Progress in Light-Duty OPGCI Engine Design and Testing

Reed Hanson, Sebastian Strauss, Fabien Redon and Ashwin Salvi

Achates Power Incorporated, San Diego CA, USA

Abstract

The Achates Power Opposed-Piston Engine architecture provides fundamental advantages that increase thermal efficiency over current poppet valve four-stroke engines. In this paper, an overview of the status of the current light-duty opposed-piston engine project is given along with preliminary gasoline compression ignition (GCI) combustion engine test data.

By using GCI in the opposed-piston engine, significant NO_x and soot reductions can be seen compared to current compression ignition engines at similar thermal efficiencies.

The initial results show that encouraging combustion efficiency, load, stability, noise and thermal efficiency can be achieved by applying GCI to the opposed-piston engine.

Keywords: GCI, opposed-piston engine, emissions, efficiency

Introduction

Opposed-piston, two-stroke engines were invented in the 1800's in Europe and subsequently developed for a wide variety of applications ranging from aircraft to light and heavy-duty vehicles and prime movers for power generation [1-7].

Initially developed for easy manufacturability and high power density, opposed-piston (OP) two-stroke engines have demonstrated superior fuel efficiency compared to their four-stroke counterparts.

The general benefit of the OP Engine is the lower heat transfer losses due to reduced surface area to volume ratio, resulting from the elimination of the cylinder head, thus producing more indicated work. Secondary benefits are the simpler engine design and reduced part count.

Because of these benefits, it is worth revisiting the engine design and developing a modern version utilizing the latest know-how and technologies. The current light-duty (LD) engine project is part of a contract from the U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) to develop a gasoline compression-ignition variant of the Achates Power OP Engine. This project is a collaboration between Achates Power, Delphi Automotive and Argonne National Laboratory (ANL); with Delphi developing the GCI fuel system and ANL providing single cylinder engine (SCE) testing and CFD analysis.

The main and unique aspect of the project is the application of GCI combustion, which is a low temperature combustion mode that uses compression ignition of gasoline, instead of spark ignition. By using compression ignition a higher compression ratio can be used along with lean air-fuel ratios and unthrottled operation, allowing for large increases in thermal efficiency over conventional spark ignition engines. GCI also offers high efficiencies and low emissions due to the low combustion temperatures and has been an ongoing research topic over the last decade in many research laboratories and universities all over the world [8-15].

GCI is being researched because it is possible to simultaneously reduce soot and NO_x emissions while maintaining or even improving indicated thermal efficiency (ITE) over current engines. Conversely, HC and CO emissions are increased compared to current diesel engines, but are on par with spark ignition engines.

Low-load GCI operation has been challenging for conventional engines due to low cylinder gas temperatures, resulting in poor autoignition characteristics. On the opposite side, high-load operation suffers from increased combustion noise due to high cylinder pressure rise rates.

The OP Engine architecture is favorable for GCI because the exhaust residual fraction is larger and can be easily controlled in a much wider range, increasing gas temperatures at low-loads for better ignitability. Additionally, high-load operation can be easier as the peak load BMEP is lower than conventional four-stroke engines.

OPGCI Engine Overview

The engine discussed in the paper is a LD OPGCI design with three cylinders and 2.7L displacement, suitable for large passenger vehicles, pickup trucks, SUVs and minivans. A computer rendering of this engine is shown in Figure 1.

Engine specifications are given in Table 1. As can be seen, the engine will feature an 80 mm bore and 177 mm stroke, to give a large stroke to bore ratio of 2.2 for reduced heat transfer losses. The compression ratio will be similar to current LD four-stroke diesel engines at 16.1:1.

Table 1 OPGCI engine specifications

Number cylinders	#	3
Bore	mm	80
Stroke	mm	177
S/B	-	2.2
Displacement	L	2.7
Compression Ratio	-	16.1
Rated Power	kW	200
Rated Torque	Nm	650

Figure 1 Rendering of the light-duty OPGCI engine

The OPGCI engine is targeted to achieve 200 kW (270hp) and a peak torque value of 650 Nm, as shown in Figure 2.

