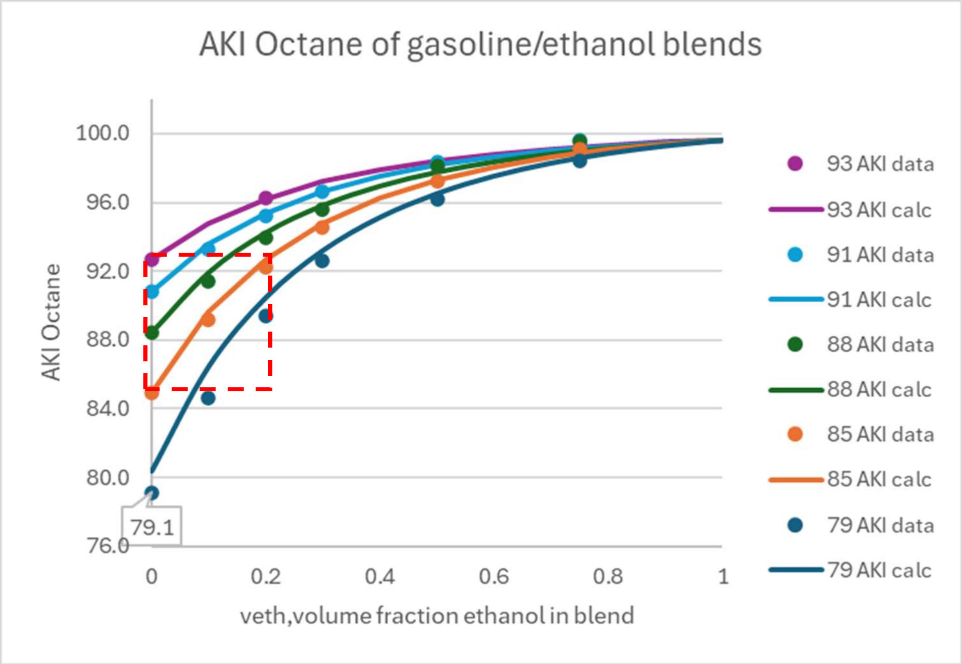

Figure 3 AKI Octane of blended gasolines, Source: SAE paper (Reference 1) and Hoekstra Trading LLC

The data points in Figure 3 are the measured octane values of the blends. I used equation 7 from Reference 1 to calculate the curves in Figure 3. That equation is copied below as Equation 2:

$$ON_{blend} = (1 - x_{eth})ON_{gas} + x_{eth}ON_{eth} + P_g x_{eth}(1 - x_{et}\ )(ON_{eth} - ON_{gas})$$

Equation 2

Where:

x_{et} = *mole* fraction of ethanol in the blend

P_g = an empirically determined scaling parameter for gasoline-ethanol blends

(The other symbols in Equation 2 are defined in Section 3.2 of this report).

The first two terms of Equation 2 take the same form as the linear blending Equation 1. But Equation 2 differs from Equation 1 in two ways:

1. x_{eth} is the *molar* fraction of ethanol in the blend. For reasons explained in Reference 1, molar fraction is technically more correct and works better than *liquid volume* fraction.
2. The third term, involving the parameter P_g, has been added to the equation to account for other factors that increase ethanol's octane contribution as explained

in Reference 1. The value of P_g was determined from the Reference 1 data and reported in Reference 1.[4]

To calculate the curves in Figure 3, I applied equation 2 to first calculate the RON and MON values for each blended gasoline, then averaged those to calculate their AKIs.

The fact that the curves in Figure 3 go through the data points confirms that my calculations using equation 2 describe the measured octane values well.

To enable use of the simpler volumetric blending equation 1 that is in day-to-day use, the data in the segment of current interest (indicated by the red box in Figure 3) is approximated in Figure 4 by a linear relationship showing AKI vs. v_{eth}, the volume fraction ethanol in the blend.

