Practical Applications of Opposed-Piston Engine Technology to Reduce Fuel Consumption and Emissions

2013-01-2754
Published
11/27/2013

Suramya Naik
Achates Power, Inc.

David Johnson, John Koszewnik, Laurence Fromm, Fabien Redon, Gerhard Regner, and Kevin Fuqua
Achates Power Inc

doi:10.4271/2013-01-2754

ABSTRACT

Opposed-piston (OP) engines have attracted the interest of the automotive industry in recent years because of their potential for significantly improved fuel economy. Opposed-piston, two-stroke (OP2S) engine technology amplifies this fuel efficiency advantage and offers lower cost and weight due to fewer parts.

While OP engines can help automotive manufacturers comply with current, and future, efficiency standards, there is still work required to prepare the engines for production. This work is mainly related to packaging and durability.

At Achates Power, the OP2S technology is being developed for various applications such as commercial vehicles (heavy- and medium-duty), SUVs, pick-up trucks and passenger cars (i.e. light-duty), military vehicles, large ships and stationary power (generator sets).

Included in this paper is a review of the previously published OP engine efficiency advantages (thermodynamics, combustion and air system) as well as the architecture's historical challenges. Also included is:

1. An overview of the packaging-related challenges of OP2S engines using opportunities with the dual-crank, Junkers Jumo-style design with power take-out options, vertical engine installation and bore-to-bore distance.

2. Different design parameters of the OP2S engine and their optimization for various applications.

3. Details of OP2S engines for various applications, including packaging concepts and performance and emissions results.

These results suggest that the technology is ready to produce an economically and environmentally sustainable OP powertrain-one that is clean, fuel efficient and can fit into existing vehicles, be manufactured in today's engine plants, and run on a variety of fuels.

INTRODUCTION

First introduced in the late 1800s and once widely used for ground, marine and aviation applications, the opposed-piston, two-stroke engine features an unparalleled combination of power density and fuel efficiency [1] that has yet to be matched by any other powertrain. Despite these advantages, however, OP2S engines-like their two-stroke counterparts-suffered from high soot as well as poor oil control. Unable to meet modern emissions standards, production eventually ceased for OP engines used in on-road applications.

Leveraging today's technologies-such as computational tools, fuel-system advancements (high pressure common rail) and precision manufacturing-the OP engine has been successfully modernized, demonstrating the following when compared to leading, conventional diesel engines:

1. 15-21% lower cycle-average brake-specific fuel consumption, depending on the application, with similar engine-out emissions levels [3][6]

2. Less than 0.1% fuel-specific oil consumption [3]

3. Reduced cost, weight and complexity due to no engine head or valve train

LITERATURE REVIEW

With increased interest in OP technology-as well as two-strokes in general-in the industry, there has been a steep rise in published literature since 2009.

SAE published a book with details of historical OP engines titled "Opposed Piston Engines: Evolution, Use, and Future Applications" authored by M. Flint and J. P. Pirault [1]. This book is an excellent source of information on earlier OP engines, especially the famous Junkers Jumo engines that were used in World War 2 aircraft.

There have been several important SAE papers published related to the OP2S technology. In the SAE paper titled "Thermodynamic Benefits of Opposed-Piston Two-Stroke Engines", Herold et al has explained the fundamental advantages of OP engines by comparing a theoretical four-stroke with OP2S engines of similar size and power [2].

In two other papers published in 2011 [6][7], Achates Power documented its first set of medium-duty engine data that was calculated from a multi-cylinder engine model that utilized single-cylinder test cell measurements. The papers also explained how the data was measured, using a 1D model to predict multi-cylinder performance.

The issue of higher oil consumption with two-strokes, especially with the OP2S, has been addressed well in the 2011 ASME paper from Callahan et al [9]. The paper described several measures to control the oil consumption while still providing sufficient lubrication for good durability.

The cylinder cooling requirements of OP engines are different than in regular, four-stroke engines, and this has been addressed in SAE paper 2012-01-1215 by Lee et al [8]. The paper describes a new impingement cooling strategy for OP engines that produces the most effective cooling and delivers the least temperature differential across the length of the cylinder.

More design solutions for OP engines, like bi-axial bearing design, are explained in a recent SAE paper from Regner et al [3]. The paper also showcased the latest performance and emissions results for a medium-duty truck application from Achates Power together with the process that was followed for generating the data using single-cylinder measurements.

In recent years, several works on the OP technology were published for light-duty (car) applications. At the Emissions 2012 conference in Ypsilanti, MI, Kalebjian et al presented a paper showcasing how the OP technology can be beneficial for meeting striker light-duty emissions standards by rapid catalyst light-off-drastically cutting down cold-start emissions [5]. In another light-duty work recently presented by Redon at SAE's High Efficiency IC Engine Symposium, the OP2S diesel light-duty concept design, package and projected fuel efficiency numbers were presented [19].

An interesting work of CFD simulation for optimizing the OP2S combustion system has been published very recently by Venugopal and Abani in SAE paper 2013-26-0114 [4].

Other good sources of information are blogs written on OP engines. Some of these blogs address topics such as the difference between the OP2S compared to regular two-stroke engines, turbocharger efficiency for OP2S engine applications, and the effect of design parameters like stroke-to-bore ratio for OP engines [12][13][14][15].

Two among the several SAE papers-2012-01-0831 authored by Pohorelsky et al [18] on the two-stroke air system architecture and 2012-01-0704 authored by Ostrowski et al [17] on the use of a supercharger in modern automotive engines-can help the reader better understand the air system architecture for OP2S engines.

OPPOSED-PISTON, TWO-STROKE TECHNOLOGY

OP2S Fundamental Advantages

The fundamental advantages of the OP2S have been described in previously published technical papers [1][2].

Summarizing, the OP2S diesel engine has the following efficiency advantages compared to a conventional, four-stroke diesel engine of comparable power and emission standards:

1. The OP engine has favorable surface area/volume ratios during combustion compared to equal displacement four-stroke engines, reducing heat transfer during combustion.

2. OP2S engines enable reduced fuel per combustion event in a larger cylinder (almost twice as large with half the number of cylinders compared to conventional, four-strokes) for the same power, resulting in leaner combustion at the same boost level and improved thermal efficiency.

3. 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 faster combustion improves thermal efficiency by reaching closer to constant volume combustion.

The aforementioned fundamental OP2S thermal efficiency advantages are further amplified by:

1. Lower heat loss due to reduced cylinder counts leading to larger cylinders and higher wall temperatures of two piston crowns compared to a cylinder head.

2. Further reduction in the surface area/volume ratio and better scavenging by using a greater than 2.0 stroke-to-bore ratio [2][15].

3. Reduced pumping work thanks to uniflow scavenging with the OP architecture giving a higher effective flow area than comparable four-strokes or a single piston, two-stroke uniflow or loop scavenged engine [13].

4. A decoupled pumping process from the piston motion due to the two-stroke architecture, which allows alignment of the engine operation with a maximum compressor efficiency line [12].

5. Lower NOx characteristics as a result of lower BMEP requirements because of the two-stroke cycle operation [14].

Combustion System Advantages

Achates Power has developed a proprietary combustion system [16] composed of two identical pistons coming together to form an elongated ellipsoidal combustion volume where the injectors are located at the end of the long axis [4] (Figure 1).

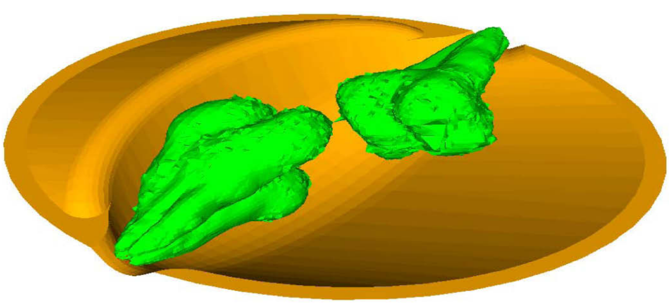


Figure 1. Schematic of the combustion system with plumes coming out of two side-mounted injectors.

