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Production and Use of Fuel Ethanol from Corn or Wheat

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A bill enacted by the 1977 session of the Minnesota State Legislature asked the University of Minnesota to study the feasibility of blending grain alcohol (ethanol) with diesel oil and gasoline and using the blends as a motor fuel. Two projects were undertaken: an engineering study on the use of ethanol-diesel oil blends in diesel engines and an economic study of commercial alcohol production and use of blended fuels. A summary of the results is given here.

Production of Ethanol from Starch Grains

The production of ethanol, or grain alcohol, proceeds through four distinct steps, shown in Figure 1. While each ethanol production plant may use different equipment or different processes, they all go through these four steps.

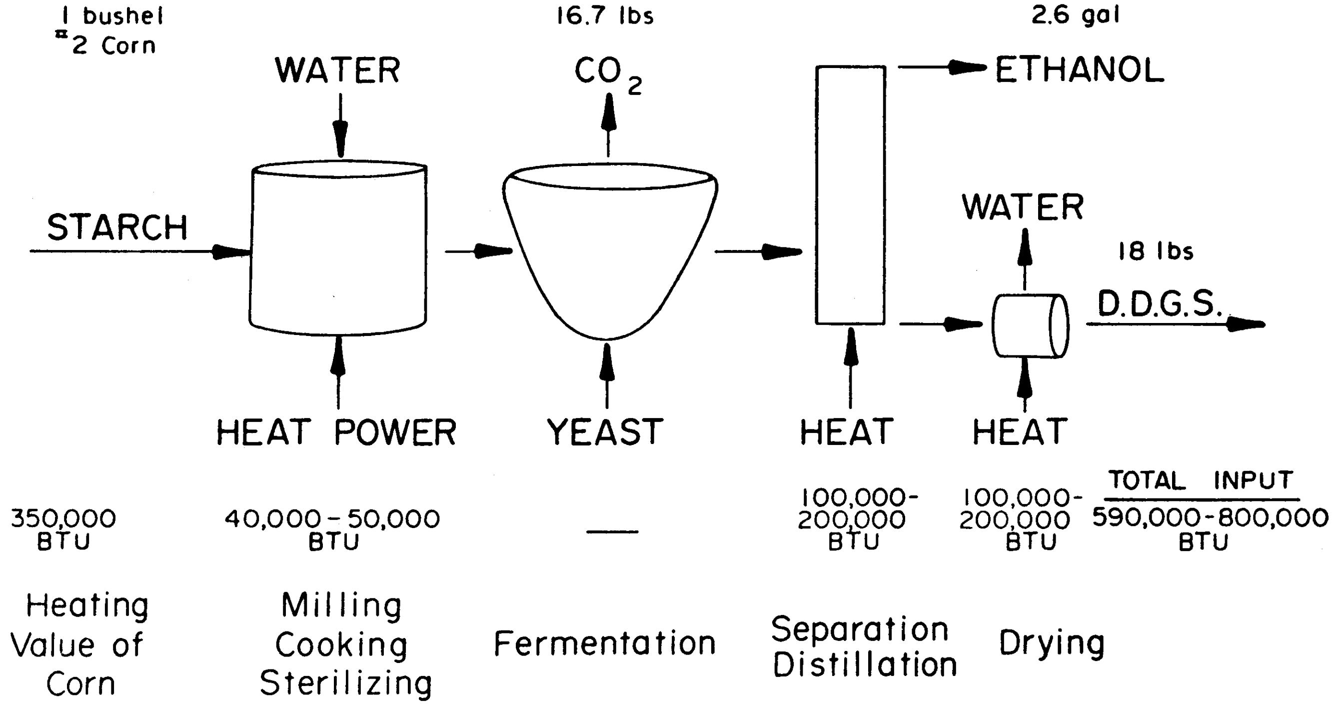
The first step is to convert the starch in the grains into sugar. This is done by milling the grain, diluting it with water, heating this mash, and adding the enzyme amylase, which is obtained from malted barley or produced by a special fungus. If the feedstock is sugar beets or molasses or some other sugar source, this step can be eliminated and the mash fermented directly.