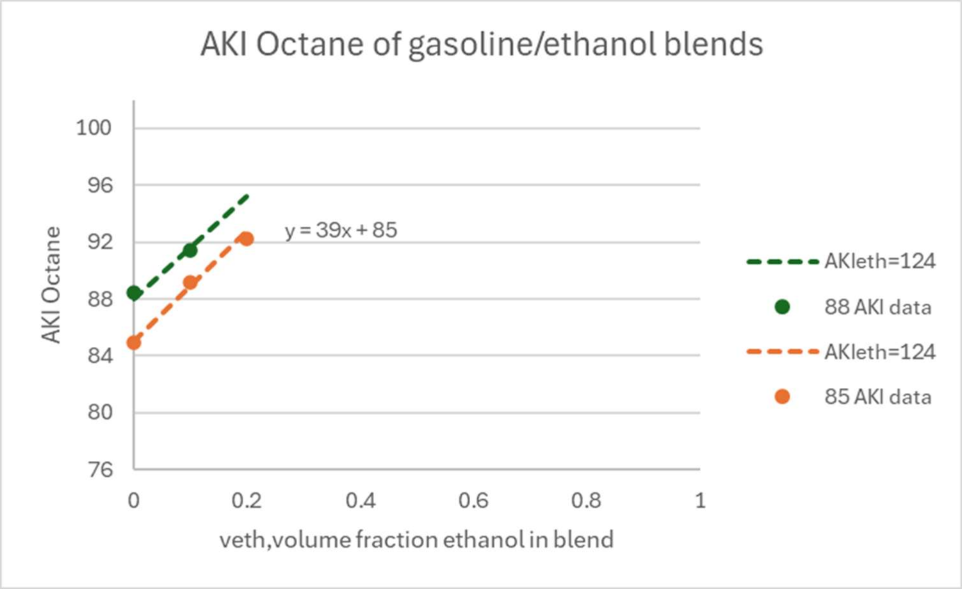

Figure 4 Linear equation for AKI vs. v_{eth} *defines the slope (* $AKI_{eth} - AKI_{gas}$*) = 39 for the range of interest. Source: Hoekstra Trading LLC*

That linear relationship describes the data well in this range and can be written as:

$$AKI_{blend} = AKI_{gas} + \left(AKI_{et} \; - \; AKI_{gas}\right) * v_{eth}$$

which is a re-arrangement of the linear volumetric blending equation 1, applied to AKI octane. From the form of this linear equation, we can see the slope of the line on Figure 4 is

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[4] For my calculations, I used P_g=0.465 for RON and P_g=1.075 for MON, which are the averages of the ranges reported in Reference 1.

$(AKI_{eth} - AKI_{gas})$, which, as shown on the chart, equals 39. With AKI_{gas} equal to 85, that means the implied AKI_{eth} for linear volumetric blending in this range = 39 + 85 = 124:

Result 2: AKI_{eth}= 124 AKI-gal/gal ethanol

Notice that, with volume fraction measured in gal ethanol/gal blend, the unit of measure of this slope is AKI-gal/gal ethanol. That is the *quantity of octane (in AKI-gal*) delivered to the blend per unit volume of ethanol, which is analogous to a *concentration of octane* in ethanol.

3.3.3. Derived cost of ethanol octane in 2025

The cost of ethanol octane is the cost of a gallon of ethanol divided by the quantity of octane it delivers to the blend, calculated as follows, where strikethrough font indicates cancelling units:

Cost of an ethanol octane gallon = P_{eth} in $/~~gal ethanol~~ / 124 AKI-gal/~~gal ethanol~~

Result 3: Cost of ethanol octane = P_{eth} /124 $/AKI-gal

Where P_{eth} = market price of ethanol in $/gal ethanol

With a January 2025 ethanol price of $1.71/gal, the cost of ethanol octane in 2025 is:

1.71/124 = 0.014 $/AKI-gal = 1.4 ¢/AKI-gal.

Result 4: Derived 2025 cost of ethanol octane = 1.4 ¢/AKI-gal.

The same method can be used to calculate the cost of other octane additives. For example, the octane additive toluene has a blending octane value of 111. With the price of toluene at $3.21/gal, the cost of toluene octane is $3.21/111 = 2.9 ¢/AKI-gal.

3.4. COST OF REFINERY OCTANE

3.4.1. Data basis

While ethanol and toluene are individual chemical compounds with fixed octane values, refinery gasoline is a chemical soup containing 450 different compounds. The chemistry of the soup is changed by doing chemical reactions in the refinery to change its octane. The methods used to change the chemistry are different for different refineries.

<u>The cost of refinery octane</u> is derived here from data published by MathPro in Reference 2. MathPro is a company with deep expertise in gasoline and refinery process technology, economics and optimization. They used their refinery linear programming models to analyze the refining economics of contemplated future higher RON octane standards. Their analysis identified the refining changes and costs for increasing refinery octane-gallon production in the U.S. to enable supply of higher octane E10, E20, and E30 gasolines, using data for year 2017.

In the short run, the cost of refinery octane depends mostly on refineries' catalytic reforming capabilities. Catalytic reforming is the only refining process that can be controlled to operate over a wide range of severity to change the composition of the product (reformate) in ways that increase its octane to over 95 AKI. Increasing reforming severity increases the octane of reformate and reduces reformate production rate. To maintain constant production rate then requires running more crude oil which implies higher cost per octane-gallon produced.

When a refinery's octane-gallon production capacity is reached, capital investment can further increase its octane-gallon production capacity.

This MathPro study quantified these costs for pertinent cases and is, I believe, the best available basis for estimating the cost of increasing refinery octane production in the U.S.

3.4.2. Deriving the cost of refinery octane in 2017

Table 2 and Figure 5 show MathPro's results for the cases studied, taken from Table S11 of Reference 2.