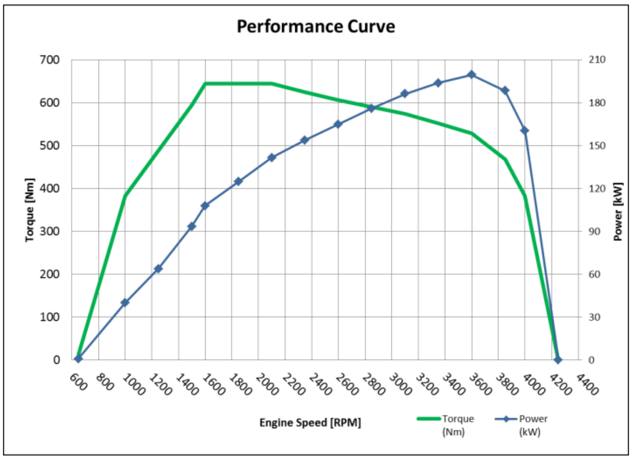

Figure 2 OPGCI engine torque and power curves

OPGCI Engine Design

Another unique feature of the OP Engine is that there are two separate crankshafts that are connected and synchronized to send power to the transmission. For the OPGCI engine, a three-gear system is used to keep the friction losses to a minimum by limiting the number of gear meshes, as shown in Figure 3. Additional friction reducing technologies, such as a variable displacement oil pump and low tension single plane front end accessory drive (FEAD) are used.

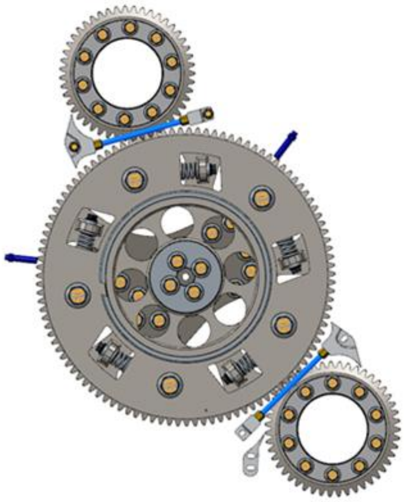

Figure 3 OPGCI engine gear train

While the engine is designed to fit into a light-duty vehicle it retains some features typical of a research engine, such as the removable cylinder liners which are optimized for cooling to manage thermal loads at peak output.

OPGCI Engine Air System

The air system of the OPGCI engine is also unique compared to standard four-stroke engines. The OPGCI engine will utilize both a roots-style supercharger, required for low-load scavenging, and a variable geometry turbocharger.

The engine will also feature a hybrid high and low pressure EGR system for maximum flexibility in achieving low pumping losses while delivering the desired EGR rate.

Finally, the engine will feature an aftertreatment system capable of meeting the project target of US Tier3 Bin125 emissions, meaning 125 mg/mile for HC+NO_x over the US FTP75 test cycle, as shown in Figure 4.

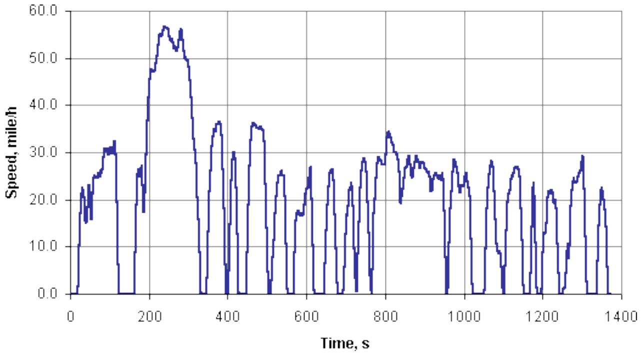

Figure 4 US FTP75 Test cycle speed vs time [16]

The chosen aftertreatment system will feature a pre-turbo oxidation catalyst for fast warmup and to reduce HC from GCI combustion. After that is a second high efficiency oxidation catalyst, then an ammonia based SCRF for NO_x and soot reduction. The complete system diagram is shown in Figure 5.

