New 2.7L 650 Nm Opposed-Piston Engine for Light Commercial Vehicles

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ABSTRACT: Achates Power has spent the past 12 years modernizing this historically efficient engine architecture to deliver a step-wise improvement in brake thermal efficiency (BTE) over the most advanced conventional four-stroke engines. In addition, with the elimination of parts such as the cylinder head and valve train, it is also less complex and less costly to produce - making it even more appealing to manufacturers.

This paper highlights the work done, to date, on the Opposed-Piston Gasoline Compressions Ignition engine 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.

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. This paper highlights the specifications and work done on the Opposed-Pistion Gasonline Compression Ignition (OPGCI) Engine.

The opposed-piston engine delivers a step-wise improvement in brake thermal efficiency over the most advanced conventional four-stroke engines and will help OEMs meet pending emissions and fuel economy regulations in a cost effective manner. This paper will provide an overview of the Opposed-Piston Engine and its inherent efficiency benefits, as well as performance and emissions results from prototype engines. These results will demonstrate the OP Engine's ability to substantially improve fuel economy over the best engines in the same class, and comply with U.S. 2025 (Tier 3) /Euro 6 emissions standards.

2. OPPOSED-PISTON GASOLINE COMPRESSION IGNITION (OPGCI) DESCRIPTION

2.1 Engine Architecture

The multi-cylinder OPGCI Engine platform is based on the Achates Power single-cylinder OP Engine and shares similarities to the research engine. Table 1 shows the specifications and the performance attributes for the multi-cylinder OPGCI Engine.

Table 1: Achates Power 2.7L OPGCI Engine specification

Displacement	2.7 L
Arrangement, number of cylinders.	Inline 3
Bore	80 mm
Total Stroke	177 mm
Stroke-to-Bore Ratio	2.2
Nominal Power (kW @ rpm)	270 @ 3600
Max. Torque (Nm @ rpm)	650 Nm @ 1600-2100

This engine was conceived as a technology demonstrator with research capabilities, and serves as a test-platform. It will be integrated into a driveable vehicle for further validation and testing.

2.2 Engine Design Features

The OPGCI engine takes advantage of the ability of the OP Engine to run on a variety of fuel sources. The final 2.7L OP

Engine can be configured to run on diesel, as well as gasoline. This requires changes to the fuel system, but so far the OP Engine architecture has proven to be an efficienct at handling multiple fuel sources.

The OPGCI power cylinder features removable cylinder liners with optimized cooling for high power density. Three gears, coonected to the engine in a crank-crank connection help to reduce NVH and optimize friction.

2.3 Air System

The air system is a key enabler of the efficiency of the OP Engine. The OPGCI air system features a low temperature cooling circuit for charge air coolers. A variable geometry turbocharger, and an Eaton R900 supercharger, with a two-speed drive, provide the necessary airflow. Currently, the system uses an available production aftertreatment system, adapted to work with the OPGCI configuration.

