Diesel Engine Alternatives

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ABSTRACT

There are basically three different modes of combustion possible for use in reciprocating engines. These include, diffusion burning, as occurs in current diesel engines, flame propagation combustion such as used in conventional SI engines, and homogeneous combustion such as is used in the SwRI HCCI engine. Diesel engines currently offer significant fuel consumption benefits relative to other powerplants for on and off road applications; however, costs and efficiency may become problems as the emissions standards become even more stringent. This presentation presents a discussion of the potentials of HCCI and flame propagation engines as alternatives to the diesel engines. It is suggested that as the emissions standards become more and more stringent, the advantages of the diesel may disappear. The potential for HCCI is limited by the availability of the appropriate fuel. The potential of flame propagation engines is limited by several factors including knock, EGR tolerance, high BMEP operation, and throttling. These limitations are discussed in the context of potential for improvement of the efficiency of the flame propagation engine.

INTRODUCTION

The heavy-duty vehicle market in the US is currently dominated by the use of the diesel engine. These engines, similar to their light-duty counterparts, are turbo charged, charged cooled, and advanced injection system equipped engines. It is likely that these engines will also be equipped with high-pressure common rail injection systems, or systems with equivalent pressure, injection rate, and multiple injection event capable systems. There are currently very few gasoline-fueled engines in the US heavy-duty fleet.

The vast majority of the fuel is burned in diffusion flames in conventional modern diesel engine. This mode of combustion is characterized by high flame temperature (locally the adiabatic flame temperature), with correspondingly high NO_x formation rates. Also, the heterogeneous diffusion-burning mode leads to elevated pyrolysis reactions in the fuel rich regions, and high soot formation rates. The NO_x and soot formation mechanisms have opposing relationships with the combustion temperatures and there are generally trade-offs in the in-engine emissions control strategies that are used to control these pollutants.

The conventional gasoline spark ignition engine incorporates flame propagation as the primary mode of combustion. In these flame propagation engines the soot formation mechanisms are suppressed and the NO_x formation is dependent on the thermodynamic conditions and the equivalence ratio.

An alternate mode of combustion, Homogeneous Charge Compression Ignition (HCCI), is currently receiving a great deal of attention as a potential low emission, high-efficiency alternative to flame propagation and diffusion combustion. HCCI is characterized by premixing the fuel and air and initiating reaction by compression heating. The reactions are distributed throughout the combustion chamber, so that the local and overall reaction duration is reduced, reaction temperatures are low due to overall lean conditions, and soot formation reactions are suppressed due to premixing of the fuel and air.

It is felt that all three modes of combustion, diffusion burning, flame propagation, and homogeneous combustion, must be considered when planning future low-emissions vehicle systems. **It is very important, however, that the various technologies be compared at the same tail pipe emissions level and same cost.** Fuel selection may become less clear in the future low emissions engines. For instance, some modes of operation in GDI (gasoline direct injection) involve diffusion burning. HCCI engine development is progressing using both gasoline and diesel fuel. Flame propagation engines may represent the most restrictive selection in terms of the fuel use due to ignition and knock issues.

FLAME PROPAGATION ENGINES

Southwest Research Institute (SwRI) has been working on all three modes of combustion. The Clean Diesel Consortium, including the newly initiated Clean Diesel IV, have focused on diffusion combustion (diesel) engines and HCCI. In addition, recent experiments at SwRI have focused on defining the advantages, limits, and potential of gasoline flame propagation engines. The work was performed in a single cylinder, Caterpillar 3501 engine. This is a very large bore engine (3 liter/cylinder) that was first converted to natural gas, and then to PFI gasoline operation. The engine was equipped with both a conventional spark ignition system as well as a direct injection micro-pilot injection system. The engine set-up also included an external compressor and engine backpressure control system that were used to simulate turbo charging. A high-pressure EGR system was also installed on the engine and several camshafts were available for a variety of Miller Cycle options. Figure 1 is a schematic of the engine test set-up.

