New developments for Opposed-Piston Engine

Tailpipe emissions analysis and test results, funded research for gasoline compression ignition

Fabien G. Redon$^{1)}$ **Laurence Fromm** $^{2)}$

1) Achates Power, Inc. 4060 Sorrento Valley Blvd, San Diego, CA, U.S.A. (E-mail: redon@achatespower.com)
2) Achates Power, Inc. 4060 Sorrento Valley Blvd, San Diego, CA, U.S.A. (E-mail: fromm@achatespower.com)

ABSTRACT: The Achates Power Opposed Piston Engine delivers a demonstrable incremental improvement in brake thermal efficiency compared with the most advanced conventional four-stroke engines. With the elimination of components such as the entire cylinder head and valvetrain, the Achates Power OP engine is also less complex and costly to produce.

This paper presents the promising results of new steady-state fuel consumption and transient tailpipe emissions analysis and discusses the advantages of the OP engine as an ideal platform for incorporating gasoline compression ignition (GCI) technology, the study of which recently was funded by the U.S. Department of Energy's Advanced Research Projects Agency–Energy.

KEY WORDS: **Standardized: heat engine, compression ignition engine, emissions gas, fuel injection, fuel spray.** Free: Opposed-Piston Engine, gasoline compression ignition (A1)

1. INTRODUCTION

Achates Power, Inc. (API) has been dedicated to modernizing the opposed-piston engine since its inception in 2004 and has solved various mechanical challenges faced by this engine architecture, including oil consumption, piston cooling, cylinder cooling, and wrist pin lubrication. API also has developed a unique set of performance, emissions and combustion-system control strategies that enable the Achates Power Opposed-Piston Engine (OP Engine) to meet current and future emissions while delivering excellent fuel consumption.

Initial work was conducted on a single-cylinder prototype to minimize cost and complexity and to accelerate turnaround time. In 2014, development and testing was directed to a 4.9L, multi-cylinder engine. Using the multi-cylinder engine, steady-state performance and emission results were generated[2].

In partnership with Johnson Matthey a detailed analysis was performed to confirm that the engine out emissions level is compatible with US EPA2010[6].

With the initial steady-state calibration established, the next step was to demonstrate the transient capability of the engine[1]. It is critical to advance the understanding of the transient behavior of the OP Engine by testing it on transient cycles in order to assess the ability of the engine to match the cycle while maintaining acceptable emissions output. This paper highlights the results from testing the OP Engine on the FTP (Federal Test Procedure), a transient cycle for heavy-duty on-road engines and then compares those results to the HD FTP test figures from the 2011 Cummins ISB 6.7L engine[3,5].

Recently, Advanced Research Projects Agency – Energy (ARPA-E) awarded $9M to Achates Power, Argonne National Laboratory and Delphi Automotive to develop a gasoline compression-ignition (GCI) version of the Achates Power OP Engine. The grant is one of the largest awarded by the ARPA-E in its history.

2. FUNDAMENTAL OP ENGINE ADVANTAGES

2.1. Reduced Heat Losses

The Achates Power Opposed-Piston Engine (OP Engine), which includes two pistons facing each other in the same cylinder, offers the opportunity to combine the stroke of both pistons to increase the effective stroke-to-bore ratio of the cylinder. As a thought experiment, when a two-cylinder conventional engine with 1.1 stroke-to-bore is re-architected as a single-cylinder opposed-piston engine with both pistons operating in the same bore, it results in an opposed-piston engine with 2.2 stroke-to-bore ratio. This can be accomplished while maintaining the engine and piston speed of the conventional four-stroke engine. To achieve the same stroke-to-bore ratio with a conventional four-stroke engine, the mean piston speed would double for the same engine speed.

An additional benefit of the reduced heat losses in the opposed-piston engine, especially for commercial vehicles, is the reduction in fan power and radiator size, further contributing to vehicle-level fuel savings.

2.2. Leaner Combustion

When configuring an opposed-piston, two-stroke engine of the same displacement as a four-stroke engine – for example, converting a six-cylinder, conventional engine into a three-cylinder, opposed-piston engine – the output that each cylinder offers is the same. The two-stroke opposed-piston engine fires each of the three cylinders for every crankshaft revolution, while the four-stroke engine fires each of its six cylinders in one out of two revolutions.