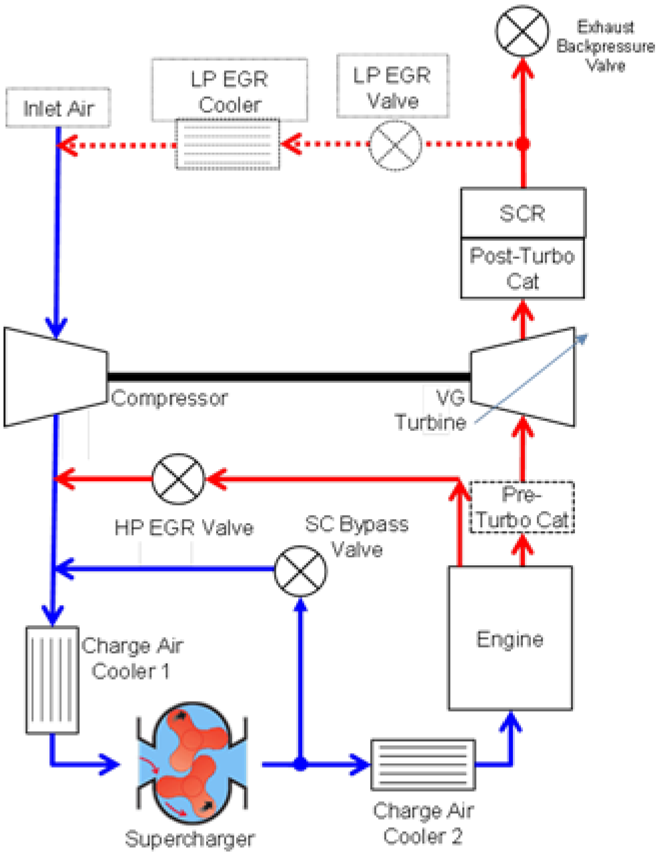
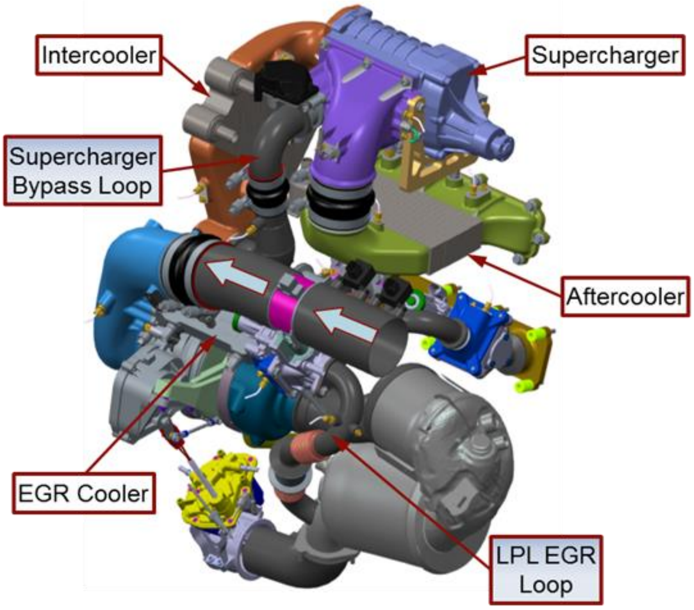


Figure 1: Air Path Schematic

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

Figure 2: 2.7L OPGCI Engine Airsystem



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.

2.4 OPGCI Fuel System

The OP Engine architecture uses diametrically opposed dual-injectors per each cylinder, this configuration allows for minimal wetting and a very controlled fuel stratification in the combustion chamber. (Figure 3) A comparable four-stroke configuration to the OPGCI three-cylinder would be a six-cylinder four-stroke engine, with six injectors. This single injector set-up leaves a high probability for fuel in crevice volumes, with the spray hitting the cylinder wall.

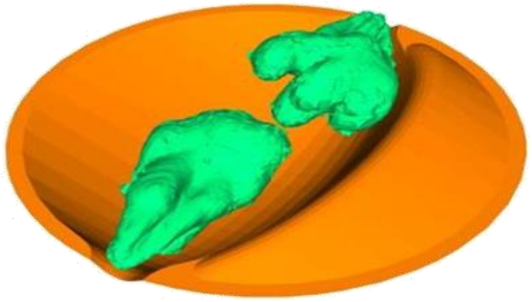


Figure 3: OP Engine Piston Crown w/Fuel Spray

In the four-stroke engine, the amount of fuel used is similar to the OP Engine, however the OP Engine features a larger combustion chamber and 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.

The system used in the GCI (Figure 4) features two, independently-controlled FIE systems, which are partitioned for left and right. The proprietary combustion system design provides high mixing , using both pistons to form the combustion chamber. Two diesel unit pumps, driven by the intake crankshaft, produce prerssure up to 2500 bar to the GDi injectors. The injectors are interchangeable with DFI injectors, and work with the existinig 2.7L OP Engine architecture.

3. FUNDAMENTAL OP ENGINE ADVANTAGES

3.1. 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. 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.

