Direct Injection Ethanol Boosted Gasoline Engines: Biofuel Leveraging For Cost Effective Reduction of Oil Dependence and CO_2 Emissions

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ABSTRACT

Ethanol biofuel could play an important role in reducing petroleum consumption by enabling a substantial increase in the fuel efficiency of gasoline engine vehicles. This ethanol boosted engine concept uses a small amount ethanol to increase the efficiency of use of a much larger amount of gasoline by approximately 30%. Gasoline consumption and the corresponding CO_2 emissions would thereby be reduced by approximately 25%. In combination with the additional reduction that results from the substitution of ethanol for gasoline as a fuel, the overall reduction in gasoline consumption and CO_2 emissions is greater than 30%. The concept uses appropriately controlled direct injection of ethanol into the engine cylinders. The direct injection provides suppression of engine knock at high pressure. This allows high pressure operation of a much smaller, highly turbocharged engine with the same performance as a larger engine. The engine can also use a higher compression ratio. The engine downsizing and higher compression ratio results in a large increase in fuel efficiency. This approach involves only modest changes to the present gasoline engine systems and fueling infrastructure. The increase in vehicle cost could be modest (approximately $600) and the fuel savings payback time could be approximately 2 years. This leveraged use of ethanol to increase gasoline engine efficiency could substantially increase its energy value and help to alleviate concerns about a low energy output/ input ratio (energy provided by the ethanol/energy needed to produce the ethanol). Thus the ethanol boosting concept can facilitate increased use of biofuel in addition to providing a cost-effective way to increase gasoline engine efficiency.

Introduction

Increasing concerns about global climate change and energy security call for cost-effective new approaches to reduce use of fossil fuels in cars and other light duty vehicles. Recent legislation in California as well as the Kyoto protocol for greenhouse gas reduction set challenging goals for reduction of CO_2 emissions. The California legislation phases in requirements for reducing CO_2 generation by 30% by 2015. Other states may follow California in setting this goal. Cost effective approaches using near term technology are needed to achieve the widespread use necessary to meet the goals for reduced fossil fuel consumption.

Ethanol biofuel could play an important role in meeting these goals by enabling a substantial increase in the efficiency of gasoline engines. In this paper, we discuss an ethanol boosted engine concept where a relatively small amount ethanol is used to increase the efficiency of use of a much larger amount of gasoline by approximately 30%. Gasoline consumption and the corresponding CO_2 emissions would thereby be reduced by 25%. In combination with the additional reduction that results from the substitution of ethanol for gasoline as a fuel, the overall reduction in gasoline consumption and CO_2 emissions is greater than 30%. This approach involves only modest changes to the present gasoline engine systems and fueling infrastructure. The increase in vehicle cost could be modest (approximately $600). This leveraged use of ethanol could substantially increase its energy value and help to alleviate concerns about a low energy output/ input ratio (energy provided by the ethanol/energy need to produce the ethanol).

Direct Injection (DI) Ethanol Boosting

A substantial increase in gasoline engine efficiency can potentially be achieved by use of a strongly turbocharged small engine to match the performance of a much larger engine. The aggressive turbocharging (or supercharging) provides increased boosting of naturally aspirated cylinder pressure. The engine thus produces increased torque and power when needed[1]. This downsized engine at the loads used in typical urban driving has a higher efficiency due to its low friction while providing the maximum torque and power capability of a much larger engine. Engine efficiency can also be increased by use of higher compression ratio.

The approach of increasing efficiency by engine downsizing and higher compression ratio in standard gasoline engines is strongly limited by the problem of engine knock. Knock, the undesired rapid gasoline energy release due to autoignition of the end gas, can damage the engine. It occurs at high values of torque, when the pressure and temperature of the gasoline/air mixture exceed certain levels. High octane gasoline (e.g. 93 octane number vs. 87 octane number for regular gasoline) and certain changes in engine operation can be used to prevent knock and allow operation at higher maximum values of torque and power. However, the knock constraint is still very limiting.

The ethanol boosted gasoline engine concept facilitates realization of the full potential for highly pressure boosted, high compression ratio engine operation by greatly alleviating the knock constraint. This is accomplished by appropriately controlled direct injection (DI) of ethanol into the cylinder. Direct injection of ethanol acts as an effective powerful knock suppressant. The fraction of the fuel provided by the ethanol is varied “on-the-fly” according to the need for knock suppression. It is zero at low torque where knock suppression is not needed and can be as high as 100% when maximum knock suppression is needed at high torque. As shown in figure 1, ethanol from a small separate fuel tank is directly injected into the cylinders (in contrast to conventional port injection of gasoline into the manifold). The concept uses the direct fuel injector technology that is now being employed in production gasoline engine vehicles.

Ethanol has a high fuel octane number (a blending octane number of 110)[2]. Moreover, appropriate direct injection of ethanol can provide an even larger additional knock suppression effect due to the substantial air charge cooling resulting from its high heat of vaporization. Our calculations indicate that by increasing the fraction of the fuel provided by ethanol up to 100 percent when needed at high values of torque, an engine could operate without knock at more than twice the torque and power levels that would otherwise be possible. The level of knock suppression can be greater than that of fuel with an octane rating of 130 octane numbers injected into the engine intake.