For the current purpose, we focus on the first 2 cases (highlighted in gold) which involve increasing refinery octane-gallon production to raise the RON of refined gasoline to levels that produce a U.S. gasoline pool of 95 (in case A) and 98 (in case B), when blended with 10% ethanol, in each case producing a single octane grade suitable for use throughout the U.S.:

Table 2 Refining cost for increasing octane-gal production Source: MathPro (Reference 2)

Refining cost for increasing octane-gal production			
Blend	**RON**	% ethanol	Refining cost, $/gal
E10	**95**	10	$0.03
	98	10	$0.18
E20	**95**	20	$0.01
	98	20	$0.05
	100	20	$0.13
E30	**95**	30	$0.00
	98	30	$0.02
	100	30	$0.05
	102	30	$0.12

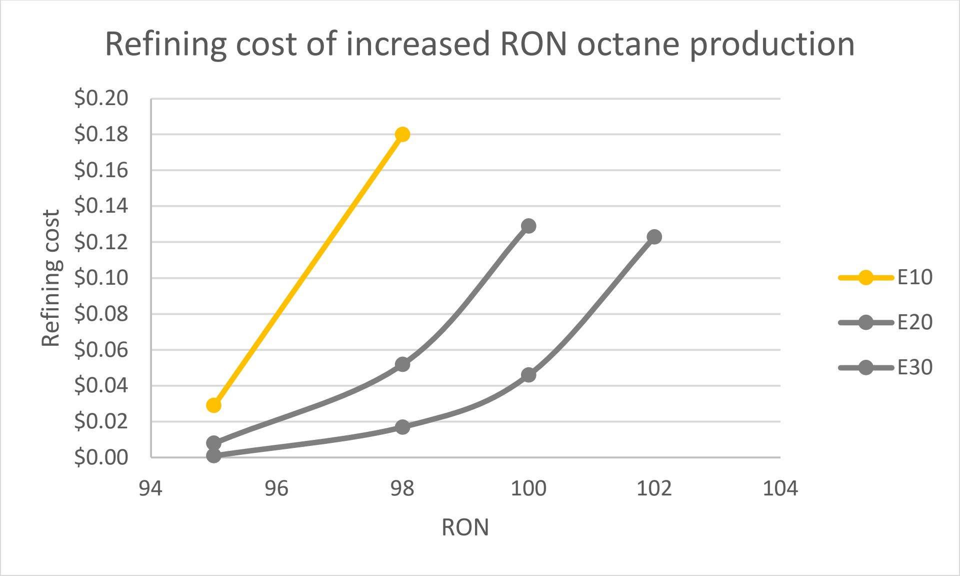

Figure 5 Refining cost of increased refinery RON octane production in U.S. Source: MathPro (Reference 2)

To apply these results to calculations involving *AKI* octane, in Figure 6, I have charted this data versus the AKI octane (instead of RON octane) of the corresponding gasoline pools, with the E10 data highlighted in gold:[5]

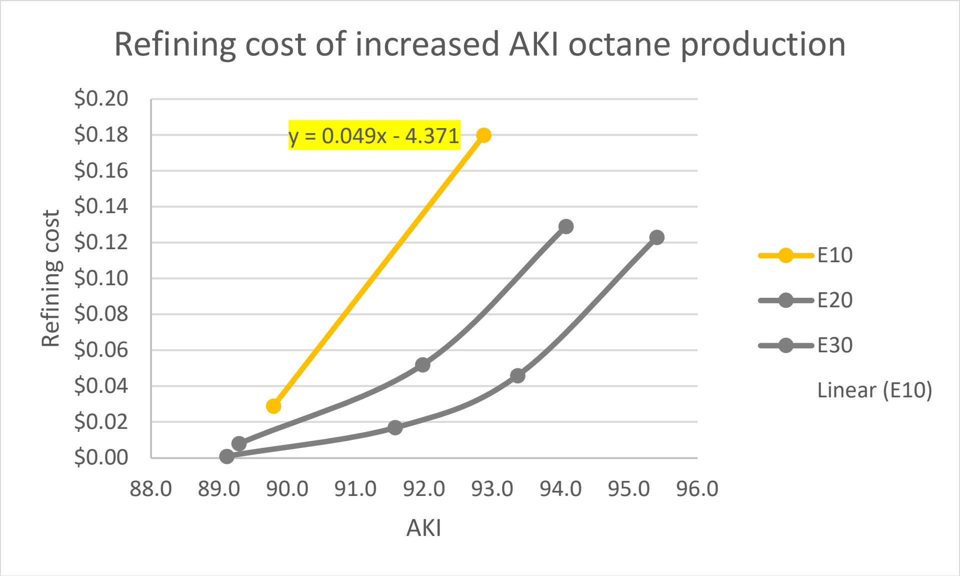

Figure 6 Refining cost of increased AKI octane production in U.S. Source: MathPro (Reference 2) and Hoekstra Trading LLC

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[5] To convert the 95 and 98 RON octanes of the MathPro cases to AKI values, I calculated the MON for those cases using the molar volume method given in the SAE Reference 1 paper (without the P_{gas} term).

