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Achates Power Opposed-Piston Engine Cost Comparison

Achates Power was formed to modernize and commercialize the Opposed-Piston (OP) Engine architecture. Novel solutions to historic challenges have enabled designs that demonstrate simultaneous reduction in tailpipe NO_X levels while offering improved fuel economy at similar weight and power relative to state of the art four-stroke internal combustion (IC) engines. To assess the relative cost of an OP engine, Achates Power commissioned an independent study for the predicted engine manufacturing and assembly cost. FEV was selected to conduct the study because they have a robust process and comparative benchmarks for existing four-stroke engines from prior publicly available studies.

Summary

- Achates Power's Opposed-Piston Engine Architecture provides:
  - 11% cost savings compared to a current production four-stroke, inline-six cylinder engine
  - 6% cost savings excluding exhaust aftertreatment hardware
  - Compliance with 2027 CO_2 and Ultralow NO_X Regulations
- Achates Power has significantly fewer components to assemble:
  - With no need for a cylinder head, the OP engine eliminates five unique components out of 60 total
  - Removing the valvetrain eliminates 40 unique components out of 200 total (not including fasteners)

Engineers from Achates Power and FEV compared a 7.9L OP commercial vehicle engine to an 11L conventional commercial vehicle engine of similar power and torque. Both engines operate on diesel fuel. This comparison targeted commercial engines, and the results can be scaled to larger (class 8, heavy-duty) engines and smaller (mid-range) engines.

As noted in Table 1, the OP engine was configured to meet ultralow NO_X standards of 0.02 g NO_X /bhp·hr on the FTP cycle, while the conventional engine was configured to meet current EPA standards ten times higher, 0.2 g NO_X/bhp·hr. Similarly, the CO_2 emissions of the OP engine will meet the 2027 regulation of 432g/bhp·hr on the SET cycle while the four-stroke engine only complies with the 2017 regulation of 460g/bhp·hr.

In the comparison, the elimination of the cylinder head and valvetrain more than offsets the cost increases from the crank drive, air system and cylinder block resulting in a 6% lower cost for the core OP engine compared to four-stroke benchmark engines of similar capability. Adding the reduction associated with aftertreatment volumes results in a total (engine and emissions control) cost reduction of 11.5%. **An ultralow NO_X, 2027 Green House Gas (GHG) compliant OP Engine is expected to cost 11.5% less than a current production conventional engine of similar power, torque and 2017 NO_X and GHG levels.** The Manufacturers of Emissions Controls Association (MECA) estimates that the additional emissions control hardware required for four stroke engines to meet the ultralow NO_X and GHG standards is at least \$1,500 but may be as much as \$4,800 for the aftertreatment and required engine updates for a Class 8 truck engine, depending on the warranty and durability requirements.

	2027 Achates OP	2017 Four-Stroke
Configuration	3 Cyln, 7.9L	6 Cyln, 11.0L
Cost	**–11%**	(Baseline)
Tailpipe NO_X (g/bhp·hr) (FTP)	0.02	0.20
CO_2 Emissions (g/bhp·hr) (SET)	<432	460

Table 1: Engine Comparisons

Costing Approach:

FEV's process starts with a complete bill of materials. To support this requirement, Achates Power generated detailed CAD models for every component within a production intent OP Engine assembly. By assigning appropriate material density to the CAD models, this helped ensure that the engine assembly weight was accurately captured. Once the bill of materials is complete, the components are organized into a sub-system structure for effective comparisons. For the "off the shelf" components that are used (fasteners, accessories, etc.), FEV reviews their database for the most comparable specification part. For relatively simple custom components, a "direct estimate" is used, based on the component material, mass and assumed manufacturing processes. For all others, FEV uses their "direct cost" methodology.

