Opposed-Piston, Two-Stroke Diesel Engine Advantages in Meeting Higher Fuel Efficiency and Emissions Standards

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Summary

Known for its record-setting combination of fuel efficiency and power density, the opposed-piston, two-stroke (OP2S) diesel engine was once widely used in ground, marine and aviation applications. Despite advancements in two-stroke technology, however, the engines suffered from high NOx and soot as well as poor oil control. As a result, their use in on-road applications ceased with the introduction of modern emissions standards. With today's cutting-edge technologies—including computational fluid dynamics, finite element analysis and high pressure common rail fuel injectors—Achates Power has successfully modernized the opposed-piston, two-stroke engine. The result: a powertrain that has demonstrated the following when compared to leading, conventional diesels:

- 21 percent lower cycle average brake-specific fuel consumption
- Similar engine-out emissions levels
- Less than 0.1 percent fuel-specific oil consumption
- Reduced cost, weight and complexity

In addition to highlighting the latest Achates Power performance and emissions results, this technical paper will provide a brief historical overview of the opposed-piston engine along with a discussion of its fundamental architectural advantages:

- Thermodynamics
- Pumping work
- Transient operation
- Combustion

Also included is a synopsis of the challenges that have affected historical opposed-piston engines and how Achates Power has addressed such things as:

- Wrist pin durability
- Piston and cylinder thermal management
- Oil consumption

- Cylinder durability

1 The Engine Dilemma: How to Reduce Emissions, Increase Efficiency and Manage Costs Simultaneously?

Technologies to reduce tailpipe emissions from passenger vehicles and commercial vehicles are well known. The U.S. and Europe lead in establishing ever-lower standards, as described in the table below:

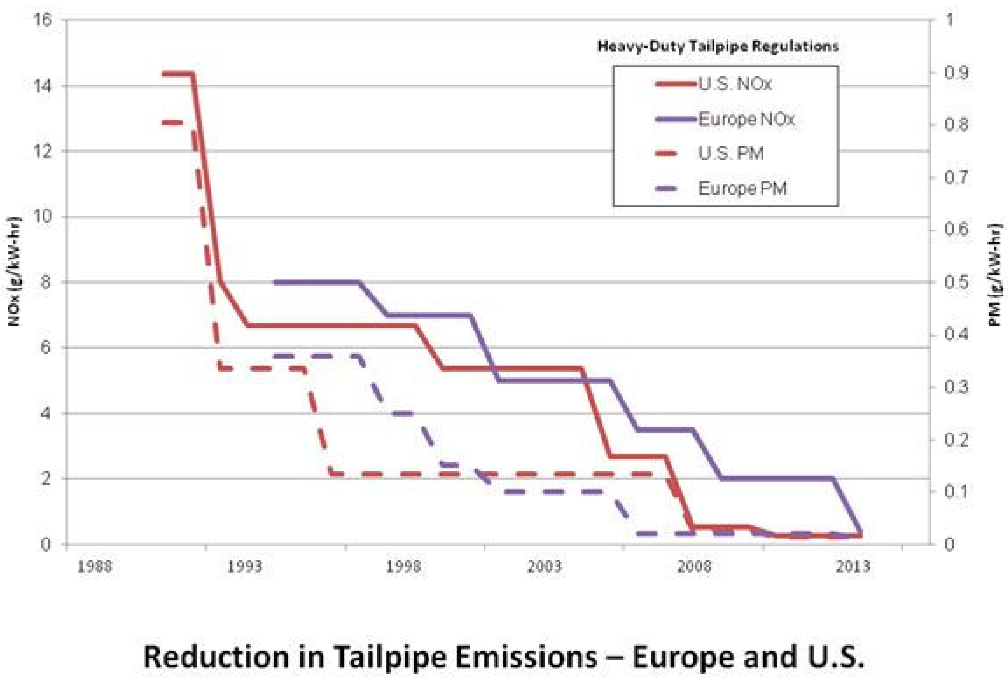

Fig. 1: Heavy-duty tailpipe regulations and their impact on emissions.

Most other major countries around the world are adopting similar standards. The urgency is particularly acute in several large, developing countries where the combination of rapid population growth, steady economic expansion and high population density results in air quality that is not acceptable to an increasing number of regulators and residents.

While clean diesel technology is well established, the technology adoption presents numerous challenges. One challenge is fuel quality—sulfur contaminates diesel aftertreatment systems so ultra low sulfur diesel fuel is required for the lowest emissions standards. Beyond fuel quality, emissions mitigation technology presents two challenges to the engine. The first is design and calibration changes significantly reduce fuel economy. The chart below shows the increase in brake-specific fuel consumption from 1999 to 2007 in the U.S. as more stringent emissions standards were introduced.