Therefore the amount of fuel injected for each combustion event is similar, but the cylinder volume is more than 50% greater for the opposed-piston engine. So for the same boost conditions, the opposed-piston engine will achieve leaner combustion, which increases the ratio of specific heat. Increasing the ratio of specific heat increases the work extraction per unit of volume expansion during the expansion stroke.

2.3 Quicker and Earlier Combustion at the Same Pressure Rise Rate

The larger combustion volume for the given amount of energy released also enables shorter combustion duration while preserving the same maximum pressure rise rate. The quicker combustion improves thermal efficiency by reaching a condition closer to constant volume combustion. The lower heat losses as described above lead to a 50% burn location closer to the minimum volume.

The aforementioned fundamental opposed-piston two-stroke (OP2S) thermal-efficiency advantages are further amplified by:

- Lower heat loss due to higher wall temperature of the two piston crowns compared to a cylinder head (reduced temperature delta).
- Reduced pumping work due to uniflow scavenging with the OP2S architecture resulting in higher effective flow area than a comparable four-stroke or a single-piston two-stroke uniflow or loop-scavenged engine.
- Decoupling of pumping process from the piston motion because the two-stroke architecture allows alignment of the engine operation with a maximum compressor efficiency plot.

3. EFFICIENCY AND EMISSIONS ENABLERS

3.1 Combustion System

Achates Power has developed a proprietary combustion system[3] composed of two identical pistons coming together to form an elongated and ellipsoidal combustion volume where the injectors are located at the end of the long axis.

This advanced combustion system allows the following:

- High turbulence, mixing and air utilization with both swirl and tumble charge motion with the high turbulent kinetic energy available at the time of auto ignition.
- Ellipsoidal combustion chamber resulting in air entrainment into the spray plumes from two sides.
- Inter-digitated, mid-cylinder penetration of fuel plumes enabling larger $\lambda=1$ iso-surfaces.
- Excellent control at lower fuel-flow rates because of two small injectors instead of a single, higher flow rate.
- Multiple injection events and optimization flexibility with strategies such as injector staggering and rate-shaping.

The result is no direct fuel spray impingement on the piston walls and minimal flame-wall interaction during combustion. This improves performance and emissions with fewer hot spots on the piston surfaces that further reduce heat losses.

3.2 Air System

To provide a sufficient amount of air for combustion, two-stroke engines need to maintain an appropriate pressure difference between the intake and exhaust ports. For automotive applications, which require the engine to change speed and load in a transient manner, external means of air pumping are required; there are various potential arrangements using both a turbocharger and supercharger.

Advantages of such an air system:

- The compressor provides high pressure ahead of the supercharger, which then further boosts intake flow. This means that low supercharger pressure ratios are sufficient for high intake manifold density, reducing pumping work.
- The maximum required compressor pressure ratio is lower compared to turbocharger-only air systems of four-stroke engines.
- The use of a supercharger recirculation valve allows greater control of the flow through the engine, thus providing flexibility for precise control of boost, scavenging ratio, and trapped residuals to minimize pumping work and NOx formation across the engine map.
- Lowering the flow through the engine by decreasing the pressure difference across the engine reduces the pumping penalty at low load points. This, together with having no dedicated intake and exhaust stroke for moving mass to and from the cylinders improves BSFC.
- The supercharger and recirculation valve improve transient response.
- Accurate control of the engine pressure differential provides good cold start and catalyst light off capabilities. Low-speed torque is increased by

selecting the appropriate gear ratios on the supercharger.

- Facilitating EGR with a supercharger reduces the required pumping work.
- Cool air and EGR together reduces fouling of the coolers.

4. TEST BED DESCRIPTION

4.1 Engine Architecture

The multi-cylinder OP Engine platform used to generate the results presented in this paper is heavily based on the single-cylinder OP Engine and shares most of its power cylinder components. **Error! Reference source not found.**Table 1 shows the specifications and the performance attributes for the multi-cylinder OP Engine.

Table 1: Multi-cylinder Achates Power OP engine specification

Displacement	4.9 L
Arrangement, number of cylinders.	Inline 3
Bore	98.4 mm
Total Stroke	215.9 mm
Stroke-to-Bore Ratio	2.2
Compression Ratio	15.4:1
Nominal Power (kW @ rpm)	205 @ 2200
Max. Torque (Nm @ rpm)	1100 Nm @ 1200-1600

Even though this engine was conceived as a research and test-platform, it powered all the accessories that were required to operate it. These accessories included lubrication oil pumps, a high-pressure fuel pump, a supercharger and a supercharger drive and water pumps. In order to provide realistic pumping operation, exhaust pressure was modified in real-time by using a backpressure valve to simulate the aftertreatment system.