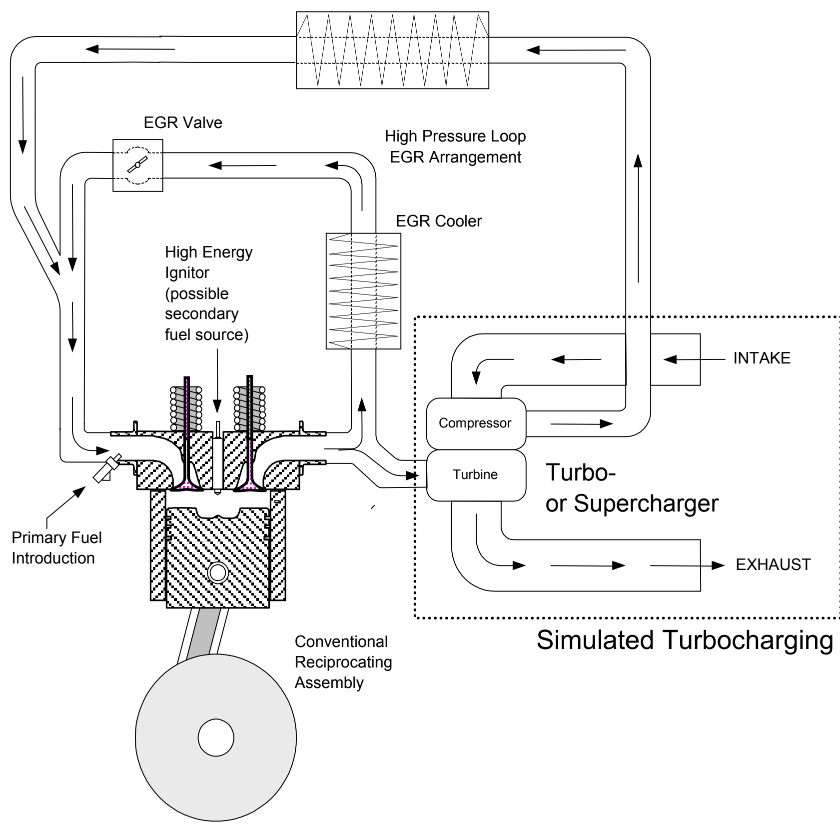

Figure 1. Schematic of Caterpillar 3501 Test Engine Set-up

As noted in the figure, the turbo charger was simulated using an external compressor and a backpressure control valve. In all cases that pressures were adjusted appropriately to account for a 65 percent efficient turbo charger. The intake and exhaust manifold pressures were thus adjusted to account for the turbocharger work.

The cam shaft and piston selections used for these experiments provided a geometric compression ratio of 15:1 and LIVC Miller Cycle compression ratio of 10:1. Operation on the conventional spark ignition system displayed the typical limitations of knock tolerance as BMEP was increased, and combustion stability as EGR was added to provide for wider knock tolerance. These limitations were dramatically improved as the operation was changed to operation on a micro-pilot of diesel fuel, where the diesel fuel micro-pilot served the function of a high-energy ignition system. In all cases, the micro-pilot quantity was limited to less than 1 percent of the total energy input. All test results reported here were for an engine speed of 1200 rpm.

Figure 2 is a plot of the engine thermal efficiency and NO_x emissions as functions of the BMEP level. As can be seen the single-cylinder efficiency ranges up to 35 percent at NO_x levels of 0.06 g/hp-hr, as compared to the base line gasoline engine, with an efficiency of 30 percent and a NO_x level of 0.4 g/hp-hr. This represents a 17 percent improvement through the use of massive EGR combined with the use of a high-energy ignition system. The high-energy ignition is needed to ignite the highly diluted mixture, with up to 40 percent EGR, as can be seen in Figure 3. Engine power output and power density were maintained through the use of high boost as the EGR level was increased.

