2019-01-0565 Published 02 Apr 2019

Flex Fuel Gasoline-Alcohol Engine for Near Zero Emissions Plug-In Hybrid Long-Haul Trucks

Daniel Cohn and Leslie Bromberg Massachusetts Institute of Technology

Citation: Cohn, D. and Bromberg, L., "Flex Fuel Gasoline-Alcohol Engine for Near Zero Emissions Plug-In Hybrid Long-Haul Trucks," SAE Technical Paper 2019-01-0565, 2019, doi:10.4271/2019-01-0565.

Abstract

Internal combustion engines for plug-in hybrid heavy duty trucks, especially long haul trucks, could play an important role in facilitating use of battery power. Power from a low carbon electricity source could thereby be employed without an unattractive vehicle cost increase or range limitation. The ideal engine should be powered by a widely available affordable liquid fuel, should minimize air pollutant emissions, and should provide lower greenhouse gas emissions. Diesel engines could fall short in meeting these objectives, especially because of high emissions. In this paper we analyze the potential for a flex fuel gasoline-alcohol engine approach for a series hybrid powertrain. In this approach the engine would provide comparable (or possibly greater) efficiency than a diesel engine while also providing 90 around lower NOx emissions than present cleanest diesel engine vehicles. Ethanol or methanol would be employed to increase knock resistance. Engines that could be deployed in the relatively near term could also use high rpm operation and /or water injection, to allow operation with a very small amount of alcohol in addition to a low concentration mixture such as E10 (or possibly with no additional alcohol). Further NOx reduction (by use of higher levels of EGR) and increased efficiency (by use of alcohol enhance heat recovery) could potentially be obtained over a longer term. While the analysis shows the potential for substantial benefits of using this approach, more detailed engine modeling is needed to provide more accurate illustrative engine features.

Introduction

Between 2030 and 2030 diesel fuel is expected to be the most used fuel in the global transportation fuel mix. This is due to the rapid growth in the heavy duty vehicle sector which is dominated by diesel fueled vehicles [1].

Heavy duty vehicles produce more worldwide outdoor air pollution than light duty vehicles. They are one of the main worldwide outdoors sources of urban air pollution [2].

Heavy duty vehicles are also a substantial contributor to greenhouse gas production. Presently around 20% of worldwide energy- related worldwide greenhouse gas emissions are from the transport sector and these emissions are increasing more rapidly that emissions from other major energy use sectors [3]. Around 7 gigatons of CO_2 emissions per year are produced from the transport sector and around 2 gigatons per year from heavy duty vehicles

Long haul heavy trucks with the largest diesel engines are the dominant consumers of diesel fuel and the largest producers of air pollutants and greenhouse gas among heavy duty vehicles. Powering these vehicles with batteries charged by externally provided electricity from renewable sources is needed to meet greenhouse gas reduction goals. Power provided by low carbon intensity liquid fuels can also play an important role.

Large scale deployment of battery only powered propulsion in heavy duty trucks, especially long haul trucks faces the barriers of the high cost of electrical energy storage in batteries and range limitations. These barriers can be reduced by use of plug-in series hybrid powertrain where an internal combustion engine drives a generator which is also produces electricity. This can accelerate the use of battery power in heavy duty vehicles.

One mode of plug series hybrid power operation is range extender operation where the vehicle is initially propelled with motors using electricity provided by the externally charged battery; and when the externally charged battery power is exhausted the internal combustion engine is used to provide the electricity that powers the motors. In other modes of operation the electricity from the externally charged battery can be used over longer periods of time.

The ideal engine for a range extender or other plug-in hybrid power train should be powered by a readily available, affordable room temperature liquid fuel. Use of a room temperature liquid fuel provides the advantages that include a much lower onboard fuel storage cost and lower fueling infrastructure cost. The engine should also minimize air pollutant and provide lower greenhouse gas emissions.

Diesel engine vehicle use compression ignition (CI) and could fall short in meeting these objectives, especially because of high emissions of nitrogen oxides (NOx). In addition diesel is a high CO_2 generating fuel; and flex fuel operation with alcohols which are attractive alternative liquid fuels that can have lower greenhouse emissions, is difficult in a diesel engine.

In this paper we analyze a potential approach for using spark ignition (SI) flex fuel gasoline-alcohol engines to meet the above goals. The alcohol could be ethanol or methanol. This approach can be attractive because these SI engines could provide efficiency that is comparable to (or potentially higher than) the efficiency of present diesel engines [4, 5].

By using stoichiometric operation and the highly effective three way (TWC) catalyst for exhaust treatment a spark ignition engine could provide around a 90 % reduction in tailpipe NOx relative to the present cleanest diesel engines which that use complex and expensive exhaust treatment. This low NOx emissions level has been achieved in SI gasoline engines in light duty vehicles. It has also been achieved in SI natural gas heavy duty vehicles. The Cummins Westport 9 liter SI natural gas engine has been certified for the 2018 California Air Resources Board optional low NOx standard of 0.02g/bhp-hr, a 90% reduction relative to engines operating at the current EPA NOx limit of 0.2g/bhp-hr [6, 7].

Under conventional operation, SI and diesel have similar NOx engine-out emissions. But the single SCR exhaust treatment cell for diesel engines is only about 80-90% effective, while the 3-way catalyst can be as effective as 99%. However, significant reductions of NOx from the 0. 2 g/bhp-hr level emitted by present diesel engine vehicles with state of the art exhaust treatment technology is possible with new technology; and is made easier by a greater amount of operation that does not involve transients, which could be the case for a diesel engine in a series hybrid powertrain [8].

Controlling emissions during cold start is challenging for both the diesel and SI engines. The series hybrid will have prolonged warm operation with low temperature start-up events, as the engine is operated at a single point. Under these circumstances, TWC operate more effectively at lower temperatures than SCR catalysts, although efforts are under way to improve the low temperature performance of both systems. It is possible to operate the engine to maintain sufficient temperature in the catalyst. Under these conditions, because of the higher temperature of the SI exhaust, the required operating time of the engine (just to assure that the catalyst temperature is adequate), is shorter than for a comparable CI engine.

The SI engines could be operated in a flexible fuel mode ranging from operation that ranges from using only a small amount alcohol addition to gasoline or a low concentration gasoline-alcohol blend (such as E10) to use of 100% alcohol. In some cases it may be able operate without additional alcohol.

Operation using high alcohol concentrations or 100% alcohol could provide substantial greenhouse gas emissions reductions relative to diesel engines. Alcohols could provide the best opportunities for a lower carbon liquid fuel due to the superior efficiency with which it can be produced from a wide range of feedstocks by both thermal chemical and biological processes. In addition methanol is the easiest fuel to produce from renewable electricity [9, 10]. And use of alcohol can also reduce greenhouse gas emissions and enhanced exhaust heat recovery.

Another potential benefit is the lower cost of the SI engine system because the lower costs of the exhaust treatment system, fuel injector and reduced size engine.

The high efficiency of the flex fuel gasoline-alcohol engines is obtained by providing increased suppression of engine knock and /or reducing the need for knock suppression. One means of doing this is the use of additional alcohol beyond the use of alcohol in low concentration blends such as E10 and M15. Another means is to reduce the knock requirement by operation at higher rpm, which reduce the torque required for a given amount of engine power.

An key part of this analysis involves computer modeling assessment of a combination of features that will enable these engines to achieve an efficiency that is comparable to present diesel engines with only a modest amount or possibly no externally provided alcohol, thereby minimizing or eliminating the need for the availability of alcohol in any form other than widely available low concentration blends (such as E10 or M15). Providing this capability could limit the amount of an additional fluid to the same small fraction of the main fuel use that is the case for diesel exhaust fluid used to reduce NOx emissions in from diesel engine vehicles using urea-SCR exhaust treatment systems; or completely eliminate the need for a second fluid.

The features that are assessed for minimizing the additional alcohol requirement include use of higher rpm operation, direct injection fueling, use of water for knock suppression, and optimal choice of compression ratio.