The slope of the gold line is 0.049 $/AKI-gallon of E10. Along this gold line, the increase in refining cost (y-axis) represents the increasing cost of making the same E10 gasoline volume with higher AKI refinery gasoline. Therefore I take this slope as a direct estimate of the cost of producing additional refinery octane-gallons in the U.S., in $/AKI-gal, at the time of this study (2017).

Result 5: Cost of refinery octane in 2017 = 4.9¢/AKI-gal

To provide additional context on the refining costs for increasing refinery octane-gal production, Table 3 summarizes the specific requirements and costs detailed in the MathPro study for moving along this gold line from a 95 RON to a 98 RON gasoline pool by increasing the octane of refinery gasoline to increase the RON of E10.

Table 3 Refining changes to increase RON of E10 gasoline Source: MathPro (Reference 2)

	RON 95	**RON 98**	**Difference**
Gasoline pool volume (K bbl/d)	8,536	8,536	0
Investment ($MM)	4,454	27,071	22,617
Reforming Throughput (Kbbl/d)	2,634	3,927	1,293
Reforming severity (RON of reformate)	99.3	103.6	4.3
Per-gallon refining cost ¢/gal	2.9	18.0	15.1
Crude Throughput (K bbl/d)	14,691	15,309	618
Annual refining cost ($MM/y)	3,843	23,521	19,678
Increase in CO2 emissions (Million MT/y)	2	17	15

The 4th column (labeled Difference), shows that moving from 95 to 98 RON with E10 requires $22.6 billion of capital investment (most of which is for reforming and isomerization unit revamps, capacity expansions, and new build units), increasing reforming throughput by 1.3 billion bbl/d, increasing reformate octane by 4.3 RON to 103.6, increasing crude throughput by 618 thousand bbl/d (to provide additional feedstock for increased octane-barrel production), with increased refining cost of $19.7 billion/year.

The MathPro study also defines the cost of refinery octane production for blending higher ethanol-gasoline blends (E20 and E30) which is beyond the scope of this study.

3.4.3. Inflation adjustment from 2017 to 2025

The costs for increased production of refinery octane are roughly 30% capital investment and 70% refinery operations cost. I applied the Chemical Manufacturing Producer Price Index for inflation from 2017 through 2024, which scales the number up by 28% or 1.4 ¢/gal.

Result 6: Inflation adjustment for refinery octane cost, 2017-2024 = 1.4 ¢/gal

3.4.4. Derived cost of refinery octane in 2025

The resulting 2025 refinery octane cost is 6.3 ¢/AKI-gal, as summarized in Table 4.

Table 4 Cost of refinery octane in ¢/AKI-gal Source: Hoekstra Trading LLC

Cost of refinery octane, ¢/AKI-gal	
2017 cost	4.9
Inflation adjustment	+1.4
2025 cost	6.3

Result 7: Cost of refinery octane in 2025 = 6.3 ¢/AKI-gal

3.5. ECONOMICS OF ETHANOL/REFINERY OCTANE SUBSTITUTION

There are 3 elements to the cost of increasing the ethanol content of gasoline:

1) The cost of the additional ethanol
2) A credit for the cost of the refinery gasoline it displaces
3) A credit for the additional octane that ethanol adds to the blended pool[6]

We are using the following octane, price, and cost values as input data:

- Ethanol octane = 124 AKI-gal/gal
- Ethanol price (P_{eth}) = \$1.71/gal
- Refinery gasoline octane = 89 AKI-gal/gal
- Refinery gasoline price (P_{gas}) = \$2.28/gal
- Refining cost of incremental octane (C_{octane}) = \$0.063/AKI-gal

Consider the cost of adding 1 gallon of ethanol ($Q_{et} = 1$) to a starting pool of 100 gallons of 89 AKI refinery gasoline. The original 100 gallons contain 89*100 = 8,900 AKI-gal of octane.

3.5.1. Cost of volume substitution

The energy equivalence condition says that adding 1 gallon of ethanol ($Q_{eth} = 1.00$ gal) requires removing 0.67 gallons of refinery gasoline ($Q_{gas} = 0.67$ gal). The pool then consists of 99.33 gallons of refinery gasoline and 1 gallon of ethanol, for a total pool volume of 100.33 gallons, and the volume fraction ethanol, V_{eth} = 1/100.33 = 0.00997.