Determining the "direct cost" is a multi-step process. The first step is to lay out the manufacturing process flow. Then the cost model databases and process parameter models are updated with the rates and assumptions to be used for the project. In this case, 50k units per year was used with manufacturing lines operating at 85% utilization. This includes both direct manufacturing costs for all parts (material, labor, etc.) and indirect manufacturing costs for supplier parts (scrap, profit, engineering, testing, etc.). The cost is intended to represent the effective cost to the engine manufacturer (not what the engine manufacturer would sell the engine to a vehicle manufacturer for). Capital associated with tooling the line for the in-house manufacturing is not amortized in this analysis for either the OP Engine design, or the four-stroke benchmark design. The manufacturing process flow is then incorporated into a worksheet that accounts for the material used, cycle time, utilization, etc. and the component "should cost" estimate is generated. The most substantial components (i.e. cylinder blocks) are presumed to be machined in the United States for both the OP and the comparison four stroke engines. The data is then compiled and reported.

Design Overview:

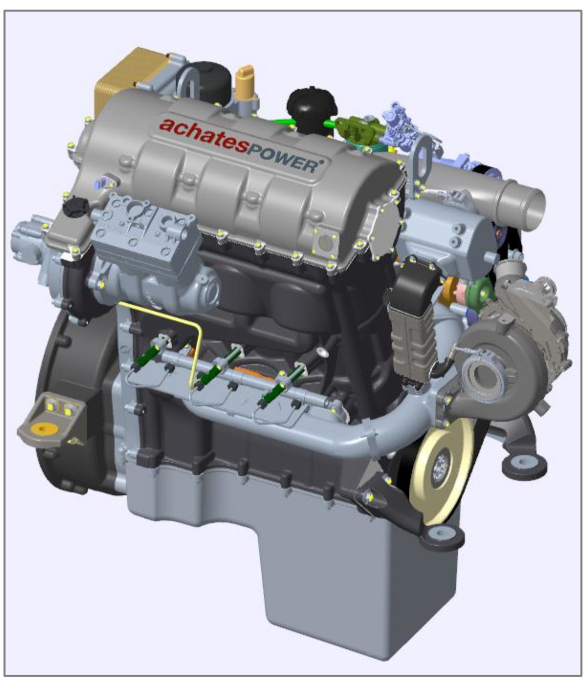

Figure 1: CAD rendering of 7.9L Opposed-Piston Engine

The CAD models generated for this study represent the latest in Achates Power technology and design. The engine (as shown in Figure 1) is a 7.9L swept displacement three-cylinder. The two crankshafts are coupled by a geartrain with two idler gears and two crank gears. A parent metal block casting with patented center impingement cooling around the cylinders forms the primary structure. Through studs maintain a compressive load within the structure even when subjected to peak combustion pressures. The material for the block is grey cast iron with a nominal 6mm wall thickness. A dual sided exhaust chest evacuates into log manifolds that feed a front mounted turbocharger. The air handling system includes an electrically driven turbocharger, and a dedicated exhaust gas recirculation (EGR) pump for the high pressure EGR system. An engine brake is included (an Achates patented bleeder system) that offers braking performance equivalent to the four-stroke systems without the need to time the valve action to the crank position. The fuel injection system is a high pressure, common rail system with two injectors per cylinder. Accessories and auxiliaries are typical for the industry with the exception of the belt starter generator, which is used to support the additional electrical load of the electrically driven turbocharger. This study anticipates that the industry will have converted to 48V systems by the time this engine reaches production. This initial CAD study resulted in comparable total engine weight to existing four-stroke benchmarks with similar power and torque capabilities.

Comparative Results:

Since the absolute values of the cost results are highly dependent on various input assumptions, the focus of this study is the relative comparison to appropriate benchmark four-stroke engines. To the extent possible, the boundary conditions and analysis assumptions were similar between the four-stroke and the OP Engine cost estimates, ensuring that the comparative results were valid. FEV's categorization of all parts into predefined subsystems allows a clear separation between functional areas that are the same/similar and those that contribute to significant cost differences. These subsystems and their relative costs are shown in Figure 2.

