Opposed-Piston Engine Commercialization Pathway

In-use and dynamometer testing of the heavy-duty diesel opposed-piston (OP) engine demonstrates the potential of the engine architecture to deliver significantly lower criteria emissions (90%+ NO_x reduction) and lower CO_2 (10%+) while offering competitive power, torque and reliability at no additional cost compared to today's heavy-duty diesel engines, even while enabling a pathway to zero-emissions.

This document describes the effort required to commercialize the OP engine for volume production and summarizes the case for doing so.

Summary

- The opposed-piston engine demonstrates the potential to meet the most challenging enacted and proposed emissions and CO_2 regulations.
- Volume production of an opposed-piston heavy-duty diesel engine is the fastest, most effective, and cost-efficient way to reduce harmful environmental impacts of transportation
- The opposed-piston engine represents the next in a series of advanced engine technologies that enable more sustainable transportation.

Motivation

Significant reduction in air pollution

Heavy-duty diesel engines emit oxides of nitrogen (NO_x) and other pollutants that are linked to premature death, respiratory illness, cardiovascular problems, and other adverse health impacts. Reducing NO_x emissions from heavy-duty vehicles is critical to attain and maintain National Ambient Air Quality Standards (NAAQS) in many regions across the United States. Moreover, these diesel engine emissions have an outsized impact on the 72 million people that live within 200 meters of a truck freight route who, on average, have lower incomes than the population at large[1].

Public policy must balance costs and benefits. While the benefits of cleaner air and improved human and environmental health are attractive, what are the costs? While estimated costs to meet ultralow NO_x standards for heavy-duty diesel trucks, as enacted by the California Air Resources Board (CARB) and proposed by the Environmental Protection Agency (EPA) vary, the Truck and Engine Manufacturers Association (EMA) estimates that meeting these rules would cost $29,000 per truck.

In the U.S. alone, over 210,000 heavy-duty (Class 8) trucks are sold each year requiring more than $6,000,000,000 each year to meet the ultralow NO_x regulations if the EMA figures are correct.

[1] Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards, Environmental Protection Agency, March 28, 2022. https://www.govinfo.gov/content/pkg/FR-2022-03-28/pdf/2022-04934.pdf

As outlined below, a heavy-duty diesel opposed-piston engine demonstration suggests it the engine platform will be able to meet the most stringent CARB and EPA NO_x emissions limits on both dynamometer testing and in use while also delivering a reduction in fuel consumption vs. a model year 2021 truck. Moreover, the OP engine does not require any additional emissions control technology to meet ultralow emissions and since its base engine costs less than the engine in the reference truck it will cost no more than today's engine and perhaps as much as $1,000 per engine less.

The rest of this document will outline the steps needed to commercialize the OP engine. A rule of thumb, validated by several industry experts, is that it costs $300M - $400M[2] to commercialize a high-volume (~55,000 units per year) heavy-duty engine design. Taking the mid-point and multiplying by four to cover the entire market would require a *one-time* investment of $1.4B to convert the entire annual U.S. Class 8 heavy-duty truck production volume to ultralow emissions. Compared to an *annual* cost of $6B+ for the alternative, this looks attractive.

Amortizing the $1.4B capital investment over a 10-year period yields a cost per unit of $665. As described in some detail below, an FEV study estimates than an OP engine will cost about $1,000 per unit less than a current conventional engine (and will still meet future stringent ultralow emissions) suggesting that the required capital expense to commercialize an OP engine will yield a positive return even absent considerations of regulatory compliance.

A Class 8 heavy-duty truck travels around 100,000 miles per year during the first several years of service, and averages around 7 miles per gallon of diesel fuel. At the current[3] national average fuel price of $5.10 per gallon, an average truck will consume $72,857 of fuel each year. If the OP heavy diesel engine reduces fuel consumption by 10% it will save $7,286 per truck per year.

<u>Significant reduction in fuel consumption and CO_2 emissions</u>

The fuel savings potential of the OP engine could be significant. To use one example, Walmart fleet drivers log approximately 700 million miles each year[4]. If their trucks average 7 miles per gallon, Walmart consumes 100,000,000 gallons of diesel fuel each year. A 10% reduction saves 10,000,000 gallons of diesel fuel, a commensurate amount of CO_2, and over $50 million annually.

Given the lower cost to purchase and the lower cost to use, investing in the capital plant to manufacture opposed-piston diesel engines is warranted, even absent the significant health benefits of ultralow emissions.