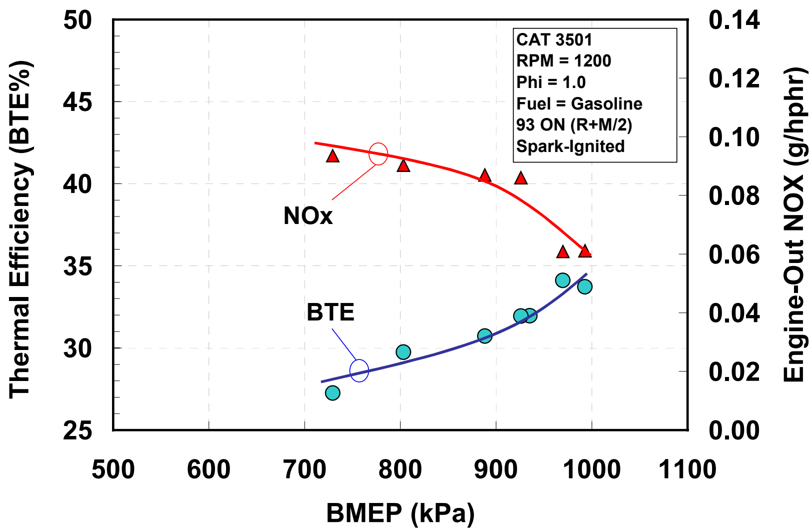

Figure 2. Thermal Efficiency and Engine-Out NO_x Emissions as Function of the BMEP Level

Also plotted in Figure 3 are the Coefficient of Variation (COV) of the IMEP, a measure of engine combustion stability and the unburned hydrocarbon emissions. As can be seen both measures of the engine combustion stability and combustion efficiency are well within the acceptable ranges.

The results from the single cylinder engine experiments have been extrapolated to a multi-cylinder prediction using a Caterpillar supplied correlation for the 3500 engine. This correlation is based on comparisons that Caterpillar have made between the single and various multi-cylinder versions of the 3500 engine. The results of these predictions are presented in Figure 4, where it can be seen that 39 percent efficiency is predicted in the multi-cylinder engine.

The results of these experiments indicate that relative simple changes can be made to the base engine to allow for achievement of the targeted efficiency improvements and the engine out NO_x emissions. It should be noted, however, that there are other issues that must be considered, including the increased heat rejection requirements that will be imposed by switching from diffusion combustion to flame propagation mode. The exhaust temperatures will also increase, so that exhaust valve and head durability will be issues. Knock tolerance is a significant limiting factor in all flame propagation engines, and while it was addressed in the work reported above through the use of massive EGR, it necessitates the use of high-energy ignition. While port fuel injection was used in the SwRI work, better knock tolerance may be achieved and the requirements on the ignition system may be mitigated through the use of direct in-cylinder fuel injection.

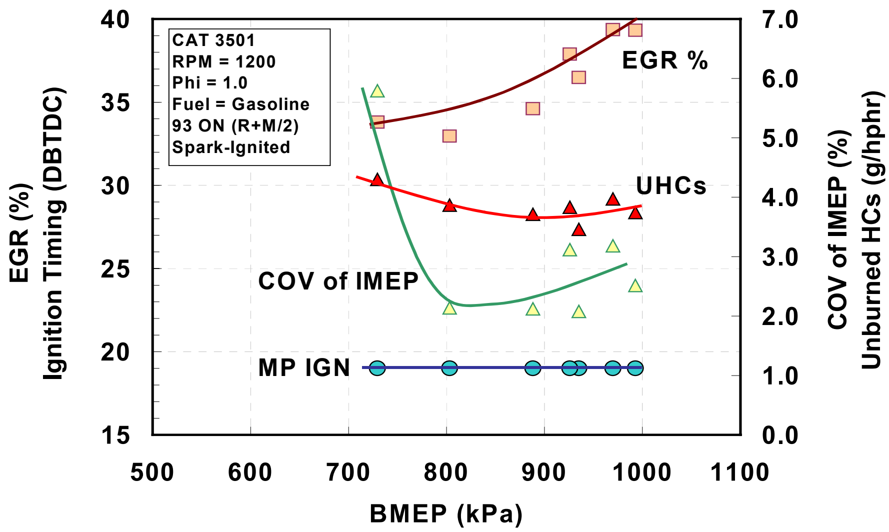

Figure 3. EGR, Ignition Timing, COV of IMEP, and Unburned Hydrocarbons versus BMEP