Based on this analysis, illustrative parameters are determined for near term engine possibilities. These parameters do not represent the results of detailed engine analysis; they are meant to show what engine characteristics could be examined in future studies.

Possibilities are assessed for further improvements in this approach through the inclusion to prechamber jet ignition technology that could potentially increase efficiency and/or provide a further large decease in NOx by enabling greater use of engine gas recirculation (EGR). Another further improvement that is assessed in is the use of alcohol enhanced exhaust heat recovery to increase efficiency when neat alcohol or a high concentration alcohol mixture of alcohol and gasoline is used in the flex fuel engine.

Features of Higher Efficiency Gasoline Engines

The engine in a series hybrid powertrain can be run most of the time at a fixed power level since the change in vehicle power can be provided by the stored energy in the battery. It can be operated with open throttle and other conditions where the engine efficiency is greatest. In addition, can be operated most or all of the time at around the average power needed over a drive cycle when the engine is on, thus reducing the engine power requirement. For a long haul truck, where a high fraction of the driving is at high torque and power, the average power can be in the 50 to 70% of the maximum power that is needed. This fraction is smaller for trucks that which operate more of the time at lower torque and power.

A major reason for extensive use of diesel engines in heavy duty vehicles has been their higher efficiency compared to gasoline engines. The resulting lower fuel cost is especially important for these commercial vehicles.

Present spark ignition (SI) gasoline engines using turbocharging and direct injection and compression ratios around 10 are around 10% less efficient than diesel engines at wide open throttle which is used in series hybrid operation (and around 20 % less efficient at part load operation). Because the plug-in series hybrid engines do not need to be operated at light load, where SI engines are particularly inefficient, the difference between conventional SI and DI engines is substantially reduced, compared to engines that are needed to provide adjustable power during a driving cycle.

A combination of two changes in SI gasoline engine operation can remove the remaining efficiency gap. Diesel-like high efficiency or greater in flex-fuel gasoline SI engines can be in engines that operate mainly (and in some cases, entirely) on gasoline.

One change, described below, is to operate at a higher compression ratio (*e.g.* 14) than the typical compression ratio of 10 for a gasoline turbocharged direct injection (GTDI) engine, or the compression ratio of 12 for a gasoline direct injection (GDI) engine which is naturally aspirated.

Operation at compression ratio of 14 requires an increase in knock resistance relative to than provided by gasoline. The increase in knock resistance can be provided by higher octane fuel, through the addition of alcohol to the gasoline or to a low blend of gasoline-alcohol (such as E10) that fuels the engine. The alcohol can be provided by using an alcohol -gasoline mixture blend with a higher alcohol concentration in an engine with a single injector. Alternatively, the higher alcohol concentration fuel could be provided by using a dual fuel engine where 100% alcohol or a high alcohol concentration gasoline-alcohol mixture (such as E85) is added by a separately controlled fuel injection system.

The second change for reducing the efficiency gap is to use a smaller size gasoline engine relative to a diesel engine that produces the same torque or power [4, 5]. Engine power rather than torque is the appropriate parameter for comparison of engines used for series hybrid powertrains.

One means of providing a smaller size gasoline engine (which is equivalent to increasing its power density), is to fully take advantage of the higher BMEP that can be obtained from an SI gasoline engine relative to a diesel engine due to its stoichiometric fuel air ratio. In contrast to an SI gasoline engine the maximum torque that can be obtained from the same size diesel engine is lower due to its lean operation along with the EGR needed to address emissions. The more dilute fuel/non fuel ratio in the cylinders reduces the amount of fuel that can be used for a given maximum cylinder pressure.

The higher BMEP (brake mean effective pressure) operation in a SI engine requires additional knock resistance. As is the case with higher compression ratio operation the higher knock resistance can be obtained with use of additional alcohol.

Figure 1 shows various ways that the alcohol can be added to the gasoline. Figure 1a shows how the two fuels could be added in a fixed ratio from a single injector. It is desirable that the single injector be a direct injector so as to provide increased knock resistance from evaporative cooling of the fuel/air mixture. The two fuels could be either from a premixed gasoline -alcohol blend in a single tank or from two separate tanks, one for gasoline and one for alcohol. The two fuels from the two tanks could be mixed in the direct injector nozzle or in the common rail.

FIGURE 1 Schematic system for use of two fuels: (a) single injection from a blend in a single tank, or single injection from two fuels that are mixed upstream from the single injector (either DI of PFI injection); (b) separate injection from two tanks, through either two DI injectors, two PFI injectors or a DI and a PFI injector.

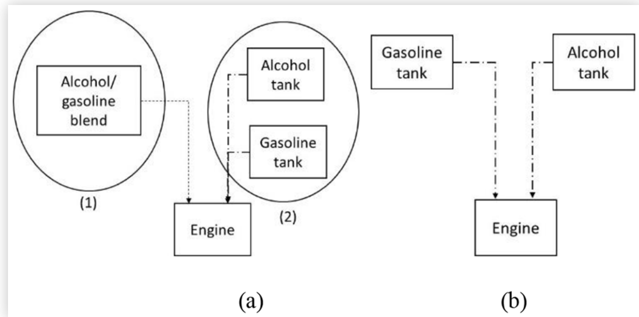


Figure 1b shows a second option in which different fuels could be provided by two separately controlled injectors in a dual fuel engine, In addition, water could be used to provide additional knock resistance by providing cooling of the fuel /air mixture. The fuel injection could be through the inlet port, (PFI) or direct injection (DI) into the cylinder. In order to minimize the requirement for the high octane alcohol fuel, it is often desirable to inject gasoline directly, to also use the evaporative cooling of the gasoline, especially under conditions where the alcohol based fuel is a small fraction of the total fuel.

We have used computer modeling to provide illustrative parameters for a higher compression ratio and higher BMEP gasoline-alcohol engine that provides the same power as a representative diesel engine for a series hybrid vehicle. These parameters are shown in the second column in Table 1. The illustrative diesel engine provides the same average vehicle torque and power as an engine used in a non-hybrid power train in a long haul truck.

The illustrative diesel engine is an 11 liter engine that produces 300 kW of power. This power level is representative of the power level for a diesel engine in a series hybrid powertrain which that is replaces a conventional powertrain that uses 380 kW (500 hp) diesel engine. A 380 kW diesel engine is representative of a 13 liter diesel engine used in a long haul truck.

The illustrative 7 liter turbocharged gasoline -alcohol engine provides the same power as the 11 liter turbodiesel engine.

It is assumed that the for most driving patterns of heavy duty vehicles, it is possible to use the plug-in series hybrid engine to provide about 80% of the peak power for long duration, long haul operation. This means that although the electric drive can provide 380 kW of peak power, in our illustrative cases the vehicle cannot maintain it for extended

TABLE 1 Comparison between an illustrative diesel engine and an illustrative SI flex fuel gasoline -alcohol engines used in a series hybrid powertrain for a long haul heavy duty truck. The second column is for the SI engine operated at higher BMEP than a diesel engine with the same rpm. The third column is for the SI engine operated at a higher rpm and lower BMEP than the diesel engine

		Conventional diesel	SI engine higher BMEP	SI engine higher speed
Power	(kW)	300	300	300
Compression ratio		14.1	14	14
Displacement	l	11	7	7
Engine speed	rpm	1800	1800	3600
BMEP	bar	18	26	14
NOx emissions	ppm	200	25	25
NOx aftertreatment		SCR	TWC	TWC
Relative efficiency		1	1.02	1
Relative efficiency including urea when SCR is used		0.98	1	1

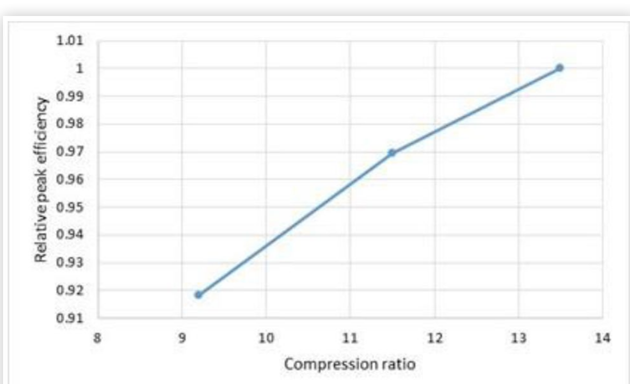
periods of time, since the recharging of the battery, limited by the internal combustion engine, is around 300 kW.