Summary of Previous Work

<u>Performance and Emissions Advantages</u>

Achates Power has undertaken significant testing of the 10.6L heavy-duty diesel opposed piston engine.

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[2] The variance is due to numerous factors, including whether existing plant capacity can be reconfigured for the new design.

[3] April 18, 2022

[4] https://corporate.walmart.com/newsroom/business/20160602/a-behind-the-scenes-look-at-how-walmart-delivers

The company first reported dynamometer test results against the established (Federal Test Procedure (FTP) and Supplemental Emissions Test (SET)) and new (low load, idle) protocols. The engine demonstrated the ability to comply with the most stringent CARB (2027) NO_x regulations. These tests used engine measurements with full-aged (450,000) aftertreatment system models from BASF. Even at the fully aged point, the engine had a compliance margin of 30% or more against all cycles. Achates Power continues to test and develop the engine. It is the process of testing tailpipe emissions with an aftertreatment system aged to 800,000 miles by Southwest Research Institute's Exhaust Composition Transient Operation Laboratory using the Diesel Accelerate Aging Cycles in order to confirm emissions compliance with a fully aged aftertreatment system.

The tests also showed compliance with the most stringent EPA (2027) Greenhouse Gas II CO_2 requirements, with a compliance margin of 4% or better on both the FTP and SET cycles.

More recently, Achates Power reported in-use results while the 10.6L heavy-duty diesel engine was installed in a Peterbilt 579 truck and used in fleet service by a major retailer. In-use tailpipe emissions were measured by researchers at the University of California Riverside using a Portable Emissions Measurement System. While the demonstration is on-going, initial in-use tailpipe measurements show the ability to meet the most stringent in-use NO_x limits from CARB and proposed by EPA (2031) with a compliance margin of 52% or greater to the most stringent proposed EPA limit.

"The PEMS measurements conducted by UC-Riverside for CALSTART on the Peterbilt 579 powered by the Achates Power 10.6L heavy-duty opposed-piston engine demonstrated NO_x emissions control far better than other diesel engines we have tested. This first round of measurements performed over 3 days in December 2021 in the California San Joaquin Valley with ambient temperatures in the mid-40s °F while the vehicle was in active fleet operation showed between a 99% and 50% margin to the most stringent EPA 2031+ in-use NO_x proposed Regulations, which is outstanding."

Kent Johnson
Principle Investigator, Emissions & Fuels Research
College of Engineering – Center for Environmental Research and Technology
University of California, Riverside

The fleet operator also measured a 10%+ fuel economy improvement from the Peterbilt truck with the Achates Power opposed piston engine vs. a model year 2021 reference truck operating the same routes with similar loads during initial testing. Since the transmission shift schedule was not optimized for the opposed-piston engine, further improvements in efficiency and drivability are possible.

Notably, the opposed-piston engine demonstrated ultralow emissions in all these dynamometer and in-use scenarios using only today's conventional underfloor aftertreatment system components. No additional emissions control technology (on or off engine) is required to meet ultralow emissions regulations.

In summary, the Achates Power opposed-piston engine has demonstrated its potential to meet the most stringent proposed and enacted regulations for both CO_2 and tailpipe emissions by both CARB and EPA for heavy-duty diesel engines.

Cost

Achates Power engaged FEV to undertake a detailed cost study of a commercial vehicle opposed-piston diesel engine compared to a conventional engine of the same power and torque. For the study, FEV held inputs into the costing models constant – they used the same unit volume, sourcing strategy, overhead rates, etc. for both cost estimates. FEV looked at all the components in all the subsystems of both engines. Comparing just base engines (without aftertreatment systems), FEV concludes that the OP engine costs about 6% less than the conventional engine, largely because the OP engine eliminates the cylinder head and the valve system.

Because the OP engine does not need additional emissions control technology (compared to model year 2022 heavy-duty diesel engines) to meet ultralow emissions its cost advantage will grow as emission standards get more stringent.

Engine Oil Consumption and Reliability

Heavy duty diesel engines are expected to operate for a million miles or more. As it progresses into volume production, a heavy-duty opposed piston engine design will undergo extensive design validation, as would any new engine design. The design validation and initial durability testing has been reported by Achates Power.

Using a sulfur trace method to measure oil consumption in real time, Achates Power has measured engine oil consumption on par with conventional diesel engines. Initial durability results are good, showing the potential for the engine architecture to meet the commercial requirements of the commercial vehicle market.