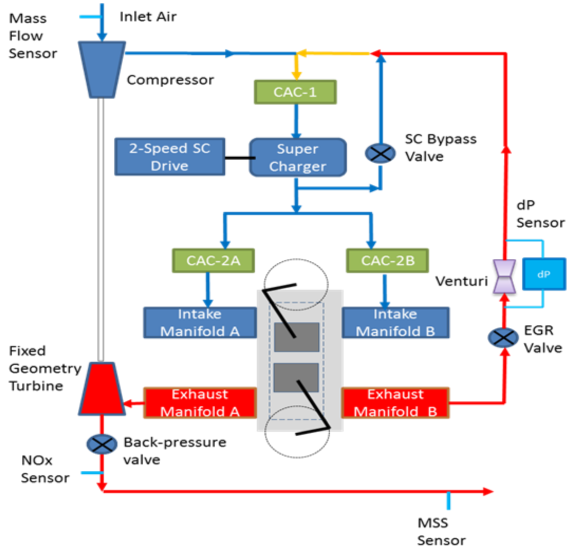

Figure 1: Air Path Schematic

4.2 Steady state engine measurement

As mentioned earlier, the Achates Power A48-316 engine was created as a research platform to quickly iterate through different designs. In creating such a platform, some compromises were made versus how a production engine would be designed.

In spite of the negative impact of the additional friction of the research engine, steady-state fuel consumption measurement for the test engine — while meeting engine-out emissions compatible with US EPA 2010 — is compelling enough to showcase the potential benefits of OP2S engine.

The cycle average BSFC for this data set is 200 g/kWh with best point BSFC of 192 g/kWh. The cycle average results are shown in Table 2.

Table 2: SET cycle average results for A48-316 engine

13 Mode SET Cycle Results		
Cycle Average Results		
BSFC	200	g/kWh
BSNOx	2.58	g/bhp-hr
BSSoot	0.016	g/bhp-hr
BSCO	0.98	g/bhp-hr
BSHC	0.07	g/bhp-hr

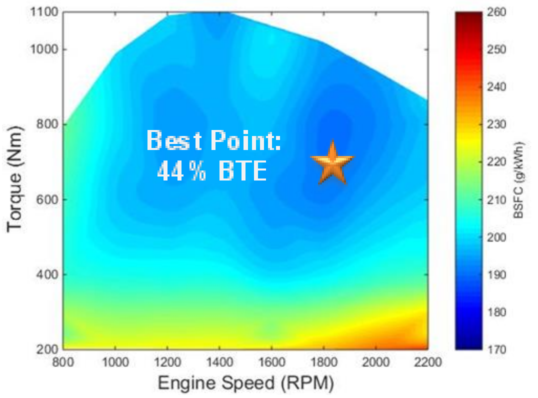

Figure 2: Measured BSFC map of A48-316 engine

Figure 2, 3a and 3b show the fuel, soot and NOx map respectively for the entire torque curve of the engine. The engine has a flat fuel map as can be seen in Fig 3. For the 12 operating modes at A, B and C speed the difference between the best point and cycle average is only 8 g/kWh. A grounds-up design for 4.9L engine with optimized friction and air-handling is expected to deliver 182 g/kWh cycle average BSFC with best-point efficiency of 176 g/kWh.