This combustion system allows:

1. High turbulence, mixing and air utilization with both swirl and tumble charge motion

2. An ellipsoidal combustion chamber resulting in air entrainment into the spray plumes from two sides

3. Inter-digitated, mid-cylinder penetration of fuel plumes enabling larger λ=1 iso-surfaces

4. Excellent control at lower fuel flow rates because of two small injectors instead of one large one

5. Multiple injection events and optimization flexibility with strategies such as injector staggering and rate-shaping [4]

The result is no direct fuel spray impingement on the piston walls and minimal flame-wall interaction during combustion. This improves performance and emissions [3] with fewer hot spots on the piston surfaces, enhancing piston thermal management and increasing engine durability [4].

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 (i.e. to scavenge exhaust out of the cylinder after combustion and push in fresh air mass).

For applications that require the engine to change speed and load in a transient manner, such as automotive applications, external means of air pumping are required. The layout as described in Figure 2 is the preferred configuration among the various possible configurations of the air system with a turbocharger and supercharger combination [18].

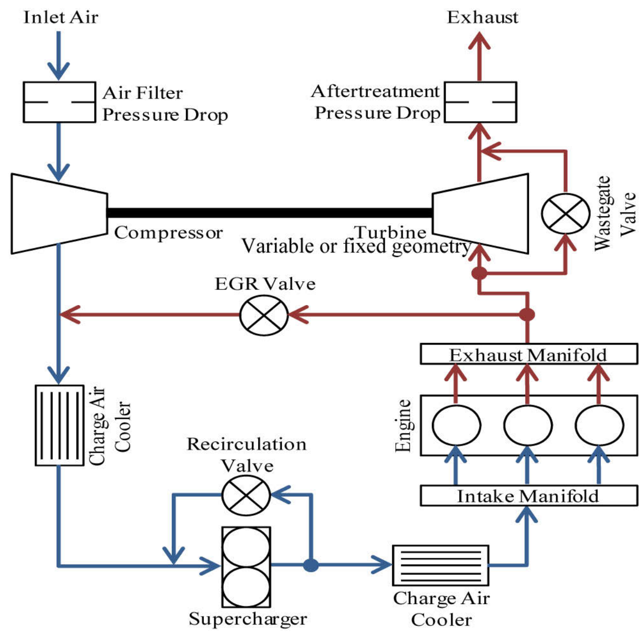


Figure 2. OP2S preferred air system layout.

Advantages of such an air system are summarized as follows:

1. The compressor provides high pressure before the supercharger, which is multiplied by the supercharger. This means low supercharger pressure ratios are sufficient for high intake manifold density, reducing pumping work.

2. The maximum required compressor pressure ratio is lower compared to regular turbo-only air systems of four-stroke engines. This reduces maximum compressor-out temperatures and does not require titanium wheels for high compressor durability.

3. The use of a supercharger recirculation valve allows greater control of the flow through the engine, thus providing flexibility for precise control of emissions and for optimization across the engine map while reducing pumping.

4. 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 from and to the cylinder improves BSFC.

5. Improved transient response due to the supercharger and recirculation valve [17].

6. Very good cold start and catalyst light off capability due to accurate control of the engine pressure difference [5].

7. Increased low-speed torque by selecting the appropriate gear ratios on the supercharger [3].

8. Increased capability to drive EGR with a lower pumping penalty compared to a conventional, turbocharged four-stroke engine as it is driven by a supercharger [3].

9. Ability to cool both air and EGR together reduces fouling of the cooler [3][10].

Other Advantages

The opposed-piston engines offer other advantages in addition to fuel economy. These include:

1. Fewer parts and, therefore, lower cost and weight than conventional engines [1] (see Table 1).

2. Excellent balancing because the reciprocating masses of opposing pistons balance each other out.

Table 1. Component differences between conventional four-stroke and OP2S parts.

Only on Conventional Four-Stroke	Only on OP Engine
Cylinder Head	Crank Connection Mechanism
Camshaft	Supercharger
Valve-train	
Timing Drive	
Balance Shaft	

Common Differences in Main Components	Conventional Four-Stroke	Opposed-Piston, Two-Stroke
Crankshafts	1	2, with half throws on each
Charge Coolers	1	2

EXPERIMENTAL WORK SHOWCASING OP2S ADVANTAGES

Since 2012, the Achates Power OP2S single-cylinder engines with two crankshafts that are connected by a gear train have been tested on two dynamometers. The engine has a 98.4 mm bore and 215.9 mm stroke, with displaced volume of 1.64 L. It also has a 2000 bar injection pressure-capable common-rail fuel injection system and is supplied with coolant and oil through the separate coolant and oil carts in the test cell.

The test cell is equipped with low-speed pressure and temperature sensors as well as Kistler high-speed pressure sensors that can measure the pressure at the interval of 0.5 degree crank angle. These high-speed pressure sensors are utilized for in-cylinder pressure measurements as well as in the intake and exhaust manifolds. In-house data processing software is used together with Labview to record and process the data. The test cell also has emissions analyzers to measure the concentrations of CO2, CO, O2, HC and NOx on the exhaust side and intake CO2. Exhaust soot is measured with an AVL smoke meter.

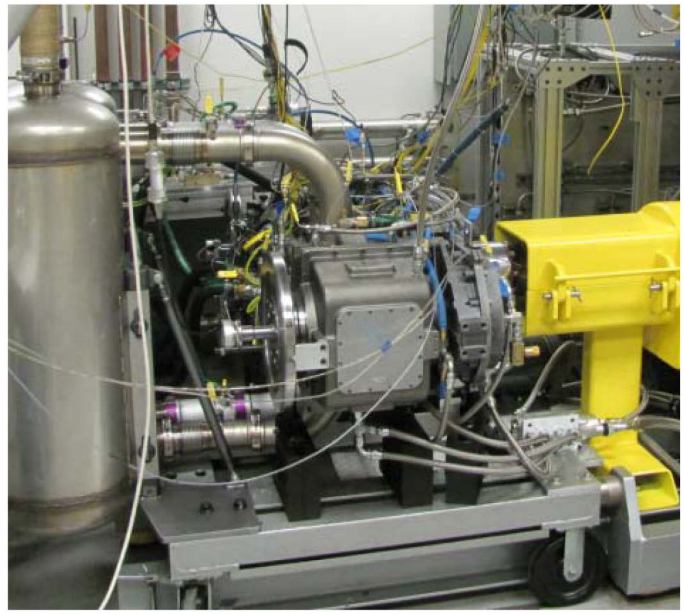


Figure 3. Single-cylinder research engine installed in test cell.

As a test to compare the OP engine's best thermal efficiency with that of a four-stroke, the 1.64L single-cylinder engine was run with 1200 rpm, 8.8 bar IMEP that is equal to 160 kW power at 1200 rpm for a 10.8L OP engine. This reflects highway operating conditions. The four-stroke engines used in long haul trucks are usually at their best thermal efficiency at this low-speed 160 kW operating condition. The details of the hardware and test parameters are listed in Table 2.

Table 2. Test operating condition.

Bore	98.4	mm
Stroke	215.9	mm
# of Cylinders	1	-
Swept Volume	1.64	Liters
Trapped Compression Ratio	17.4	-
Engine Speed	1200	Rpm
Fuel Mass	62.7	mg/rev
Rail Pressure	1200	bar
Injection Timing	-6	deg aMV
Air-Fuel Ratio	28.4	-
EGR rate	30.4	%
Intake Manifold Pressure	2.1	bar

The engine was run with the parameters highlighted in Table 2, the data was recorded in Labview and the results were post-processed using in-house software. Table 3 details these results.

Table 3. Test results.

IMEP	8.8	bar
Indicated Thermal Efficiency	53.5	%
Indicated Power	28.9	kW
Indicated Torque	229.1	N-m
Peak Pressure	142.0	bar
MPRR	8.4	bar/deg
Peak Temperature	1839	K
ISFC	156.8	g/kW-hr
ISCO	0.08	g/kW-hr
$ISNO_X$	3.772	g/kW-hr
ISHC	0.211	g/kW-hr
ISSoot	0.005	g/kW-hr
CA10	-3.4	deg aMV
CA50	2.0	deg aMV
CA90	15.4	deg aMV
Burn Duration (10-90)	18.8	deg CA

As shown in Table 3, the indicated thermal efficiency calculated from the measured in-cylinder pressure trace is 53.5%, which is very good for such a small engine, compared to about 49% ITE that is normally seen in current four-stroke diesel engines for trucks usually bigger than 10L. The 10-90% burn duration is only 18.8 degrees. Figure 4 shows the in-cylinder pressure trace, apparent heat release rate and cumulative burn curves for this measurement.