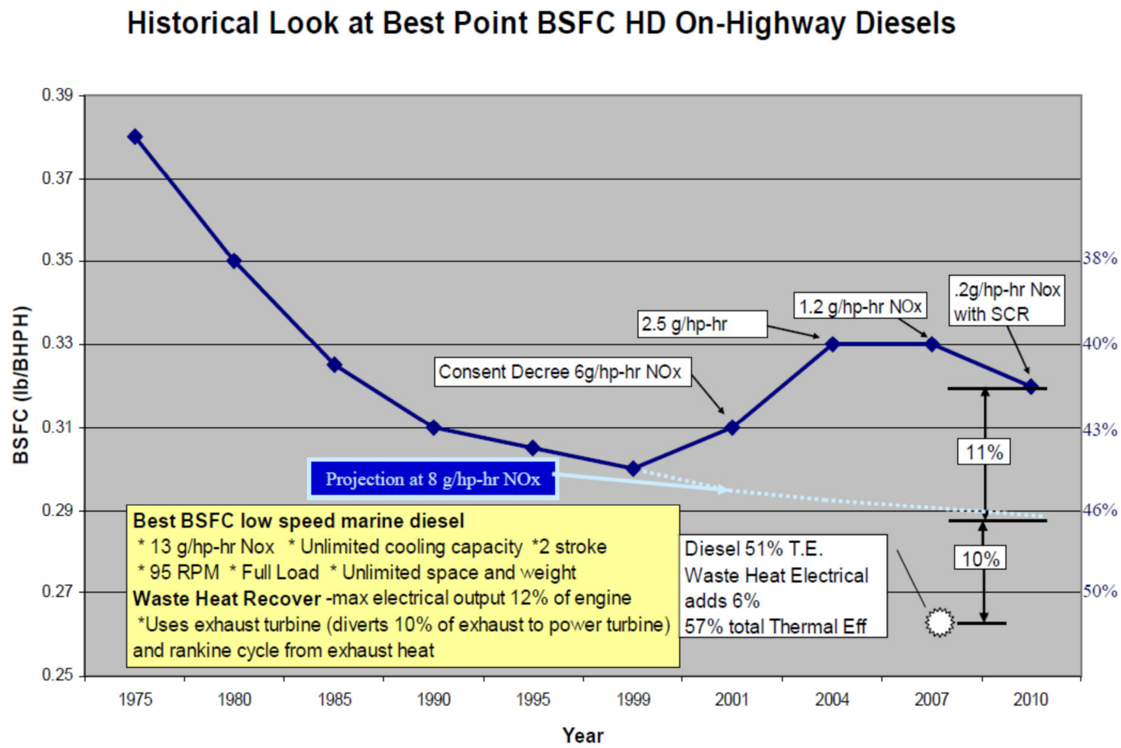

Fig. 2: The increase in brake-specific fuel consumption as more stringent emissions standards were introduced. Source: Tony Greszler, Volvo, October 2009. Reproduced from "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles" [1].

Emissions mitigation equipment is also expensive, substantially increasing the price of cars and trucks.

As China, India and other countries adopt tougher emissions standards, they can expect to face the same dilemma experienced in the U.S. and Europe, but more acute due to lower per-capita GDP: higher purchasing cost and higher operating costs.

While the graphs above relate to commercial vehicle engines, the same dilemma exists for passenger vehicles too.

The opposed-piston, two-stroke offers a way out of the dilemma—an engine architecture that combines low emissions, low fuel consumption and low cost.

2 Opposed-Piston, Two-Stroke Technology

2.1 Low Emissions

2.1.1 Low NOx

The fundamental advantages of the OP2S have been described in technical papers previously [2], [3] and [4].

The OP2S engine has several characteristics that make it well suited for clean diesel operation. First, it operates at relatively low brake mean effective pressure (BMEP).

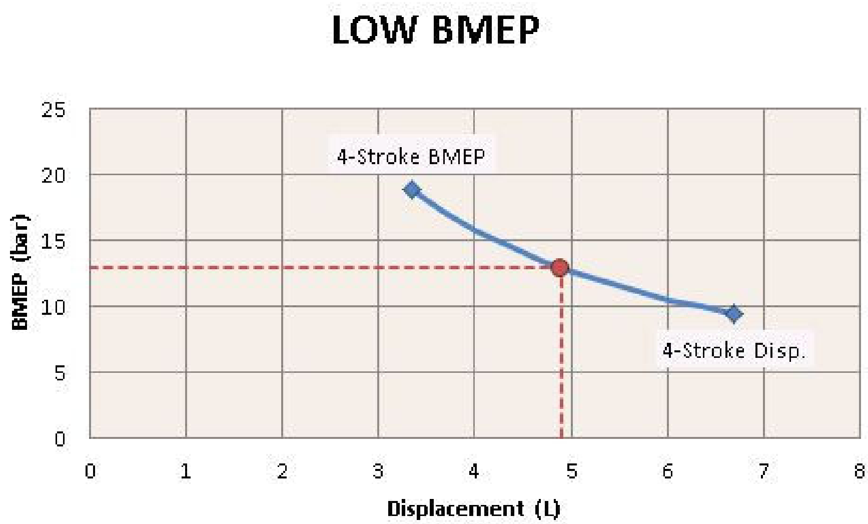

Fig. 3: The range of displacement/BMEP combinations available when designing an OP2S engine to match the power and torque of a 6.7L conventional engine.