The second step is the actual fermentation. Special yeasts are added to the mash. These yeasts convert the sugar into alcohol and carbon dioxide. The alcohol is diluted with a considerable amount of water at this point, and it must be separated from the water. Separation is usually accomplished by distilling the alcohol-water mixture. The product alcohol comes out of one part of the still and the unfermented portion of the mash plus the water comes out of another part of the still. When corn is used as a feedstock, all of the protein originally in the corn ends up in the unfermented portion of the mash, and about one-third of the energy originally in the corn ends up in this unfermented portion. The rest of the energy that was in the corn is now in the alcohol. The unfermented grains usually are dried to a safe storage moisture content and sold as distiller's dried grains plus solubles (DDGS).

Figure 1 also shows the energy and material inputs and outputs at each step of the process. The process energy inputs are primarily in the form of steam and electrical power. The actual energy inputs will depend on the process design and equipment selection and will fall somewhere in the ranges indicated. The overall inputs to the process could range from 590,000 Btu per bushel of corn to 800,000 Btu per bushel of corn. The energy outputs from the process are 210,000 Btu per bushel of the heating value of the ethanol and 135,000 Btu per bushel for the feeding value of the DDGS, for a total output of 345,000 Btu/bushel.

These figures are representative of a well-designed, commercial-scale factory processing more than 1,000,000 bushels of corn a year. Smaller factories will require more energy at each stage, but they may be able to eliminate the drying stage if the unfermented portion of the mash is fed wet to livestock on a continuous basis.

Figure 1. Production of ethanol from corn.



Cost of Producing Ethanol from Grain

The cost of producing ethanol was estimated for two plant sizes with annual capacities of 17 million and 34 million gallons of alcohol. These plants process 20,000 and 40,000 bushels of corn per day, respectively. Economies of size were found to exist because ownership costs and operating costs per gallon of capacity both decreased as plant size was increased.

Initial investment costs are $24,275,000 for the 17 million gallon plant and $37,990,000 for the 34 million gallon plant. The estimated annual ownership costs of depreciation, interest, insurance and real estate taxes are $.145 per gallon for the 17 and 34 million gallon plants, respectively. Operating costs include corn, electricity, fuel oil and other costs.

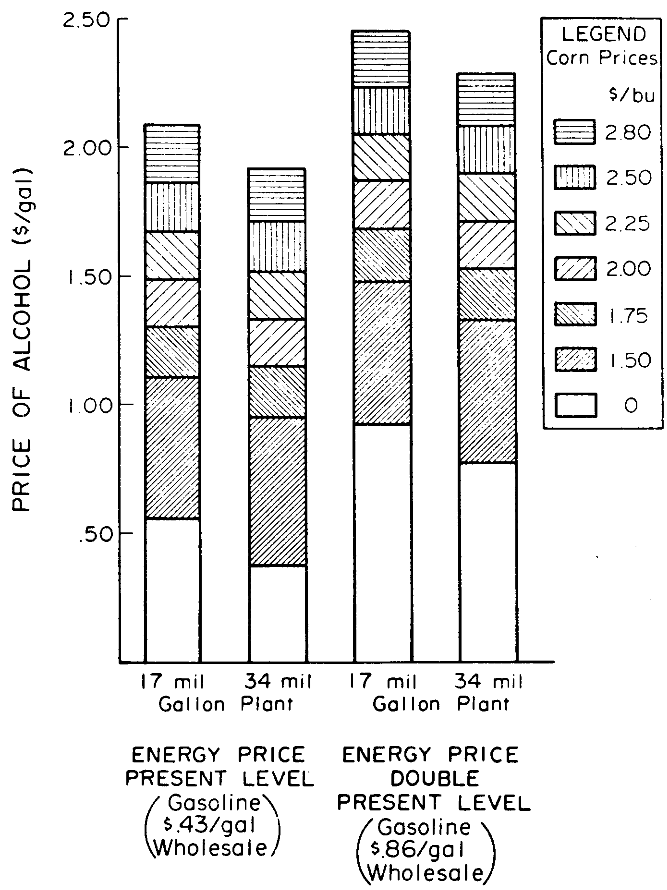
A credit was allowed for the value of the distiller's dried grains and solubles (DDGS) produced as a by-product of the operation. The resultant costs of alcohol are base costs; no profit margin or distribution costs are included.

Since fuel enters into the cost of producing alcohol, the cost of alcohol depends partly on fuel prices. In this analysis 1977-78 energy prices were used. The analysis also was done for a doubling of these energy prices. The graph in Figure 2 illustrates the cost of producing alcohol for both 17 and 34 million gallon plants at present energy prices and at prices doubled from present levels.