Table 1 shows relative NOx emissions for the alcohol enhanced gasoline vs the diesel engine. It is assumed that the diesel engine uses state of the art exhaust treatment employing a urea-SCR (selective catalytic reduction) system. The exhaust from the flex fuel gasoline-alcohol engine is treated with the highly effective three-way catalytic converter (TWC) technology that can be utilized in engines operated with a stoichiometric fuel air ratio. The use of this exhaust treatment technology in an SI engines operation provides around a factor of 10 reduction in NOx relative to a diesel engine with urea-SCR. This reduction has been shown in both light and heavy duty vehicles [5].

We have used a compression ratio of 14 for the diesel engine as we have extensive data on the operation of such an engine. Present diesel engines operate at higher compression ratios, and the efficiency advantage of the diesel would thus be somewhat higher (1-2 %) than that of the engine considered in the table. However, this efficiency advantage of diesel could be negated when the overall efficiency which includes the use of urea for urea-SCR is taken into account.

Table 1 also shows the efficiency of the alcohol enhanced gasoline engine relative to the efficiency of the diesel engine,

FIGURE 2 Peak brake thermal efficiency of SI engine operating at 1800 rpm, 300 kW relative to a diesel engine. Brake thermal efficiency is independent on fuel used [13].



at the point of highest power operation (300 kW). The efficiency is calculated using the model for engine performance developed by Blumberg [11]. The table also shows the relative efficiency when the energy loss from production of urea is taken into account.

Figure 2 shows the relative peak efficiency of the 7 liter high BMEP flex fuel gasoline-alcohol engine relative to the diesel engine as a function of compression ratio. There is about a 1% absolute increase in efficiency in efficiency as the compression ratio increases from 12 to 14. The corresponding relative increase in efficiency is around 2.5% [12, 13]

Use of Knock Model to Calculate Alcohol Requirements

In order to determine the alcohol requirement for preventing knock we have used a model that we have developed. Being able to operate the minimum fraction of fuel that must be provided by alcohol in a mixture with gasoline (or E10) is important in insuring that concerns on limitations on alcohol availability or a high alcohol price are minimized.

Our model has been benched marked with experimental data [14]. Knock is difficult to predict, in particular because of the stochastic nature of the process. There are substantial cycle-to-cycle variations in cylinder, even when the engine is operating under steady-state conditions. The cycle-to-cycle variations are due to differences in combustion of the air/fuel mixture, due to variations in the velocity field, variation of the residuals in the cylinder, changes in composition of air, fuel or residuals in the cylinder and in particular, close to the spark.

Analyzing the average cycle can provide some information, but in order to better understand the nature of the process we need to incorporate the cycle-to-cycle variations, as not all cycles experience knock.

Another issue with knock is the limited description of the gasoline. Gasoline is a mixture of a large set of compounds. The complex mixtures is simplified by characterizing the gasoline by two numbers: the Research Octane (RON) and the Motor Octane (MON) numbers. In order to eliminate the uncertainty of the fuel formulation, we have modeled the engine with primary reference fuels (PRF), mixtures of n-heptane and iso-octane. We have compared the experimental results using PRF to predict the knock-onset.

The use of primary reference fuels (PRF), mixtures of iso-octane and n-heptane in the work by Jo [14], provided an ideal opportunity to test the chemistry-based nature of knock. Experimental data is used to determine the knocking characteristics of the fuel. Then we choose several cycles with pressure higher than the borderline knocking cycle, and several just below it, trying to determine through modelling whether the cycles with pressures higher than borderline knock are knocking, and those below are the borderline knock do not knock. However, benchmarking the results to PRF limits the accuracy of the model.

One major unknown in the model is the initial temperature of the cycle (we know the pressure, which is measured, and can calculate combustion timing for the individual cycles). Using the experimentally measured pressure profiles, we determine the in-cylinder temperatures using GTPower as a function of combustion timing. We then integrate the chemistry in the unburnt air-fuel mixture using different experimental pressure profiles, using the residuals estimated in the GTPower calculations, as a function of the initial temperature. For simplicity, we start the chemical kinetic calculations at 20 CA BTDC, relatively late in the cycle by before any significant chemistry has occurred in the unburnt air-fuel mixture. The CHEMKIN simulations assume an adiabatic unburnt air-fuel mixture, using the Mehl mechanism [15].

If there is autoignition of the air-fuel mixture prior to CA90 timing (timing that results in combustion of 90% of the fuel), we assume that the model predicts knock. If it happens later in the cycle, we assume that there is no knock. As we can only estimate the temperature (not measured, only interpreted from the engine simulation), and the local variability of the temperature in cylinder is not known, we vary the temperature until there is autoignition at CA90, and call that condition borderline knock.

We have verified the model with experimentally determined results, at three different points using PRF, have been used to investigate knock. GTPower has been used to evaluate the engine conditions for actual engine cycles, not of the average cycle (which does not knock) [13].

Using our knock model we have calculated the lowest fraction of fuel that must be supplied by ethanol in order to suppress knock in the 7 liter engine where the gasoline is in the form of E10. It is assumed that the gasoline octane is 91 PRF. The results are indicative of the trends, rather than precise prediction of the engine performance.

Figure 3a shows minimum required fraction of fuel provided by E85 (85% ethanol by volume) that prevents knock, as a function of the engine power, at 1800 rpm and a compression ratio of 14. The minimum required fraction is shown for several means of injection of the fuels. As the BMEP is reduced there is a lower minimum value E85 fraction required to prevent knock. For DI gasoline and DI E85 the required minimum fraction at 26 Bar BMEP and 300 kW is around 0.4 This fraction could be reduced to around 0.2 for a compression ratio of 12 with resulting relative decrease in efficiency of around 2.5%. The corresponding brake thermal efficiency for operation at borderline knock shown in Figure 3a and is not affected by the choice of fueling method, but is a function of the torque.

DI E85 gasoline and DI gasoline provided the lowest fraction due to the increased knock resistance from the vaporization cooling from both the gasoline and the ethanol. Open-valve PFI of E85 and PFI gasoline, which provides some vaporization cooling from port fuel injection, results in a modest increase in the minimum E85 fraction relative to DI E85 and PFI gasoline. Avoiding use of DI can make it easier to use a modified diesel engine where the spark plug could be placed in the cylinder opening that been used for the diesel fuel injector.

It is possible to substantially increase the power for improved operational capability, without exceeding the peak pressure limitation in the engine (similar to that of the heavy diesel engine), to about 500 kW (around 650 hp). The E85 fraction would increase to 100%. The power can be increased by a combination of increased BMEP and increased rpm.

FIGURE 3a E85 at borderline knock, for various means of injecting the gasoline and the E85 into the illustrative 7 liter SI engine of Table 1 operating at 1800 rpm and using a compression ratio of 14.

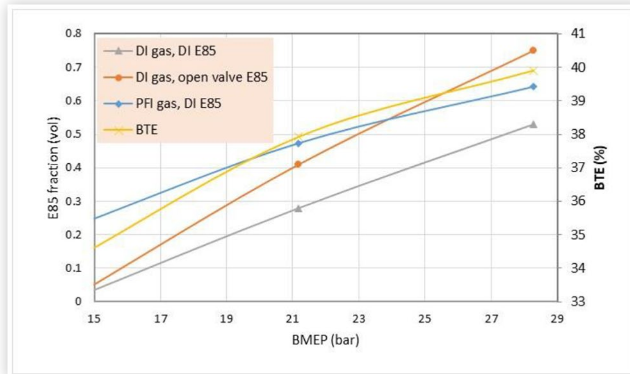


FIGURE 3b Peak pressure as a function of BMEP for the engine in 3b with a compression ratio of 14, with 7.5 CAD spark retard.