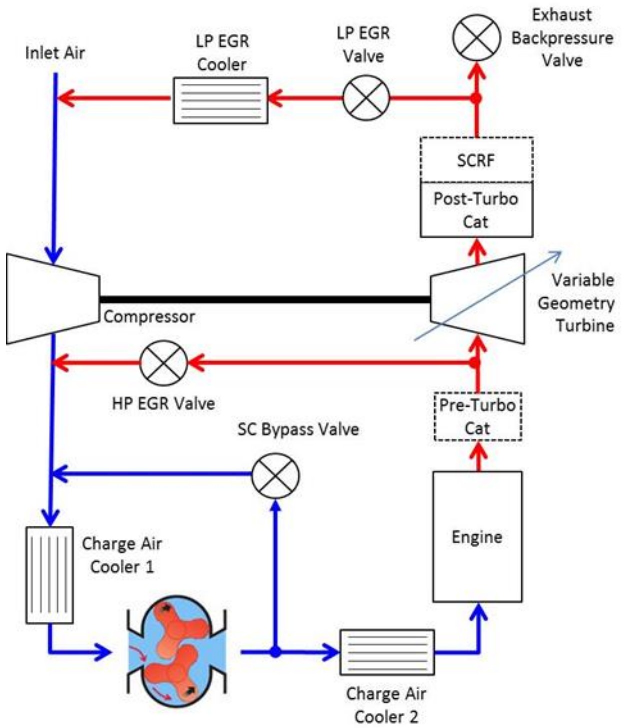

Figure 5 OPGCI complete airsystem diagram

OPGCI Fuel System

The fuel system is also unique to the OPGCI engine. The OP Engine configuration enables an advantageous fuel injector layout. Two diametrically opposed injectors are used for increased fuel spray control, achieving peak combustion performance over the operating map of the engine. The OPGCI engine will utilize two independently controlled fuel rails by two separate fuel pumps so that the fuel pressure can be varied between injectors. The system is capable of 2500 bar using the two unit pumps. Significant work is being conducted to optimize the injector spray geometry for the common rail injection system. The complete fuel system is shown in Figure 6.

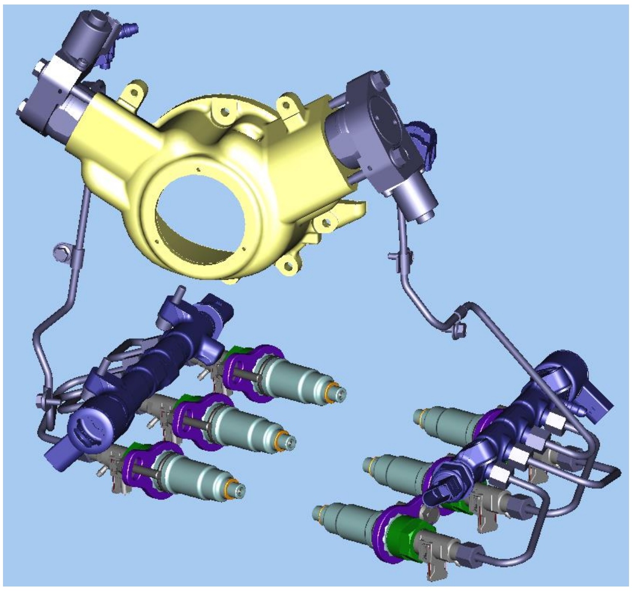

Figure 6 OPGCI fuel system

ANL Engine Test Cell

In order to get combustion results ahead of the OPGCI engine build, the 1.64L Achates Power single cylinder engine (SCE) was set up at ANL for initial GCI combustion testing. This engine has been well studied and is used for combustion and power-cylinder development testing at Achates Power. The SCE specifications are shown in Table 2.