The cost of corn ranges from 0 to $2.80, and the price of DDGS is set at $100 per ton. If the corn price increases beyond $2.80 per bushel, the price of DDGS and thus the by-product feed credit relates to the price of corn on a pound-for-pound basis. The cost of alcohol will continue to rise at these higher corn prices as the increased cost of corn outweighs the increased feed credit since a bushel of corn yields only 18 pounds of DDGS.

This graph illustrates two points. First, alcohol produced in the larger plant costs less than alcohol produced in the smaller plant. Second, the cost of producing alcohol increases as energy prices increase.

Figure 2. Cost of ethanol with varying plant size, energy costs and corn prices.



Use of Gasohol as a Spark-Ignition Motor Fuel

The use of a 10 percent ethanol, 90 percent gasoline motor fuel mixture has been researched extensively. Blends with higher alcohol contents also have been tested. Following is a summary of the use of gasohol blends.

Advantages

- The addition of ethanol to very low octane fuels generally has the effect of increasing the octane number, which in turn reduces engine knock. The blending of ethanol with higher octane fuels does not appreciably raise the octane number of these fuels.
- Engines with generally rich carburetor settings have lower hydrocarbon and carbon monoxide emissions with a gasohol fuel blend. Engines with lean carburetor settings have no change in hydrocarbon and carbon monoxide emissions with the gasohol blend. Any reduction in emissions is not, however, enough to warrant eliminating pollution control equipment.

Disadvantages

- Nearly all mileage tests comparing gasohol and unleaded gasoline, including tests of the Environmental Protection Agency (EPA), indicate a mileage decrease of three to seven percent. Some tests show that under certain conditions mileage may be the same, but no carefully controlled tests indicate a mileage increase. This is to be expected since a gallon of gasohol contains less energy than a gallon of gasoline.
- Engines with lean carburetor settings have increased nitrogen oxide emissions. In many cases this increase is enough to put the engine out of compliance with EPA emission regulations.
- Increases in cylinder wall and piston ring wear have been noticed on engines fueled with gasohol.
- Evaporative hydrocarbon emissions from engine carburetors are more than doubled.
- The ethanol-gasoline blend must be kept relatively water-free or else phase separation will occur. The problems are not quite as severe as they are with alcohol-diesel oil blends, but special care must be used in storing and using the blend to keep it as water-free as possible. The problems become more severe as temperatures drop.

Use of Dieselhol as a Diesel Engine Fuel

A diesel engine in a farm tractor could be fueled with ethyl alcohol in one of the following ways:

- Alcohol simply could be substituted for the diesel oil normally used. This method would require major design changes in new engines and fuel systems to assure proper ignition of the alcohol and lubrication of the injection system.
- The alcohol could be introduced into the intake air to supply a certain proportion of the fuel required per cycle, with the remainder of the fuel being diesel oil injected by the normal injection system. The injected diesel oil would assure reliable ignition of the charge. This method is commonly called "fumigation."
- Premix diesel oil and alcohol before it goes into the tractor engine fuel system.

Much research has been done and reported on "fumigation" using both ethyl and methyl alcohol and also LP gas. Premixing alcohol with diesel oil for use in a diesel engine presents some significant engineering problems, and very little research on this has been reported. Engineering studies were conducted on a premixed fuel blend of #1 diesel oil and ethanol in varying proportions. The research was done with farm tractor engines not modified or adjusted to compensate for alcohol in the fuel.

Influence of Water on Blend Stability

Introducing small quantities of water to an alcohol-diesel oil blend can cause phase separation. The initial blend of diesel fuel alcohol where water is added separates into two distinct layers: (1) alcohol and water with trace amounts of fuel and (2) fuel with trace amounts of alcohol and water.

The separation temperature is the temperature above which a given blend of fuel alcohol water will remain mixed and below which it will separate into two layers. Thus, for a given temperature the water content of the blend must be below a certain value for the blend to remain stable. Alternately, for a given water content the temperature must remain above separation temperature for the blend to remain stable. For each blend ratio the separation temperature was determined for a given water content.

Figure 3 shows that the amount of water that can be tolerated in the blend increases as the alcohol content of the blend increased. The data also shows that as the temperature of a given blend decreases, the quantity of water to cause separation decreases.

