Ethanol in Gasoline, a Technical Perspective

2015 version 1.1

There seems to be a universal hatred for the use of ethanol in gasoline on this board. In my opinion, a little ethanol in gasoline is not a bad thing. If you're not interested in 15,000 words on why, but just want your bike to run better, skip ahead to the last page. I plan to steer clear of the political and environmental aspects of ethanol and focus on the technical ones (although economics will undoubtedly enter the picture). My thinking is that since E10 ***is*** gasoline where I live (Midwest US) and its ethanol content is already subsidized, I may as well make the best of it.

Back in the early days of aviation, when the maximum compression ratio on gasoline was around 5:1, ethanol was recognized as a "superior" fuel because it allowed a compression ratio of 7:1. But it was comparatively expensive and required a much greater volume to do the same work (in other words, the miles per gallon was poor). Long before the idea of octane rating was even conceived, ethanol was know to inhibit engine "knock". Today we assign pure ethanol an octane number of 98 based on the (R+M)/2 method (which is the method by which pump gas is labeled). However, its Blending Octane Number is much higher. When ethanol is added to gasoline, the resulting octane rating of the blend is more than a straight linear blending equation would predict. This makes ethanol a very effective octane booster and – in my opinion – makes a compelling argument for its inclusion in gasoline.

Probably the best layman's description I've heard for gasoline is that it's a "chemical soup". Pure gasoline (without ethanol) is a mixture of hundreds of different hydrocarbon compounds. Hydrocarbons contain hydrogen and carbon atoms in different quantities and arrangements. They can vary from quite light with 4 carbon atoms to fairly heavy with 12 carbon atoms. As an example of a light hydrocarbon molecule, the gas butane (which is commonly added to gasoline in the winter months) has a chemical formula of C_4H_{10}. For thermochemical calculations, a useful approximation of gasoline as a single hydrocarbon compound is C_8H_{15}.

In contrast, pure ethanol, which is an alcohol (and exactly the same stuff you drink) is a single substance. It's also made up of hydrogen and carbon (so it's a fuel), but contains oxygen too (this is the reason it is referred to as an "oxygenate" when added to gasoline). Its chemical formula is usually written as C_2H_5OH. Ethanol is not the only oxygenate to have been used in gasoline. Over the years, ethers like TAME (C_6H_8O), MTBE ($C_5H_{12}O$), and ETBE ($C_5H_{12}O$) have also been used.

A quick digression about beverage alcohol versus motor fuel. A motor fuel must be "denatured" (rendered unfit for human consumption) before leaving the manufacturer. Denaturing is accomplished by adding a small amount (maybe 1 - 2%) of gasoline to the ethanol before it leaves the ethanol plant. This is entirely a tax thing as beverage alcohol is taxed at a higher rate than motor fuel.

Another alcohol you may recognize is methanol (aka wood alcohol) – chemical formula CH_3OH. This fuel has long been used in racing. It is famous for its intake-charge cooling effect (due to a high latent heat of evaporation). Engines drinking methanol can run comparatively-high compression ratios. I said "drinking" because it's also famous for high fuel consumption – more than twice that of gasoline.

Hydrogen and carbon are the two elements most commonly used as fuels. Sulfur could be used as a fuel too, but its drawbacks far outweigh any benefits. In fact, chemical engineers go to great lengths to exclude sulfur from hydrocarbon fuels because of the corrosion damage it can do.

When hydrogen and/or carbon combine with oxygen from the atmosphere an exothermic (heat-releasing) chemical reaction occurs. The reaction is said to be stoichiometric (from the Greek meaning "first principle measure") when all the fuel and all the oxidizer combine completely. You can think of it as the ratio at which the hydrogen, carbon, and oxygen atoms all find dance partners. Ideally, only water vapor (H_2O) and carbon dioxide (CO_2) are released. None of the original fuel or oxidizer remains unreacted. By the way, this never actually happens inside a real engine. In a gasoline engine as much as 1% of the oxygen never gets to combine with fuel no matter how rich you make the mixture. Air is about one-quarter (23.2%) oxygen by mass. So something like 4% of the air inducted can go unreacted – but stoichiometry is a nice expedient.

