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Achates Power Opposed-Piston Heavy Duty Diesel Engine Demonstration Performance Results

Summary

- Achates Power's 10.6L Opposed-Piston Diesel Engine interim test results:
  - 437 g / bhp-hr CO_2 on the SET cycle, 5% lower than today's engine and within 1% of the 2027 EPA GHG II requirement
  - 0.02 g / bhp-hr NO_x on the FTP cycle, as measured on an aftertreatment test system
  - Opportunity to further reduce aftertreatment system cost and complexity, and reduce compliance risk and cost.

Achates Power is part of a project led by CALSTART and funded by the California Air Resources Board (CARB) to demonstrate a low CO_2, ultralow NO_X Opposed-Piston (OP) heavy-duty diesel engine. In addition to CARB, the South Coast Air Quality Management District, the San Joaquin Valley Air Pollution Control District, and the Sacramento Metro Air Quality Management District are providing funding for the program.

Achates Power is part of an extensive team that will demonstrate the OP heavy-duty diesel engine in a Peterbilt 579 tractor. The team also includes Delphi Technologies, BASF, Corning, Eaton, Faurecia, Tenneco, Aramco Services, and Southwest Research Institute.

This document provides an update on current testing of the 10.6L OP heavy duty diesel engine that is the subject of this project.

NO_X is a criteria pollutant, as well as a precursor to ozone and $PM_{2.5}$, and therefore contributes to ambient pollution that adversely affects human health and the environment. More than 128 million people in the U.S. live in counties designated nonattainment for ozone or $PM_{2.5}$. Worldwide, 93% of children grow up with air polluted above health guidelines.

Heavy-duty commercial vehicles are among the largest contributors of both CO_2 and NO_X among mobile sources and are particularly resistant to substitution by other powertrain sources. As such, a heavy-duty diesel engine that provides required power, torque, and reliability with substantially lower CO_2 and NO_X will substantially contribute to more sustainable transportation. The goal of the CARB project is to demonstrate such an engine.

Project Goals:

Required power & torque: The engine delivers 450 hp and 2375 Nm

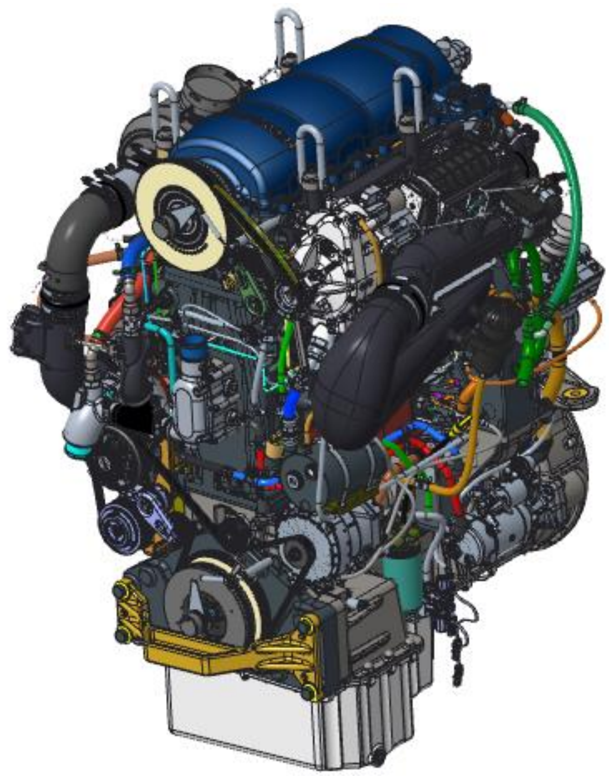
Lower CO_2: The current U.S. EPA requirement for Class 8 trucks is that they emit no more than 460 g CO_2 / bhp-h on the SET cycle. The ultimate requirement is 432 g / bhp-h in 2027. The project goal is to at least meet the 2027 requirement.

Ultra-low NO_X ($ULNO_X$): The current U.S. EPA requirement for NO_X is that they emit no more than 0.2 g / bhp-h on the HD FTP cycle. **The project goal is to reduce this by 90%**, to just 0.02 g / bhp-h.

Practical demonstration: The OP heavy-duty diesel engine will be integrated into a Peterbilt 579 tractor and driven in-service demonstrating acceptable fit and integration, noise, vibration, harshness, drivability, and reliability.

Engine and Aftertreatment System Design:

Engine: The team designed, built, and is testing a 3-cylinder, 10.6L opposed piston diesel engine with a stroke/bore ratio of 2.6.