The large increase in knock resistance and allowed inlet manifold pressure can make possible a factor of 2 decrease in engine size (e.g. a 4 cylinder engine instead of an 8 cylinder engine) along with a significant increase in compression ratio (for example, from 10 to 12). This type of operation could provide an increase in efficiency of 30% or more. The combination of direct injection and an a turbocharger with appropriate low rpm response provide the desired response capability

Because of the limited supply of ethanol relative to gasoline and its higher cost, it is desirable to minimize the amount of ethanol that is required to meet the knock resistance requirement. By use of an optimized fuel management system, the required ethanol energy consumption over a drive cycle can be kept to less than 10% of the gasoline energy consumption

This low ratio of ethanol to gasoline consumption is achieved by using the direct ethanol injection only during high values of torque where knock suppression is required and by minimizing the ethanol/gasoline ratio at each point in the drive cycle. During the large fraction of the drive cycle where the torque and power are low, the engine would use only gasoline introduced into the engine by conventional port fueling. When knock suppression is needed at high torque, the fraction of directly injected ethanol is increased with increasing torque. In this way, the knock suppression benefit of a given amount of ethanol is optimized.

In contrast, present operation of gasoline engines when ethanol is blended with gasoline involves utilization of a constant ratio of ethanol to gasoline throughout the drive cycle (typically 10 percent ethanol by volume) since the ethanol and gasoline are premixed prior to fueling and use in the engine. In this case. the knock suppression benefit of the ethanol is not used efficiently. It is not needed during the substantial fraction of the time during which the torque is low.

Injection of the ethanol with an appropriate spatial distribution can further reduce the relative amount of ethanol consumed over a drive cycle. It may be possible to reduce the ratio of ethanol energy consumption to gasoline energy consumption over a drive cycle to less than 3%.

Gasoline consumption is reduced both by increase in engine efficiency and by the substitution of ethanol for gasoline. The small amount of ethanol use has a strong leveraging effect on reducing gasoline consumption by increasing the efficiency of the use of a much larger amount of gasoline. For an ethanol/gasoline energy consumption ratio of 10% over a drive cycle, gasoline consumption could be reduced by approximately 31% with approximately 25% coming from higher engine efficiency. If adequate ethanol is available and a greater reduction in gasoline consumption is desired, the fraction of ethanol used can be increased. Because of the increase in efficiency, the air pollutant emissions of an ethanol boosted gasoline engine vehicle could be suppressed to levels below the already low levels of state of the art gasoline engine vehicles.

The vehicle modifications and costs are relatively modest. The main additional costs for a direct injection ethanol boosted gasoline engine would come from the cost of the turbocharger, the direct fuel injection system, and a small extra fuel tank. These costs would be partially offset by the smaller engine size. We estimate the net additional cost to be around $600.

Table 1 shows projected features of the DI ethanol boosted gasoline engine concept. A comparison is made to gasoline hybrid and turbodiesel vehicles. The gasoline consumption savings for the DI ethanol boosted gasoline engine are given for different amounts of ethanol energy traction used over a drive cycle. The gasoline consumption reduction is about 31% for 10% ethanol energy fraction. When ethanol becomes more plentiful and the cost is reduced, it may be desirable to use larger amounts of ethanol than the minimum needed for the knock free operation. The additional cost of the hybrid vehicle is substantial because of the electric powertrain cost, particularly the battery. The turbodiesel also has a substantial additional cost when the cost of an advanced exhaust aftertreatment system, which is likely to be required for use in the U.S. is included. The ethanol boosted gasoline engine concept could have a much shorter payback time than these other options.

Ethanol Fueling and Supply

Ethanol is a readily useable and safe fuel. It could be transported by the present gasoline tanker truck distribution system.

The small separate ethanol tank could be located next to the gasoline tank for ease of filling. The fueling of the separate ethanol tank could be carried out in a variety of ways. These include:

- Use of containers of ethanol (e.g. one gallon size) at service stations, homes, or other locations. This approach may be especially attractive for the initial introduction of ethanol vehicles.

- Use of existing underground storage tanks and pumps at service stations (could replace one of the octane grades). A “biofuel highway” of service stations could be put in place in California. This approach might be first utilized at fueling stations for fleet vehicles.

The present ethanol production in the U.S. is more than 3 billion gallons/yr. The amount of energy in a gallon of ethanol is about two thirds of that in a gallon of gasoline. This amount of ethanol production is about 2 of U.S. gasoline usage on an energy basis.

U.S. ethanol production is increasing and the efficiency of the conventional process is improving. In addition, the production of ethanol from cellulosic material shows promise for increasing supply and reducing cost. Brazil and Canada also have substantial ethanol production capability.