Table 2 API SCE Specifications

Number cylinders	#	1
Bore	mm	98.4
Stroke	mm	215.9
S/B	-	2.2
Displacement	L	1.64
Compression Ratio	-	15.4

The SCE is connected to an AC dyno for load control. The soot emissions are measured by an AVL 415S smoke meter and the gaseous emissions by a five gas AVL i60 bench.

Due to the prototype nature of the SCE, the EGR and engine coolant are provided by external carts that can give the same conditions as a full multi-cylinder engine (MCE).

The fuel flow rate is measured by a ReSol system, which has a Coriolis type flow meter. The airflow is measured by choked flow orifice rack system. Finally, the fuel injection system is controlled by a National Instruments system. The current fuel injection system is a common rail with 1800 bar maximum fuel pressure. For gasoline use, a lubricity

additive is mixed with the fuel and there is a max pressure limit of 1200 bar for component durability.
The fuel used in the project is a certification gasoline based on US Tier3 commercial fuel specifications. This fuel is an E10 blend with 87 AKI ((RON+MON)/2) and low sulfur. Fuel specifications are shown in Table 3.

Table 3 E10 Fuel Specifications

Fuel		Gasoline
Ethanol	%vol	10
RON	-	91
MON	-	83
AKI	-	87

Preliminary GCI Results

In the US, the FTP75 test is used to regulate LD vehicle emissions and fuel economy. This test has operating conditions from idle to 5 bar IMEP. A 10-mode steady state approximation of the FTP test is used to give an estimation of the cycle averaged results, similar to [17]. The selected 10 modes are shown in Figure 7, with the power-weighting indicated by the size of the data markers. As can be seen, light-duty vehicles operate mostly at low-loads. Air system boundary conditions and initial fuel injection parameters were investigated by both 1-D and 3-D CFD modeling.

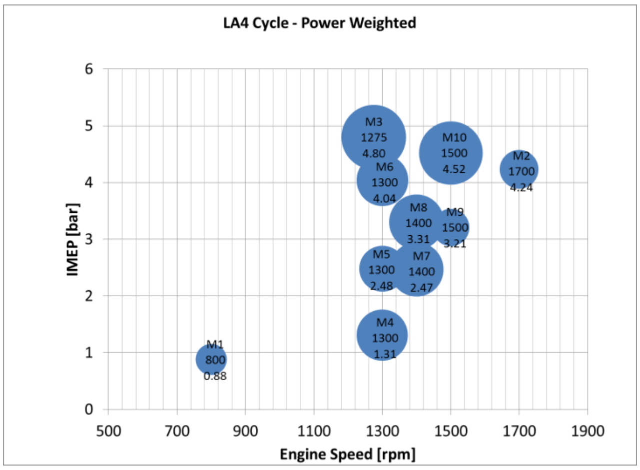

Figure 7 10 mode points used to simulate operation of a LD vehicle on the US FTP75 certification cycle

Typically, these types of loads are challenging for GCI, as four-stroke engines have low intake temperatures and low internal exhaust residual, which makes autoignition of low cetane number fuels (like gasoline) difficult. Because of this, GCI combustion at low-loads is typically highly premixed and loud, making noise, vibration and harshness (NVH) requirements difficult to meet. LD vehicles are very sensitive to NVH requirements for customer acceptance.
The OPGCI engine can offer significant improvements in low-load efficiency and combustion noise over conventional four-stroke engines due to the increased flexibility in the trapped exhaust residual fraction. By using a high internal residual fraction, combustion efficiency for the OPGCI engine is >96% over a broad range of IMEP, as shown in Figure 8. These test points are the same ones used in Figure 7. This efficiency is very good for GCI, as four-stroke GCI typically has less than 95% combustion efficiency [15]. OPGCI combustion efficiency further increases as loads and combustion temperatures increase.