The stoichiometric air-fuel ratio (AFR) is about 14.6:1 by mass for gasoline. I say ***about*** because it depends on the exact hydrocarbons present in the gasoline. In other words, 14.6 pounds (or grams, or any mass unit you like) of air is consumed per unit mass of fuel. Whereas for ethanol, the ratio is 9.0:1, exactly. Remember, ethanol is a single substance rather than a chemical soup. An important point to note is that, generally speaking, the smaller the AFR number, the "thirstier" the engine will be when run on that fuel – the lower the miles per gallon it will get.

It is also important to note that a stoichiometric mixture is often discussed solely because it's chemically easy to analyze. (It is also the only mixture ratio where a 3-way catalytic converter can clean up exhaust emissions, and this is the real reason it's used in the automotive world.) Maximum torque is always produced on the rich side of stoichiometric (a smaller AFR number). People usually want to see a number they can relate to, like 12.5:1. I prefer to stay away from that and just say "richer" because the exact AFR for maximum torque varies according to a lot of factors – not the least of which is ***how*** it's measured. Similarly, the best fuel economy is found on the lean side of stoichiometric because that's were the highest thermal efficiency occurs. (You get the biggest push on the piston per unit of fuel burned.)

You may question my use of the word "torque" throughout this writeup. If you are uncomfortable with that, replace it with horsepower. I started out by writing horsepower (which seems to be more readily understood), but it is also one step farther removed from what is actually changing. Power is the time-rate application of torque. Power equals torque times RPM (with the appropriate constant employed, depending on the units used).

The torque produced by an engine is determined by a complex array of factors, but the single most important one is how much air it can ingest (and retain). The more air in the cylinder, the more fuel that can be burned, which releases more heat, which causes more pressure, which yields a greater push on the piston.

An oxygen-bearing fuel (like ethanol) can be thought of as a "chemical supercharger". That is, the fuel itself brings some oxygen to augment the oxygen in the air. The most dramatic example of this concept is the use of nitromethane (chemical formula CH_3NO_2) in top fuel dragsters. The stoichiometric AFR for nitromethane is 1.7:1. Talk about poor MPG!

Speaking of chemical superchargers, another example of such is nitrous oxide (N_2O). Returning to the world of piston-engine aircraft (incidentally, this is where all the really good pioneering research on internal combustion engines occurred – automotive and motorsports applications were just trickle-down applications) where attempts were made to introduce pure oxygen into the intake plumbing. The result was extremely high combustion temperatures that quickly melted pistons and valves. It turns out that all that “inert” nitrogen in the air is necessary. Although the nitrogen plays no part in the combustion reaction (other than forming some oxides of nitrogen at very high temperatures), it does add mass to the “working fluid” inside the cylinder. This mass gets heated along with the combustion products. Its expansion pushes on the piston while helping maintain a reasonable temperature. Thus, with nitrous oxide there are two atoms of temperature-moderating nitrogen “along for the ride” with each atom of oxygen.

The chemical combination of (and equation for) fuel and oxidizer is by mass, but liquid fuels are sold by volume. So, just knowing the stoichiometric ratio is insufficient to calculate fuel consumption. Before I get into the the arithmetic, note two things:

1. Air-fuel ratio is typically a “gravimetric” (based on weight) measurement, but it is equally valid to talk about it in volumetric terms. In fact, this will make comparisons of different fuels easier to follow.

2. The reciprocal of air-fuel ratio (AFR) is fuel-air ratio (FAR). If the air-fuel ratio is 10:1, the fuel-air ratio is 0.1:1 (0.1 unit of fuel per unit of air).

In order to see how much fuel gets burned, we need to do a **fuel** volumetric analysis. For that, we need to know the density (aka specific gravity) of the fuel. This is easy to determine for a pure substance like ethanol (0.79) or nitromethane (1.139). The specific gravity of gasoline is a little more variable (remember it's a chemical soup), but 0.74 is a reasonable value. See the table below.