Because it operates on the two-stroke cycle, the OP2S engine has a power stroke in each cylinder during each engine revolution, so it has inherently high power density. This power density can be used to reduce displacement or to reduce BMEP. In practice, it is often advantageous to reduce both, simultaneously. The chart above shows the range of displacement/BMEP combinations when designing an OP2S engine to match the power and torque of a 6.7L conventional engine. At one extreme, the OP2S engine could have the same displacement and half the effective BMEP. At the other extreme, it could have half the displacement and the same BMEP. In practice, a 5L engine delivers both reduced displacement—reducing the size, weight and cost of the engine—and reducing BMEP simultaneously. Because the OP2S engine has lower BMEP, fewer calibration tradeoffs are required to keep peak cylinder temperatures low to prevent NOx formation.

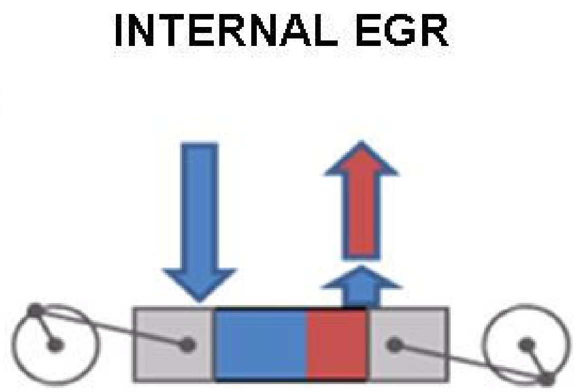

Fig. 4: The OP2S has a natural EGR advantage.

Moreover, as a two-stroke engine the OP2S engine has a natural EGR advantage. At low loads, the cylinder only has to be partially scavenged because piston and cylinder thermal loads remain relatively low. Retaining exhaust gas dilutes the incoming charge and requires less external exhaust gas recirculation (EGR) to manage NOx formation. This reduces the pumping work required in the gas exchange, improving brake thermal efficiency while keeping NOx to a manageable level.

2.1.2 Low PM

The OP2S engine also has several advantages that lead to low particulate matter. The OP2S engine can support a high air-fuel ratio without excessive pumping work. To describe this, it is useful to compare the equivalent power units below.

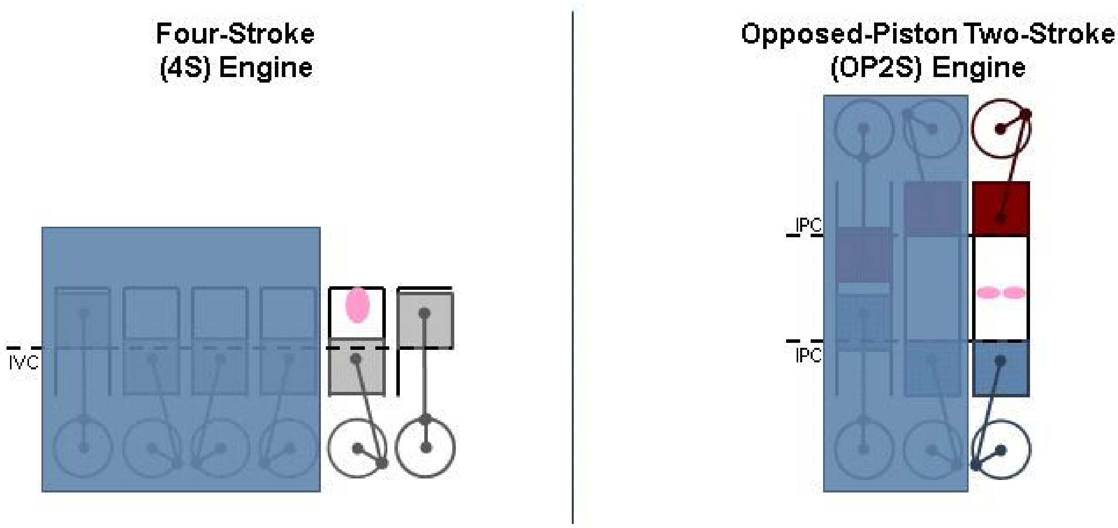

Fig. 5: Comparing the four-stroke engine to the opposed-piston, two-stroke engine.

A theoretical comparison is made between a conventional four-stroke engine and an opposed-piston, two-stroke engine. The four-stroke engine is a six-cylinder engine, shown on the left. To keep as many factors constant as possible, the OP2S engine on the right has the same bore, trapped compression ratio and geometric displacement. Since OP2S engines have ports on the side of the cylinder for gas exchange, the trapped displacement—the portion of the cylinder after both the intake and exhaust ports are closed—is less than the geometric displacement. Note that the trapped displacement is 1.6L per cylinder in this example; 60% more than that of the four-stroke engine.

Since the two engines were configured to generate the same power, two cylinders (and two pistons) from the four-stroke engine generate the same power as one cylinder (and two pistons) of the OP2S engine. On one revolution of the engine, one unit of fuel is injected into cylinder five of the four-stroke engine and into cylinder three of the OP2S engine. On the next revolution of the engine, one unit of fuel is injected into cylinder six of the four-stroke engine and into cylinder three of the OP2S engine. Each cylinder, therefore, gets roughly the same quantity of fuel in each combustion cycle. But, as noted above, the OP2S cylinder is 60% larger than the four-stroke engine.

At the same boost level, therefore, the OP engine operates leaner. Not only does this result in more efficient operation, but when combined with good mixing, it produces low PM.