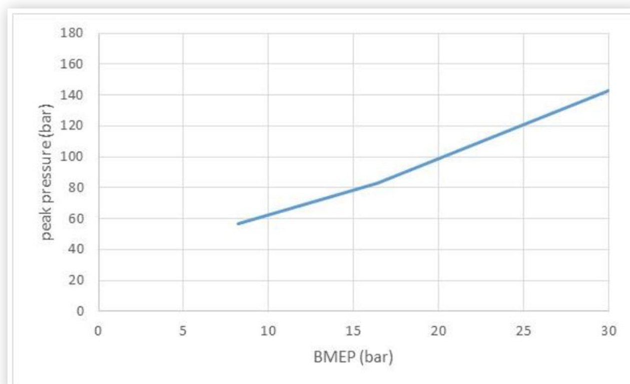


FIGURE 4 Fraction of E85 as a function of compression ratio, for 3 different modes of injection of the two fuels (gasoline, E85); for the illustrative engine of table 1 operating at 1800 rpm

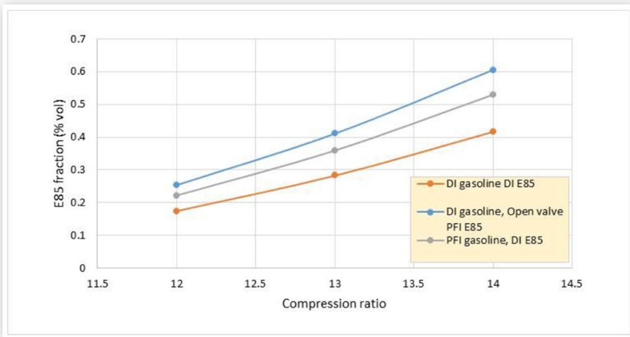


Figure 3b shows the dependence of the average-cycle peak cylinder pressure on BMEP, for the engine in Figure 3a, with 7.5 CAD spark retard.

Figure 4 shows the minimum ethanol fraction as a function of compression ratio for an engine with three different modes of injection. For DI of gasoline and E85 the minimum E85 fraction at a compression ratio of 14 is around 0.4. When the compression ratio is reduced to 12 the minimum fraction is around 0.2. As mentioned previously this decrease in compression ratio would reduce peak brake thermal efficiency by a relative amount of around 2.5%.

The use of high BMEP in the 7 liter engine would require a stronger block and other stronger components than is used in most gasoline direct injection engines. One option for providing these components would be to modify a diesel engine. As mentioned above, diesel port fuel injection could be open-valve PFI or standard closed valve PFI. We estimate that at 25 bar BMEP, the peak-pressure would average ~ 120 bar with a compression ratio of 14, with mild spark retard.

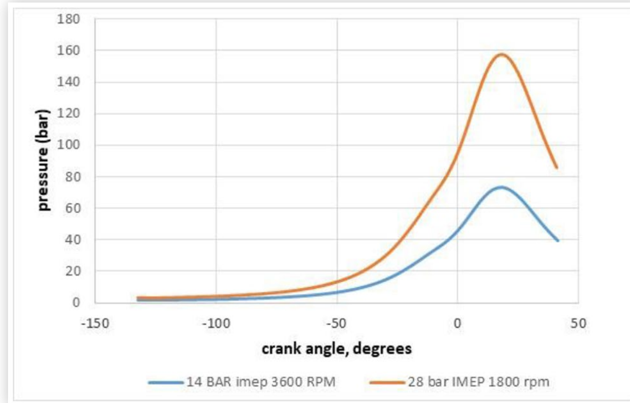
Another option could be to use the strong compacted graphite iron block of the type that is used in some modern light duty vehicle engines.

As an alternative to downsizing provided by higher BMEP operation than is presently employed in SI gasoline engines, downsizing could be provided by operating the series hybrid SI gasoline engines at around the same BMEP of diesel engines (which is around the same as that of GTDI engines along with increasing the average engine speed to 1.5-2 times that of the diesel engine. This is possible because of the faster combustion rate of SI engines.

For example, the 7 liter SI gasoline engine described above could be operated at 3600 rpm in contrast to 1800 rpm for the diesel. The operating parameters for this high rpm version for the 7 liter engine are shown in the last column in Table 1. The dependence of efficiency as a function of compression ratio is the same as in Figure 2. We have investigated the increased engine speed using GTPower, including friction, heat losses. We have assumed constant combustion duration (in crank angles) and kept CA50 fixed.

Figure 5 shows the average pressure for the conditions of same power with 1800 and 3600 rpm, for an engine with a compression ratio of 14.

FIGURE 5 Cylinder pressure for 28 bar, 1800 rpm and 14 bar, 3600 rpm. 7.5 CAD spark retard (average cycle)



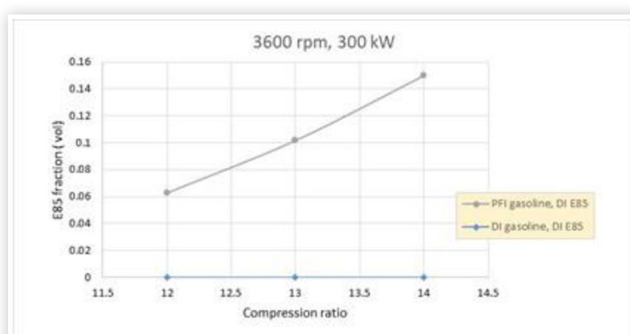
Because the addition of alcohol for knock suppression in this case is only needed to enable higher compression ratio operation than a GTDI engine, the minimum alcohol fraction is substantially less than for the case of high BMEP operation.

Figure 6 shows the dependence of required ethanol fraction on compression ratio for the high rpm (3600 rpm) engine operation mode. The required ethanol fraction varies from 35% at a compression ratio of 14 to 6% at a compression ratio of 12 for PFI gasoline-DI E85. For the case of DI gasoline and DI ethanol, our computer modeling indicates that there is no need for additional E85 to avoid knock, and the engine can be fed with DI gasoline without knock for compression ratios of 12-14.

At 3600 rpm, the BMEP is about 14 bar, and the inlet manifold is around 1 bar, roughly corresponding to naturally aspirated operation.

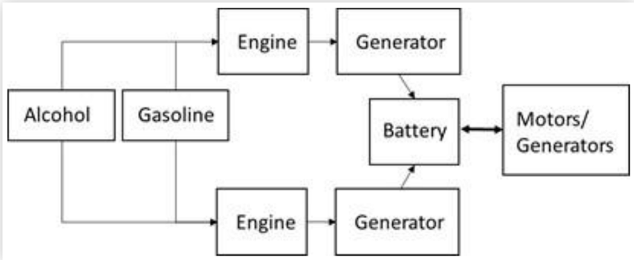
The efficiency of the 7 liter engine using 3600 rpm operation may deteriorate somewhat with higher rpm due the longer crank duration of the combustion. This deterioration should be small in state of the art engines [16, 17]. A 2% deterioration was used in Table 1. However, a 2 % reduction in efficiency could be an important factor in the long haul heavy duty vehicle sector where fuel cost is a key consideration.

FIGURE 6 Dependence of minimum required ethanol fraction for 3600 rpm, 300 kW operation for the illustrative engine of table 1 the as a function of compression ratio. Note that for DI gasoline and E85, there is no need for E85 addition.



© 2019 Massachusets Institute of Technology. All Rights Reserved.

FIGURE 7 Illustrative system with two small SI engines/ generators in a series hybrid vehicle.



If needed the reduction in efficiency at higher rpm could be potentially addressed by use of ,a faster combustion using a more powerful spark source or a prechamber (as described below), which is fueled with gasoline and/or alcohol), could be employed to address this issue.