Moreover, the OP engine architecture represents a reduction in mechanical complexity relative to conventional engines. Both the overall number of components and the number of moving components is significantly reduced in the Achates Power OP engine design. By eliminating the cylinder head and valve train, for example, 45 unique part numbers and 260 overall components are removed.

By contrast, to meet ultralow emissions standards, conventional diesel engines are increasing in complexity[5] with the addition of a second, close-coupled aftertreatment system, exhaust heaters, and cylinder deactivation. Each of these technologies is unproven in commercial vehicle applications and represent new durability challenges, along with the increase in cost, complexity, and compliance risk.

Commercialization Process

A typical path for commercial vehicle engine commercialization is extensive development and validation during a prototype stage. From there, it takes around 6 years for a new commercial vehicle engine to enter volume production, split into two roughly equal stages. During the first stage, the production-intent design is created,

[5] Hadl, Klaus, Raser, Bernhard, Sacher, Thomas, Graf, Gernot: “Solutions for Lowest NOx and CO2 Emissions on Heavy-Duty Engines,” MTZ Worldwide, Volume 82, pps 16-22. March 2021

developed and validated. Prototype engines are deployed and used for validation. The second stage consists of industrialization – the manufacturing plant, supply chain, and service infrastructure are developed. Regulatory certification is obtained. Vehicle integration is completed. Achates Power expects the heavy-duty OP engine to follow this commercialization timeline.

Components, Designs, and Industrialization

The OP engine has an advantage because it uses common materials, manufacturing tools, and processes. Existing manufacturing machines can be deployed to make OP engine components. Of the big five engine components – crankcase, crankshaft, connecting rod, cylinder head, and camshaft – the OP engine eliminates the latter two. Overall, as noted above, the OP engine part count is much smaller than that of a conventional engine. The main materials are standard in the industry, including grey cast iron and SAE 4x40 steel. Conventional manufacturing tools and processes are used to make OP engine components.

Moreover, most of the components used by the OP engine are well-proven and are derived from high volume conventional engine components, including high pressure common rail fuel systems (tanks, rails, pumps, injectors), charge air coolers, oil pump, oil cooler, oil filter, water pump, thermostat, control valves and other accessories such as starter/generator.

In terms of industrialization of the OP engine, most of today's four stroke infrastructure can be utilized. The following tables illustrate the similarities and differences required for infrastructure and manufacturing of an OP heavy-duty truck engine:

Infrastructure Area	Achates OP Diesel Requirements
Fueling	*No new infrastructure needed*
Service network	*Same as today for both parts and servicing*
Truck design	*Only minor changes. Fits in existing engine compartments*
Supply Chain	*Same as today*
Manufacturing plants	*Same as today*

Engine Sub-system	Achates OP v. current HD engines
Cylinder Block	*Grey iron, requires re-tooling*
Cylinder head	*Eliminated*
Crankshaft	*Forged steel, requires re-tooling only*
Camshaft and valvetrain	*Eliminated*
Power Cylinder	*Similar*
Air handing	*Requires driven turbocharger and EGR pump*
Aftertreatment	*Same as today*

Production intent Design – Weight / Size / Cost

Prototype engines tend to be bigger and heavier than production-intent derivatives, for a few reasons. For one, size and weight are not very important in prototypes. For another, prototype engines often must accommodate off-the-shelf catalogue components (for timing & cost compliance) and other custom components are designed so that they are robust and can be easily instrumented, adapted and modified during development. The OP engine is no different.

Achates Power is part of two projects that have turned prototypes into production-intent designs, and the process illustrates the potential to create OP engines that are competitive in size and weight while superior in performance, emissions, and cost.