Because of the present small ratio of ethanol to gasoline production, the proposed strongly leveraged use of ethanol with a high ratio of gasoline to ethanol use can play an important role in maximizing the benefit of ethanol in reducing CO_2 emissions.

The increase in U.S. ethanol production needed to fuel half of the cars and light duty vehicles in California using DI ethanol boosted operation with a 7% ethanol/gasoline energy ratio would be about 20 percent.

Various blends of ethanol with other fuels may also be used as the anti-knock agent in the separate tank. For example, E85 (which is 85% ethanol and 15% gasoline) may be used. Methanol, another alcohol with high vaporization energy, might also be used.

Leveraged Increase in Ethanol Value

Because of the leveraging effect of increasing the efficiency of gasoline use, the energy value of ethanol can be substantially increased.

For illustration of the potential leveraging that could be obtained, consider the case where one gallon of ethanol increases the efficiency of use of 10 gallons of gasoline by 30%. In this case, the amount of gasoline that is needed for a given amount of driving is reduced by approximately 2.5 gallons. Since one gallon of ethanol has the same energy as approximately 0.7 gallons of gasoline, the total gasoline savings is:

> 0.7 gallons (from direct displacement of gasoline) + 2.5 gallons (effective displacement due to efficiency increase) = 3.2 gallons

The most recent estimate for the energy output/input ratio for ethanol (energy provided by the ethanol divided by energy needed to produce the ethanol) is 1.67.[3] For the illustrative case discussed above, the ethanol energy contribution could be effectively increased by a factor of 4.6 which is the ratio of the leveraged energy output value (3.2 gallons) to the substitution energy output value (0.7 gallons). In this case, the energy output/input ratio would be 7.5. Hence the economic value of ethanol could be greatly increased. In addition, in contrast to the case where ethanol is blended with gasoline prior to use in the vehicle (the way ethanol is presently used in the U.S.), in DI ethanol boosted gasoline operation, it is possible to use ethanol that is not completely dewatered. This can significantly reduce the cost of ethanol. Moreover, ethanol boosting could allow the use of lower octane gasoline than would otherwise be the case, thus reducing gasoline costs.

This effective higher energy value and lower cost of ethanol could help to substantially expand its use.

DI Ethanol Boosting Concept Development

The DI ethanol boosting concept does not require the development of completely new automotive components. Existing components would be modified and used together in a new way. Nevertheless, it would likely take 2 to 3 years to produce a commercial prototype demonstration vehicle after initiating an aggressive development program.

The steps that would be involved are:

- Concept development and validation on engine test stand
- Development of engine and fuel management strategy for optimal use of DI ethanol octane enhancement
- System integration including an appropriate turbocharger (or supercharger) with direct injection to provide good dynamic response
- Vehicular demonstration

Conclusions

The DI ethanol boosted gasoline engine concept could provide a cost effective way to meet near term goals of reducing gasoline consumption and CO_2 emissions by 30 percent. The fuel savings payback time for the increased vehicle cost of approximately $600 could be about 2 years. The energy output/energy input ratio for ethanol could be effectively increased from a presently estimated value of 1.67 to a much greater value. The DI ethanol boost gasoline engine concept could lead to a substantial increase in the use of ethanol and help to facilitate the market penetration of this renewable biofuel.

Figure 1. Fuel management system for “on-the-fly” direct injection of ethanol. A knock sensor would be used to determine when ethanol is needed and how much should be used.

Engine System	Efficiency Gain	Gasoline Consumption Reduction	Emissions	Extra Cost	Payback Time
DI ethanol boosted gasoline engine	~30%	~27% (5%ethanol) ~31% (10% ethanol) ~38% (20% ethanol)	Lower than baseline gasoline engine	~$600	~2 yrs
Direct Injection Turbo Diesel	$\geq$ 30%	N/A	Higher than gasoline engine (even with exhaust aftertreatment)	~$2500 (includes exhaust afterteatment cost)	~8 yrs
Gasoline Engine Hybrid	30% - 60%	25% to 37%	Lower than baseline gasoline engine	~$3000 - $5000	~10 yrs

Table 1. Efficiency gain, emissions, and extra cost of the DI ethanol boosted gasoline engine concept compared to present naturally aspirated, port fuel injected gasoline engine with conventional compression ratio. The gasoline savings is the sum of the increase in efficiency of gasoline use and the direct substitution of ethanol for gasoline. Gasoline consumption reduction is given for different percentages of fuel energy over a drive cycle that is provided by ethanol. The direct injection turbo diesel and the gasoline engine hybrid vehicle are also compared to the present naturally aspirated gasoline engine. The gasoline engine hybrid efficiency is for a combined representative city and highway driving cycle.

References

1. J. Stokes et al, “A Gasoline Engine Concept For Improved Fuel Economy – The Lean Boost System,” SAE paper 2001-01-2902

2. J.B. Heywood, “ Internal Combustion Engine Fundamentals,” McGraw Hill, 1988, p. 477

3. H. Sapouri et al, “The 2001 Net Energy Balance Of Corn- Ethanol (Preliminary),” Ethanol News Special, Jan 28, 2005