The use of higher rpm operation could remove the need for a stronger block needed for higher BMEP operation enable the employment of a higher compression version of a presently used GDTI or GDI engines (i.e. naturally aspirated) for the internal combustion engine. The use of a GDI engine could relax possible temperature limitations on high rpm operation that could result from use of turbocharging.

It is possible to use two modified GTDI or GDI engines to provide the required electrical power. Each would be integrated with its own generator. The use of two engines would provide a greater range of options for using present-day engines which maintain high efficiency at higher rpm. This configuration is shown in Figure 7. It shows the various electrical components that are utilized. One potential advantage of using two engines is because of the much larger availability of smaller SI engines, at lower costs. Another advantage is that it also allows the possibility of operating the system at half power with high efficiency by using a single engine.

It is also possible to use a combination of both higher BMEP and higher RPM operation. However, a significant increase in BMEP could require use of stronger engine components than used in GTDI engines along with a greater minimum fraction of alcohol.

Use of Prechamber Alcohol Jet Ignition

Prechamber jet ignition could provide a substantially better ignition source for the fuel in an engine cylinder which is the main chamber. The use of a prechamber could remove the disadvantage of a deterioration of efficiency with higher rpm operation and/or enable the use of higher engine gas recirculation (EGR) to further reduce NOx emissions. A significant further reduction of NOx (*e.g.* from 0.02 g/bhp-hr to the 0.005 g/bhp-hr - 0.01 g/bhp-hr range) could be possible with the use heavy EGR in addition to the use of the three way catalyst.

This technology involves the use of a small spark ignited prechamber for each cylinder. The better ignition capability that is provided can be used to increase the combustion rate and to thereby reduce the deterioration of efficiency at high engine speed [18].

A spark in the prechamber ignites a hot mixture of fuel and air, which is typically rich. A jet is expelled into the main cylinder and ignites the fuel in the main chamber over a much larger region than possible with a spark plug. A gasoline fueled prechamber jet ignition has been employed so as to send a hot turbulent jet of gas into the cylinder which was also fueled with gasoline. The hot turbulent jet approach provided substantially improved ignition using only 1-2% of the total fuel in the prechamber [19].

Our computational modeling indicates that the capability of this and other prechambers can be substantially improved by optimized use of alcohol in the prechamber. Gasoline is not a preferred fuel to be used for combustion in the prechamber, as it has large quench thickness that adversely affects the combustion in a small chamber. In addition, soot limits the range of fuel-air ratios in gasoline fueled prechamber.

Substantially improved engine operation could be obtained by using alcohol or a high concentration alcohol -gasoline mixture in the prechamber (which we refer to as "alcohol jet ignition," or "AJI") while the main chamber is fueled with gasoline or a lower concentration alcohol-gasoline mixture such as E10. The engine could also be fueled with alcohol or a high concentration alcohol -gasoline mixture including use of the same alcohol fuel in the prechamber and the main chamber.

The use of alcohol in the prechamber reduces sooting, thereby allowing a wider fuel- air ratio range in AJI operation. The use of the wider fuel -air ratio range can increase the combustion rate in the main chamber. For a given prechamber with a given fuel air ratio, alcohol can be used so as to reduce soot relative to operation of the AJI operation with gasoline.

The use of alcohol also provides a higher flame speed and increases combustion stability in the prechamber and in the main chamber. Both ethanol and methanol have a higher flame speed than gasoline. The flame speed of methanol is higher than that of ethanol.

It is possible to vary the equivalence ratio in the prechamber to adjust the hydrogen and thermal impacts on combustion in the main chamber. As the equivalence ratio of the prechamber decreases, the thermal impact decreases (lower temperature of the jet), while the level of hydrogen/CO increases (higher concentration of H_2 and CO). One hypothesis is in AJI the ignition mechanism in the main chamber is autoignition of zones with the hot hydrogen rich gas.. Our preliminary simulations indicate that the thermal effect (from the hot syngas) is more important in decreasing the autoignition delay than the presence of the hydrogen.

The use of alcohol rather than gasoline can reduce the prechamber volume and thus the amount of fuel needed for AJI operation. Our preliminary calculations indicate that with optimal design it could be possible to provide improved combustion with an alcohol use in AJI that is substantially less than 2% of the fuel use in the engine cylinder that it ignites.

The alcohol could be provided by external fill of a separate tank or by onboard separation of alcohol from a low to modest alcohol-gasoline mixture such as E10, E20, E30 or M15 [20, 21, 22, 23].

The reduced soot formation and higher flame speed from alcohol use with AJI can be used so as to provide an improved combustion rate and less deterioration of engine efficiency at high rpm than would occur if gasoline or a low concentration alcohol gasoline mixture were used in the prechamber.

In addition to enabling higher efficiency operation at higher rpm, AJI can also improve knock suppression by providing faster combustion in the main chamber. The improved knock resistance in the main chamber can reduce the amount of alcohol in the main chamber that is needed to prevent knock. This reduction can be greater than the amount of alcohol that is used for AJI.

The use of one, two or all of the above benefits of AJI can increase the efficiency of alcohol-enabled higher efficiency gasoline operation in a high rpm engine for a given total amount of alcohol (alcohol used in the prechamber plus alcohol used in the engine cylinders). Or it can reduce the total alcohol that is consumed for a given efficiency over a driving period. It can also provide combinations of lower total alcohol use and higher efficiency.

The alcohol fuel can be obtained from the second tank in a dual fuel engine. The second tank can be refilled from onboard separation of a component from the fuel in the main tank (gasoline/alcohol blends), or can be periodically refueled externally. Since the amount of the fuel (by energy) required is small, refueling operations can be infrequent.

For successful operation of the pre-chamber, it is necessary to vaporize the liquid fuel, without the production of soot. It may also be advantageous to use coatings on the wall to facilitate operation. These coating could be catalytic in nature.

Alcohol could be injected into the prechamber early in the compression stroke or before as a liquid, and it can vaporize there, scavenging the residuals from the previous combustion cycle. Various alcohols can be used, hydrous or neat methanol or ethanol, or high blends of alcohols and hydrocarbons. Flamability and peak pressure in the prechamber will be increased by removing residuals from the prechamber, generating faster, hotter jets that improve the combustion in the main chamber.

The prechamber can also be used to reduce cold start emissions. In this case, because of the robustness of the ignition process that is provided by the pre-chamber, less fuel enrichment in the main chamber is needed during cold start. A strong spark in the prechamber can be robust enough to ignite the air/fuel in the prechamber, even in the presence of wall wetting.

Cold start emissions, and in particularly hydrocarbon emissions, can be reduced by adjusting the equivalence ratio in the main chamber during the cold start. The adjustment of the equivalence ratio in the main chamber may only last a few seconds, as it is likely that NOx emissions during this time will be high. Thus the time of operation with these conditions should be limited. This approach could be used for gasoline fueled prechamber operation as well as for alcohol fueled prechamber operation.

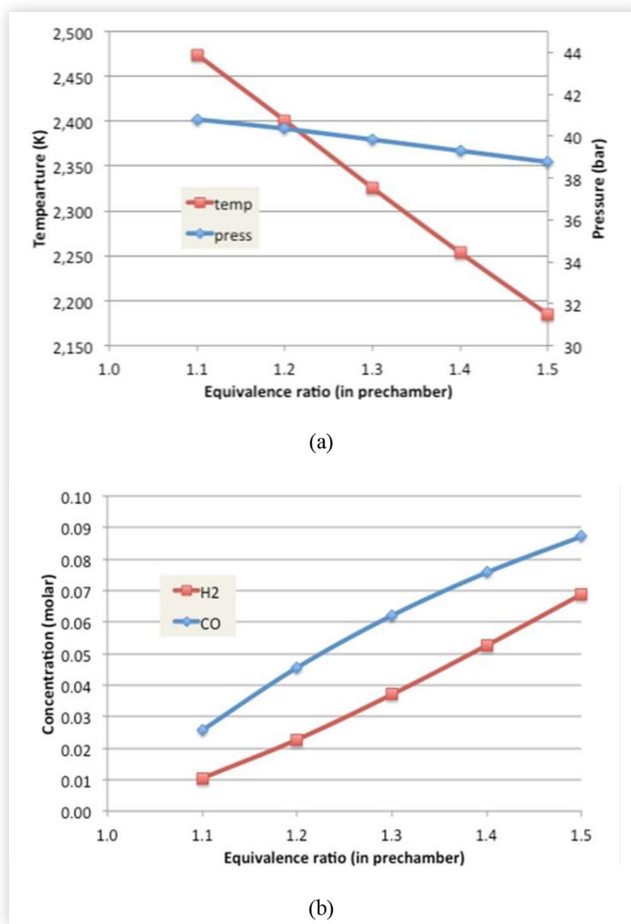
The equivalence ratio used in the AJI can be adjusted for different environmental conditions (such as temperature, for cold start).