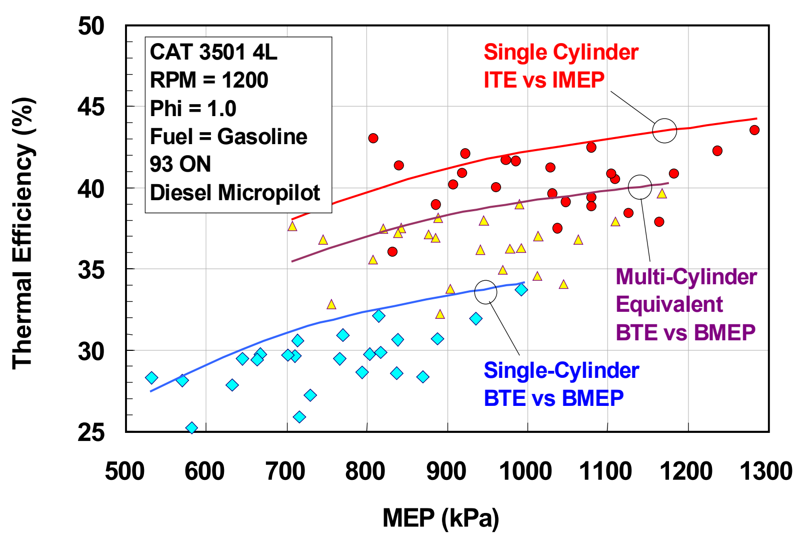

Figure 4. Thermal Efficiency versus BMEP for Single and Multi-Cylinder Engine

DIFFUSION BURN ENGINES

In Clean Diesel IV, SwRI is working aggressively on the development of both diffusion burn and HCCI engines. The main issues with diffusion burn engines are those associated with application of post combustion control systems in these lean burn engines. Particulate emissions (PM) must be controlled using some form of catalyzed PM trap. These devices affect the fuel consumption through the effect on engine backpressure, as well as through the effects associated with active trap regeneration. Lean NOx control poses even more serious problems, whether SCR, lean NOx catalysts, or lean NOx adsorbers are used. The lean NOx problems are associated with accomplishment of the NO reduction reactions in the oxygen rich exhaust of a diesel engine. The lean NOx adsorber and lean NOx catalyst technologies have significant fuel consumption penalties associated with the creation of a reducing atmosphere. Urea SCR has the lowest fuel consumption penalty of the available after treatment technologies, but this approach requires the use of urea, which must be supplied to the vehicle in proportion to the fuel consumption. It should also be remembered that the engine out emissions must be very low, for all three systems, in order to achieve the required 2010 level. Aggressive injection timing and EGR schedules are required to meet the low engine out levels needed for 90 percent effective after treatment systems. So in addition to the direct impact of the after treatment system on the engine efficiency, the required timing and EGR strategies will also have a significant effect on the fuel consumption. If the standards become more stringent than the current Tier II on-road light-duty, the 2010 heavy-duty on-road, and the Tier 4 off-road standards, the engine-out emissions requirements and the after treatment efficiency requirements will become even more severe.

The emissions-efficiency trade-off analyses for diesel and gasoline engines are shown schematically in Figure 5. This figure represents a best estimate of the fuel consumption of future diesel and gasoline engines. The diesel line (shown in red) shows an increase in fuel consumption of about 5 percent in going from the 1998 emissions levels to the required 2004 level. This agrees fairly well with fleet operator observations. The projection for 2010 is another 15 percent, if it is assumed that lean NOx adsorber technology is used for NOx control. The slope of the line changed very quickly as the standards become more stringent. In addition to significant fuel consumption penalties, these future diesel systems will also be much more expensive.