The combustion system developed by Achates Power, described in Section 2.3, provides excellent mixing.

As a result of the features highlighted in this section, relatively few calibration tradeoffs need to made to meet even Euro VI and U.S. EPA 2010 emissions standards so that the engine combines low emissions with low fuel consumption. The detailed performance and emissions data presented in Table 3 of Reference [4] provides a good example.

2.2 Low Fuel Consumption

The fundamental thermodynamic efficiency advantages of the OP2S have been described in technical papers previously [2], [3] and [4].

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

- The OP engine has favorable surface area/volume ratios during combustion compared to equal displacement four-stroke engines, reducing heat transfer during combustion.
- OP2S engines enable reduced fuel per combustion event in a larger cylinder (almost twice as large with half the number of cylinders compared to a

conventional four-stroke) for the same power, resulting in leaner combustion at the same boost level and improved thermal efficiency (see Section 2.1.2).

- The two-stroke cycle (with reduced fuel per cylinder volume) together with the separating motion of two pistons, creates a larger volume per crank angle, enables a shorter combustion duration at the same maximum pressure rise rate and improves thermal efficiency.

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

- Lower heat loss due to reduced cylinder counts leading to larger cylinders and the higher wall temperature of two piston crowns compared to a cylinder head.
- Further reduction in surface area/volume ratio and better scavenging by using a greater than 2.0 stroke-to-bore ratio [3][13].
- Reduced pumping work thanks to uniflow scavenging with the OP architecture giving a higher effective flow area than comparable four-stroke or single piston, two-stroke uniflow or loop scavenged engines [11].
- Decoupled pumping process from the piston motion due to the two-stroke architecture allows alignment of the engine operation with a maximum compressor efficiency line [10].
- Lower NOx characteristics as a result of lower BMEP requirements because of the two-stroke cycle operation [12].

2.3 Combustion System Advantages

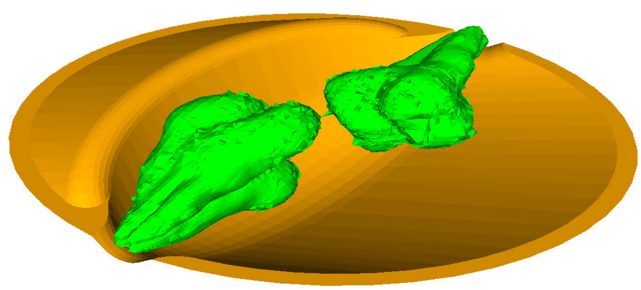

Fig. 6: Schematic of the combustion system with plumes coming out of two side-mounted injectors.

Achates Power has developed a proprietary combustion system [14] 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 [5] (Figure 6).

This combustion system allows:

- High turbulence, mixing and air utilization with both swirl and tumble charge motion
- Ellipsoidal combustion chamber resulting in air entrainment into the spray plumes from two sides

- Inter-digitated, mid-cylinder penetration of fuel plumes enabling larger λ=1 iso-surfaces
- Excellent control at lower fuel flow rates because of two small injectors instead of one large one
- Multiple injection events and optimization flexibility with strategies such as injector staggering and rate-shaping [5]

The result is no direct fuel spray impingement on the piston walls and minimal flame-wall interaction during combustion. This further improves performance and emissions [4] with fewer hot spots on the piston surfaces, enhancing piston thermal management and increasing engine durability [5].

2.4 Low Cost

In addition to low emissions and low fuel consumption, the OP2S engine has a favorable cost position.

- The OP2S engine does not have a cylinder head, typically the most expensive part of the engine.
- The OP2S engine does not have a valve train, which typically contributes to the highest part count in an engine.
- The OP2S usually has a smaller displacement than a comparable conventional engine, reducing weight and material cost (see 2.1.1).

The component differences between conventional and OP2S engines are summarized below:

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

Tab. 1: Component differences between conventional and OP2S engines.

3 Resolving the Historical Challenges of the OP2S Architecture

While opposed-piston engines eliminate many engine components that are among the most common to fail in conventional engines—cylinder head, cylinder head gasket, exhaust valves, cams, etc.—they introduce new design features that have to be fully validated.

3.1 Wrist Pin Durability

Since wrist pins for two-stroke engines are primarily under continuous compressive load, it is challenging to adequately lubricate the bearing. Without a force reversal on the wrist pin, lubricating oil fails to migrate to all surfaces of the pin, leading to premature wear.

To address this failure mode, a biaxial bearing (which is illustrated below) has been designed and developed. This bearing design uses two distinct, non-concentric journals to carry the load. The motion and geometry of the pin and carrier alternately load and unload different portions of the bearing so that the full bearing is squeeze-film lubricated in each engine cycle.

Similar designs have been used successfully in production on crosshead two-stroke marine engines and two-stroke locomotive engines. The type of wrist pin is well understood.

A biaxial bearing has been designed, built and tested to operate up to 200 bar peak cylinder. Additionally, experimentally-calibrated and proprietary analytical models have been developed to determine minimum oil film thickness, density and film pressure of different bearing design alternatives, which enable rapid design evolution.