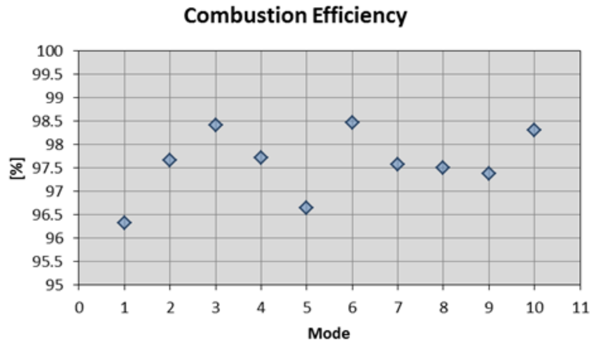

Figure 8 Combustion efficiency of LD operating points on the 10 mode cycle approximation

Figure 9 shows ITE over the FTP loads. As can be seen, the ITE quickly approaches 48%, which is significantly higher than spark ignition and equal to diesel combustion in this engine. These promising results are achieved with a combustion system originally designed for diesel mixing-controlled diffusion-flame combustion. Combustion system optimization will be conducted to further increase ITE and combustion efficiency.

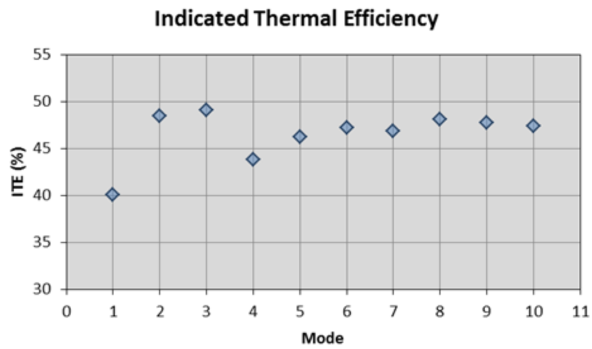

Figure 9 Indicated thermal efficiency of LD operating points on the 10-mode cycle approximation

Mode 1

For the 10-mode light-duty cycle approximation, the idle point (Mode 1) is heavily time-weighted, so it is of interest to get good efficiency and emissions there in terms of improving the cycle average.

As shown in Figure 7, mode 1 is 800 rpm and 1 bar IMEP for an MCE, however the SCE cannot be operated below 1100 rpm due to driveline design limits, so the simulated idle condition is 1100 rpm and 1 bar IMEP for the SCE.

Boundary conditions used for the SCE tests were similar to diesel conditions in the same engine, which were generated from simulations to account for real turbomachinery and their associated pumping losses. The intake pressure was slightly above ambient to achieve scavenging and the charge temperature was kept at the same level as the diesel baseline operating conditions.

Typically, low intake temperatures (<80 deg C) are not possible for four-stroke GCI as gasoline fuel needs 40-60 deg C higher temperature than diesel fuel to achieve autoignition. By using high internal residual fractions (>50%), which are available with the OP Engine, autoignition of gasoline can be achieved with 40 deg C intake temperature. On top of the internal residual, external EGR can be further added to control the NO_x emissions.

Figure 10 shows the cylinder pressure and HRR for the mode 1 condition. As can be seen, all the fuel was injected before combustion, typical of GCI, resulting in low soot and NOx emissions. The combustion is able to be phased near minimum volume for high ITE as combustion noise was below the target value.