Many of the subsystems have content and/or functions that are the same between the engine architectures. As such, multiple subsystems are estimated to cost within $50 of each other. This is true for the "Frame and Mounting", "Timing Drive", "Accessory Drive", "Air Intake", "Lubrication", "Cooling Engine", "Breather", "Electrical and Electronic", and "Engine Final Assembly" subsystems. Of these, the "Timing Drive" is perhaps the most unexpected. The four-stroke timing system is subjected to considerably lower load, so the gears may be smaller. However, the requirement to drive two camshafts at half crankshaft speed results in higher part count. The geartrain in the OP Engine combines torque from the two crankshafts. As a result, the face width is larger, and the gears are heavier but there are fewer parts. Nevertheless, the subsystem cost estimates are within $10 of each other.

The remaining subsystems are where the bulk cost differences are found. The "Fuel Induction" subsystem costs more for the OP Engine since it requires an extra fuel rail and the associated lines to connect to the pumps. The "Crank Drive" for the OP Engine costs more than the benchmark four-stroke engine since the OP Engine has a second crankshaft, and the pistons are longer. The cost is not double the four-stroke, since the size of each OP Engine crankshaft is roughly half the size of the four-stroke. The OP Engine "Cylinder Block" subsystem is considerably larger, and the casting is more complex with roughly double the number of separate sand cores required. This is partially offset by the cost associated with the four-stroke engine wet liner and front cover designs, but the OP Engine "Cylinder Block" subsystem estimate is $111 more than the four-stroke benchmark. An important note is that specific design choices (such as wet liner vs. parent metal bore) will drive different cost results. This study considers just one potential design for an OP Engine.

The air handling and related subsystems are also expected to cost more for the OP Engine than traditional four-stroke engines since two-stroke engines do not have a power cylinder pumping loop. In this design, the OP Engine features an EGR pump, an electrically driven turbocharger and a high capacity 48V motor-generator unit (MGU) to supply the electrified turbocharger with the required electrical power. Other options for air handling system designs exist, including mechanically driven superchargers, twin turbochargers, etc. Depending on the application, a different selection of hardware may be preferred (which will influence cost).

While those subsystems increase the cost of the OP Engine, the remaining subsystems reduce cost. The OP Engine does not require either the "Cylinder Head" subsystem or the "Valvetrain" subsystem. These alone account for over 11% of the total four-stroke engine cost. Eliminating those subsystems not only