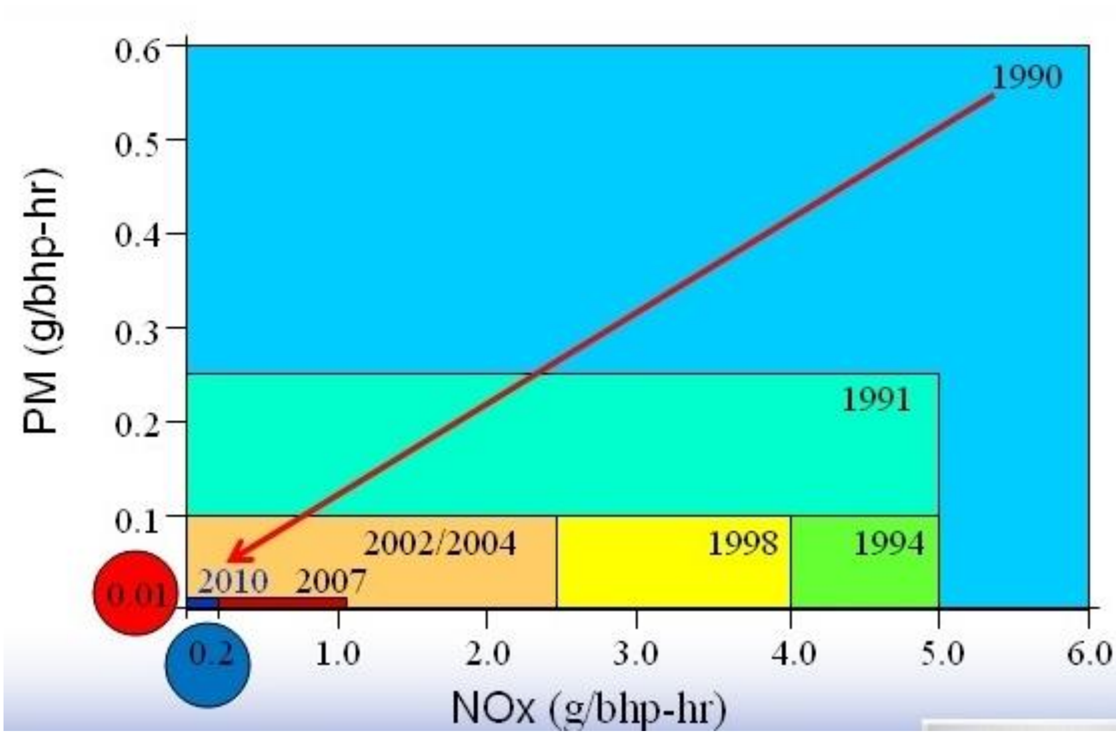
The first project is the Advanced Combat Engine. Designed by Cummins with support from Achates Power, the 1000 hp Advanced Combat Engine, based on OP engine technology developed by Achates Power, is currently being tested by the U.S. Army and sets new benchmarks in terms of engine and powerpack power density (power per unit volume).

The second project is the light-duty truck engine. The engine was originally designed as a 2.7L engine for a full-size pickup truck (and integrated, for driving demonstrations, in a Ford-150). The Advanced Research Program Agency-Energy (ARPA-E) of the U.S. Department of Energy funded the project to demonstrate best-in-class efficiency for a pickup truck engine. Based on successful demonstration of the engine, ARPA-E funded a follow-on project to create an engine design capable from production development. With Ricardo as a major subcontractor on the project, Achates Power led a project that created a 2.5L version of the engine with the same power and torque, but with about half the weight (down to about 250 kg) in a smaller volume. The new engine design is competitive in size and weight to high volume conventional engines of the same power and torque.

These projects illustrate that prototype OP engines can evolve into production designs with competitive size and weight.

Industry History

Since the first NO_x limit was placed on commercial vehicle engines by the EPA in 1974 (hydrocarbons + NO_x could not exceed 16 g/hhp-hr on the FTP cycle), regulatory limits on NO_x have been reduced by 98.75% to the current national standard of 0.2 g / bhp-hr. Limits on tailpipe PM have decreased by 98.3% since they were first imposed in 1990, as depicted in the chart below.



A number of sophisticated and new technologies were utilized to so dramatically reduce tailpipe emissions, including:

- Engine control modules
- Exhaust gas recirculation (EGR)
- Charge air cooling
- High pressure common rail fuel systems
- Cooled EGR
- Diesel particulate filters (with hydrocarbon injection)
- On-board diagnostics
- Selective catalyst reduction

All these new technologies required design and validation before adoption. But each proved successful and robust, and enabled the industry to substantially reduce its environmental impact even as the number of trucks and vehicle miles driven increased.

Already enacted CARB regulations and proposed EPA regulations require another 90% reduction in NO_x and a 50% reduction in PM, along with new low-load, idle, and in-use NO_x limits.

The opposed-piston engine represents the next advanced engine technology, able to let the industry meet this still greater challenge. But different than the technologies listed above, the OP engine actually reduces the complexity of the overall system enabling – for the first time – significant and important improvements in emissions reduction and efficiency with lower cost, complexity, and compliance risk.