To insure blend stability throughout the temperature range encountered by tractors in the cropping season (above 40°F), a blend of #1 diesel oil and ethanol should not have a water content exceeding about 0.05 percent by volume. This would include water from any source, such as residual water from the alcohol, water contamination from shipping or handling, and condensation in storage tanks. On a practical basis absolute alcohol would be required for any blended fuel consisting of #1 diesel oil and ethanol premixed.

Horsepower and Fuel Consumption Tests

Horsepower and fuel consumption tests were run on a 1962 Ford diesel tractor engine and on a 1978 John Deere diesel. The Ford engine was tested at a rated speed of 1,800 rpm. The John Deere diesel engine was tested at 2,000 rpm. The engines were not modified or adjusted in any way to attempt to compensate for the ethanol present in the blended fuels. The

Figure 3. Maximum quantity of water that can be added to blends of diesel oil-ethanol without separation.

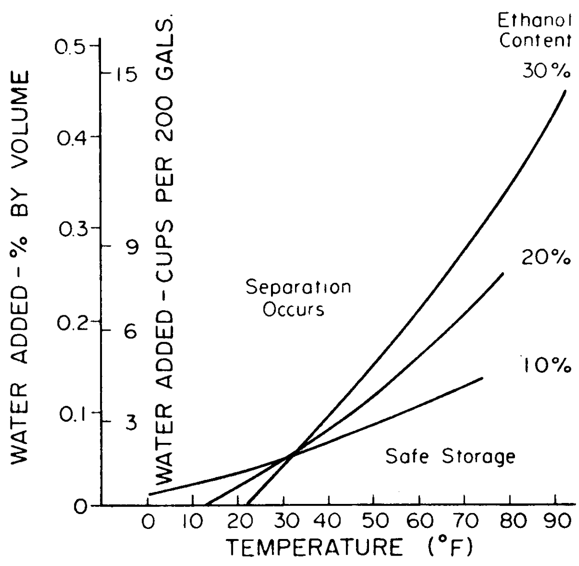


Figure 4. Maximum brake horsepower output of test engines.

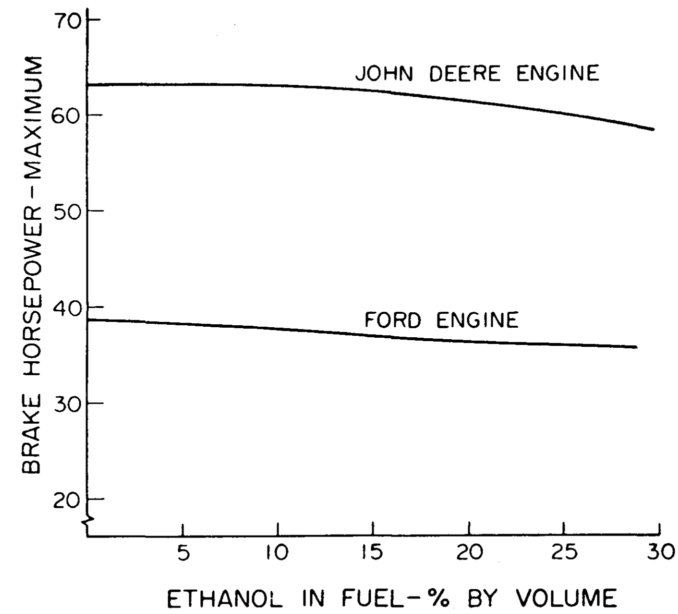
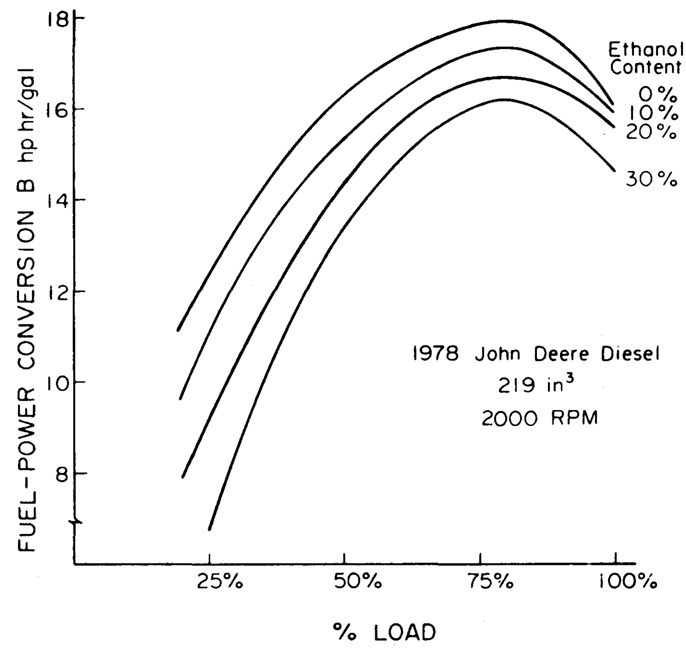