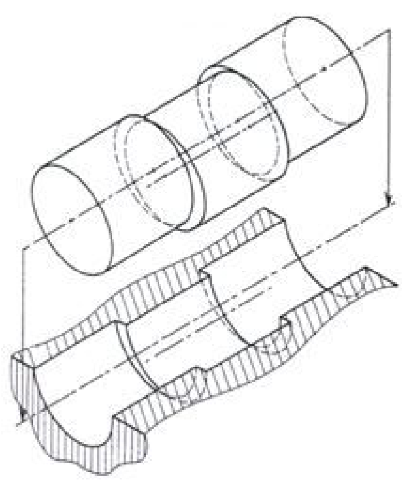

Fig. 7: The biaxial bearing design uses two non-concentric journals to carry the load.

3.2 Piston and Cylinder Thermal Management

Since two-stroke engines fire in every cylinder during every engine revolution, they tend to have high thermal loads on the piston and cylinders. The Achates Power design has several advantages over many other two-stroke engines:

- The very high thermal efficiency, described previously, results in less heat being transferred to the combustion chamber surface than in other two-stroke engines.
- The engine has moderate BMEP and gas temperatures compared to some two-stroke engines (see section 2.1.1).
- Proven impingement cooling solutions for both pistons and cylinders have been developed to manage piston and cylinder thermal loads.

Beyond this, management of piston and liner temperatures require a total systems approach, including:

- Selection of the appropriate injector spray patterns and piston bowl geometries to reduce heat flux into the piston crown.
- Port timing selections that manage trapped air charge temperatures.
- Use of appropriate calibration settings, such as air/fuel ratios and beginning of injection timing.
- Optimal flow rates of the piston cooling jets and fill ratios for the galleries.

One of the key cylinder cooling objectives is to maintain a uniform temperature axially along the bore to minimize bore distortion and allow use of lower friction piston rings. This is accomplished by introducing the impingement cooling along the outside circumference of the middle of the cylinder, which is the area of highest heat transfer. This also allows the coolant flows along the exhaust side and the intake side of the cylinder to be metered separately, recognizing that there will be higher heat transfer on the exhaust side.

Analytic methods are used to design and analyze cylinder cooling solutions. These methods include performing conjugate heat transfer analysis using computational fluid dynamics, accounting for the dynamic effects of swirl and piston motion [7].

Technical goals for maximum piston temperatures have been developed to prevent oil degradation, ring jacking and carbon build-up. Experimentally calibrated and proprietary analytical models are used to evaluate thermal loading and thermal management of piston and cylinder design alternatives, which enables rapid design evolution.

3.3 Oil Consumption and Cylinder Durability

Ported engines have historically been known to have problems with excessive oil consumption, driven by a tradeoff between low oil consumption and acceptable cylinder and piston durability. The oil consumption goal of Achates Power for engines is 0.1% of fuel (fuel-specific oil consumption = 0.1%), well within range of commercial acceptance.

A Da Vinci sulfur trace system is in use that enables the measurement of oil consumption in real time [8].

Mitigation techniques to reduce oil consumption, as needed, include:

- Modifying oil ring tension
- Modifying scraper element conformability
- Modifying ring end gaps, end chamfers and land chamfers
- Modifying ring groove tilt, pinch, keystone angle, texture and flatness
- Modifying ring side clearance, cross sealing and side sealing
- Modifying volume behind ring and volume between rings
- Modifying bore texture and form after honing and form at operating temperature
- Modifying cylinder cooling design and operation to change liner temperature
- Unique honing approaches

By using the Da Vinci sulfur trace system, the measurement of an oil consumption map for the engine can be done within a few hours. The figure below shows the map covered by the 13 modes of the steady-state emissions test cycle. The cycle-averaged, fuel-specific oil consumption is measured to 0.114%. The maximum measured shown is 0.171% and the minimum is 0.072%. These are exceptional values for a two-stroke engine and approach those of best-in-class four-stroke engines.

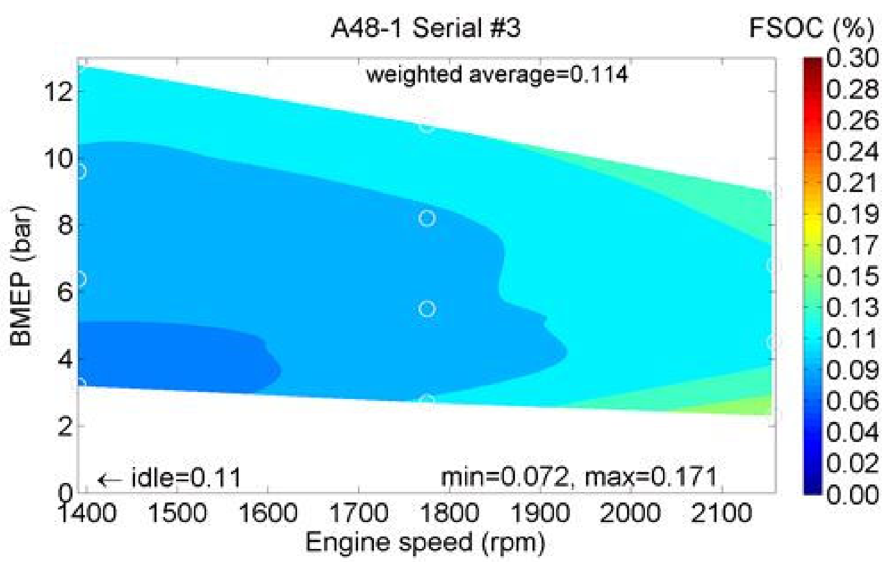

Fig. 8: Fuel-specific oil consumption.