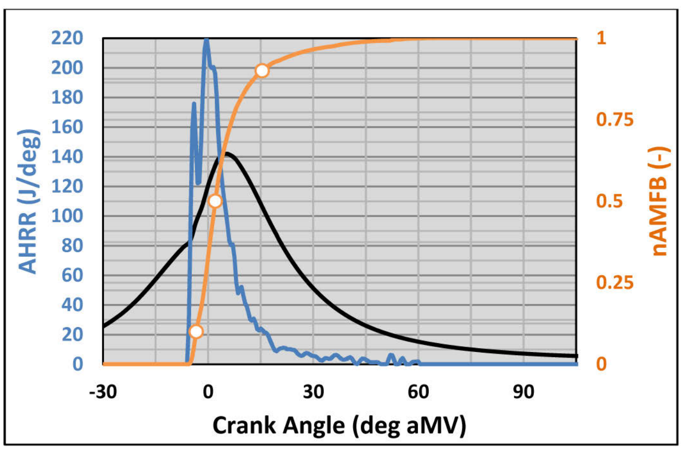


Figure 4. Measured in-cylinder pressure, apparent heat release rate and cumulative burn.

As seen in Figure 4, the heat is released at a much faster rate and 90% of the combustion is done by 15.4 degrees after the minimum volume. Despite this, the maximum in-cylinder pressure is about 140 bar, lower than what most of the four-stroke engines see for such low speed and high power.

The Log PV diagram in Figure 5 shows the in-cylinder pressure increasing as fast as the fuel gets burned near minimum volume and does not reduce because of excessive heat losses that are typical for four-stroke engines at TDC. This lower heat loss at minimum volume is the result of an OP advantage in the reduced surface area-to-volume ratio. The peak cylinder pressures are still lower than conventional, four-stroke engines because the pressure at port closing is lower than boost pressures usually seen in four-stroke engines for such good combustion. This data set clearly proves the superiority of the OP2S diesel engine over conventional, four-stroke diesels.

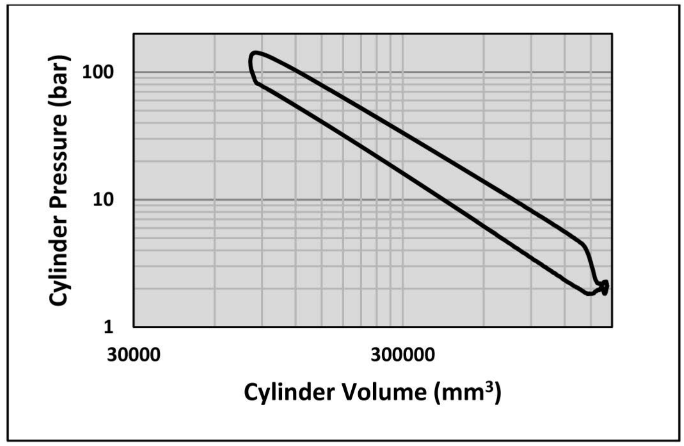


Figure 5. Log PV diagram for the measured data.

RESOLVING HISTORICAL CHALLENGES OF THE OP2S ARCHITECTURE

Historically, two-stroke engines have suffered from higher oil consumption, while struggling to provide adequate lubrication to the wrist pin and manage piston temperatures. Additionally, the opposed-piston architecture makes cylinder liner cooling difficult and the well-functioning wet sump lubrication system difficult to design. The need to connect two crankshafts, while making the design packageable, is also challenging.

Recent technical developments have helped overcome these technical challenges and this has been detailed in earlier publications [3].

A weighted average Fuel-Specific Oil Consumption (FSOC) of 0.114% has been demonstrated on 13-mode ESC [3] using techniques like appropriate oil ring tension, modifying piston rings, optimizing volume behind and between rings, and modifying bore texture and honing [9].

Unlike a four-stroke engine, which lifts the wrist pin from its carrier during intake, the reason for the premature wear on the wrist pins in the two-stroke engine is its continuous compressive load. This results in no migration of lubricating oil to all surfaces of the pin. The bi-axial bearing design uses non-concentric journals that can load and unload different portions providing minimum oil film thickness necessary for prolonged life. Achates Power's in-house analytical tools were used for quick design iterations and the development of a biaxial bearing with proven durability at 200 bar peak cylinder pressures [3].

OP engines have maximum heat load at the middle of the cylinder at the circumference because combustion takes place there. Impingement cooling along the circumference at the outer surface of the cylinder has been proven to be effective in maintaining a uniform temperature axially along the bore, minimizing the bore distortion [8]. Impingement cooling at the middle of the cylinder also allows separate coolant flow rates between the exhaust and intake sides, allowing for higher mass flow on the exhaust side to address higher heat loads [8]. Reducing temperature at top ring reversal is another enabler for low oil consumption.

The durability of the hardware has been proven by running a rated-power condition (i.e. 53 kW/cylinder @ 2160 rpm) for hundreds of hours in the test cell [3]. The testing showed no signs of potential failures on any of the engine components and indicated the potential to fulfill heavy-duty durability requirements.

ADDRESSING PACKAGING CHALLENGES OF OP2S ENGINE

Dual-Crank, Junkers Jumo-Style Design

The Junkers Jumo-style architecture, with adopting advancements in gear technology, allows for efficient space utilization under the hood. The usual OP2S engine is taller in vertical dimension, but shorter in length than conventional, four-stroke engines because it has half the number of cylinders. This leaves a much larger space for the radiator and fan as well as enables aerodynamic improvements in the vehicle design.

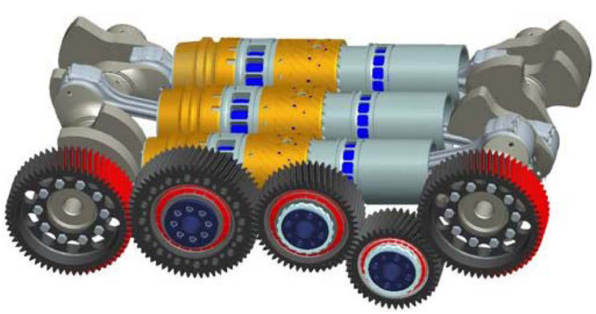


Figure 6. Cutaway of power module concept, showing internal gear train.

Figure 6 shows the Junkers Jumo-style, two crankshaft, opposed-piston power cylinder in a horizontal configuration with a connecting crank train. The power-out shaft can be connected to any of the idlers in the geartrain for packaging flexibility. Because the exhaust crank leads the intake, the torque produced is higher on the exhaust side. To minimize the power transmission losses through the geartrain, it is a good practice to use the idler gear near the exhaust crank if the direct connection to the exhaust is not possible because of the packaging restriction.

Vertical Engine Installation

The OP engine can work with both dry and wet sump lubrication systems in a horizontal configuration (i.e. with cylinder axis parallel to the ground). However, for packaging considerations, the engine may have to be mounted vertically. This raises a question as to whether the oil from the top sump can successfully be drained out or not without excessive oil passing through the rings, ending up in the cylinder when the engine is stopped.

A sump and block design was developed that can accommodate oil draining down from the top sump in a vertical configuration. The engine can be installed in a perfectly vertical position or inclined at some angle. The design has addressed solutions for potential failure modes of excessive oil consumption during start up and in regular operation of the engine. As shown in Figure 7, the vertically mounted, single-cylinder OP2S engine was installed in a test facility at Achates Power. The tests have verified that the engine operates normally in the vertical orientation with steady-state oil consumption similar to a horizontal configuration and acceptable oil consumption at engine startup.