The cost of this substitution is the cost of the 1 gallon of ethanol minus the cost of the 0.67 gallons of refinery gasoline it displaces. I call this the *cost of volume substitution* ($C_{volume\ substitution}$), which calculates to \$0.182 as shown in equation 2:

$$C_{volume\ substitution} = Q_{eth} * P_{eth} - Q_{gas} * P_{gas}$$

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[6] The effect of ethanol substitution on other gasoline properties is not addressed in this work.

$$C_{volume\ substitution} = 1.00 * \$1.71 - 0.67 * \$2.28 = \$0.18$$

Equation 2

Converting this from $ to $/gal of blended pool, the cost of volume substitution is

$$C_{volume\ substitution} = \$0.18 / 100.33 \text{ gal} = \$0.0018/\text{gal of blended pool}$$

3.5.2. Cost of octane substitution

An octane-gallon balance says the octane-gallons added to the pool (1 gal ethanol * 124 AKI-gal/gal ethanol), minus the octane-gallons removed from the pool (0.67 gal refinery gasoline * 89 AKI-gal/gal refinery gasoline) equals the net octane-gallon increase of the pool (ΔO_{blend}). That difference computes to 64.4 octane-gallons:

$$\Delta O_{blend} = 1.00 * 124 - 0.67 * 89 = 64.4 \text{ AKI-gal}$$

To check this - the octane content of the pool is the sum of the octane contributions of its two components, which, after the volume substitution, is: 1 gal ethanol * 124 AKI-gal/gal + 99.33 gal refinery gasoline * 89 AKI-gal/gal = 8,964.4 AKI-gal. (The octane of the pool is 8.964.4 AKI-gal/100.33 gal = 89.35 AKI).

Compared to the original pool octane content of 8,900.0 AKI-gal, the substitution has increased the octane content of the pool by 64.4 AKI-gal. With the cost of volume substitution already accounted for, this increase in pool octane content is a bonus that results in a credit to the cost of substitution that I call the *cost of octane substitution*.

To value these extra octane-gallons, we consider the cost of the alternative to produce them in the form of refinery octane-gallons. That cost, in $/gal of blended gasoline, is calculated as follows:

$$C_{octane\ substitution} = C_{octane} * \Delta O_{blend}$$

$$C_{octane\ substitution} = -\$0.063/\text{AKI gal} * 64.4 \text{ AKI-gal} = -\$4.06$$

Converting this from $ to $/gal of blended pool, the cost of octane substitution is:

$$C_{octane\ substitution} = -\$4.06 / 100.33 = -\$0.0404/\text{gal}$$

3.5.3. Cost of substitution

The total cost of substitution is:

$$C_{substitution} = C_{volume\ substitution} + C_{octane\ substitution}$$

$$C_{substitution} = \$0.0018/\text{gal} - \$0.0404/\text{gal} = -\$0.0386/\text{gal of blended pool}$$

Table 5 and Figure 7 show the results of this calculation for different quantities of ethanol addition. The above example calculation for 1 gallon ethanol added is highlighted in bold font.

Table 5 Cost of increasing ethanol content of gasoline ***with constant refinery gasoline AKI Source: Hoekstra Trading LLC***

Pool composition, gal			Octane			Cost of components		costs, $/gal blend		
Gal eth added	Pool volume, gal	Ethanol fraction, Veth	Pool octane content, AKI-gal	Refinery gasoline octane, AKI	Blended pool octane, AKI	Ceth, $	Cgas, $	Cvolume substitution $/gal	Coctane substitution $/gal	Csubstitution $/gal
0.00	100.00	0.00	8,900.0	89.0	89.00	$0.00	$0.00	$0.0000	$0.0000	$0.0000
1.00	**100.33**	**0.00997**	**8,964.4**	89.0	**89.35**	**$1.71**	**-$1.53**	**$0.0018**	**-$0.0404**	**-$0.0386**
2.00	100.66	0.01987	9,028.7	89.0	89.70	$3.42	-$3.06	$0.0036	-$0.0806	-$0.0770
3.00	100.99	0.02971	9,093.1	89.0	90.04	$5.13	-$4.58	$0.0054	-$0.1205	-$0.1150
4.00	101.32	0.03948	9,157.5	89.0	90.38	$6.84	-$6.11	$0.0072	-$0.1601	-$0.1529
5.00	101.65	0.04919	9,221.9	89.0	90.72	$8.55	-$7.64	$0.0090	-$0.1995	-$0.1905
6.00	101.98	0.05884	9,286.2	89.0	91.06	$10.26	-$9.17	$0.0107	-$0.2386	-$0.2279
7.00	102.31	0.06842	9,350.6	89.0	91.39	$11.97	-$10.69	$0.0125	-$0.2775	-$0.2650
8.00	102.64	0.07794	9,415.0	89.0	91.73	$13.68	-$12.22	$0.0142	-$0.3161	-$0.3019
9.00	102.97	0.08740	9,479.3	89.0	92.06	$15.39	-$13.75	$0.0159	-$0.3545	-$0.3385
10.00	103.30	0.09681	9,543.7	89.0	92.39	$17.10	-$15.28	$0.0177	-$0.3926	-$0.3749
11.00	103.63	0.10615	9,608.1	89.0	92.72	$18.81	-$16.80	$0.0194	-$0.4305	-$0.4111
12.00	103.96	0.11543	9,672.4	89.0	93.04	$20.52	-$18.33	$0.0211	-$0.4681	-$0.4470
13.00	104.29	0.12465	9,736.8	89.0	93.36	$22.23	-$19.86	$0.0227	-$0.5055	-$0.4828
14.00	104.62	0.13382	9,801.2	89.0	93.68	$23.94	-$21.39	$0.0244	-$0.5427	-$0.5183
15.00	104.95	0.14293	9,865.6	89.0	94.00	$25.65	-$22.91	$0.0261	-$0.5796	-$0.5535
16.00	105.28	0.15198	9,929.9	89.0	94.32	$27.36	-$24.44	$0.0277	-$0.6163	-$0.5886
17.00	105.61	0.16097	9,994.3	89.0	94.63	$29.07	-$25.97	$0.0294	-$0.6528	-$0.6234
18.00	105.94	0.16991	10,058.7	89.0	94.95	$30.78	-$27.50	$0.0310	-$0.6890	-$0.6580
19.00	106.27	0.17879	10,123.0	89.0	95.26	$32.49	-$29.02	$0.0326	-$0.7250	-$0.6924
20.00	106.60	0.18762	10,187.4	89.0	95.57	$34.20	-$30.55	$0.0342	-$0.7608	-$0.7266