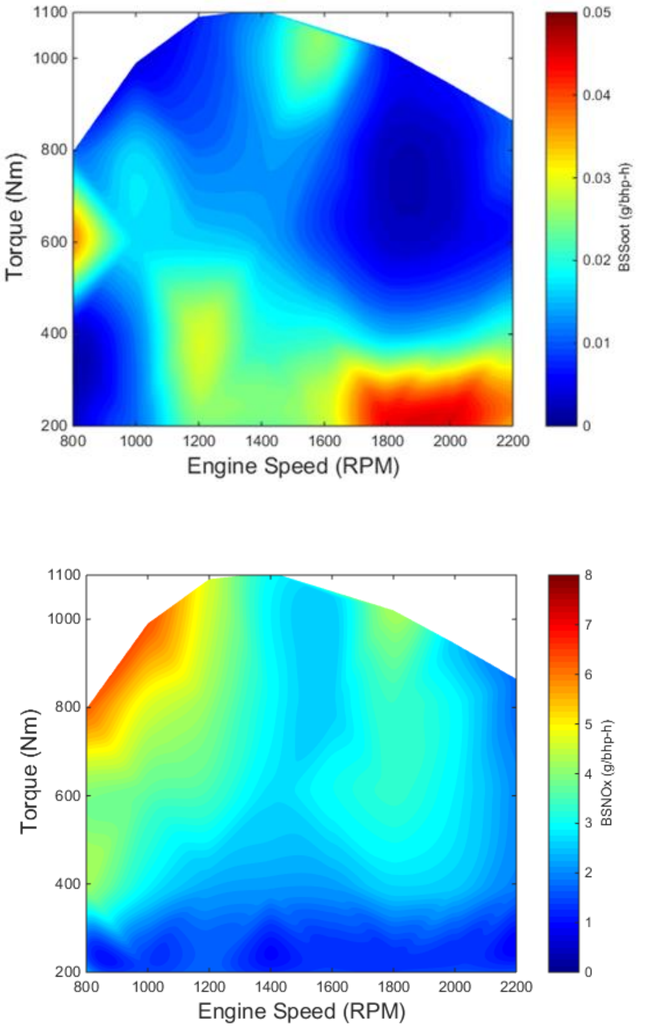

Figure 3: (a) Measured BSSoot in g/bhp-hr for A48-316 engine, (b) Measured BSNOx in g/bhp-hr for A48-316 engine

5. TAILPIPE EMISSIONS ANALYSIS

Engine out emission results from a Supplemental Emissions Test (SET) cycle show that the Achates Power Opposed-Piston Engine has very low CO and HC emissions. The OP Engine's enhanced BSFC, however, means engine-out exhaust temperature can be lower than comparable four-stroke engines, which may challenge the periodic soot removal from the aftertreatment system. However, engine-out NOx is relatively high (~3.5g/kwh), which would assist the passive regeneration of a diesel particulate filter (DPF), leading to balance point. In addition, to meet EPA10 regulation limits, the NOx conversion across the after-treatment system (ATS) should be high.

Johnson Matthey investigated its patented Selective Catalytic Reduction Technologies (SCRT) aftertreatment system – the 4-way emission-control technology suitable for this engine[6].

Fully developed and validated high fidelity models for diesel oxidation catalyst, coated Filter (CSF), SCR (Cu-based) and ASC (Cu-based) formulations have been used in this study.

The results show that more than 96% NOx conversion can be achieved. NH_3 slip from Selective Catalytic Reduction (SCR) during high temperature excursions is oxidized in the Ammonia Slip Catalyst (ASC). The ASC catalyst is a dual layer catalyst with Diesel Oxidation Catalyst (DOC) functionality in the bottom layer and Cu-SCR in the top layer. The selectivity of this catalyst to N_2 is high. However, there will be some NOx remake at high temperatures which may affect the overall (tailpipe) NOx conversion efficiency. The tailpipe NOx emissions are provided in Table 3 which clearly shows that the NOx target limit can be easily reached with the proposed ATS.

Table 3: Engine out and tailpipe emissions for a 13 mode SET cycle

	Engine out (g/kwh)	**Tailpipe (g/kwh)**	
		Case 1	**Case 2**
CO	1.264	0	0
THC	0.102	0.011	0.008
NOx	3.47	0.138	0.120
N_2O	0	0.103	0.112

6. HD FTP CYCLE TRANSIENT TESTING

The heavy-duty FTP transient cycle is used for regulatory emission testing of heavy-duty on-road engines in the US. The cycle includes the "motoring" segment, and, therefore requires a DC or AC electric dynamometer capable of both absorbing and supplying power. Since the API test cell is equipped with an eddy-current absorbing unit, motoring is not possible. During the motoring portion of the cycle, 10% of maximum brake-torque relative to the engine speed is commanded. Such an arrangement allows for generation of power during the motoring segment but it also results in a fuel-consumption penalty during those segments.

Furthermore, the FTP cycle test consists of a cold-start test followed by minimum of three hot-start tests separated by 20 minute intervals. Overall FTP results are obtained by using a weighting factor of 1/7 and 6/7 for the cold and hot-start results, respectively. The test results presented and discussed in this paper are confined to the hot-start portion of the FTP cycle.