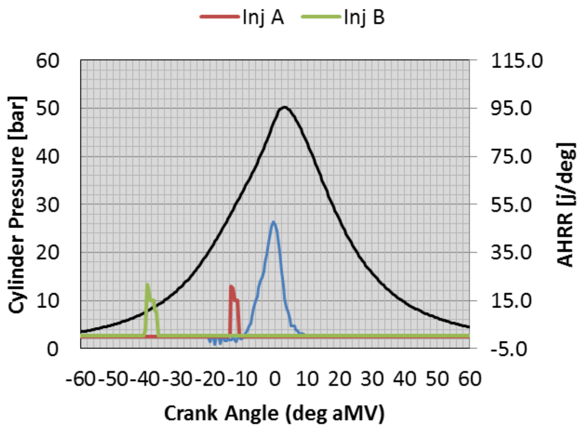

Figure 10 Mode 1 cylinder pressure, AHRR and injector current traces

The injection strategy used was an early pilot/early main strategy, determined via engine testing and CFD. An early pilot injection is used to premix part of the charge for reduced soot and NO_x emissions. The main injection is then used to control CA50. Since the ignition delay of gasoline is longer than diesel, this injection strategy allows for all the fuel to be injected before combustion starts. Mode 1 engine operating conditions are shown in Table 4. It is interesting to note that the pilot injection was performed by one injector and the main by the other injector, allowing for better injection quantity control at this low-load condition.

Table 4 Mode 1 operating conditions

Pilot SOI	deg aMV	-40
Main SOI	deg aMV	-14
Pilot fraction	%mass	60
Rail pressure	bar	250
Int Temperature	deg C	38
Int Pressure	bar	1.07
Int residual fraction	%	56.6
Ext EGR	%	35.4
AFR_delivered	-	32.9

Emissions and efficiency are shown in Table 5. At mode 1, the premixed charge and EGR resulted in low NO_x and soot emissions. HC and CO emissions were increased relative to diesel combustion, but were low compared to literature values for GCI, which can be as high as 5 g/kWh.

With combustion efficiency above 96%, which is high for GCI combustion at low-loads, HC and CO emissions were well controlled. Combustion noise is also of importance for light-duty vehicles for customer acceptance, the OPGCI engine had 75 dBa at mode 1, which is well below the targets set for the program. Combustion stability is also of interest as low-load GCI has typically had poor combustion stability. OPGCI results show to have good combustion stability with a standard deviation of 2.5 kPa IMEP. Finally, ITE of this idle condition is similar to diesel levels in this engine at 39%.

Table 5 Mode 1 emissions and efficiency

NO_x	g/kWh	0.6
HC	g/kWh	1.9
CO	g/kWh	22.3
Soot	FSN	0.02
CNL	dBa	75.4
MPRR	bar/deg	1.8
ITE	%	39
Comb efficiency	%	96.1

Mode 8

The next point of interest is mode 8, because it is in the middle of the FTP points (Figure 7) and is a good approximation for the rest of the FTP points. Mode 8 is 3.1 bar IMEP at 1400 rpm. Similar to mode 1, the AFR, EGR, intake pressure and temperature were set to the same values as with the diesel OP Engine. As shown in Table 6, there was less internal residual needed for ignition than mode 1. The external EGR

rate is similar to mode 1, which gives an indicated NOx emissions value of 0.6 g/kWh.
Figure 11 shows the cylinder pressure and HRR for the mode 8 condition. As with mode 1, all the fuel was injected before combustion, resulting in low soot and NO_x emissions. The combustion is also able to be phased near minimum volume for max ITE as combustion noise was acceptable.

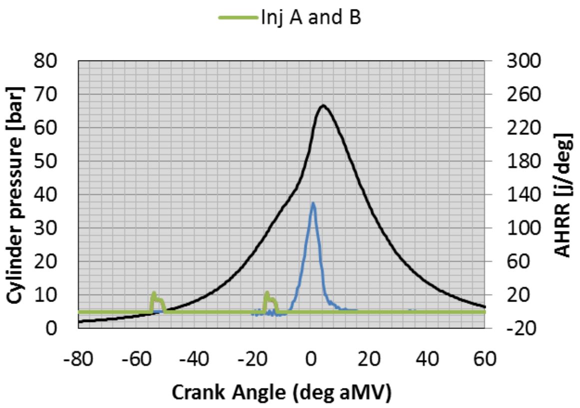

Figure 11 Mode 8 cylinder pressure, AHRR and injector current traces

Mode 8 also used a double injection strategy. The pilot injection timing was slightly earlier than mode 1 to give more time for premixing. Rail pressure was also increased over mode 1, but is slightly lower than what would be expected from a diesel engine.