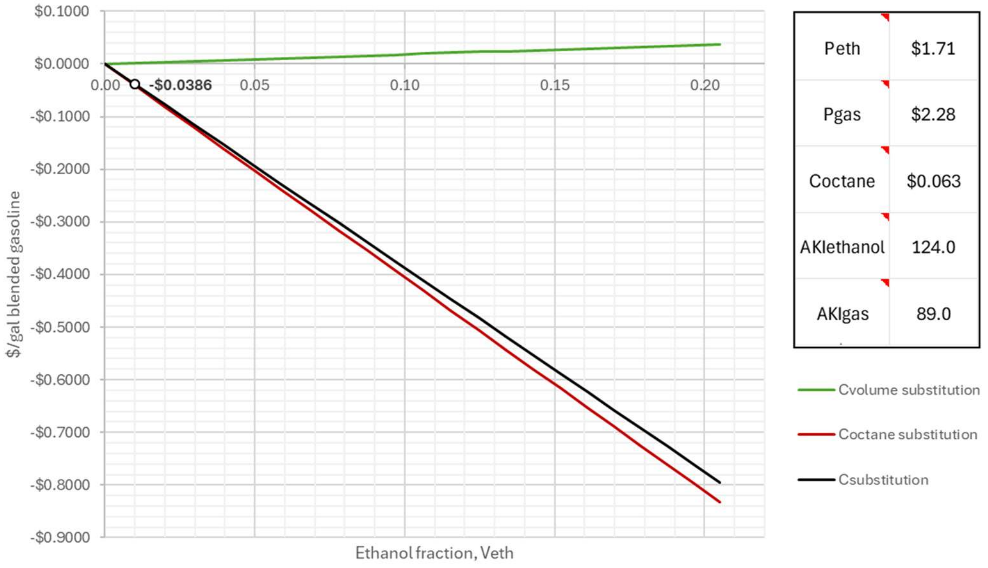

Figure 7 cost of volume substitution (green), cost of octane substitution (red) and total cost of substitution (black) for energy-equivalent gasoline pools with the specified input values Source: Hoekstra Trading LLC

Also shown on Figure 7 is the data point representing the example calculation for 1 gallon ethanol added, with a cost of -\$0.0386/gal, (or -3.9 cents/gal to the nearest tenth of a penny).

The (negative) cost of octane substitution far outweighs the (smaller, positive) cost of volume substitution such that the net effect is a substantial cost reduction. The total cost of substitution is almost (but not quite) linear with respect to the volume fraction ethanol in the blend. To a very close approximation, the –3.9 cents/gal for adding 1% ethanol can be multiplied by the % ethanol in the blend to get the cost of substitution for higher ethanol blends. So, for example, the cost of substitution for 10% ethanol (E10) is -39 cents/gal.

Result 8: For today's E10 gasoline, the high octane value of ethanol is adding a net of 39 cents/gal worth of octane to the U.S. gasoline pool — to say this another way, if ethanol was removed from the U.S. gasoline pool, replacing its current octane-gallon contribution with refinery octane would increase the wholesale cost of gasoline by 39 ¢/gal or \$54 billion/y.

3.5.4. Capturing ethanol's octane value by reducing refining cost

In the above calculation, the octane of the refinery gasoline was assumed to stay constant at 89 AKI and the blended pool's octane increased as ethanol was added, meaning the extra ethanol octane-gallons and their value accumulated in the pool as ethanol was added.

There are different ways to capture the value of the extra ethanol octane. One way is to reduce refining severity to reduce the octane of the refinery gasoline, thus reducing refinery gasoline production cost while keeping pool octane constant. Suppose that, as the ethanol content is increased, we reduce the octane of the refinery gasoline by enough to keep the blended pool octane constant at 89.0 AKI.