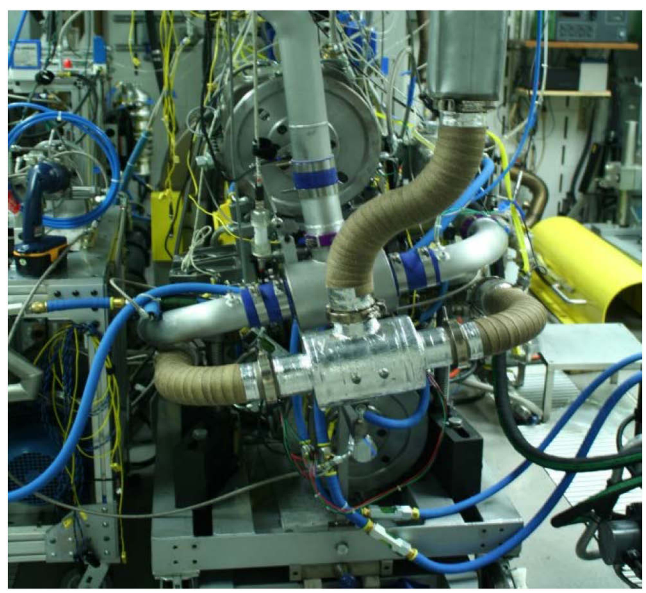


Figure 7. Single-cylinder engine installed vertically for testing.

Bore-to-Bore Distance

While the OP2S engine is taller in vertical dimension, it is also a short engine because it has half the number of cylinders compared to a conventional, four-stroke engine. This allows the engine to fit before or after the front axle if the distance between the cylinders is optimized. The total weight of the engine can also be reduced by reducing the bore-to-bore distance. Several concept designs were developed to minimize the bore-to-bore distance without compromising the air system (i.e. intake and exhaust manifold designs). The system feeds air from two sides of the cylinder while optimizing the design for minimum side-to-side variation as well as minimum port-to-port and cylinder-to-cylinder mass flow variation. The design ensures an efficient scavenging process while allowing a tight bore-to-bore distance for easier packaging.

APPLICATION-SPECIFIC DESIGN PARAMETERS

The engine specification is a process that considers trade-offs between various parameters like fuel economy, power density, heat rejection, NVH, cost, weight and other factors. While it is desirable to reduce cost and weight for all applications, other requirements are application specific.

Table 4 shows different engine specification priorities for various applications.

Table 4. Application-specific requirements. (H: High, M: Medium, L: Low)

	Car	Light Truck	Medium Truck	Heavy Truck	Military
Fuel Economy	M	H	H	H	M
Power Density	H	M	L	L	H
Heat Rejection	M	M	M	M	H
NVH	H	H	M	L	L
Durability	M	M	H	H	M

The engine torque curves are defined based on these application-specific requirements. Figure 8 shows the Achates Power OP2S engine BMEP curves for various applications. The shaded areas of the map illustrate operating conditions that are important for fuel economy and emissions requirements under real-world driving conditions.

As seen from Figure 8, typically, light-duty applications (such as passenger cars) require high power density, which mandates a higher speed range. However, the low speed and low load points are more important for fuel economy in real-world driving and test cycles. Durability for this application is less important than better NVH and fuel economy.

For light- and medium-duty truck applications, the power density of the engine is typically lower than light-duty engines. And, therefore, the speed range is smaller with highly weighted points close to full load and at lower-to-medium speeds. Durability and NVH requirements are medium, but fuel economy is more important than light-duty engines.

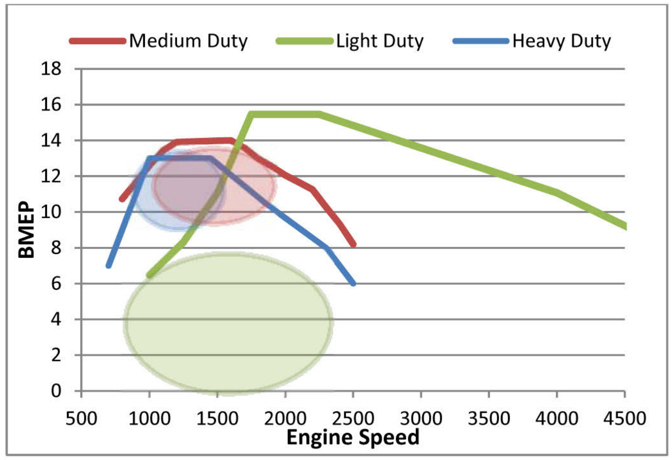


Figure 8. Achates Power OP2S engine torque curves for various applications. Shaded areas indicate highly weighted operating conditions.

The heavy-duty engines, which are typically bigger than 9L and are used for long haul trucks, emphasize fuel economy and durability. The engines have lower power density as they are optimized for better fuel economy and have a smaller speed range. The engines are mostly run at lower speeds and higher loads where the BSFC is best in a typical four-stroke engine map. NVH considerations are given less importance.

Military applications, however, require high power density and lower heat rejection as the most important parameters, rather than emissions. Durability and fuel economy needs are moderate; however, higher fuel economy helps achieve lower heat rejection.

The engine size, stroke-to-bore ratio, air system (ports, turbocharger and supercharger) and combustion system (pistons, injectors) have to be carefully selected and optimized for achieving the application-specific requirements.

Engine Size and Stroke-to-Bore Ratio

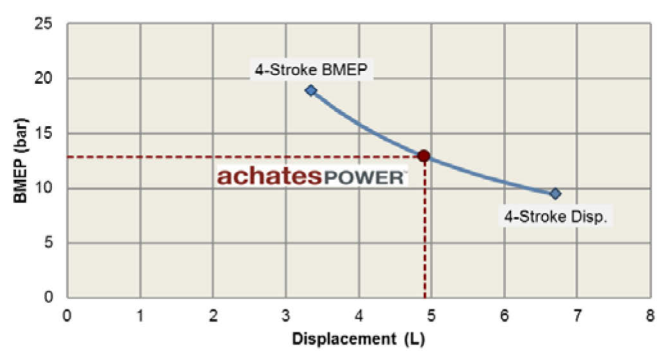


Figure 9. BMEP/displacement trade-off for sizing two-stroke engine compared with four-stroke 6.7L engine.

Figure 9 shows a BMEP/displacement trade-off for a two-stroke engine. Having a combustion event at every stroke, the two-stroke engine requires only half the BMEP compared to an equivalent size four-stroke engine for the same power requirement at the same engine speed. In other words, two-stroke engines can be sized to half of the equivalent four-stroke engine if the speed and BMEP of the engine is the same as a four-stroke engine. This gives a two-stroke engine twice the power density of the four-stroke engine as well as a benefit in cost, weight and packaging. However, in a two-stroke engine, a portion of the piston stroke and, therefore, cylinder volume is used for the scavenging process, which reduces the effective volume-about 75-85% of the swept volume in an OP2S. Moreover, the fuel economy of larger OP2S engines is better because of favorable surface area-to-volume ratios and leaner operating conditions at bigger volume, even though the power-cylinder friction increases with larger engines. Larger engines with lower BMEP also produce lower engine-out NOx because the maximum combustion temperatures are lower compared to engines that have higher BMEP. Together with these fuel economy and emissions advantages for larger engines, the piston and cylinder cooling requirements, and the resulting durability considerations also make a lower BMEP two-stroke engine with larger displacement a pragmatic solution. For most automotive applications, modern OP2S engines can be designed with approximately 60-85% displacement of equivalent four-stroke engines. However, the high power density and low packaging space applications-like military vehicles-may require smaller OP2S engines with higher BMEP.

Once the engine size is determined based on the application requirements, the stroke-to-bore ratio is another important parameter that needs to be appropriately selected. Papers published previously [3] have described the effect of a larger stroke-to-bore ratio on brake thermal efficiency.

The main reasons for this improvement in BTE with higher stroke-to-bore ratios are better scavenging efficiency (thus lower pumping losses) and lower surface area-to-volume ratios [3] in the cylinder (leading to better indicated thermal efficiency). Therefore, a higher stroke-to-bore ratio is desirable for applications that require better fuel efficiency.

For applications that necessitate high power density and a high engine speed, the stroke-to-bore ratio may have to be reduced to keep the mean piston speeds in a reasonable range at a rated power condition, while still allowing a bigger displacement engine using a larger bore size. The larger bore also increases the piston area available to dissipate heat in the case of a high power density application, which helps with piston cooling and, therefore, improves durability. For the same power requirement and engine size, the engine power produced per piston area is reduced with a lower stroke-to-bore ratio as seen in Figure 10. Therefore, for higher power density applications, such as light-duty vehicles, OP2S engines are designed with lower stroke-to-bore ratios compared to other on-road automotive applications. For military applications, however, the stroke-to-bore ratio is decided based on both power density and heat-rejection requirements.