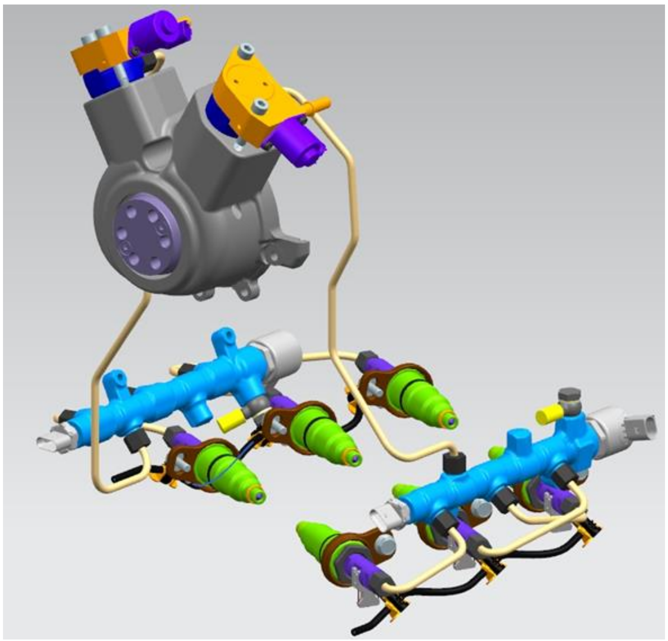


Figure 4: 2.7L OPGCI Engine Fuel System

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

3.2. 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.

3.3 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.

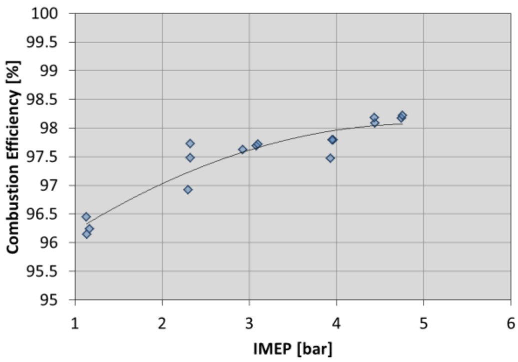
The aforementioned fundamental opposed-piston two-stroke (OP2S) thermal-efficiency advantages are further amplified by:

- 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.

3.4 OPGCI Low Load Operation

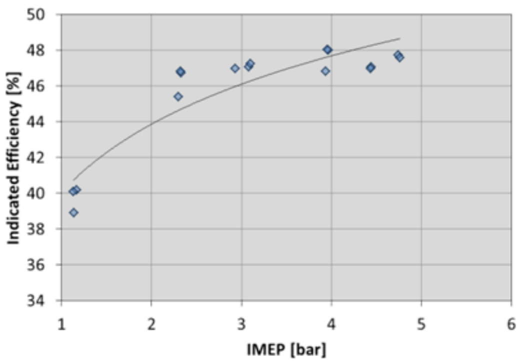
- One of the key advantages of the OP Engine is the it's low load operation. The Two-stroke OP Engine makes

Table 2: Combustion Efficiency



high-efficiency, low-load GCI operation possible with a greater than 96% combustion efficiency. This is achieved because of the high exhaust residual and enabled with practical hardware and fuels. (Tables 2, 3)

Table 3: Indicated Efficiency



3.4.1 OPGCI Low Load Operation

Achates Power has developed a proprietary combustion system 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. (Figure 3)

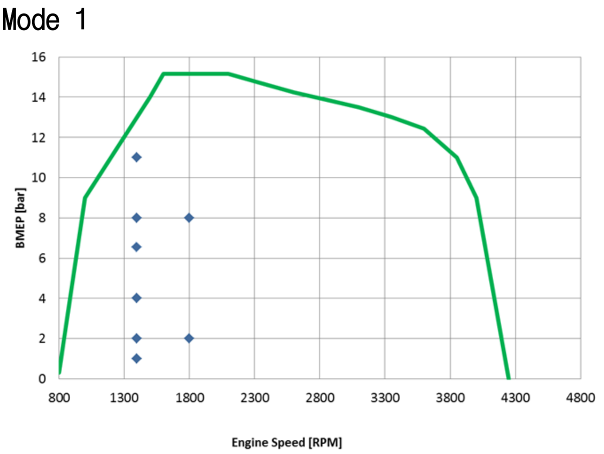


Table 4

Three specific load points of interest were taken, one being idle, another being and FTP type load of 3.1 bar IMEP and a high load (80%) condition.