Figure 5. Fuel power conversion for John Deere test engine.



maximum brake horsepower output of the two engines is shown in Figure 4.

As the alcohol content of the fuel increases, maximum horsepower decreases slightly. A 30 percent ethanol content resulted in a decrease of about 8 percent of maximum horsepower produced with diesel oil for each engine. Some of this reduction probably could have been avoided by adjusting the fuel delivery system on the engines.

The two main factors that limit output as the ethanol content of the fuel increases are the lesser quantity of heat units injected per cycle because of the lower heating value of ethanol, and the relatively poor combustion properties of ethanol in the diesel engine. Combustion studies on the Ford engine showed that increased ethanol content resulted in longer delays between the time fuel is injected and the time it starts to burn. Also the delay time increased as the load decreased.

When a mixture of diesel oil and ethanol is considered as a replacement fuel for diesel oil in the farm tractor, fuel consumption expressed as horsepower-hours per gallon of fuel is of great practical importance. Tractor fuel is bought and handled on a gallon or volume basis. Brake horsepower-hours per gallon indicate the quantity of useful work that the engine will perform for each gallon of fuel consumed.

All the test results indicate that engines will produce less useful work under similar conditions when fueled with diesel oil-ethanol blend compared to their performance with diesel oil. The performance of diesel oil-ethanol blends compares less favorably with diesel oil as the percentage of ethanol in the blend increases or the load on the engine decreases. This is shown graphically in Figure 5.

Although noise levels were not measured, when the engines were operated on fuel containing ethanol, noise levels were perceptively greater than when the engines were operated on diesel oil. With an ethanol content of 30 percent in the fuel, both engines were extremely noisy. Diesel knock associated with long ignition delay times was noticeable with a 10 percent ethanol blend.

Leakage at various fittings in the fuel system and past the injector plungers increased when fuels with a higher ethanol content were used. This could be due to the blends having a lower viscosity or less effective lubrication qualities with accompanying wear or to the effects of alcohol on 0-rings and seals.

Other studies found that alcohol carbureted into the intake air slightly increases cylinder-piston ring wear. Based on this information and the lower viscosity and lesser lubricity of diesel oil-alcohol blends compared to diesel oil, it seems likely that the fuel injection system and the cylinder wear surfaces would be subjected to increased wear if ethanol were premixed with diesel oil and used to fuel a tractor engine. The tests, however, provided no quantitative wear measurements.

Field Demonstration

The objective of the field demonstration phase of the project was to determine and demonstrate the feasibility of using a mixture of diesel oil and ethanol to fuel a diesel-powered farm tractor. The fuel was to be premixed before it was placed in the fuel tank of an unmodified tractor. The field demonstration took place at the University's North Central Experiment Station at Grand Rapids.

The study was basically a comparison of the fuel consumption and operating characteristics of two nearly identical diesel tractors performing a variety of typical farm operations. One tractor was operated on a mixture of 90 percent diesel oil and 10 percent absolute ethanol and the other on diesel oil. The tractors used in the test were Ford 7600 diesel tractors, both rated at 84 horsepower.

In almost every case, fuel consumption of the tractor with the mixture exceeded that of the tractor with the diesel oil alone. In most cases, the difference exceeded 10 percent. These results are consistent with the lab test results.