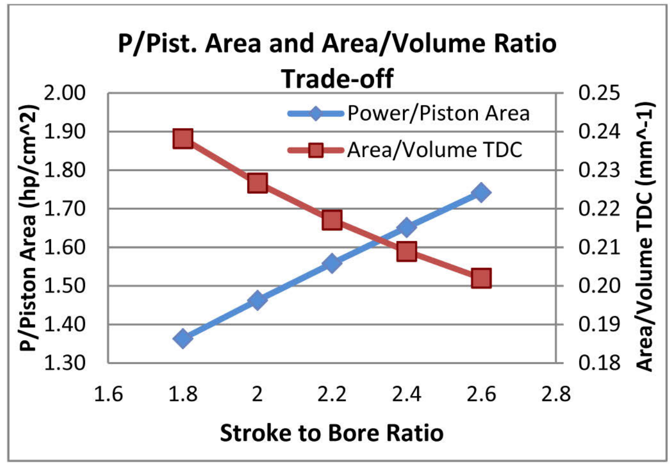


Figure 10. Combined effect of stroke/bore ratio on BTE.

Port Sizing

The intake and exhaust ports in the OP2S engine have to be sized appropriately based on the power, air and EGR flow requirements. In two-stroke engines, flow through the cylinder during the scavenging process is characterized by the scavenging efficiency versus scavenging ratio curve as shown in Figure 11. The actual characteristics curve of a two-stroke engine is somewhere between two theoretical curves- perfect scavenging that assumes no mixing of intake air with residuals and prefect mixing that assumes all incoming fresh charge mixes instantly with the entire in-cylinder mass.

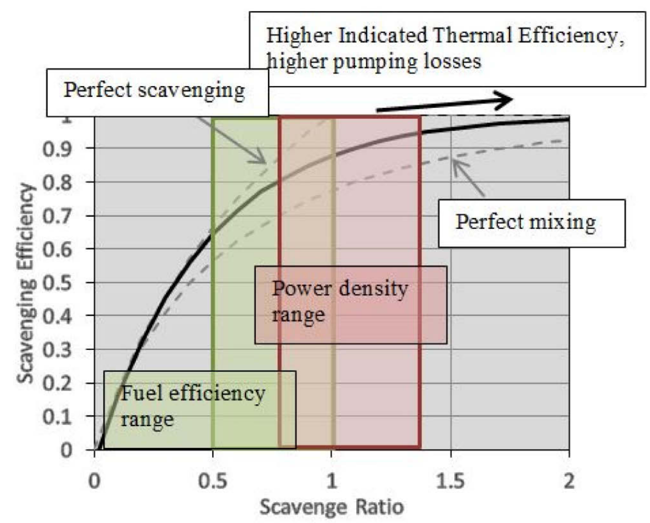


Figure 11. Scavenge ratio versus scavenging efficiency relationship of a two-stroke engine.

At lower speeds, the engine allows more time for the ports to be open and, thus, more time for the scavenging process per cycle. Therefore, the pressure difference required across the intake and exhaust to move the air plus EGR mass is lower at lower speeds and higher for higher speeds. This also results in higher scavenge ratios at lower speeds and lower scavenge ratios at higher speeds. Higher scavenge ratios reduce trapped temperature by increasing scavenging efficiency (i.e. by removing more residuals from the previous thermodynamic cycle). These lower trapped temperatures improve indicated thermal efficiency-by reducing in-cylinder heat losses-and reduce NOx. However, the trapping efficiency decreases with higher scavenge ratios because some of the fresh air and EGR mass from the intake side do not get trapped in the cylinder, but escape to the exhaust side during scavenging. Therefore, the pumping losses are higher at higher scavenge ratios compared to lower scavenge ratios where trapping efficiency is higher.

Based on the aforementioned facts, the ports of the OP2S engines are designed differently for different applications. For automotive applications, such as medium- and heavy-duty trucks that have a smaller engine speed ranges, the ports are designed small enough so that the scavenge ratio range is somewhere between 0.5 and 1 for most of the engine operating conditions. This prevents excessive scavenge ratios and thus reduces pumping losses at low speed, full load conditions, while still keeping the trapped temperature low enough at high speed conditions for durability. For the high power density applications-such as military vehicles-bigger ports are used to keep the scavenge ratio greater than 1 for high load conditions so that less than 10% of the residuals from previous cycles are left inside the cylinder at the end of the scavenging process. This approach does jeopardize fuel economy with increased pumping losses, but it also allows a higher amount of fuel injection per cycle with a maximum combustion temperature that is still reasonable for durability.

Crank Phasing

OP2S engines have two cranks and the exhaust crank usually leads to the intake crank in order to open the exhaust ports for blowdown of the exhaust gases to occur prior to the opening of the intake ports. The phasing between the exhaust and intake cranks, together with the exhaust and intake port sizes, determine how much exhaust port area is available for the blowdown event.

The requirement of the blowdown area on the exhaust port is directly proportional to the fuel energy released in the cylinder during combustion, or the load on the engine, which is increasing the pressures of the trapped gases. The main goal of the blowdown event is to have the cylinder pressures sufficiently reduced at the time the intake ports open, so that the in-cylinder pressures are lower than the intake manifold pressures at the start of the scavenging process. This prevents back flow of residuals into the intake side and reduces pumping losses. However, too much blowdown area on the exhaust ports requires the exhaust ports to open earlier in the expansion stroke, reducing the expansion ratio of the engine and the indicated thermal efficiency.

The phasing between the exhaust and intake cranks can change the timing of the exhaust port opening compared to the minimum volume and the blowdown time on the exhaust ports for the same port heights. Figures 12 and 13 explain the effect of crank lead, with blowdown areas shaded in red and scavenging areas shaded in blue. Figure 12 shows higher blowdown and an earlier opening of the exhaust ports with a 12-degree lead of exhaust crank compared to Figure 13 with 0-degree phasing between the exhaust and intake cranks for the same port heights. The scavenging area shown in blue is the same for both crank lead cases.

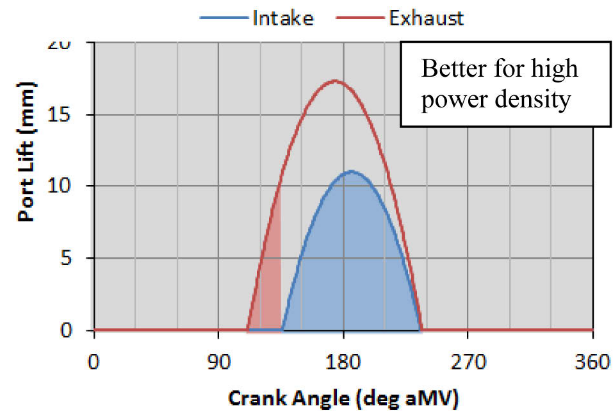


Figure 12. Exhaust and intake port areas for 12-degree exhaust crank lead.

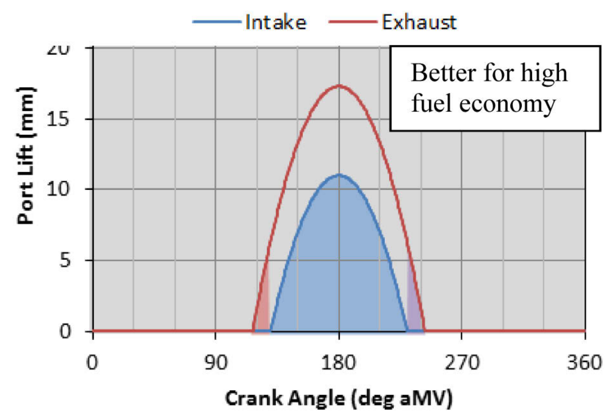


Figure 13. Exhaust and intake port areas for 0-degree exhaust crank lead.