In addition, poorly designed ported engines have been known to have problems with piston ring clipping, where the ring makes metal-to-metal contact with a port timing edge. This contact abrades the material and eventually leads to scuffing or excessive wear of the liner so a number of design solutions were developed to mitigate this problem.

One such solution is using experimentally calibrated, proprietary analytical models to evaluate the ring clipping potential of different design alternatives, which enables rapid design evolution. Current mitigation actions have included:

- Reducing port widths to limit ring excursion
- Designing unique port geometries that limit contact stress and radial acceleration of the ring as it traverses the ports
- Design of the free ends of the ring to guide the rings back into the port without clipping

4 Examples of Achates Power OP2S Engine in Various Applications

4.1 Medium-Duty Truck Application

One automotive segment that can benefit from the fuel economy advantages of the OP2S technology is the medium-duty truck. Figure 9 shows a 4.9 liter, 3-cylinder OP2S engine. This engine would be a perfect replacement for a 6.7 liter, 6-cylinder four-stroke as is found in some medium-duty trucks. With the engine installed slanted, as seen below, the OP2S engine is able to be the same height as the 6.7 liter, 6-cylinder. Table 2 shows details of Achates Power 4.9L OP2S diesel engine for a medium-duty truck application.

Cylinder Arrangement/Number	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	U.S. 2010 / Euro 6

Tab. 2: OP2S engine configuration for medium-duty truck.

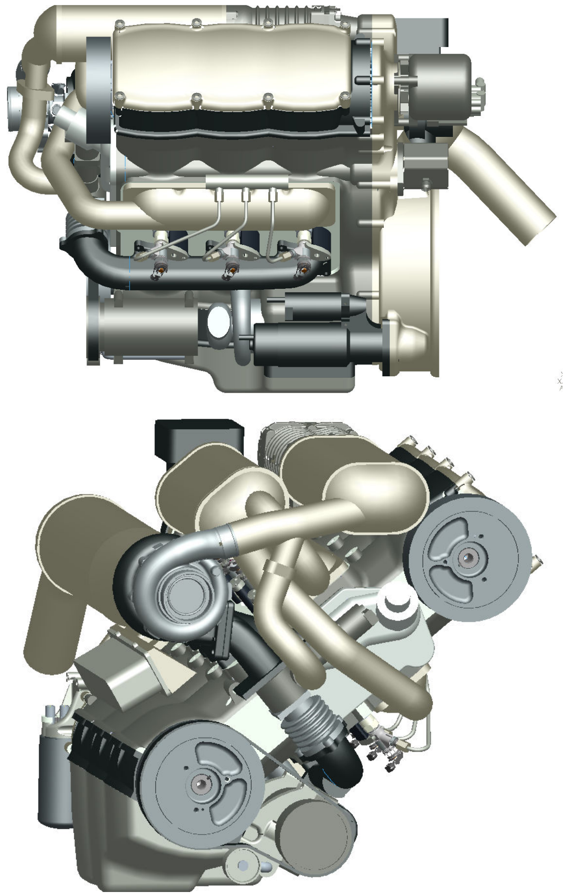

Fig. 9: 4.9L OP2S engine for medium-duty truck.

As seen in Figure 10, the 4.9L engine as designed per the specification of the Table 2, 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 [9]). The BSFC map was generated using single cylinder measured data and the process of generating multi-cylinder 1D modeling results are explained in earlier papers [4] [6]. The BSFC map is also considerably flat compared to a conventional, medium-duty four-stroke engine [16]. When compared to a conventional four-stroke [16], the medium-duty OP2S is expected to have up to a 21% lower cycle-averaged BSFC with similar engine-out emissions [4] [6].

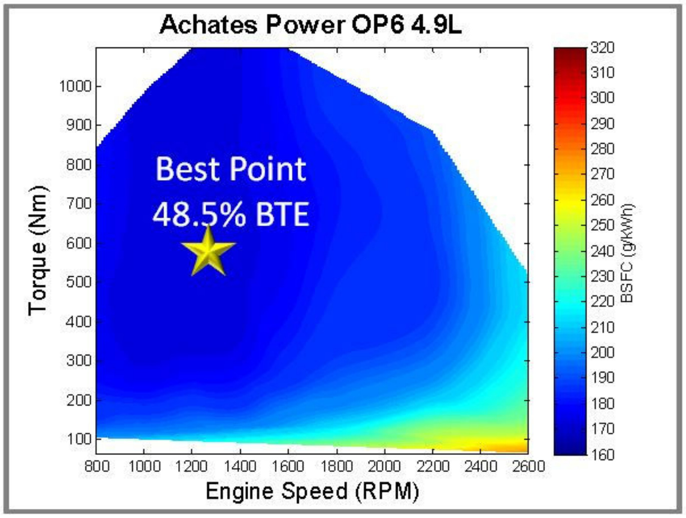

Fig. 10: BSFC map of 4.9L medium-duty OP2S engine with U.S. 2010 emissions with SCR and DPF in aftertreatment.