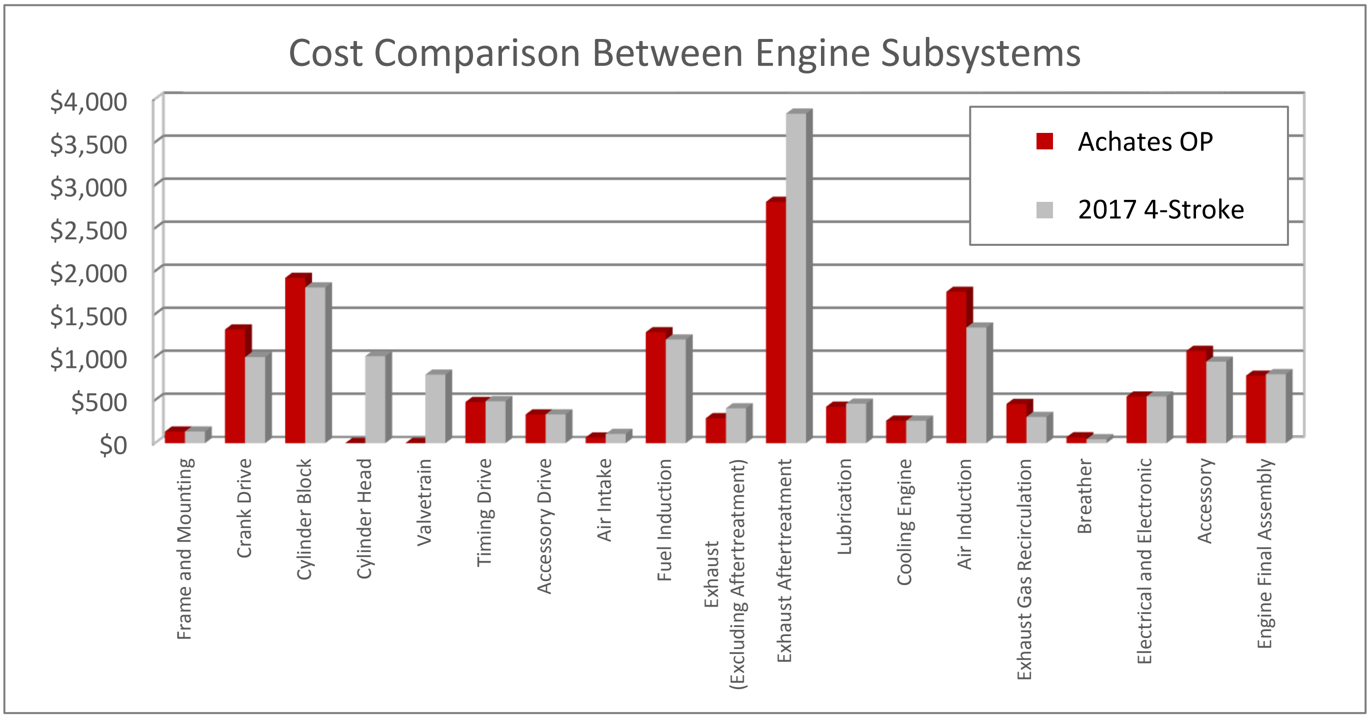

Figure 2: Engine Subsystem Cost Comparison

reduces engine cost, but also reduces total part count (four-stroke engine has 45 unique part numbers and 260 components to assemble per engine in these subsystems).

The final subsystem where the OP Engine shows a significant cost advantage over four-stroke engines is the aftertreatment. OP Engines are capable of faster catalyst light-off during cold start and can generate lower NO_X levels during that period. These enable conventional aftertreatment system with single stage SCR to deliver <0.02 g/bhp·hr (Ultra-low NO_X 2027 regulation levels) of tailpipe NO_X. Additionally, OP Engines have a narrower range of exhaust outlet temperatures. These factors enable the aftertreatment brick volumes to be smaller than equivalent four-stroke engines. Compared to current aftertreatment sizes for four-stroke engines, the OP Engine aftertreatment volume is expected to have 31% less substrate volume (with similar PGM loading) while simultaneously delivering Ultra-low tailpipe NO_X. These results are in line with the Achates 2019 SIAT technical paper comparing ATS size, Cold-Start WHTC and WHSC Testing Results on Multi-Cylinder Opposed-Piston Engine Demonstrating Low CO_2 Emissions while Meeting BS-VI Emissions and Enabling Aftertreatment Downsizing. That reduction corresponds to a $1025 reduction in expected aftertreatment cost.

Independent studies (Technology Feasibility for Heavy-Duty Diesel Trucks in Achieving 90% Lower NO_X Standards in 2027, MECA) have shown that four-stroke engines will require additional aftertreatment content to meet the Ultra-low NO_X standards for 2027. That same study outlines some enabling technologies but does not detail the cost associated with meeting CO_2 requirements. MECA estimates the cost increase for Class 8 four-stroke engines to meet 2027 targets is at least $1500 but may be as much as $4800 for the aftertreatment and required engine updates, depending on the warranty and durability requirements. Meeting the CO_2 regulations will increase the cost of the four-stroke engines even more. In contrast, the OP Engine design studied here is projected to meet the 2027 EPA NO_X and CO_2 requirements as currently configured.

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