The current gasoline engine technology can already meet the future emissions requirements. It is felt that gasoline engines can be developed which have competitive fuel consumption and durability to the diesel engine at the same emissions level. These engines will also offer significant cost savings over the comparable diesel engine system. The estimated cost increases for future diesel engines are presented in Tables 1 and 2, for medium and heavy-duty diesel engines, respectively.

Table 1. Estimates of Cost Increases for Various Emissions Technology Medium Duty Engines

Technology	2002/2004	2007	2010	2014
VGT/Boost	500	1500	1500	1500
EGR Valve	150	150	150	150
EGR Cooler	200	200	200	200
Advanced Injection	500	500	500	500
Variable Valves	NA	NA	700	1200
PM Filter	NA	1800	1800	1800
LNT	NA	NA	1800	2000
Controls	300	300	400	800
Actuator/Sensors	200	250	350	500
TOTALS	$1850	$4700	$7400	$8650

Table 2. Estimates of Cost Increases for Various Emissions Technology Heavy Duty Engines

Technology	2002/2004	2007	2010	2014
VGT/Boost	700	2100	2100	2100
EGR Valve	300	300	300	300
EGR Cooler	300	300	300	300
Advanced Injection	600	600	600	600
Variable Valves	NA	NA	800	1300
PM Filter	NA	3600	3600	3800
LNT	NA	NA	3600	4000
Controls	300	300	400	800
Actuator/Sensors	200	250	350	500
TOTALS	$2400	$7450	$12,050	$13,700

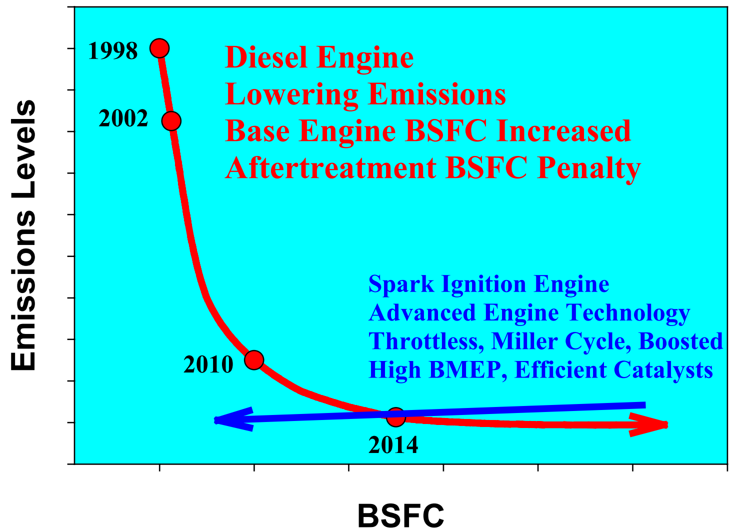

Figure 5. Emissions versus BSFC Trade-Off for Future Diesel and Gasoline Engines

As can be seen in the tables, estimated cost increases for the beyond 2010 medium and heavy-duty diesel engines are $8650 and $13,700, respectively. Using a DaimlerChrysler V-10 gasoline engine as the basis, the corresponding cost increase for a comparable medium duty gasoline engine is estimated to be $2200. A similar estimate was not possible for the heavy-duty application because there are currently no heavy-duty gasoline engines available to use as a basis.

One very interesting potential improvement for diffusion burn engines (diesels) was presented by EPA at the 2002 MIT Workshop. In this concept the engine is equipped with the catalyzed diesel PM trap and a low-pressure loop EGR system. The engine is operated at all conditions with very high levels of EGR. The results are very low level of both NOx and PM. The NOx map is presented in Figure 6.