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 11 and the best BTE is expected to be 49.2%.

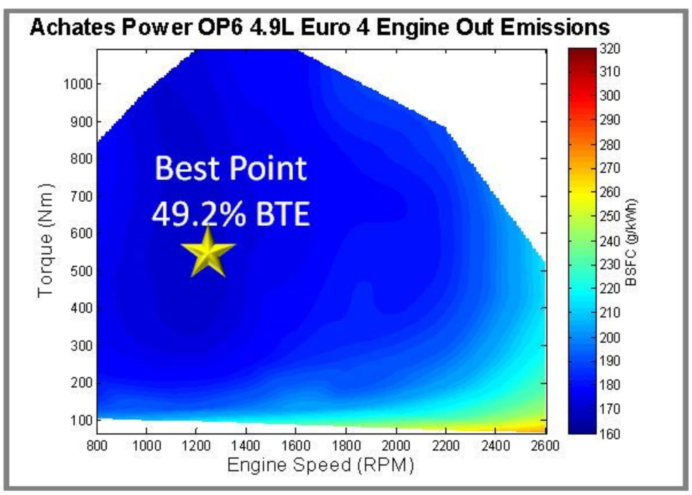

Fig. 11: BSFC map of 4.9L medium-duty OP2S engine with Euro 4 engine-out emissions and no aftertreatment.

The flat nature of the BSFC map, as seen from Figures 10 and 11, brings additional advantages as follows:

- Better real-world fuel economy
- Less application-specific calibration work
- Less driver-to-driver variations
- Fewer transmission gear shifts and simpler transmissions

- Minimal down speeding and associated driveline upgrades
- Reduced need of technologies like cylinder deactivation.

4.2 Passenger Car Application

OP2S engines with 1.5L displacement producing 129 hp for passenger car applications have been studied. The work has been presented at the 2013 SAE High Efficiency IC Engine Symposium [15]. Table 3 shows the specification of the Achates Power 1.5L OP2S diesel engine for a light-duty application, such as passenger car. The details of the package of this engine in a typical front-wheel drive sedan are shown in Figure 12.

Cylinder Arrangement/Number	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

Tab. 3: OP2S engine configuration for light-duty (car).

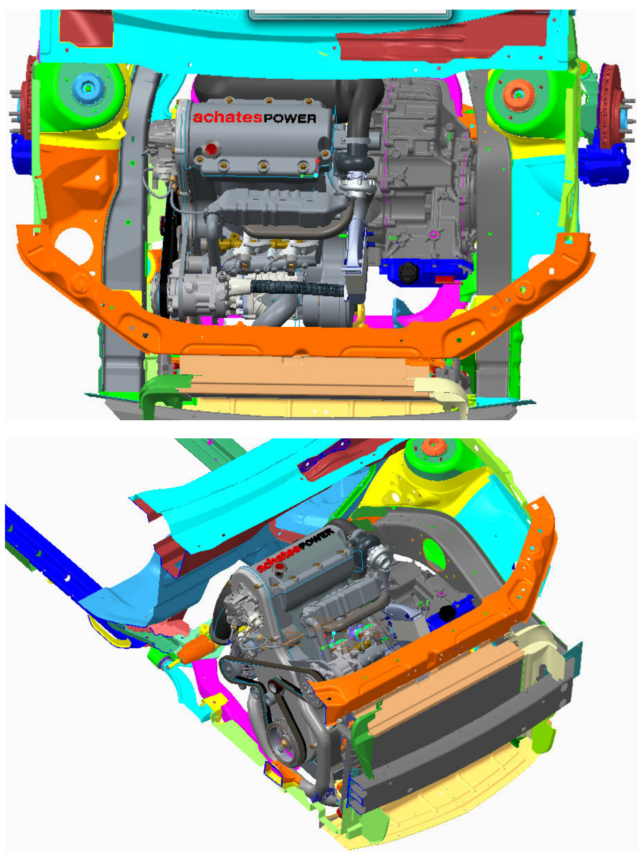

Fig. 12: CAD showing 1.5L OP2S engine packaged in passenger car application.

The fuel consumption map for Euro 6/LEV 3 engine-out emissions with this engine is shown in Figure 13. On a cycle-average basis, this OP2S light-duty engine with Euro 6 engine-out emissions is expected to give 13% better fuel economy [15] compared to a modern, conventional four-stroke engine [17] with Euro 5 engine-out emissions.