The idle point is of interest because low load GCI is difficult to achieve combustion efficiency >96% at low intake temperatures. But as shown in Figure XX, there is good combustion with 40 deg C intake temperature due to the high internal residual fraction of 56%. External EGR of 35% was used to keep NOx and soot emissions low.

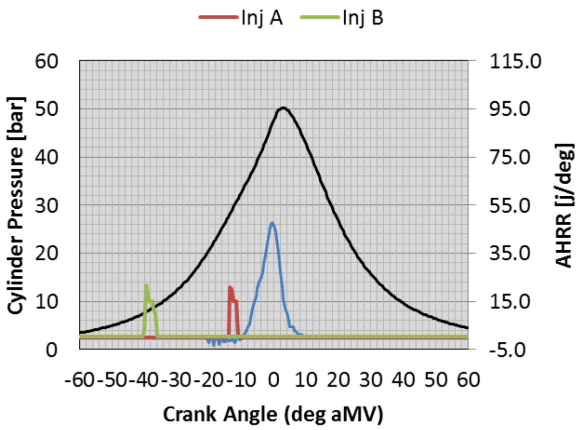


Table 5 Mode 1 cylinder pressure, AHRR and injector current traces

The high internal EGR rate helped to give high combustion stability, 2.5 kPa standard deviation of IMEP. Due to the combustion phasing, noise was also low, ~75 dBa.

The next condition of interest is the 3.1 bar IMEP case, which is common to loads in the FTP testing area.

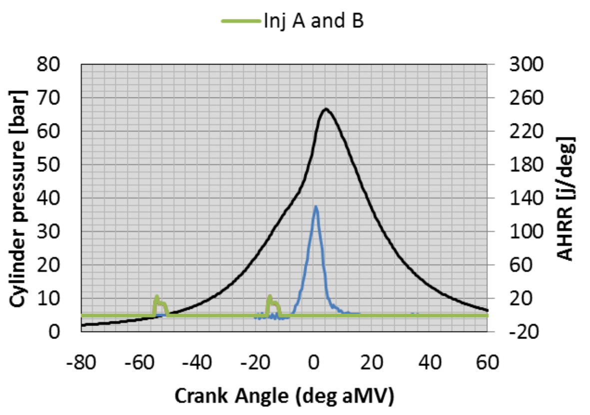


Table 6 Mode 8 cylinder pressure, AHRR and injector current traces

At this load there is similar performance to the idle condition with good combustion efficiency (97.7%) and low noise (87 dBa). With the increased load, 25% internal residual is needed compared to idle. 32% external EGR is again used to keep NOx and soot emissions low. Noise targets were also kept below light duty vehicle targets of 87 dBa. With the combustion phasing near MV and good combustion efficiency, ITE was able to be increased to 47.6%.

Finally, a high load condition was able to be reached with GCI. Using a late injection strategy, a more diesel like combustion event was achieved to give low combustion noise (90.6 dBa).