Table 6 Mode 8 operating conditions

Pilot SOI	deg aMV	-55
Main SOI	deg aMV	-16
Pilot fraction	%mass	55
Rail pressure	bar	500
Int Temperature	deg C	40
Int Pressure	bar	1.07
Int residual fraction	%	25.5
Ext EGR	%	32.1
AFR_delivered	-	28.1

Table 7 shows the emissions and efficiency at mode 8. Here the target values of NO_x+HC <5 g/kWh were also met. Soot was also very low <0.1 FSN and combustion efficiency increased to 97.7% due to the higher temperatures from the higher load.
Combustion noise was also within target values set for light-duty vehicles. ITE was increased over idle at 47.6% and the EGT was higher at 282 deg C.

Table 7 Mode 8 emissions and efficiency

NO_x	g/kWh	1.18
HC	g/kWh	1.84
CO	g/kWh	8.0
Soot	FSN	0.03
CNL	dBa	86.9
MPRR	bar/deg	4.2
ITE	%	47.6
Comb efficiency	%	97.7

High-load

The final point in the paper is a high-load point at ~75% load (1380 rpm, 10.9 bar IMEP). This point is of interest as high-load low-speed operation is typically difficult for GCI to meet for noise targets. Autoignition tends to be too rapid, with combustion occurring a small crank angle window, giving high audible noise. However, GCI combustion using late injections can allow for high-loads with acceptable combustion noise. Table 8 gives the operating conditions for the high-load condition.

Table 8 High-load operating conditions

Pre SOI	deg aMV	-80
Pilot SOI	deg aMV	-50
Main SOI	deg aMV	-8
Pilot fraction	%mass	20
Rail pressure	bar	1200
Int Temperature	deg C	37
Int Pressure	bar	2.16
Int residual fraction	%	11.2
Ext EGR	%	30.5
AFR_delivered	-	28.2

At the higher load, lower internal residual fraction was needed than at lower loads as the gas temperature was high enough to achieve ignition. Slightly less EGR was needed than the other two conditions since NO_x emissions targets are more relaxed at these elevated loads in light-duty applications.
Figure 12 shows the cylinder pressure and heat release rate for the high-load condition. Here the triple injection strategy can be seen, where most of the fuel is injected after combustion has started, unlike the other low-load conditions. While this is undesired from a NO_x and soot emissions perspective, it enables meeting the noise targets. Some other benefits of the late injection strategy include the use of SOI timing for CA50 control, and lower EGR rates for low pumping work and high BTE.

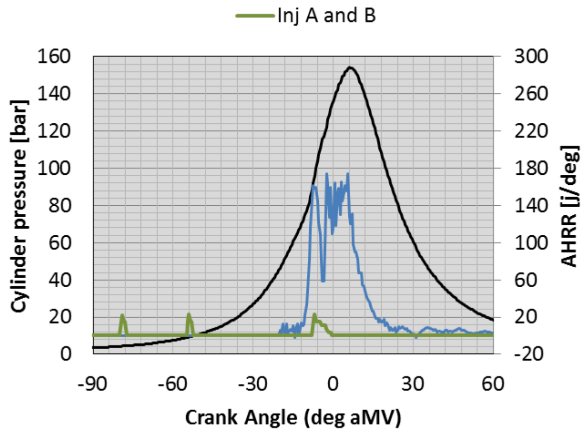

Figure 12 High-load cylinder pressure, AHRR and injector current traces

The goal for GCI combustion is to premix as much fuel as possible for NO_x and soot reduction within combustion noise limits. However, higher trapped gas temperatures at high-load limit the amount of premixed fuel before noise limits are reached. The maximum amount of premixed fuel was seen to be about 20% of the total fuel at this condition. The rest of the fuel was injected near minimum volume to reach the target load within the noise limit of 93 dBa. Late injections require diesel like rail pressures of 1200 bar for low soot emissions.