For applications-such as medium- and heavy-duty trucks that have a smaller engine speed range and the highest priority on fuel economy-the engines have smaller ports with 6 to 10 degrees crank lead based on the blowdown area requirements. For high power density applications, such as military vehicles, the ports are bigger with crank leads in the range of 8 to 14 degrees. However, for applications, such as light-duty vehicles, bigger ports are required to meet the rated power durability requirements, but having higher expansion ratios for lower speed and lower loads does bring considerable fuel economy gains. Therefore, the variable crank phasing mechanism that can allow the exhaust crank lead to change from 0 to 12 degrees is worth the cost for light-duty applications. The variable crank phasing mechanism also provides variable compression and expansion ratios, useful for applications requiring good fuel economy at lower speed and load, while still requiring high power density.

Turbocharger and Supercharger

Turbocharger and supercharger selections for OP2S engines are just as important as for any other engine in achieving good fuel economy, transient response and altitude or high temperature ambient condition operation. However, the air system layout shown in Figure 2 does require different approaches compared to conventional turbo matching.

The turbine does not need to be variable geometry because the supercharger allows sufficient flexibility to supply required air and EGR without an excessive pumping penalty for lower speed range applications like medium- and heavy-duty trucks. However, for the high-speed range applications with emphasis on low-speed, low-load points like the light duty, the variable geometry turbine does provide considerable fuel economy advantages to justify its cost. The variable vanes of the turbine allow the turbocharger to produce higher power compared to a fixed geometry turbine at lower flows and, thus, reduce supercharger power requirements. They also provide a good lever to control the pressure difference across the cylinder and, thus, the flow through the engine by delivering better exhaust pressure control. Therefore, a waste-gated fixed geometry turbocharger is recommended for medium- and heavy-duty applications while a variable geometry turbocharger is recommended for light-duty applications.

The power consumed by the supercharger changes as the air and EGR requirements change across the engine map. This demands different supercharger drive ratios (gear ratio between supercharger and engine speed) for different engine speed and load conditions. With continuously variable speed drive technology not ready for production yet, the two-drive ratio system with an option for disconnecting the supercharger and with a supercharger recirculation valve, stands out as the pragmatic solution for production at the current technology level.

Thus, for medium- and heavy-duty applications, the gear-driven supercharger with two speed ratios is found to be a good solution considering durability, cost and fuel economy trade-offs. For these applications, the lower gear ratio is selected in such a way that the engine runs with minimal pumping losses and, thus, the best fuel economy at highly weighted operating conditions, such as highway driving. This is typically at mid-speed 50-75% load conditions. The lower engine speeds and higher load conditions require higher supercharger gear ratios. The division of lower and upper gear ratios for a medium-duty application is shown in Figure 14.

The light-duty application requires higher EGR rates at lower loads and meets emissions standards without requiring EGR at full load conditions. Therefore, the supercharger gear ratio requirements are somewhat similar across the engine map. Moreover, with a variable geometry turbocharger, the fuel economy advantages of multiple supercharger gear ratios are diminishing in light-duty applications like cars or SUVs.

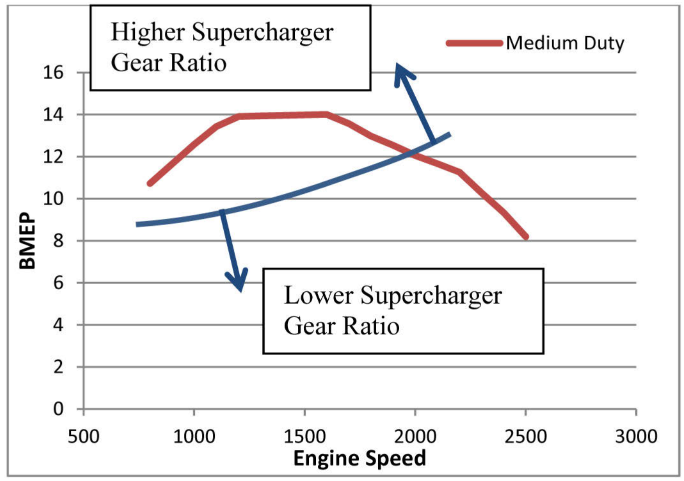


Figure 14. Selection of supercharger gear ratio split for two-speed supercharger drive in medium-duty application.

Combustion System Considerations

The piston shape-together with the appropriate intake port design-creates required air-charge motion at the start of injection. The number of holes in the injector nozzle as well as their size and angle have to be designed according to this air-charge motion during injection and combustion. The primary goal is to develop a system that can provide sufficient mixing of air and fuel with good air entrainment into the plumes for faster combustion with lower soot and CO generation while simultaneously keeping the plumes away from the piston surface and preventing them from hitting each other (as they are injected from opposite sides).

Different applications with different emissions standards require different EGR rates, swirl and tumble motion. Automotive applications with low engine-out NOx and soot require a high amount of EGR for NOx reduction while high swirl and tumble motion for efficient combustion efficiency in this high EGR environment. However, for high power density, higher engine-out emissions applications (like military vehicles), the EGR rate and in-cylinder air-charge motion at the start of combustion are relatively low. NVH requirements are also important in selecting injector nozzles. NVH requirements impose maximum pressure rise rate limitations and that controls how fast the fuel can be injected into the combustion chamber. This also decides the maximum size of the holes in the nozzles and rail pressures. Generally, the applications with higher EGR rates and air-charge motion require nozzles with smaller holes compared to no-emissions requirement applications like those for the military. For each application, the injector clocking as well as the rate of injection for each injector are also optimized to prevent plumes hitting each other and the piston. At Achates Power, genetic algorithms to optimize the combustion system parameters including number and size of holes, cone angle, angles between the holes, injector clocking and injection rates for each injector are run extensively [4] and have shown to be very beneficial for selecting combustion systems for each application.

EXAMPLES OF ACHATES POWER OP2S ENGINE IN VARIOUS APPLICATIONS

Medium-Duty Truck Application

One automotive segment that can significantly benefit from the fuel economy advantages of OP2S technology is the medium-duty truck. Figure 15 shows a 4.9L three-cylinder OP2S engine. This engine would be a good replacement for a 6.7L, six-cylinder, four-stroke as found in some medium-duty trucks. With the engine installed slanted, as shown, the OP2S engine is able to be the same height as the 6.7L, six cylinder. Table 5 shows details of the Achates Power 4.9L OP2S diesel engine for medium-duty truck applications.

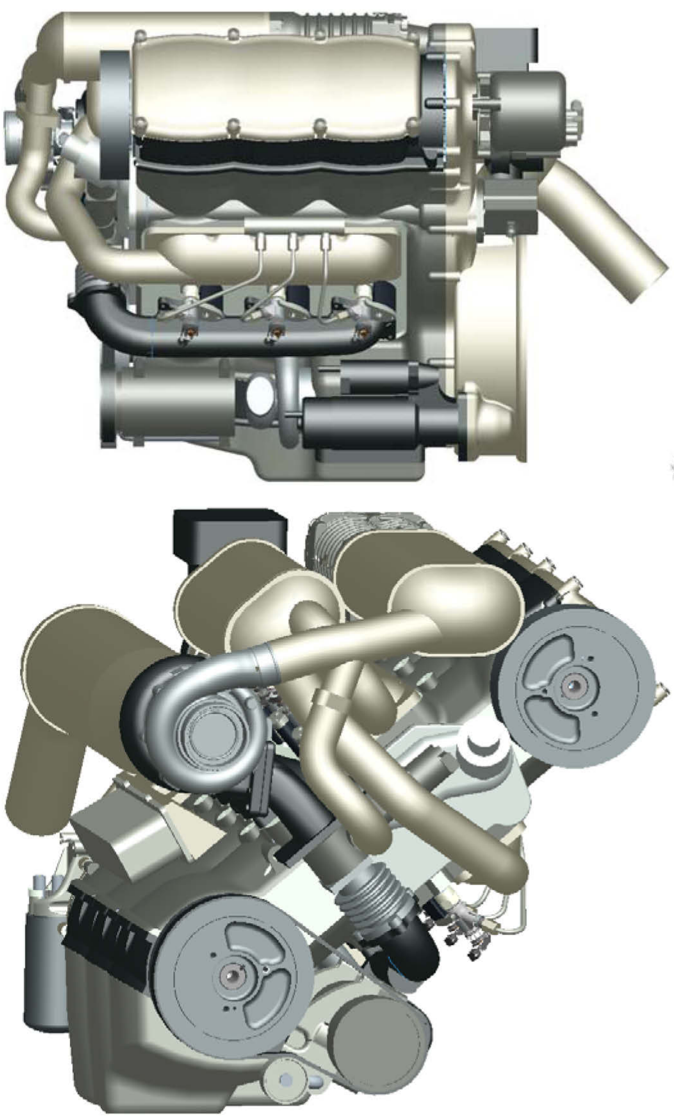


Figure 15. 4.9L OP2S engine for medium-duty truck.