6.1 Test Cycle Assumptions and Modifications

For engine mapping the following values are used

Minimum speed (Idle speed) = 800 rpm

Maximum engine speed = 2200 rpm.

6.2 Test cycle results

The engine-out brake-specific cycle average values over the FTP cycle are shown in the Table . NO_x measurement shown in the table has been corrected for humidity.

Table 4: Cycle average results from hot-start FTP cycle

BSFC (g/kW-hr)	Engine-out BS Soot (g/kW-hr)	Engine-out $BSNO_x$ (g/kW-hr)
217.3	0.056	4.3

Figure 4 shows that the torque demand during the freeway portion of the FTP cycle is easily met without generating major soot spikes; NO_x values during the freeway section are relatively higher because the engine is running near the rated speed points.

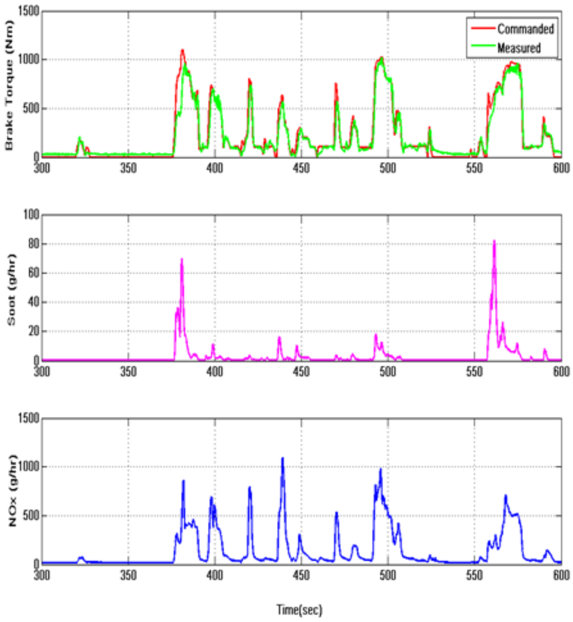

Figure 4: LA Freeway section performance

6.2 Steady-state map-based FTP cycle results

One important objective of this study was to identify the deviation from the ideal performance in the measured results for FTP cycle, as derived from the steady-state map. When simulating the measured cycle torque and cycle speed from the test on a steady-state map – for BSFC, BSNOx and BS Soot – the results between simulations and actual measurements from the FTP test are close. The simulated value represents the brake-specific values obtained if the cycle speed and torque is converted to fuel without factoring penalties due to engine transient operations such as smoke-limiter or airflow lag.

Table 5 shows that the results for the BSFC from the simulation and actual measurement are within 1.2%, thereby demonstrating the capability of the Achates Power OP Engine to match its steady-state performance even during transient operations because of the novel combustion system, flexible air-handling system and respective control strategies.

Table 5: Comparison between FTP results on Steady-state map and actual measurements

	Units	From Steady-state map	From Measure-ment
Total Fuel Consumed	(g)	**3163**	**3201**
Cycle-average BSFC	(g/kW-hr)	**215.2**	**217.3**
Engine-out cycle-average Soot	(g/kW-hr)	**0.01**	**0.056**
Engine-out cycle-average NO_x	(g/kW-hr)	**4.1**	**4.3**

6.3 Comparison with Cummins ISB 6.7L engine

Engine efficiency measurements and an energy audit were performed on a medium duty MY2011 Cummins ISB 6.7L engine in. As shown in Table 6, the performance ratings for the Cummins engine is close to Achates Power's test engine. Cummins engine was equipped with a DPF and SCR system, whereas Achates Power's OP test-engine was using a backpressure valve to simulate the ATS.

Table 6: Performance specs comparison between API's and Cummins ISB MD engines

	API OP Engine	MY2011 Cummins MD Engine[3]
Displacement (L)	4.9	6.7
Rated Power (kW)	205	242.5
Rated Speed (rpm)	2200	2400
Peak Torque (Nm) @ Speed	1100 Nm @1200-1600 rpm	1016@1600rpm
Compression Ratio	15.4 : 1	17.3 : 1
EGR	HP cooled	HP cooled
After-treatment System	Exhaust pressure simulating DPF/DOC/SCR for MD engine	DPF-SCR

7. A NEW ALTERNATIVE: OPGCI ENGINE

As detailed in the first section, Achates Power has developed the technology, tools and processes to successfully extract the potential of the diesel-fueled opposed-piston engine. But with the majority of global light-duty vehicles fueled by gasoline, there is a strong motivation to leverage Achates Power's knowledge and expertise to develop a gasoline version.