Table 9 shows the emissions and efficiency results. As with the other load points, the emissions target of NO_x+HC <5 g/kWh was still maintained. CO emissions were also lower than the low-load results due to the higher combustion temperatures, which help accelerate oxidation kinetics, resulting in combustion efficiency of 99%. High temperatures also help increase soot oxidation, and low soot was seen at 0.08 FSN. Exhaust temperatures were 355 deg C.

Finally, due to the optimal combustion phasing and high combustion efficiency, a high ITE of >52% was seen. Such a high ITE is typically seen only in heavy-duty engines and shows the inherent heat transfer advantage of the OP Engine.

Table 9 High-load emissions and efficiency

NO_x	g/kWh	3.1
HC	g/kWh	0.863
CO	g/kWh	2.21
Soot	FSN	0.08
CNL	dBa	90.6
MPRR	bar/deg	8.0
ITE	%	52.4
Comb efficiency	%	99.1

Discussion

Overall, the paper gives a status update of the LD OPGCI project and the highly encouraging GCI engine laboratory testing results from the first rounds of testing with Achates Power's Single-Cylinder Research Engine at ANL.

Note that while these test results have shown very promising results, they are far from final as significant work is in progress to fully optimize the fuel injection strategy, piston bowls, charge motion, etc. The main goal for the paper is to show that it is possible to use GCI over a wide range of operation conditions without requiring any additional hardware or complexity over the base diesel engine. The high efficiency benefit of the OP Engine can already be seen with a retrofitted, un-optimized diesel configuration running GCI.

Additionally, there is also much development work to be done with the MCE air system. Designing and testing of the turbocharger and supercharger machinery to find the best trade-off between pumping work and ITE will be very important to maximize BTE from the LD OPGCI engine.

The next steps will be to design and test an aftertreatment system which will meet project tailpipe steady-state emissions targets. Estimates suggest that commercially available SCR and oxidation catalysts should meet tailpipe emissions targets for the program. Finally, all of this work will be combined to enable transient operation for a full vehicle demonstration of the OPGCI engine.

Conclusions

A light-duty OPGCI engine is being designed to offer high efficiency gasoline operation using compression ignition. Preliminary GCI combustion testing in a single cylinder OP Engine laboratory showed that

1. OPGCI allows high combustion efficiency, even at low-loads
2. OPGCI has acceptable combustion noise, at or below light-duty target levels
3. OPGCI can operate at high-loads with low combustion noise
4. OPGCI has ITE >52% and is comparable to diesel OP Engine combustion for all operating points
5. OPGCI has low NO_x and soot, with acceptable HC and CO emissions and would be compatible with the Bin125 emission targets with conventional aftertreatment systems

Overall, the OP Engine offers a path toward enabling high efficiency and clean GCI combustion in mass production with practical hardware, low combustion noise and low emissions.

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Glossary

AFR	Air fuel ratio
aMV	After Minimum Volume
ANL	Argonne National Laboratory
API	Achates Power Incorporated
ARPA-E	Advanced Research Projects Agency – Energy
BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
CDC	Conventional Diesel Combustion
CFD	Computational Fluid Dynamics
CN	Cetane Number
CNL	Combustion Noise Level
CO	Carbon Monoxide
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FSN	Filter Smoke Number
FTP	Federal Test Procedure
GCI	Gasoline Compression Ignition
HC	Hydrocarbon
HRR	Heat Release Rate
IMEP	Indicated Mean Effective Pressure
ITE	Indicated Thermal Efficiency
LD	Light-duty
MCE	Multi Cylinder Engine

NOx	Nitrogen Oxides
NVH	Noise Vibration Harshness
OP	Opposed Piston
SCE	Single Cylinder Engine
SCR	Selective Catalyst Reduction
SOI	Start of Injection
SUV	Sport Utility Vehicle