Table 5. OP2S engine configuration for medium-duty truck.

Cylinder	Inline 3
Number of Pistons	6
Number of Injectors	6
Swept Volume/Engine (L)	5.4
Bore (mm)	98
Stroke (mm)	236
Stroke/Bore Ratio(-)	2.4
Nominal Power (kW@RPM)	202@2200
Max. Torque (Nm@RPM)	1098@1200-1600
Emission Standard	US 2010 / Euro 6

As seen in Figure 16, the 4.9L engine as designed per the specification of Table 5, is expected to achieve 48.5% best Brake Thermal Efficiency (BTE) meeting U.S. 2010 emissions with SCR and DPF (engine-out emissions are about 3 g/kWh NOx and 0.02 g/kWh soot on ESC 13 mode [11]). The BSFC map was generated using a 1D GT Power multi-cylinder model with inputs from single-cylinder measured combustion and friction data, supplier provided supercharger and turbocharger maps, and some improvements in combustion, friction and the air system during production-level technology development and optimization over the next three to four years. The process of generating multi-cylinder 1D modeling results from single-cylinder measured combustion is well explained in earlier papers [3][6][7]. The BSFC map is also considerably flat compared to a conventional medium-duty, four-stroke engine [20]. When compared to a four-stroke [20], the medium-duty OP2S is expected to have up to a 21% lower cycle-averaged BSFC with similar engine-out emissions [3][6].

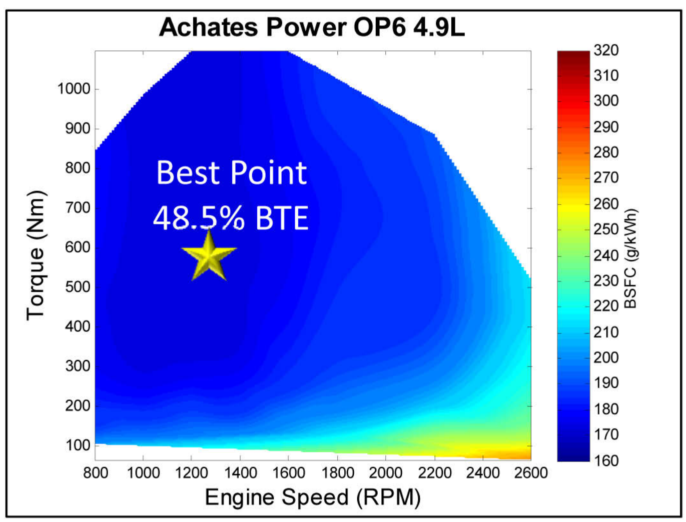


Figure 16. BSFC map of 4.9L medium-duty OP2S engine with U.S. 2010 emissions with SCR and DPF in aftertreatment.

When the model is adjusted for Euro 4 emissions requirements and the aftertreatment back pressure is reduced to account for the absence of the SCR and DPF, the expected

BSFC map is as shown in Figure 17 and the best BTE is expected to be 49.2%.

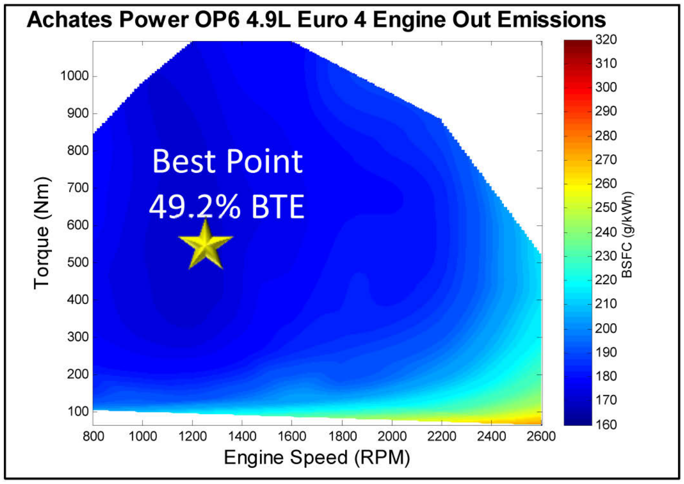


Figure 17. BSFC map of 4.9L medium-duty OP2S engine with Euro 4 engine-out emissions and no aftertreatment.

The flat nature of the BSFC map, as seen in Figures 16 and 17, brings additional advantages as follows:

1. Better real-world fuel economy
2. Less application-specific calibration work
3. Less driver-to-driver variations
4. Fewer transmission gear shifts and simpler transmissions
5. Minimal down speeding and associated driveline upgrades
6. Reduced need for technologies like cylinder de-activation.

Passenger Car Application

The OP2S engine with 1.5L displacement producing 129 hp for passenger car applications has been studied. The work has been presented at the 2013 SAE High Efficiency IC Engine Symposium [19]. Table 6 shows the specification of Achates Power 1.5L OP2S diesel engines for light-duty applications, such as passenger cars. The details of the package of this engine in a typical front-wheel drive sedan are shown in Figure 18.

Table 6. OP2S engine configuration for light-duty (car).

Cylinder	Inline 2
Number of Pistons	4
Number of Injectors	4
Swept Volume/Engine (L)	1.50
Bore (mm)	75.72
Stroke (mm)	166.57
Stroke/Bore Ratio(-)	2.2
Nominal Power (kW@RPM)	96@4000
Max. Torque (Nm@RPM)	325@1750-2250
Emission Standard	Euro 6 / LEV 3

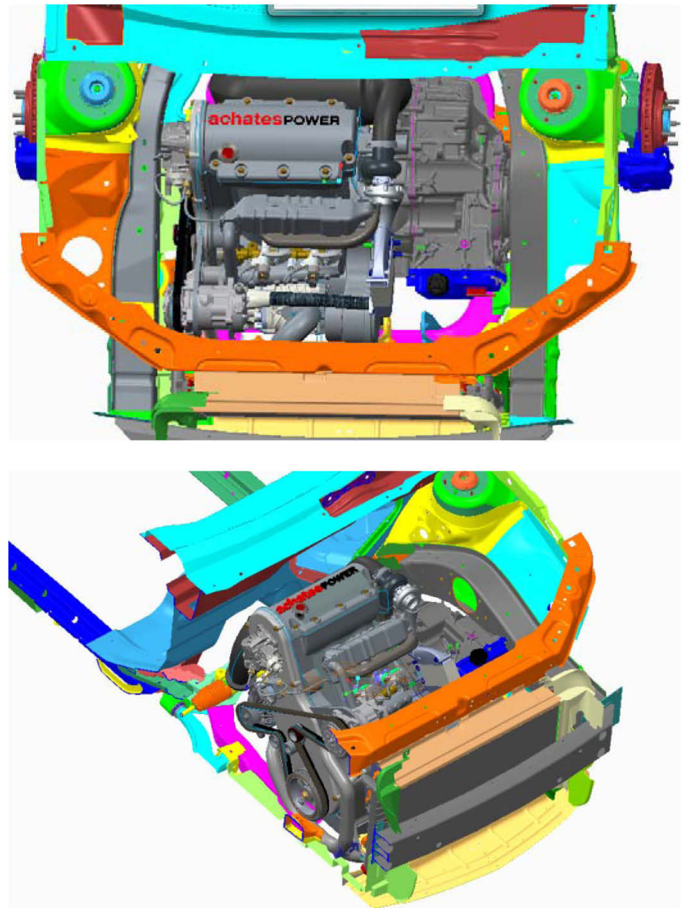


Figure 18. CAD showing 1.5L OP2S engine packaged in passenger car application.

The fuel consumption map for Euro 6/LEV 3 engine-out emissions with this engine is shown in Figure 19. On a cycle-average basis, this OP2S light-duty engine with Euro 6 engine-out emissions is expected to provide 13% better fuel economy [19] compared to a modern, conventional four-stroke engine [21] with Euro 5 engine-out emissions.