For any volume fraction ethanol (v_{eth}) the implied octane of the corresponding refinery gasoline (AKI_{gas}) can be calculated as a function of the blended pool octane (AKI_{blend}) and the ethanol blending octane value (AKI_{eth}) using equation 1 which is copied below:

$$AKI_{blend} = (1 - v_{eth}) * AKI_{gas} + v_{eth} * AKI_{eth}$$

Rearranging this equation gives equation 3 defining the refinery gasoline octane in terms of the other variables:

$$AKI_{gas} = (AKI_{blend} - v_{et} * AKI_{et})/(1 - v_{et})$$

Equation 3

Equation 3 is used to calculate AKI_{gas} vs. v_{et} for constant AKI_{blend} = 89.0. Table 6 and Figure 8 show the results of this calculation, with the main differences versus the constant refinery gasoline octane case highlighted:

Table 6 Cost of increasing ethanol content of gasoline at constant pool energy content ***with constant pool AKI*** *Source: Hoekstra Trading*

Pool composition, gal			Octane			Cost of components		Costs, $/gal blend			
Gal eth added	Pool volume, gal	Ethanol fraction, Veth	Pool octane content, AKI-gal	Refinery gasoline octane, AKI	Blended pool octane, AKI	Ceth, $	Cgas, $	Cvolume substitution $/gal	Crefinery octane $/gal	Cpool octane $/gla	Csubstitution $/gal
	100.00	0.00	8,900.0	89.00	89.00	$0.00	$0.00	$0.000	$0.000	$0.000	$0.000
1.00	100.33	0.00997	8,929.4	88.65	89.00	$1.71	-$1.53	$0.002	-$0.022	-$0.018	-$0.039
2.00	100.66	0.01987	8,958.7	88.29	89.00	$3.42	-$3.06	$0.004	-$0.044	-$0.037	-$0.077
3.00	100.99	0.02971	8,988.1	87.93	89.00	$5.13	-$4.58	$0.005	-$0.066	-$0.055	-$0.115
4.00	101.32	0.03948	9,017.5	87.56	89.00	$6.84	-$6.11	$0.007	-$0.087	-$0.073	-$0.153
5.00	101.65	0.04919	9,046.9	87.19	89.00	$8.55	-$7.64	$0.009	-$0.108	-$0.091	-$0.191
6.00	101.98	0.05884	9,076.2	86.81	89.00	$10.26	-$9.17	$0.011	-$0.130	-$0.109	-$0.228
7.00	102.31	0.06842	9,105.6	86.43	89.00	$11.97	-$10.69	$0.012	-$0.151	-$0.127	-$0.265
8.00	102.64	0.07794	9,135.0	86.04	89.00	$13.68	-$12.22	$0.014	-$0.172	-$0.144	-$0.302
9.00	102.97	0.08740	9,164.3	85.65	89.00	$15.39	-$13.75	$0.016	-$0.193	-$0.162	-$0.339
10.00	103.30	0.09681	9,193.7	85.25	89.00	$17.10	-$15.28	$0.018	-$0.213	-$0.179	-$0.375
11.00	103.63	0.10615	9,223.1	84.84	89.00	$18.81	-$16.80	$0.019	-$0.234	-$0.196	-$0.411
12.00	103.96	0.11543	9,252.4	84.43	89.00	$20.52	-$18.33	$0.021	-$0.255	-$0.214	-$0.447
13.00	104.29	0.12465	9,281.8	84.02	89.00	$22.23	-$19.86	$0.023	-$0.275	-$0.231	-$0.483
14.00	104.62	0.13382	9,311.2	83.59	89.00	$23.94	-$21.39	$0.024	-$0.295	-$0.248	-$0.518
15.00	104.95	0.14293	9,340.6	83.16	89.00	$25.65	-$22.91	$0.026	-$0.315	-$0.264	-$0.554
16.00	105.28	0.15198	9,369.9	82.73	89.00	$27.36	-$24.44	$0.028	-$0.335	-$0.281	-$0.589
17.00	105.61	0.16097	9,399.3	82.29	89.00	$29.07	-$25.97	$0.029	-$0.355	-$0.298	-$0.623
18.00	105.94	0.16991	9,428.7	81.84	89.00	$30.78	-$27.50	$0.031	-$0.375	-$0.314	-$0.658
19.00	106.27	0.17879	9,458.0	81.38	89.00	$32.49	-$29.02	$0.033	-$0.394	-$0.331	-$0.692
20.00	106.60	0.18762	9,487.4	80.92	89.00	$34.20	-$30.55	$0.034	-$0.414	-$0.347	-$0.727