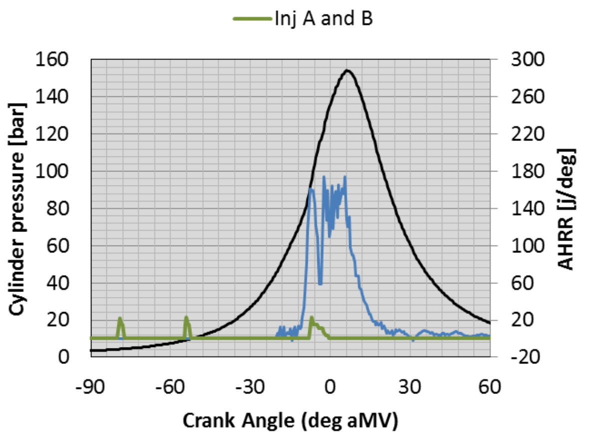


Table 7 A75 cylinder pressure, AHRR and injector current traces

Only 11% internal residual was needed for this condition as the high boost and gas temperature was sufficient for ignition of gasoline. 31% external EGR was used to keep NOx at 3 g/kWh. Soot emissions were also low, 0.08 FSN. By using such as strategy, high loads can be achieved with GCI combustion while meeting noise and emissions targets.

4. OP ENGINE EFFICIENCY AND EMISSIONS ENABLERS

4.1 Combustion System

Achates Power has developed a proprietary combustion system 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. (Figure 3)

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 λ=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.

5. THE NEW ALTERNATIVE: OPGCI ENGINE

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 was motivation to leverage Achates Power's knowledge and expertise to develop a gasoline version.

Together with Delphi Automotive and Argonne National Laboratory, Achates Power will build a three-cylinder, three-liter design suitable for large passenger vehicles, pickup trucks, SUVs and minivans.

The OP Engine, combined with Gasoline Compression Ignition technology will make an ideal high-volume engine for global vehicle markets, with fuel efficiency gains of more than 50 percent, as compared to downsized, turbo-charged direct injection gasoline engines.

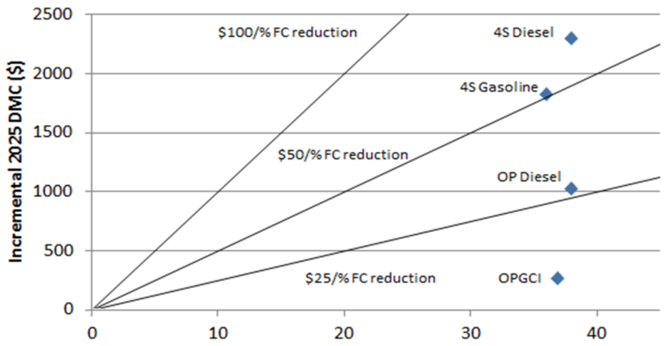


Table 4: Percent Reduction in Fuel Economy

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.

In 2015, the United States, Department of Energy's ARPA-E program awarded Achates Power, Argonne National Laboratory and Delphi Automotive a grant to develop an OPGCI engine for a light-duty application. The end result will be a 2.7L three-cylinder, Opposed-Piston Engine. Detailed information on the system design is included above. Currently the three partners have developed the base engine design (FIGURE 5) with system-wide mechanical and performance and emissions analysis conducted, including CFD analysis, and fuel system flow and and spray visualizations.

Figure 5: 2.7L OPGCI Engine

5.1 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

5.2 Combining OP & GCI

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:

5.2.1 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.

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

5.2.2 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.

5.2.3 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.

6. SUMMARY AND CONCLUSIONS:

Achates Power is developing a 2.7L Opposed-Piston Gasoline Compression Ignition (OPGCI) engine, with funding by the U.S. Department of Energy, ideal for light-duty applications. The OPGCI technology has the potential to cost-effectively deliver more than 50% improved fuel economy over conventional gasoline engines while maintaining low emissions.

Estimations of the OP Engine simulated in a pickup truck suggest a 30% improvement in fuel economy over an efficiency optimized four-stroke research diesel engine. Results indicate that with the OPGCI Engine, 2025 light-duty truck regulations in the US-market can be met and superseded without any advanced vehicle level solutions.

The 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.

Opposed-Piston Engine technology represents a significant and distinct opportunity to impact the future of vehicle emissions and fuel efficiency. The opposed-piston engine architecture demonstrates a 30% fuel efficiency advantage over a state of the art four-stroke engine with comparable horsepower and torque, overall improvement in GHG emissions, and comparable horsepower and torque to a state of the art four stroke internal combustion engine (ICE).