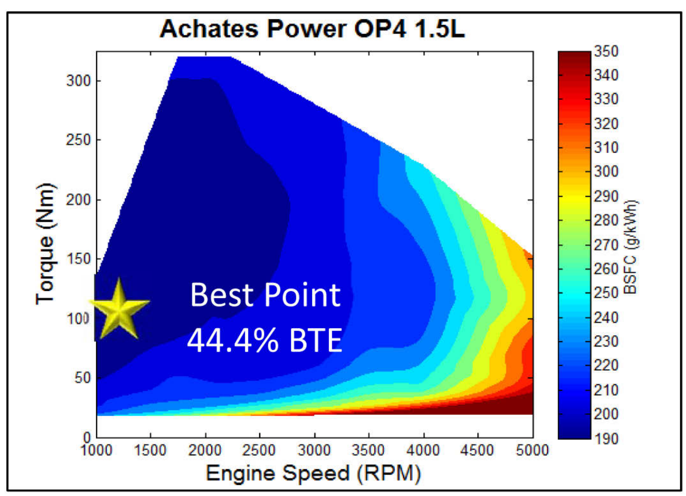
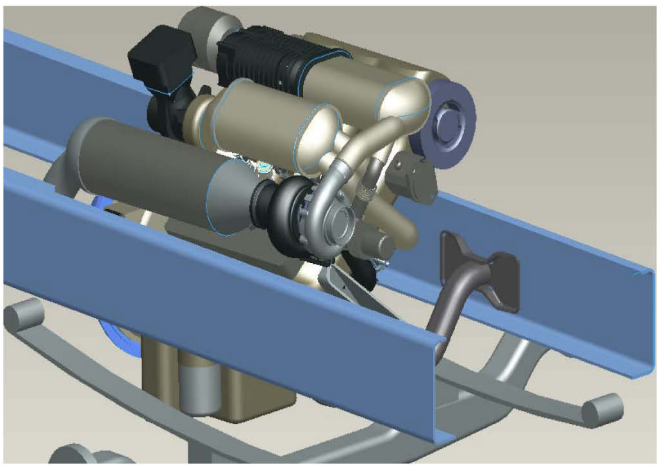


Figure 19. BSFC map of 1.5L light-duty OP2S engine with Euro 6/LEV 3 engine-out emissions.

Heavy-Duty Truck Application

Table 7. OP2S engine configuration for heavy-duty truck.

Cylinder	Inline 3
Number of Pistons	6
Number of Injectors	6
Swept Volume/Engine (L)	10.8
Bore (mm)	121
Stroke (mm)	314
Stroke/Bore Ratio(-)	2.6
Nominal Power (kW@RPM)	356@1850
Max. Torque (Nm@RPM)	2276@1000-1450
Emission Standard	US 2010 / Euro 6



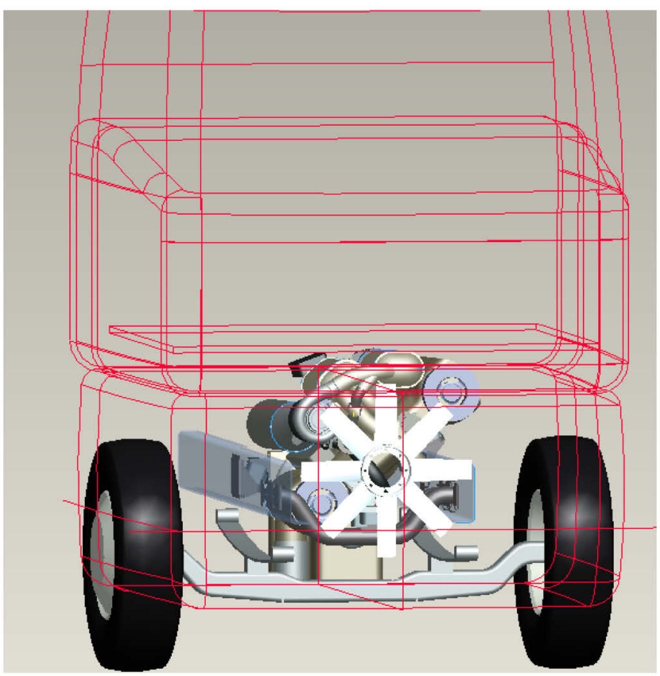


Figure 20. OP2S engine for heavy-duty truck.

The engine concept for replacing a typical 13 to 15L four-stroke conventional engine in the heavy-duty truck is presented in Figure 20. The OP2S engine is shown fitting in a typical "cab-over" truck in this figure. The engine specifications for the Achates Power OP2S engine for heavy-duty applications are listed in Table 7.

The projected BSFC map for the heavy-duty application with U.S. 2010 emission standards with SCR and DPF is shown in Figure 21 (i.e. 3 g/kWh NOx and 0.02 g/kWh soot engine-out on ESC 13 mode [11]). The best BTE is expected to reach 51.5%, which leads to a more than 19% improvement compared to currently produced four-stroke, heavy duty engines that have about 43% best BTE. The cycle-averaged fuel economy will be greater thanks to the flat BSFC map.

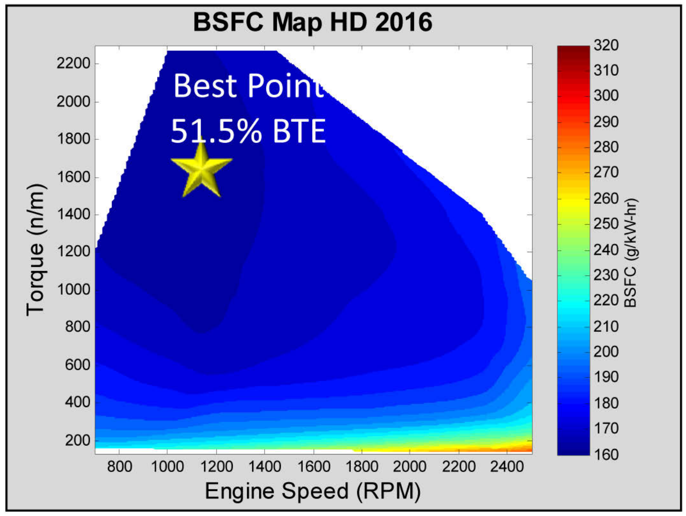


Figure 21. BSFC map of 11L heavy-duty OP2S engine with U.S. 2010 emissions with SCR and DPF in aftertreatment.

SUMMARY

The opposed-piston, two-stroke engine has fundamental fuel economy advantages proven by measurement data on a single-cylinder research engine. While the engine gives superior thermal efficiency across the engine map, the data presented in this paper for a 1200 rpm 8.8 bar IMEP operating condition with 3.77 g/kWh ISNOx and 0.005 g/kWh ISSoot showed 53.5% indicated thermal efficiency, an exceptionally good number for a 1.6L engine. The mechanical design and durability challenges have been solved with analytical tools and innovative approaches at Achates Power. The OP2S engines are being developed for light-, medium- and heavy-duty vehicles for automotive applications as well as for the military. The technology is also being readied for generator sets and large ship engines. Various innovative packaging techniques-such as a compact, integrated gear train connecting two crankshafts, vertical installation and tighter bore spacing-have made it possible to fit OP2S engines in all applications successfully. Application-specific design parameters (including stroke-to-bore ratio, port sizes and crank phasing) have been identified and optimized for various applications. The turbo machinery selection is well understood and the combustion system hardware is extensively optimized-using advanced techniques including genetic algorithms-at Achates Power to develop OP2S engines for various applications.

More than 4,500 hours of dynamometer testing was performed on the 1.6L single-cylinder engine. While the multi-cylinder engines are being developed for various applications, the 1D models developed based on these multi-cylinder designs and measured combustion have projected the best point brake thermal efficiency to be 44.4% for light-duty applications with Euro 6/LEV 3 engine-out emissions, 48.5% for medium-duty applications and 51.5% for heavy-duty applications with U.S. 2010 emissions standards and DOC, DPF and SCR assumed in the aftertreatment.

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CONTACT INFORMATION

Suramya Naik
Chief Engineer
Achates Power, Inc.
naik@achatespower.com

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

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