The Economics of Grain Ethanol-Gasoline and Ethanol-Diesel Oil Blends

Relative Costs of the Fuel Blends

In the following analysis gasoline and diesel oil are considered to be blended with grain ethanol. Gasoline and diesel oil are both considered to be blended with grain alcohol in a 9:1 ratio to make gasohol and dieselhol, respectively. This ratio implies that one-tenth gallon of alcohol (and one-tenth the cost of a gallon of alcohol) replaces one-tenth gallon of gasoline or diesel oil (and one-tenth the cost of a gallon of gasoline or diesel fuel) in the fuel blends. The cost of the fuel blend can be calculated according to these ratios.

Other studies have shown fuel consumption at best to be the same for gasohol as for gasoline. Therefore, the cost of gasohol is calculated as described above. Fuel consumption with dieselhol has been shown to be higher than with diesel oil. The fuel power conversion (hp-hr/gal) decreases with decreasing load as shown in Figure 5 for a 10 percent blend. To reconcile this variability, an average consumption increase of 4.6 percent was used. That is, an average 1.046 gallon of dieselhol is needed to do the work of one gallon of diesel fuel.

The costs of gasohol and dieselhol are shown in Figures 6 and 7, respectively. In both figures the cost of the straight fuel and the cost of corn vary, and the price of DDGS is held constant at $100 per ton. Underlying these graphs is the assumption that the cost of all energy used in production of ethanol increases proportionately.

In both Figures 6 and 7, the cost of the fuel blend is higher than the cost of the straight fuel. If the wholesale cost of gasoline is $.43 per gallon, gasohol costs $.06 more when corn is $1.75 per bushel and $.10 more when corn is $2.80 per bushel. When the price of gasoline rises to $.86 per gallon, the difference between the cost of gasoline and gasohol remains the same.

If diesel fuel is $.53 per gallon, 1.046 gallon of diesel fuel must be purchased. Thus 1.046 gallon costs $.08 more than the price of diesel fuel when corn is $1.75 per bushel and $.12 more when corn is $2.80 per bushel. When the diesel fuel price increases to $1.06 per gallon, these differences are the same.

In fact, the cost of the fuel blend lies above the equal cost line at all points; points further from the equal cost line correspond to higher corn prices. This analysis implies that the cost of the fuel blends in the range of corn and DDGS prices considered is always higher than the cost of the straight fuels, regardless of the price of energy.

Figure 6. Cost of gasohol for varying prices of gasoline and corn.

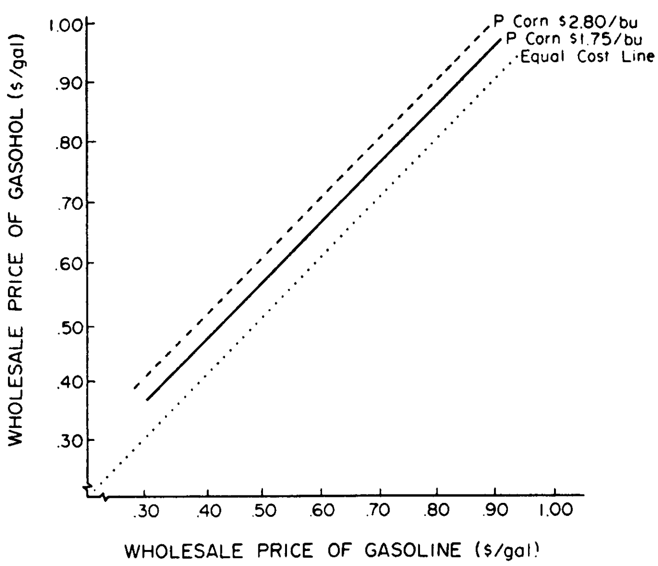
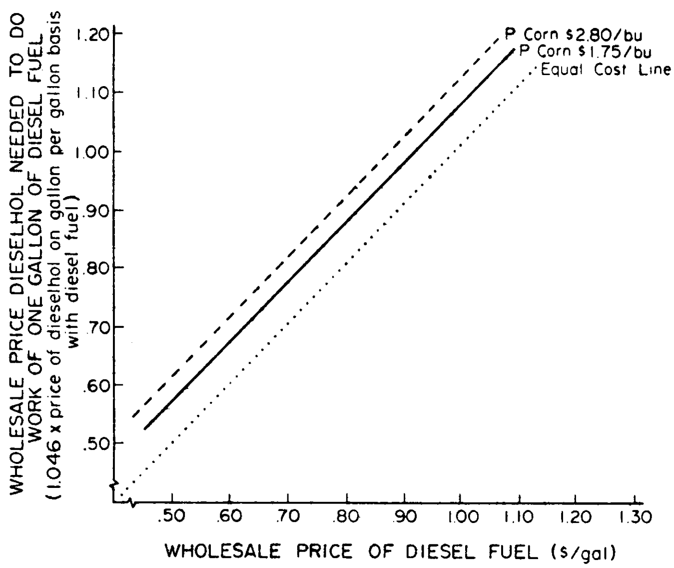


Figure 7. Cost of dieselhol for varying prices of diesel fuel and corn.