Research experience makes clear that the flexibility of the Opposed-Piston Engine in managing charge condition, fuel distribution and max BMEP can provide a perfect platform to adopt gasoline compression ignition. Not only does this present the opportunity to operate the Opposed-Piston Engine on the most universally accepted fuel, it also offers the potential to match diesel efficiency at a lower total engine cost.

Achates Power recently received a contract from the U.S. Department of Energy's ARPA-E to develop a gasoline compression-ignition variant of the Achates Power OP Engine. The initial funding will be $9 million over three years.

Together with Delphi Automotive and Argonne National Laboratory, the three organizations expect to spend $13 million during the duration of the program. The engine will be a three-cylinder, three-liter design suitable for large passenger vehicles, pickup trucks, SUVs and minivans.

7.1 GCI advantages compared with diesel

An opposed-piston, gasoline compression ignition (OPGCI) engine has the potential to be a game changer in the powertrain market. The combination of OP and GCI technologies could be the solution to pending emissions and fuel economy regulations and could emerge as the internal combustion engine (ICE) that satisfies the challenges of ground mobility for decades to come.

The OPGCI engine has the potential to be about 50% more efficient than a contemporary gasoline engine by combining the benefits of compression ignition with a readily available fuel source – gasoline – in the highly efficient Achates Power OP Engine architecture.

Delphi and Argonne have demonstrated that gasoline can be combusted without a spark plug under high compression-ratio, lean conditions and without throttling. The key is to continually produce precisely-controlled pressure, temperature and fuel-dispersion conditions inside the cylinder.

Delphi has shown its GCI engine offers diesel-like efficiency. Furthermore, GCI has an advantage over diesel in creating lower emissions.

Gasoline is a superior fuel for compression ignition because gasoline evaporates more readily than diesel and has a longer ignition delay. GCI has a mostly lean mixture more evenly distributed throughout the cylinder; with only a small portion of richer mixture at the ignition sites it therefore achieves mostly lower peak temperatures and NOx. In addition, the mostly lean local conditions also allow for low soot formation. GCI does, however, create higher hydrocarbon (HC) and carbon monoxide (CO) emissions. Fortunately, HC and CO can be mitigated with relatively inexpensive oxidation catalysts.

Another advantage GCI has over diesel is lower cost, both because of much lower cost aftertreatment requirements (GCI engines generally do not need a particulate filter and may not need selective catalyst reduction) and because of much lower-cost fuel system.

Delphi recently published results of experiments that yield 39.3% MPG improvement in combined city and highway drive cycles for a GCI engine compared to a 2.4L four-cylinder port fuel injected (PFI) engine.[4]

7.2 Combining OP & GCI

We expect that combining the OP Engine and GCI will result in a number of advantages that could improve engine efficiency by about 50% compared with spark-ignition gasoline engines. Likewise, since both OP and GCI technologies have favorable cost positions compared to conventional engines, the combined engine also should be markedly less costly to produce and maintain than conventional diesel engines.

Moreover, the OP Engine design also mitigates three technical challenges for GCI:

7.2.1 Mixture preparation

Robust and clean GCI combustion requires a stratified charge, with locally lean and rich areas, and multiple injection events. Delphi has achieved excellent GCI combustion results in conventional engine configurations with an injector inserted through the cylinder head injecting towards an approaching piston (Figure 5).

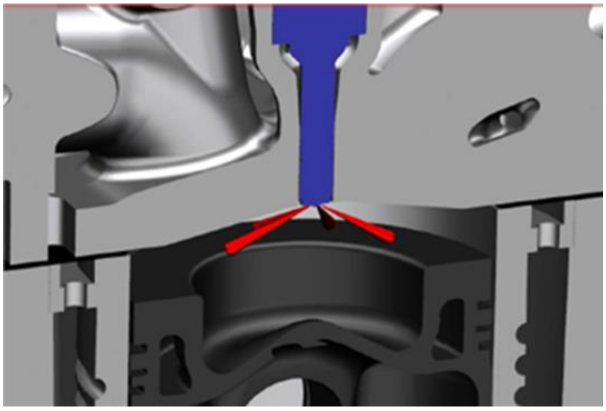

Figure 5: Conventional GCI Injection (Delphi)

But the OP injection environment offers significant potential to improve charge stratification. Diametrically opposed dual injectors spray across the diameter of cylinder (Figure 6). Each injector can be independently controlled to more easily manage staggered injections for ideal mixture distribution and, therefore, efficient and controlled heat release.