We have used computer modeling to determine characteristics of the prechamber. Because of the high temperatures during the combustion process, the prechamber chemistry has been modeled using a constant volume, constant enthalpy model, with products being in thermal equilibrium. It is assumed that the prechamber kinetics occur under constant volume, meaning that the chemistry is fast compared with the fluid dynamics, which will result in pressure relief in the prechamber. The model is useful to determine the characteristics of the prechamber, even though it is approximate. The results of the model calculation are shown in Figure 8 as a function of equivalence ratio (the fuel air ratio that is normalized to a stoichiometric fuel air ratio). It is assumed that the initial conditions are 10 bar and 640 K, typical conditions for sparking in SI engines. The prechamber can be operated at an equivalence ratio of 1.1 with a temperature greater than 2400 K or at an equivalence ratio of 1.5 with a temperature greater than 2100 K.

While operation at low equivalence ratio provides the highest temperature operation, higher equivalence ratio increases production of hydrogen and carbon monoxide which can have a beneficial impact in increasing the dilution limit in the main chamber.

The dependence of the effects of the combustion of fuel in the main chamber upon the parameters of the prechamber

FIGURE 8 Temperature and pressure (a) and molar composition of hydrogen and carbon monoxide (b) as a function of the equivalence ratio for a methanol fueled prechamber .



operation determines where it is most advantageous to operate the prechamber.

It is possible to vary the equivalence ratio in the prechamber to adjust the hydrogen to thermal impact on combustion in the main chamber. As the equivalence ratio of the prechamber is decreased, the thermal impact decreases (lower temperature), while the level of hydrogen/CO increases (higher concentration of H2 and CO

Metering the small amount of fuel that is used for the AJI (less than 2% of the fuel used in the main chamber) , with a conventional injector, would be difficult. Injectors with much smaller orifice, with fast acting action (such as piezo-electric driven injectors), would be needed.

The use of AJI with a strong spark, which could be provided by a high energy ignition system is advantageous, in that the combustion of the air/fuel mixture in the prechamber is robust, not sensitive to the actual equivalence ratio in the prechamber. Thus, the challenge of metering the additional fuel in the prechamber is eased.

In addition to minimizing the alcohol requirement for the pre-chamber operation by varying the amount of directly injected alcohol based on the region in the torque-speed space at which the engine is operating, it could also be minimized by optimizing the tradeoff between temperature and equivalence ratio as described above.

The AJI operation could be used to enable significantly higher EGR with stoichiometric fuel/air operation in the main chamber. The heavy EGR could provide a substantial reduction to already low NOx levels in stoichiometric gasoline engine operation with a three way catalyst and could also provide a modest increase in efficiency

The fuel management system can use a lookup table or feedback from engine/exhaust sensors, to adjust the equivalence ratio in the prechamber. The combustion products composition and temperature can be adjusted and varied across the vehicle operating conditions. A main chamber combustion sensor can be used to determine the alcohol addition.

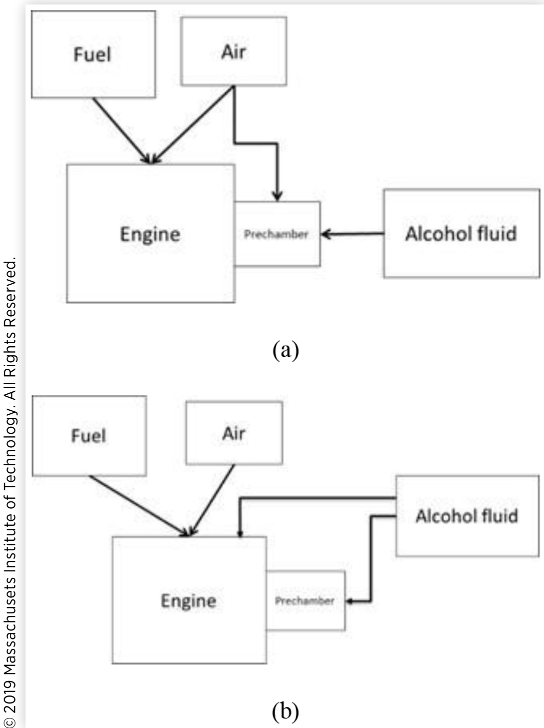
The adjustment of the prechamber equivalence ratio across the engine map can be used to reduce and preferably to operate so as to minimize the use of alcohol. The alcohol use in the prechamber could be provided on-demand with the amount depending on engine operating condition.

Figure 8 shows two options for utilize of using alcohol in an engine system that uses alcohol enhanced prechamber. In Figure 9 (a) alcohol is introduced into the prechamber and another fuel (for example, gasoline) or the same fuel is introduced into the main chamber (the engine cylinder). In Figure 9 (b) alcohol is also introduced into the main chamber.

The alcohol use in both or either of the two chambers can be varied based on the place in the torque-speed map that the engine is operating.

For knock control, it could be best to directly inject the fuel into the main chamber, in order to take advantage of the evaporative cooling of the alcohol. Alternatively the alcohol could be injected using open-valve port fuel injection which provides some evaporative cooling but not as much direct injection, or by closed-valve port fuel injection. For some applications the same alcohol fuel may be used both in the main chamber and for the AJI.

FIGURE 9 Engine operation with alcohol enhanced prechamber; (a) Alcohol is introduced into a prechamber and then into a cylinder in the engine (b). Alcohol is also introduced into the cylinder so as to prevent knock.

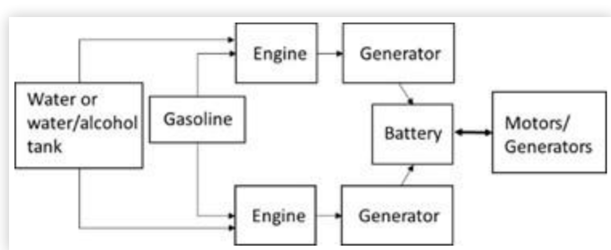


Use of Water Injection for Knock Suppression

In addition to or instead of alcohol, water could be used to provide the additional knock suppression [24, 25, 26, 27]. Use of water injection could further reduce the minimum alcohol requirement for the required knock suppression. This can be especially important for high BMEP operation.

Figure 10 shows one version of this type of system. Dual injection is employed where gasoline or a low alcohol concentration gasoline -alcohol mixture is introduced into the engine by one fueling system. A second fueling system introduces alcohol, water and/or alcohol plus water. One fueling

FIGURE 10 System for electric drive for a vehicle with engine using water , alcohol or alcohol-water mixtures for knock suppression



configuration is to for the first fueling system to use direct injection and for the second fueling system to use port fuel injection where the port fuel injection occurs with the inlet valve open so as to facilitate increased knock resistance by vaporization cooling in the cylinder.

As shown in Figure 10 the electric motor is powered by either the battery or by a generator. The battery can be charged by the engine powered generator or by a renewable electrical source. The water could either be provided by external fill of a storage tank and/or by recovery from the vehicle, for example by recovery from the exhaust using a water separator or the AC system [22]. External fill with water could be especially attractive in regions of the world that have warm climates The alcohol could be provided by a separate tank which could be supplied by external refill and/or by use of an onboard separator to derive the alcohol from an alcohol-gasoline mixture.