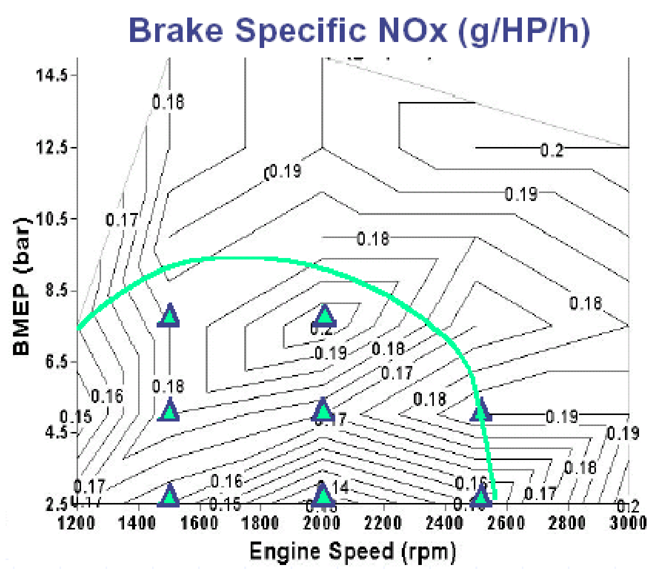

Figure 6. NOx Map for a Light Duty Diesel Engine Run with High Levels of EGR

This concept was modeled using an SwRI cycle simulation code to estimate the potential NOx and BSFC levels on these massive EGR engines. The modeling work was based on a Caterpillar 3176 engine for which a large database of AVL 8-Mode emissions data existed. The engine was equipped with a low-pressure loop EGR system and the baseline EGR levels set to meet the 2.5 g/hp-hr NOx+HC emissions level. The actual engine emissions database used to verify the operation of the NOx prediction in the cycle simulation code. Various levels of EGR and boost pressure were modeled. The following combinations of conditions were examined:

- Baseline - Good Prediction of Existing Data
- Baseline A/F and Timing + EGR + Boost
- Baseline Timing + A/F=25:1 + EGR + Boost
- A/F=15:1 + EGR + Boost + Timing Advance

The predicted NOx and BSFC are presented in Figure 7. As can be seen the model provided a good prediction of the baseline NOx level. In addition, the results indicate that the very low NOx levels could be achieved, with very acceptable BSFC levels, if very high levels of EGR can be used.

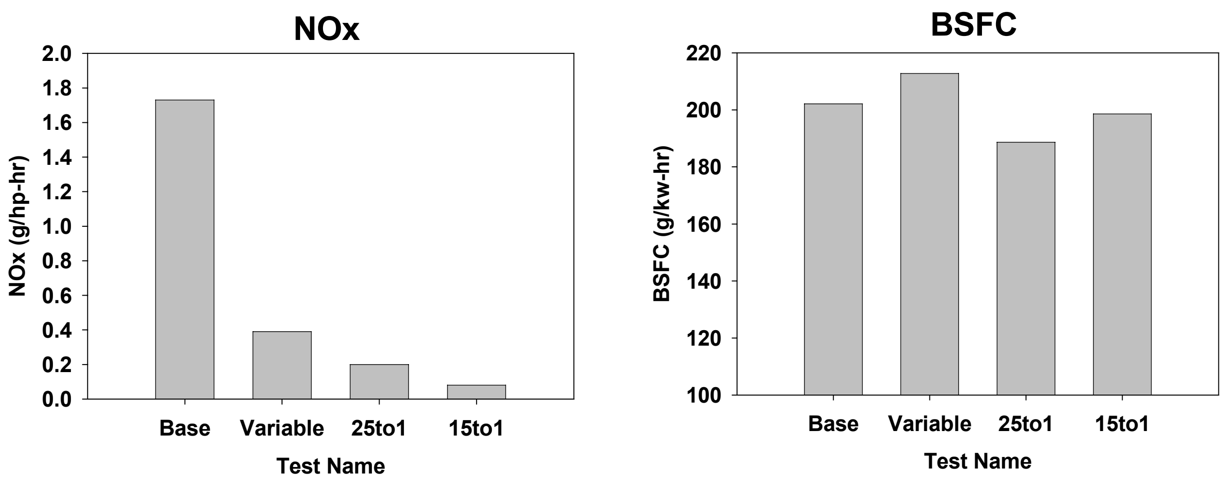

Figure 7. Predicted NOx and BSFC Levels using Various EGR Strategies

HCCI (Homogeneous Charge Compression Ignition)