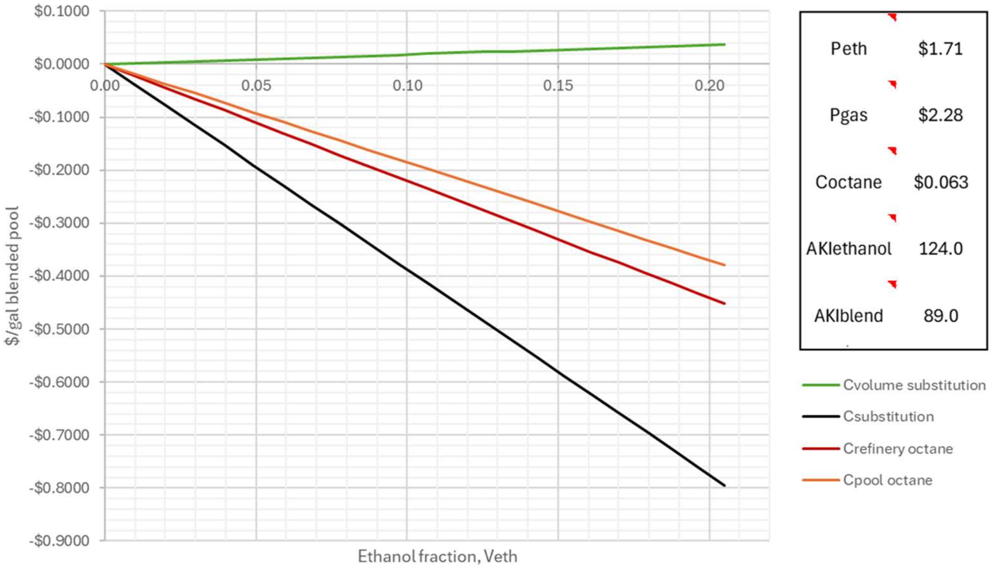

Figure 8 Cost of volume substitution (green), and total cost of substitution (black) for energy-equivalent gasoline pools. The negative cost of octane substitution is split between a lower cost for refinery octane production (red) and a credit for the additional octane-gallons retained in the pool (orange).

The blended pool octane is now constant and the refinery gasoline octane is going down as ethanol is added. The credit for octane substitution is the same as before, but it is now split between a credit for a lower refinery octane-gallon production cost ($C_{refinery\ octane}$), and a credit for the remaining extra octane-gallons retained in the pool ($C_{pool\ octane}$). This is how the extra octane contribution of ethanol has been realized historically. There is no difference in the overall cost impact. The only difference is how the value of the extra ethanol octane-gallons is realized and distributed between the refinery and the pool.

Result 9: The value of ethanol's octane contribution can be realized in different ways. One way is to reduce refinery octane production to capture part of the value in the form of lower refining cost, which is how it has been done historically in commercial practice. That does not change the total cost of substitution, only how it is captured, realized and distributed between the refinery and the pool.

4. CONCLUSIONS

1. Refinery octane production constraints have increased gasoline production costs and prices in the U.S. This has contributed to the persistent increase in the retail value of octane to 15 ¢/AKI-gal.
2. Best-available industry data implies the blending octane value of ethanol is 124 AKI-gal/gal, which, at an ethanol cost of $1.71/gal, implies the cost of ethanol octane is 1.4 ¢/AKI-gal in 2025 dollars.
3. Best-available industry data implies the cost of refinery octane is 6.3 ¢/AKI-gal in 2025 dollars.
4. The estimated cost of refinery octane is 4.5 times higher than that of ethanol octane, which implies a large economic incentive to increase the ethanol content of gasoline.
5. When ethanol is substituted for refinery gasoline at an energy-equivalent ratio of 1-to-0.67 gal/gal, the volume and octane content of the blended pool increase. The cost of substitution consists of two components — the cost of volume substitution, which depends on the relative prices of ethanol and refinery gasoline, and the cost of octane substitution which depends on their relative blending octane values.
6. For today's E10 gasoline, the (negative) cost of octane substitution far outweighs the (positive) cost of volume substitution, that is to say, the value of the higher octane of ethanol far outweighs its higher energy-equivalent cost. The energy-equivalent substitution to a level of 10 volume% ethanol (E10) implies that ethanol is adding a net of 39 cents/gal worth of octane to the U.S. E10 gasoline pool. To say this another way, if ethanol was removed from the U.S. gasoline pool, replacing its current octane contribution with refinery octane would increase refining cost and the wholesale cost of gasoline by 39 cents per gallon or $54 billion/year.
7. The value of ethanol's octane contribution can be realized in different ways. One way is to reduce refinery octane production to capture part of the value in the form

of lower refining cost. That does not change the total cost of substitution, only how it is captured, realized and distributed between the refinery and the pool.

5. FUTURE WORK

Recommended next steps in future work would be to quantify:

1. How the cost of substitution has varied over time
2. How the cost of substitution varies with changes in the variables that determine it
3. How increased fuel ethanol demand affects the ethanol price
4. How decreased refinery gasoline demand affects refinery gasoline price
5. The ethanol blend level that would minimize the total cost of octane supply
6. The optimal distribution of octane value between reduced refining cost and increased market value

These next steps are beyond the scope of the currently commissioned study.

George Hoekstra

George Hoekstra

Hoekstra Trading LLC

6. REFERENCES

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