Alcohol use can be minimized by operating as much as possible with water being used to provide the required knock resistance \; and using alcohol when water is not available

An example is to use alcohol only during the brief periods of time, such as the first 100 seconds, when the engine is cold and sufficient water is not yet available. Increased spark retard could be used during cold start to reduce the knock suppressing fluid requirement during the short periods of time when water is not available (This approach could also be employed for engines used in vehicles that do not have hybrid powertrains).

Another means for addressing operation of the engine in a hybrid powertrain when it is cold, is to operate it at low load until it is warmed up and to use stored electricity in the battery to make up for the lower electricity production from the engine. During the engine start-up, when the engine and catalysts are cold, the engine operates at low load, low power until warm enough to start generating water.

Low load, low power operation greatly reduces or eliminates the amount of alcohol or water or alcohol/water mixtures that are needed to prevent knock. Once the engine warms up and water retrieving is re-established, the engine operation can switch to high power. The exhaust system and the catalyst are thermally insulated in order to minimize the period when the engine is operational but the catalyst is cold. A temporary increase in spark retard can also be used to heat the catalyst. As the engine is only used to provide electricity when needed, turning on and off occurs at more frequent intervals than when the engine is the prime mover. It is desirable to minimize catalyst cool-down during the off-periods of the engine, and to minimize the time for achieving catalyst light off when restarted.

Flexible Fuel Operation with Alcohol Enhanced Exhaust Heat Recovery

When operated with alcohol alone or a high alcohol concentration alcohol-gasoline mixture, the engine can provide higher efficiency by use of an alcohol-enabled high performance exhaust heat recovery system.

FIGURE 11 System for electric drive that uses an open Rankine cycle for waste energy recovery. Single lines indicate fuel flow, while double lines indicate electricity flow.

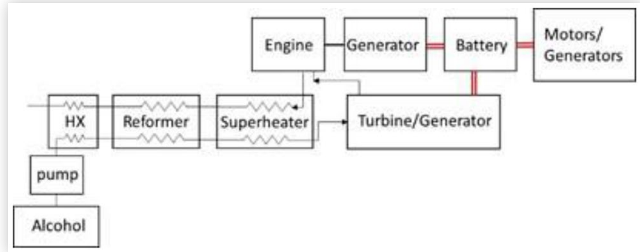


Figure 11 shows the alcohol enabled high performance exhaust heat recovery system. The high performance exhaust heat recovery is provided by using exhaust heat to endothermically reform the alcohol into hydrogen and carbon monoxide (hydrogen-rich gas) which has higher chemical energy than the alcohol and which is then introduced into the engine [6, 28, 29].

An increase in amount of the waste exhaust that is recovered can be also provided by Rankine cycle recovery of the energy from exhaust heat using pressurized alcohol as the working fluid [22]. The high pressure, high temperature syngas is employed to drive a turbine which produces electricity or is connected to the engine shaft (as in turbo-compounding), before being introduced into the engine as fuel. The electricity from the turbine could be used in both powertrains that do not employ electrical propulsion and powertrains that employ electrical propulsion.

A fraction of the alcohol is not directed to exhaust heat recovery. This diverted fraction is used to provide a greater amount of knock resistance than is provided by the hydrogen-rich gas. The diverted fraction of alcohol used to prevent knock can be reduced by use of water injection and /or high rpm operation. This enables higher efficiency operation than would otherwise be possible.

The exhaust heat recovery is facilitated by stoichiometric engine operation that provides higher temperature engine exhaust than is provided by a diesel engine which is operated with a lean fuel to air ratio.

Engines that use this exhaust heat recovery technology [20] could provide an efficiency that is around 1.15-1.20 times greater than diesel engines when the engines are operated with ethanol alone and around 1.15-1.2 times greater when operated with methanol alone.

The use of the exhaust heat recovery technology in a series hybrid is also facilitated by the relatively constant level of power operation and the use of the electricity from the Rankine turbine in the hybrid electricity system.

The higher efficiency from exhaust heat recovery in a high speed engine in a series hybrid could provide an efficiency of conversion of fuel into electricity that is 50% or greater and is comparable to hydrogen to electricity conversion in a fuel cell.

If the flex fuel engine is fueled with E85 or another high alcohol concentration alcohol-gasoline mixture, onboard fuel separation could be employed to separate the E85 into a higher concentration ethanol stream and a stream that is mostly gasoline [26, 27, 28]. The higher concentration ethanol stream which is used in the energy recovery system, would be less prone to sooting in catalytic reformer conversion to syngas.

The separated gasoline can be stored in a separate tank from the E85 and when advantageous, it can be introduced into the engine by a separate fueling system different from that which introduces the syngas from reformed high higher concentration ethanol stream. The separated gasoline can be used for cold start. A small amount of E85 can also be used as is for cold start. The same approach could be used with a high alcohol concentration methanol-gasoline mixture such as M85.

Summary/Conclusions

1. We have used computer modeling to analyze features for a SI flex- fuel gasoline -alcohol engine approach that provides an alternative to diesel engines in plug-in series hybrid powertrains for long haul heavy duty trucks. The alcohol could be ethanol or methanol. Our analysis shows that with optimized use of these features the flex fuel gasoline-alcohol engine approach could provide a comparable efficiency to a diesel engine by enabling the use of a high compression ratio (*e.g.* 14) in an SI engine that is smaller than a diesel engine while providing the same power. By using a three way catalyst and stoichiometric operation a low NOx emission level of around 0.02 g/bhp-hr could be achieved. This NOx level is around 90% lower than the 0.2g/bhp-hr level produced from present heavy duty diesel engine vehicles using state of the art exhaust treatment. However, the use of the diesel engine in a hybrid powertrain and improvements in diesel exhaust treatment technology could considerably reduce the lower NOx advantage of an SI engine. The flex fuel gasoline -alcohol approach could also provide a lower cost than use of diesel engines due to lower cost exhaust treatment, lower cost fuel injection, and use of a smaller engine. And it could facilitate greater use of alcohol fuels in flex fuel operation, thereby potentially reducing greenhouse gas reductions as well as reducing oil dependence.
2. Our computer modeling also shows that the comparable efficiency to that of a diesel engine could be potentially be provided with operation on mainly (or in some cases entirely) using direct injection of gasoline or a low concentration gasoline -alcohol mixture such as E10. This operation would facilitate use of the existing gasoline fueling infrastructure with little or no need to provide additional alcohol to provide the knock suppression needed to achieve diesel-like efficiency. Features that enable this operation include use of high rpm operation which provide a substantial reduction in the knock suppression requirement. They also include the use of water injection to supply additional knock suppression where the water is provided by water recovery from an engine that is mostly operated at constant power using in a series hybrid configuration.
3. Analysis was also performed on the potential use of an alcohol enhanced jet ignition employing small spark ignited prechambers as a substitute for a spark plug on each cylinder. The analysis showed that alcohol jet ignition can provide substantial improvement over gasoline jet ignition .It can be used to improve efficiency at high rpm and/or to enable higher EGR which can be used to further reduce NOx emissions. Using higher EGR the emissions of an SI flex fuel gasoline- alcohol vehicle could potentially be reduced to the 0.005 to 0.01 g/bhp-hr range.
4. A flex fuel gasoline -alcohol engine approach could potentially provide the lowest emission option for a near zero emissions requirement for a series hybrid range extender engine for a long haul truck that uses a room temperature liquid fuel by providing both the lowest air pollution and lowest greenhouse gas emissions when the internal combustion engine operates. This approach can be used in other plug-in modes as well as in a range extender mode. For example, the relative use of battery power, gasoline power and alcohol power can be optimized for meeting varying prices and availability of these energy sources as a long haul truck travels through various regions...The flexible fuel gasoline-alcohol series hybrid approach that is described here could also be used in other heavy duty vehicles, medium duty vehicles and in light duty trucks.
5. While this analysis provides an initial assessment of the integration of potential features for maximizing the benefits of using flex-fuel gasoline -alcohol engines for plug-n hybrid for long haul heavy duty vehicles. More detailed engine modeling is needed to provide more accurate and meaningful parameters for specific powertrains.