HCCI is a very promising engine combustion mode. In this reaction mode the fuel and air are premixed and the mixture is compressed until reaction is initiated due to compression heating. It is the one mode of reacting fuel that offers the potential for both low NOx and low PM emissions, with the added benefit of potential fuel consumption lower than a conventional diesel. SwRI has been developing various HCCI engine concepts for the past several years, with basically two concepts evolving. One approach is to use conventional fuel, such as diesel and to use HCCI at light load, with a switch to conventional diesel operation at high load. This offers the opportunity to use low emission HCCI at the light load condition where the exhaust temperatures are too low for proper operation of either LNT or SCR systems. This concept is shown graphically in Figure 8.

The second concept involves the parallel development of a specific fuel for HCCI engine operation and a full time HCCI engine. In this approach the fuel is being tailored in conjunction with the engine development to arrive at the optimum engine-fuel combination. It is the opinion of the author that full time HCCI operation will be possible only if an HCCI specific fuel is developed. Figure 9 shows a sample of the cylinder pressure trace from a single-cylinder development engine operating at 11.3 bar on one of the test HCCI fuels. Recent additional engine and fuel optimization has allowed expansion of the operating range to loads in excess of 17 bar.

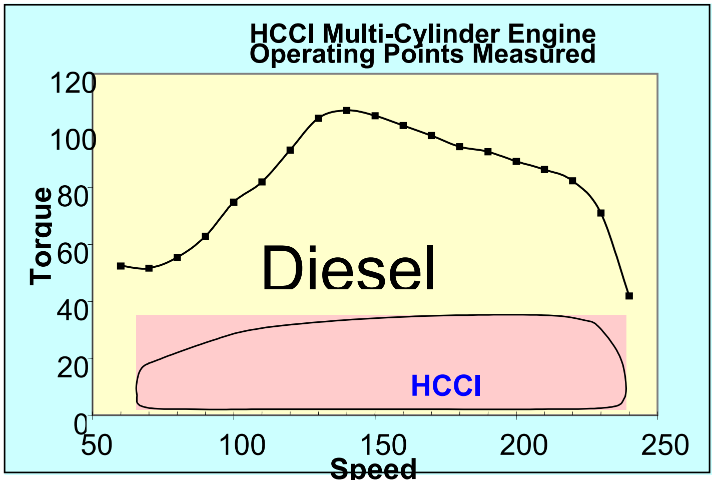

Figure 8. Mixed Mode HCCI-Diesel Engine Torque Curve

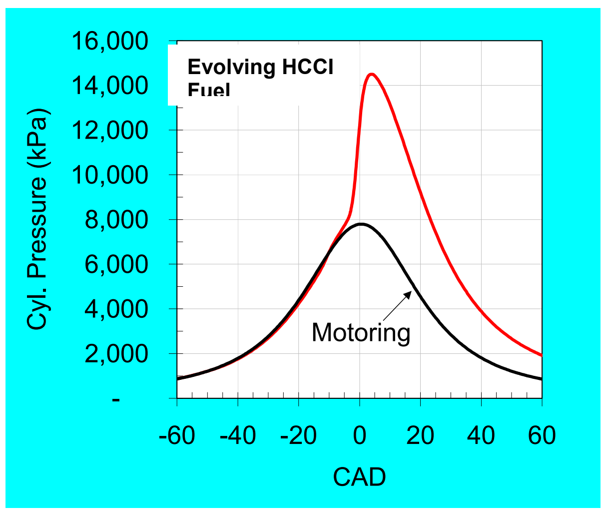

Figure 9. HCCI Engine-Fuel System Operating at 11.3 Bar MEP

SUMAMRY

The following observations are the key points of this paper:

- All Modes of Combustion Must be viewed as Potential Options for Meeting Future Emissions Standards

- Diffusion Combustion Engines are Likely to Become Less Efficient and More Expensive
  - Aggressive EGR May Help

- Flame Propagation Combustion Engines can Become More Efficient and More Durable

- Full Time HCCI Engines will Become Practical When there is a Specific HCCI Fuel