Production Pathway

At least two viable paths to market exist.

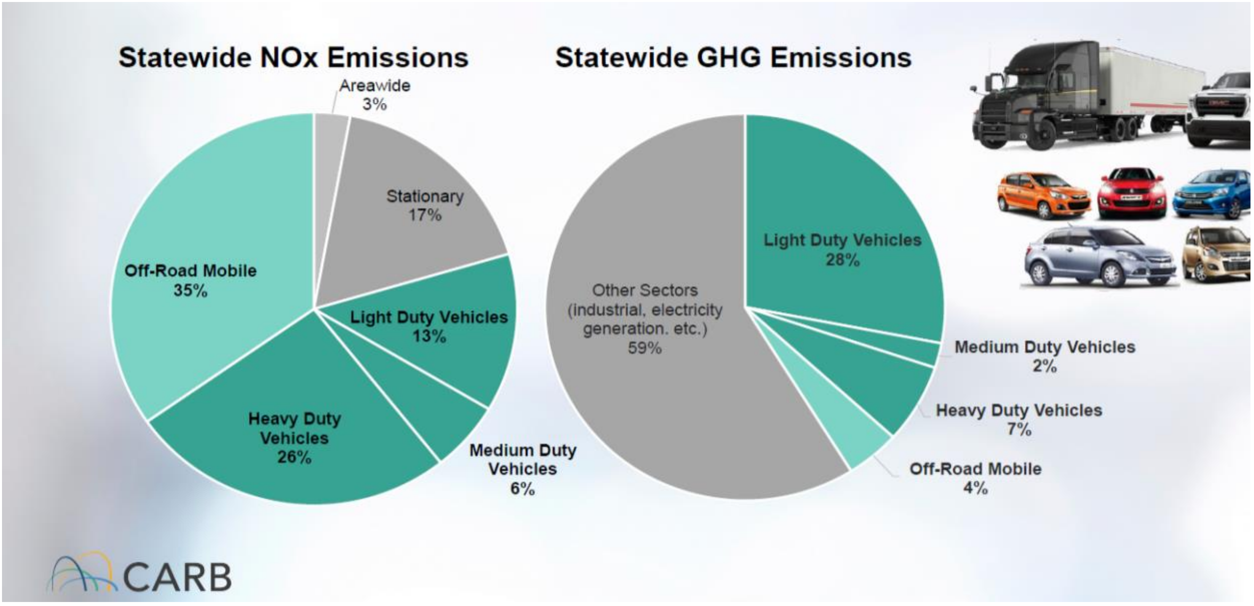
Existing commercial vehicle engine manufacturers have all the necessary capability to develop, manufacture, distribute, and service opposed-piston engines. Achates Power can work with these firms during the development and industrialization process, and will earn a royalty for a license to its OP engine technology, including designs, control software, development tools, test tools, and patents. An example of how this works in practice is the Advanced Combat Engine, developed by Cummins with support from Achates Power for the U.S. Army.

Another path to market would have Achates Power assemble of team of established organizations to the development, certification, manufacturing, integration, distribution, and support of heavy-duty opposed-piston diesel engines. Achates Power believes sufficient capacity and capital exists for this pathway.

Either pathway can result in volume production of engines after a six-year development and industrialization process.

Beyond Class 8 Diesel

Class 8 truck engines represent the first beachhead for the clean efficient OP engine. It is a good initial market since heavy-duty vehicles emit 26% of all NOx emissions in California, from both mobile and stationary sources, as outlined in the chart below.



The OP engine advantages in low tailpipe emissions and improved fuel efficiency scale into larger and smaller engines, can be applied to off-road applications as well. Combined, off-road, heavy-duty, and medium-duty engines emit 67% of all NOx in California. With broad adoption of the opposed-piston engine, this can be reduced by more than 90%.

Summary:

The opposed-piston engine architecture has good and growing evidence it can be used to meet the most stringent enacted and proposed tailpipe and CO_2 emissions regulations in the world, and can do so in a cost-effective, robust, and practical manner.

It is a necessary solution to enable more sustainable transportation.

In addition to its inherent advantages in high-efficiency, low-emissions, and low-complexity, the opposed-piston engine also has advantages in fuel flexibility, including carbon-free hydrogen combustion making a superior solution for today and tomorrow.

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