References

1. Exxon Mobil, "Outlook for Energy: A View to 2040," http://corporate.exxonmobil.com/en/energy/energyoutlook/2017-highlights/a-view-to-2040, 2017.
2. Anderson, S.C., Miller, J., Minares, R. et al., "Impacts and Mitigation of Excess Diesel-Related NOx Emissions in 11 Major Vehicle Markets," *Nature* 545:467-471, May 2017.
3. Lefevre, B. and Enrique, A., "Transport Sector Key to Closing World's Emission's Gap," World Resources Institute, Sept. 19, 2014
4. Bromberg, L. and Cohn, D., "Ultrahigh Efficiency Alcohol Engines Using Optimized Exhaust Heat Recovery," U.S. Patent 9234482 (led July 2013)
5. Cohn, D. and Bromberg, L., "Dual-Fuel Gasoline-Alcohol Engines for Heavy Duty Trucks: Lower Emissions, Flexible -Fuel Alternative to Diesel Engines," SAE Technical Paper 2018-01-0888, 2018, doi:10.4271/2018-01-0888.

6. Cummins Westport Press Release, "Cummins Westport Receives 2018 Emissions Certifications for L9N and B6.7N Natural Gas Engines," Dec. 13, 2017.
7. California Air Resources Board, "Heavy-Duty Low NOx," Dec. 12, 2017, https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm.
8. State of California Air Resources Board (CARB), "Draft Technology Assessment: Lower NOx Heavy Duty Diesel Engines," Sept. 2015.
9. Olah, G.A., Goeppert, A., and Prakash, G.K.S., *Beyond Oil and Gas: the Methanol Economy*, Third updated and enlarged edition (Wiley-VCH, 2018).
10. Shih, C.F., Zhang, T., and Li, J., "Liquid Sunshine: Opportunities and Pathways to a Green Future for All," presented at *the Meeting for "Opportunities and Challenges for Methanol as a Global Liquid Energy Carrier"*, Stanford University, July 31-Aug. 1, 2017.
11. Blumberg, P., Bromberg, L., Kang, H., and Tai, C., "Simulation of High Efficiency Heavy Duty SI Engines Using Direct Injection of Alcohol for Knock Avoidance," *SAE Int. J. Engines* 1(1):1186-1195, 2009.
12. Leone, T.G., Anderson, J.E., Davis, R.S., Iqbal, A. et al., "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency," *Environmental Science & Technology* 49(18):10778-10789, 2015, doi:10.1021/acs.est.5b01420L.
13. Lewis, R.A., "High Compression Ratio Turbo Gasoline Engine Operation Using Alcohol Enhancement," MIT thesis, Department of Mechanical Engineering, 2015, http://hdl.handle.net/1721.1/85488.
14. Jo, Y., Bromberg, L., and Heywood, J., "Optimal Use of Ethanol in Dual Fuel Applications: Effects of Engine Downsizing, Spark Retard, and Compression Ratio on Fuel Economy," *SAE Int. J. Engines* 9(2):2016, doi:10.4271/2016-01-0786.
15. Mehl, M., Pitz, W.J., Westbrook, C.K. et al., "Kinetic Modeling of Gasoline Surrogate Components and Mixture under Engine Conditions," *Proceedings of the Combustion Institute* 33:193-200, 2011.
16. Heiduk, T., Kuhn, M., Stichmeir, M., "The New 1.8 L TFSI Engine from Audi, Part 2 Mixture Formation, Combustion and Turbocharging," MTZ 07-08/2011, Vol. 72.
17. Jono, M., Taguchi, M., Shonohara, T., and Narihiro, S., "Development of a New 2.0L I4 Turbocharged Gasoline Direct Injection Engine," SAE Technical Paper 2016-01-1017, 2016, doi:10.4271/2016-01-1017.
18. Bunce, M. and Blaxill, H., "Sub-200 g/kWh BSFC on a Light Duty Gasoline Engine," SAE Technical Paper 2016-01-0709, 2016, doi:10.4271/2016-01-0709.
19. Bunce, M., Blaxill, H., Kulatilaka, W., and Jiang, N., "The Effects of Turbulent Jet Characteristics on Engine Performance Using a Pre-Chamber Combustor," SAE Technical Paper 2014-01-1195, 2014, doi:10.4271/2014-01-1195.
20. Partridge, R., Weissman, W., Ueda, T., Iwashita, Y. et al., "Onboard Gasoline Separation for Improved Vehicle Efficiency," *SAE Int. J. Fuels Lubr.* 7(2):366-378, 2014, doi:10.4271/2014-01-1200.
21. Kato. H. Kuzoka K., Kato Y., Chishina H. et al., Research on Engine System Making Effective Use of Bio-Ethanol-Blended Fuels, in *JSAE Annual Congress*, May 24, 2013
22. Kuzuoka, K., Kurotani, T., Chishima, H., and Kudo, H., "Study of High-Compression-Ratio Engine Combined with an Ethanol-Gasoline Fuel Separation System," *SAE Int. J. Engines* 7(4):1773-1780, 2014, doi:10.4271/2014-01-2614.
23. Mizuno, K., Chishima, H., Zhou, J., Carpenter, B. et al., "Study of Alcohol-Gasoline Separation Technology to Suppress Knock and Enable Higher Efficiency Engines," SAE Technical Paper 2018-01-0882, 2018, doi:10.4271/2018-01-0882.
24. Bromberg, L. and Blumberg, P., "Estimates of DI Hydrous Ethanol Utilization for Knock Avoidance and Comparison to a Measured and Simulated DI E85 Baseline," MIT Plasma Science and Fusion Center Report PSFC JA-09-33, http://library.psfc.mit.edu/catalog/reports/2000/09ja/09ja033/09ja033_abs.html.
25. Berni, F., Breda, S., D'Adamo, A. et al., "Numerical Investigation on the Effects of Water/Methanol Injection as Knock Suppressor to Increase the Fuel Efficiency of a Highly Downsized GDI Engine," SAE Technical Paper 2015-24-2499, 2015, doi:10.4271/2015-24-2499.
26. Boehm, M., Maehrle, W., Bartelt, H.-C. et al., "Functional Integration of Water Injection into the Gasoline Engine," *MTZ* 77(01):36-40, 2016.
27. Boehm, M., Durst, B., Unterweger, G. et al., "Approaches for On-Board Water Provision for Water Injection," *ATZ* 118(01):54-57, 2016.
28. Tartakovsky, L. and Sheintuch, M., "Fuel Reforming in Internal Combustion Engines," *Progress in Energy and Combustion Science* 67:88-114, 2018.
29. Poran, A. and Tartakovsky, L., "Influence of Methanol Reformate Injection Strategy on Performance, Available Exhaust Gas Enthalpy and Emissions of a Direct-Injection Spark Ignition Engine," *International Journal of Hydrogen Energy* 42(23):15652-15668, 2017.

Contact Information

Daniel R. Cohn
MIT Energy Initiative E19-319
77 Massachusetts Ave, Cambridge, MA 02139
cohn@psfc.mit.edu

Acknowledgments

This work was supported by the MIT Arthur Samberg Energy Innovation Fund

Definitions/Abbreviations

EGR - exhaust gas recirculation

AJI - Alcohol Jet Ignition

BMEP - Brake mean equivalent pressure (torque divided by displacement volume)

GTDI - Gasoline turbocharged Direct Injection.

GDI - Gasoline direct injection

DI - Direct injection

PFI - Port-fuel injection

g/bhp hr - Grams per brake horsepower hour

TWC - Three way catalyst

SCR - Selective Catalyst Reaction

ISSN 0148-7191