Fuel	Gravimetric AFR	Specific Gravity	Fuel Volume AFR	Fuel Volume FAR
Gasoline	14.6	0.74	10.8	0.093
Ethanol	9.0	0.79	7.11	0.140
Nitromethane	1.7	1.139	1.93	0.518

Let's assume the same mass of air is inducted for each of these three fuels (that's not exactly true because a fuel's latent heat of vaporization plays a part in determining the density of the air the engine inducts).

For every gallon of air gulped by an engine, it needs to burn 0.093 gallons of gasoline for a stoichiometric reaction. For ethanol, that number is 0.14 gallons. In other words, you need to burn 1.5 times (0.14 / 0.093 = 1.5) the volume of ethanol compared with pure (non-oxygenated collector car) gasoline to get a stoichiometric mixture.

But how much heat is released when you burn a stoichiometric mixture of these fuels? Up to now, I have tried to use familiar units, like gallons. But the scientific literature deals exclusively with metric units. I'm not going to convert clean metric units into old-fashioned Imperial units, especially since, in the end, I'll express everything as dimensionless ratios.

There are two measures of the amount of heat released by burning a fuel. One is called the higher heating value (HHV) and the other is called the lower heating value (LHV). Often they are called higher and lower calorific values. When comparing fuels for internal combustion engines, the LHV is always used (for reasons too deep to get bogged down in now). See footnote [1].

This brings up an important difference between ethanol and gasoline. You need to burn more of it to get the same amount of heat (and remember, heat is what drives the gas expansion that pushes the piston). Alcohols have a lower heating value than pure hydrocarbons because some of the combustible material has combined with oxygen in the molecule itself. Thus it is not available for producing heat when combined with air. Below is a table of volumetric energy content.

Fuel	Volumetric energy content (megajoules per liter)
Gasoline	31.82
Ethanol	21.29
Nitromethane	12.44

As you can see, ethanol has only about 2/3 the heating value of gasoline. Taken on its own, this should yield about 2/3 the fuel economy. That is, if you get 30 MPG on gasoline, you would get 20 MPG on pure ethanol. But there are some possible offsetting properties of ethanol that can improve the picture somewhat. These properties are exploited in vehicles designed to run on E85. The properties are: Greater latent heat of vaporization (which increases the density of the intake charge), higher octane rating (which permits the use of a higher compression ratio), and a greater ratio of products to reactants (which yields a bigger push on the piston for the same amount of heat release).

So far I've only considered published heating values, but pump gasoline typically contains varying amounts of ethanol. It's possible to numerically ratio certain properties of each component in a blended fuel. Let's consider a fuel comprising 90% gasoline and 10% ethanol (we call it E10). The volumetric energy content number looks like this:

(0.9 * 31.82) + (0.1 * 21.29) = 30.76 megajoules per liter

Recall that the energy content of collector car gas is about 31.82 MJ per liter. The ratio 30.76 over 31.82 equals 0.967. That means there's roughly 3% less energy content in E10 per unit volume of fuel than in collector car gasoline. If all other factors are the same, this should yield about a 3% decrease in fuel economy for E10 versus “non-oxy” collector car gasoline.

But high-performance enthusiasts rarely list fuel economy as their top priority. A more important question is: How much torque can be produced per unit mass of air? (Remember, air is the limiting factor because we can dump in as much fuel as we desire.) For that, we need to know the fuel's “specific energy” (heat released per unit mass of air). Those numbers look like this.

Fuel	Specific Energy (megajoules per kilogram of air)
Gasoline	2.92
Ethanol	3.00
Nitromethane	6.42

Surprisingly, pure ethanol is nearly 3% (3.00 / 2.92 = 1.027) better than pure gasoline. Without taking into consideration any of ethanol’s other desirable properties, this would equate to about 3% more torque. You can also see that, in theory, nitromethane has the potential to develop over twice (6.42 /

2.92 = 2.2) the torque of gasoline (however nitromethane is never used at 100% concentration).