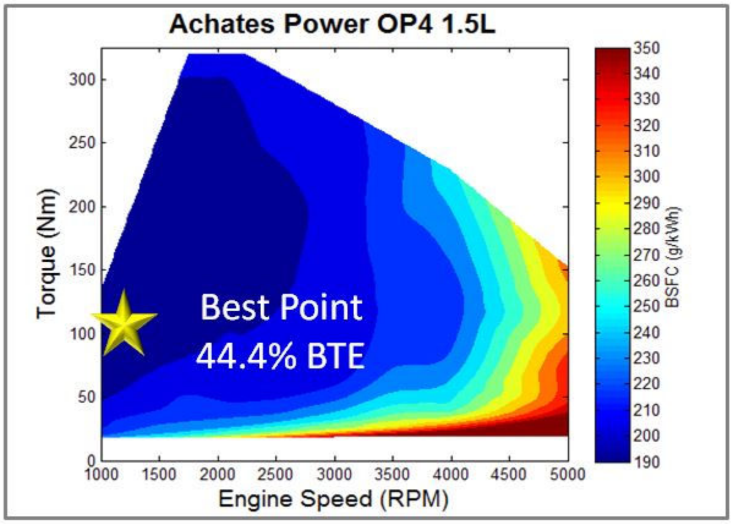

Fig. 13: BSFC map of 1.5L light-duty OP2S engine with Euro 6/LEV 3 engine-out emissions.

4.3 Heavy-Duty Truck Application

Cylinder Arrangement/Number	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	U.S. 2010 / Euro 6

Tab. 4: OP2S engine configuration for heavy-duty truck.

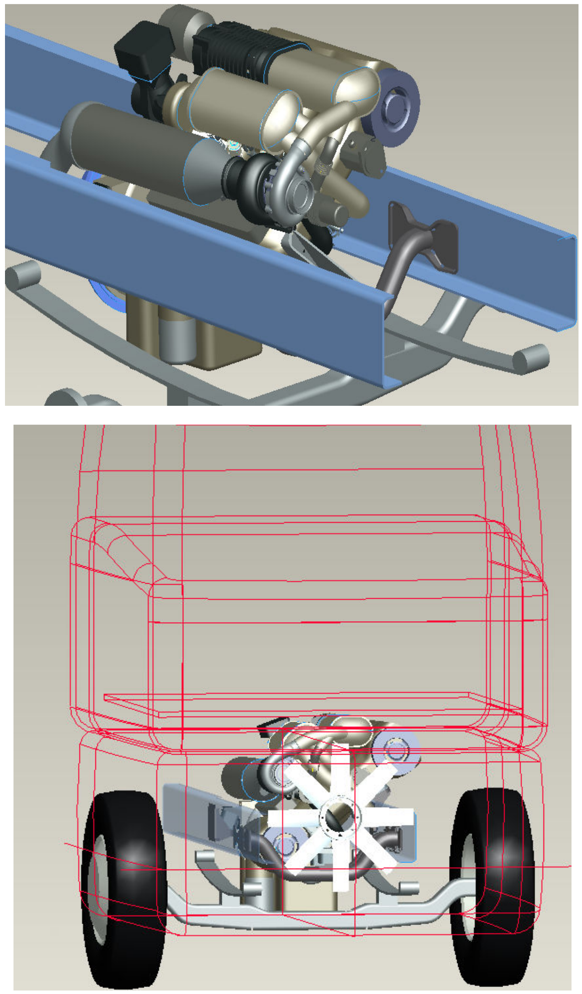

Fig. 14: OP2S engine for heavy-duty truck.

The engine concept for replacing a typical 13 to 15L four-stroke conventional engine in a heavy-duty truck is presented in Figure 14. The OP2S engine is shown fitting in a typical “cab-over” truck in this figure. The engine specifications for an Achates Power OP2S engine for a heavy-duty application are listed in Table 4.

The projected BSFC map for the heavy-duty application with U.S. 2010 emissions standards with SCR and DPF is shown in Figure 15 (i.e. 3 g/kWh NOx and 0.02 g/kWh soot engine out on ESC 13 mode [9]). 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.

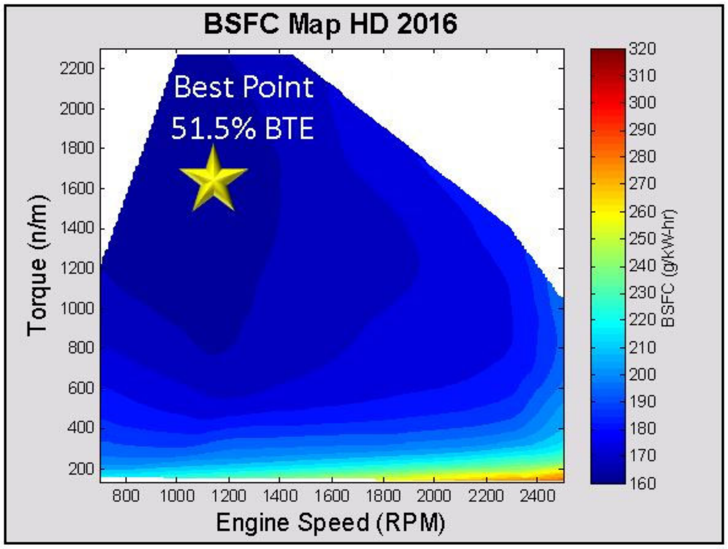

Fig. 15: BSFC map of 11L heavy-duty OP2S engine with U.S. 2010 emissions with SCR and DPF in aftertreatment.

5 Summary

The opposed-piston, two-stroke engine has fundamental advantages in producing low emissions and low fuel consumption at low cost of manufacture. The performance and emissions of the architectures have been optimized and 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.

6 References

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