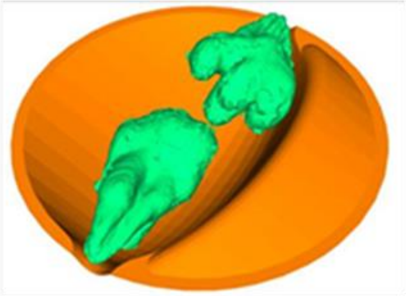

Figure 6: Achates Power Opposed-Piston Injection

7.2.2 Charge temperature management

At low loads, GCI requires higher temperatures for combustion. Engines operating at low loads generate relatively little heat. This problem is exacerbated in small engines that have high ratios of surface areas to combustion volume. Four-stroke engines normally push the entire content of the cylinder out during the exhaust stroke and therefore require a complex variable valvetrain to re-open the exhaust valve during the intake stroke to suck the exhaust back in the cylinder to increase the charge temperature to the level necessary for GCI ignition.

The OP Engine, however, can retain exhaust gas in-cylinder after combustion, even at low loads when relatively little additional intake oxygen is required. At low loads, the OP Engine can reduce the supercharger work used to boost the intake manifold pressure. This has four benefits: it reduces the amount of work by the supercharger, improving efficiency; it keeps in-cylinder temperatures high for good combustion stability; it provides a natural or internal EGR effect for low NOx combustion and, it provides high exhaust gas temperatures for catalyst light-off and sustained activity.

7.2.3 High Load Operation and Pumping

At the other extreme, GCI engines have challenges at high loads. The compression ratio of a GCI engine is higher than a conventional gasoline engine and also requires a higher level of air and EGR to control combustion. This combination creates high cylinder pressures that can limit the maximum load capability of the engine and increase combustion noise and pumping work. At high loads, four-stroke GCI engines have to make calibration tradeoffs to maintain the mechanical integrity of the engine, sacrificing both efficiency and performance.

The OP Engine design has several advantages to manage the high-load operation without as many trade-offs. The two-stroke cycle operation reduces the maximum BMEP requirement (and displacement) while maintaining performance requirements. Relatively large flow area of the ports, better alignment to turbocharger performance curves and efficient EGR pumping all contributed to reduced pumping work to meet the necessary charge conditions. Finally, the larger cylinder volume available for combustion enables faster heat-release rates without increasing combustion noise. All this allows for fewer calibration tradeoffs at high loads.

8. SUMMARY AND CONCLUSIONS:

The A48-316 multi cylinder research engine developed by Achates Power has demonstrated cycle average BSFC of 200 g/kWh for the SET cycle with the best point efficiency of 192 g/kWh. This is despite the fact that the engine friction has not been optimized in order to preserve the flexibility of the engine to act as a research platform. A grounds-up OP2S engine with optimized friction and air handling components is expected to deliver 182 g/kWh on SET cycle.

Based on the Achates Power Opposed-Piston Engine out conditions from steady state cycle, it can be seen that the tailpipe HC, CO and PM targets can be reached relatively easily. The proposed after-treatment system with appropriate urea dosing is sufficient to maintain the NOx level below the EPA10 target along with low NH_3 slip and N_2O for SET cycle. All the models used in this study are based on catalyst formulations that are commercially available.

The results in this paper show OP Engine operating advantages also extend to the aggressive transient cycles. These results demonstrate the capability of the OP Engine to not only provide significant BSFC advantage over a conventional four-stroke diesel engine, but also highlight its ability to generate engine-out emission levels that are compatible with US2010 EPA requirements with a conventional after-treatment system.

As for future advances with potentially high impact for the passenger-vehicle powertrains, the federally funded OPGCI engine can be the most cost effective and financially viable way to reduce greenhouse gas emissions because it leverages an existing fuels infrastructure and conventional-engine manufacturing processes.

The combination of the OP Engine with GCI combustion technology is expected to deliver 50% fuel economy improvement compared with a conventional gasoline engine or 30% compared with a conventional diesel engine, suggesting the way to the most cost effective solution to meeting the future greenhouse gas emissions regulations.

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