Economics

Now I want to say a little about the economics of various motor fuels. Below is a table calculated from the energy content and cost per gallon of each fuel. I normalized each in terms of 87-octane E10 pump gas having a cost of 1. The price snapshot was taken on a single date and in the same geographic area. The numbers and rankings undoubtedly can change due to a variety of factors. For example, the energy content of E85 varies by season because the volume of gasoline in it varies. By law, the minimum ethanol content is 70% in winter, 74% in fall/spring, and 79% in summer. Race gas is fairly slow to reflect changes in market conditions. Diesel pricing is influenced by season as it's chemically similar to home heating oil. Even the energy content of pump gasoline varies by season. In the end, the cost of a fuel is partly dictated by market forces (demand, competition, etc.) and partly by its cost of production (high-octane gasoline is more expensive to refine than low-octane gasoline). (And partly by government involvement, i.e., subsidies and taxes.) See table below.

Fuel	Octane Number	Price Multiple Per Energy Unit
E10 (regular)	87	1
E85 (assume 20% gasoline)	92-96	1.02
Diesel	(very low)	1.07
E10 (premium)	92	1.16
“Collector Car” Gas	93	1.25
100LL AvGas	~100	1.83
Sunoco Race	110	3.04

In case the table is not perfectly clear, here's a bit more explanation. If you fill a vehicle with premium pump gas (92 octane) it will cost about 16% more money for the same amount of energy provided by the 87-octane pump gas. But remember, these ratios can't be directly compared on a cost per mile basis because of the higher thermal efficiency ***possible*** with a higher-octane fuel. I say possible, because without a higher compression ratio (or more boost in a supercharged application), the higher octane fuel provides no benefit. (A higher compression ratio is one of the reasons diesel vehicles yield more miles per gallon.)

It's also interesting to consider the overall economics of the fuel/vehicle interaction from the perspective of miles per gallon. Such studies are usually called “wellhead to wheels”. Simply put, if it costs a factor of 2x to refine a fuel that gives 5% better MPG, that's not a tenable economic tradeoff.

Corrective Action

If you've read this far, you may be asking: How do I make use of any of this information? For me, the ease of obtaining E10 and the favorable cost make the question: How do I best tune for E10? All of my bikes (except TZ250) are tuned to run well on E10. Street bikes run on 87-octane and off-road bikes run on 92. Because fuels blended with ethanol cause an "enleaning effect", you need to install richer jetting (or EFI settings with something like a Dynojet Power Commander) for optimal performance.

Back in the 1970s when "gasohol" (10% ethanol) was introduced, the enleanment effect made some vehicles run better and some run worse. If the vehicle's carburation was already lean, this exacerbated the situation. If, on the other hand it was running rich, the oxygenated fuel actually yielded a performance benefit. (BTW, I have used collector car gas in place of E10 just to determine if richer jetting would be beneficial or not.)

As far as jetting/fueling goes, the gravimetric analysis looks like this:

$(0.9 * 14.6) + (0.1 * 9.0) = 14.0$ Thus, the stoichiometric mass AFR for E10 is about 14.0:1

and $14.0 / 14.6 = 0.96$ (about 4% leaner)

The fuel volume analysis ends up being about 3.5% leaner. In very general terms, main jets are produced in step sizes ***about*** 3% apart. But this varies by size and type of jet. Most people just want to know that they need to go "slightly richer" for E10 than non-oxy. This applies not only to the main jet, but also to the clip/needle, and pilot jet/mixture screw.

Footnote

1. The decision whether to use a fuel's LHV or HHV for calculations is based, partly, on what happens to the water produced from the combustion of the hydrogen. If the water remains as steam, it cannot release its heat of vaporization, thus producing the LHV. If the water is condensed back to the original temperature of the fuel, the HHV is obtained. With internal combustion engines, the LHV is used as the water is emitted as a vapor. However, many would argue that just because IC engines don't make use of the heat of vaporization of water, they should not be given a "free ride" when comparing energy efficiency across a variety of technologies. In this case, using the HHV levels the playing field.