Effect on Grain Markets

The production of gasohol will have some impact on the grain markets if the gasohol program is large. The price of corn, the price of soybeans and the price of DDGS will be affected.

Distiller's dried grains and solubles traditionally have been considered to be a protein supplement competitive with soybean meal (SBM). However, the use of DDGS is basically dependent on the ratio of the price of DDGS to the price of corn and the price of SBM. Distiller's dried grains and solubles competes with SBM if its price is near the price of SBM. However, if the supply of DDGS is available in quantities so that its price is competitive with corn, DDGS will substitute for corn on a pound-for-pound basis.

The effect on the grain markets is directly related to the size of the gasohol program. A state program using about one percent of a 6.2 billion bushel corn crop (the amount that would be needed for a Minnesota program) would increase the price of corn a few cents. A regional program covering several states, using at least seven percent of this corn crop, would be expected to raise corn prices about 25 cents. A national program would require 50 to 60 percent of this 6.2 billion bushel corn crop and would have a more dramatic influence on price.

A national program would increase corn prices significantly. This size of program would also make large quantities of DDGS available, decreasing its price. Initially the increased supplies of DDGS would compete as a source of protein feed for ruminant animals, resulting in lower prices for soybean meal and soybeans. As sufficiently large supplies of DDGS come onto the market the price will decline to about the price of corn (on a pound-for-pound basis) and compete with corn as a source of energy in livestock rations.

The resulting short-run increase in the price of corn and decrease in the price of soybeans would encourage producers to shift some acreage from soybeans to corn, moderating the effect on both corn and soybean prices.

The effects mentioned are difficult to quantify as removal of this amount of corn from the market and production of such a large quantity of DDGS is beyond previous experience.

Subsidies and Their Effect on Tax Revenues

The possibility of subsidizing gasohol through state and federal gasoline tax was analyzed. It was found that a subsidy of $.072 cents per gallon of gasohol would be required for corn prices of $1.75 per bushel and for wholesale gasoline priced in the range of $.43 to $.86 per gallon. This $.072 subsidy could be accomplished by eliminating the federal tax on gasoline and reducing the state tax by $.032 per gallon.

Reducing collection of state and federal gasoline taxes would reduce funding for highways. For instance, if Minnesota were to adopt a total gasohol usage program, it would require about 200 million gallons of alcohol per year. If alcohol is subsidized by $.32 per gallon ($.032 per gallon of gasohol), state tax revenues would be reduced by $64 million annually. Because the portion of the highway fund that is spent on interstate highways is matched by federal funds in a ratio of 90 federal dollars to 10 state dollars and the portion spent on secondary roads is matched 72 federal to 28 state dollars, the impact on highway funds would be much greater than the loss in state dollars.

As the price of corn rises as under a national program, the subsidy to gasohol must be increased. The maximum subsidy that can be provided through reduction of federal and state tax in Minnesota is $.13 per gallon of gasohol.

Conclusions

- There is no engineering advantage to using ethanol-petroleum fuel blends in internal combustion engines.
- Ethanol-petroleum blends having up to 10 percent ethanol could be used in unmodified engines if the mixture is maintained water-free and the owner is willing to assume the risk of possible accelerated wear of some engine parts.
- Energy supplies are not augmented by converting corn or wheat into ethanol when ethanol is produced in commercial scale plants. More energy is consumed in producing the grain and converting the grain into alcohol than is contained in alcohol and by-products.
- Production of gasohol and dieselhol is not economically feasible at current prices and costs. Increases in the wholesale price of gasoline do not alter this situation as long as fossil fuels used to produce corn and alcohol increase proportionately with the price of gasoline.
- Gasohol could be subsidized by eliminating the federal tax and reducing the state tax on gasoline, but doing so would reduce funding for highways.

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