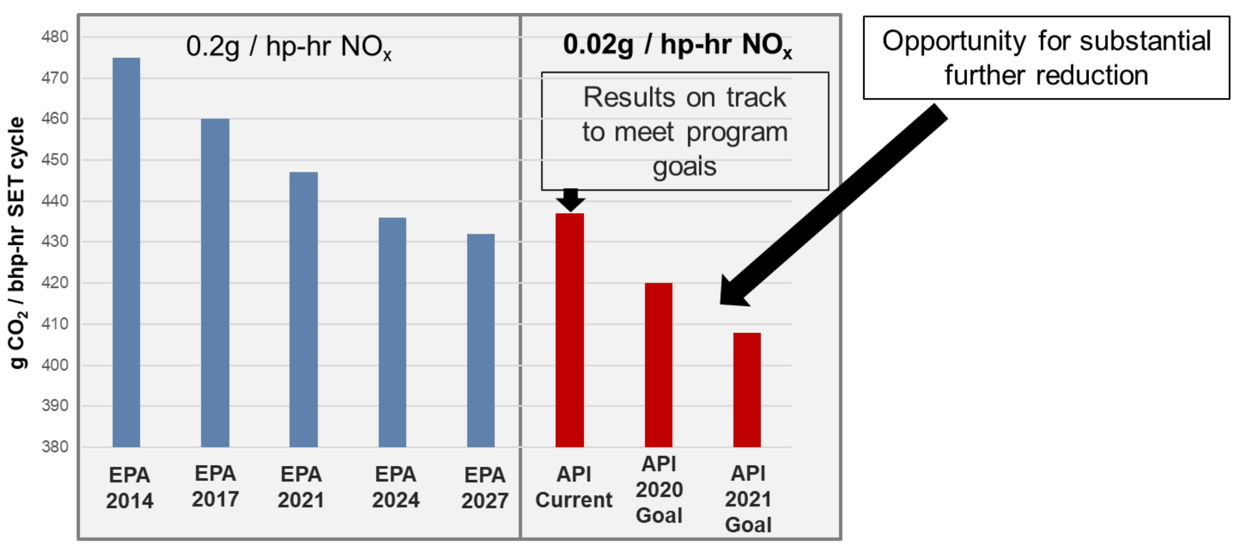
Aftertreatment System: Engineers from Achates Power, Faurecia, Aramco Services, Corning, Southwest Research Institute, and BASF worked together to configure and test an aftertreatment system. Their goals included:

- Demonstrate ULNO$_X$ with a full useful life aftertreatment system.
- Achieve the target on the first try, which resulted in a very capable, conservative design with significant opportunity for refinement, as discussed below.
- Ability to function on the demonstration truck indefinitely using field proven, production components.

The selected design includes a light-off SCR closely coupled to the engine in the engine compartment, and an under cab ATS that includes a DOC and SCR on filter.

Testing results:

Four prototype engines have been built. One is being tested and developed at Achates Power in San Diego, CA. A second is being tested and developed at Aramco Services in Novi, MI. A third is being integrated into a Peterbilt 579 tractor in Denton, TX. The fourth is a spare.



After less than a year of testing and development, the engine has run at the full load across all engine speeds, and has already achieved 437 g / bhp-h CO_2 on the SET cycle, on track to meet the 2027 CO_2 requirement with ultralow

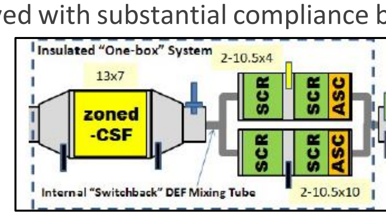
NO_X. This testing was conducted without an aftertreatment system, but with the ULNO$_X$ ATS backpressure (35 kPa) simulated to account for its impact on engine operation.

Current Aftertreatment System Configuration

Separately, the ATS was built and tested by SwRI. Achates Power measured the engine turbine-out gas speciation, flow, and temperature for a 4.9L, 3-cylinder OP engine. The exhaust flow rate was scaled to generate representative conditions of the new 10.6L diesel engine. SwRI then used their Exhaust Composition Transient Operation Laboratory (ECTO-Lab) facilities to mimic the turbine-out gas speciation, flow, and temperature and measured tailpipe emissons to determine ATS effectiveness. Tailpipe measurements of NO_X were 0.02 g / bhp-h with full useful life aged parts, very close to the model prediction of 0.018 g / bhp-h. Notably, the OP engine catalyst light off (CLO) mode was only used in the cold start part of the FTP cycle. Numerous opportunities for improvement exist, including intermediate thermal management during the hot portion of the cycle, in order to create a compliance buffer.

Aftertreatment System Simplification

Once ATS testing confirmed that the 0.02 g / bhp-h NO_X target can be achieved with substantial compliance buffer (utilizing identified improvement options), the team looked at how to simplify the ATS in order to reduce cost and complexity, and compliance risk and cost. The team studied a commercially available 'one-box' aftertreatment system. BASF aged catalyst model, using engine turbine-out gas speciation, flow and temperature, predicted the engine + ATS will

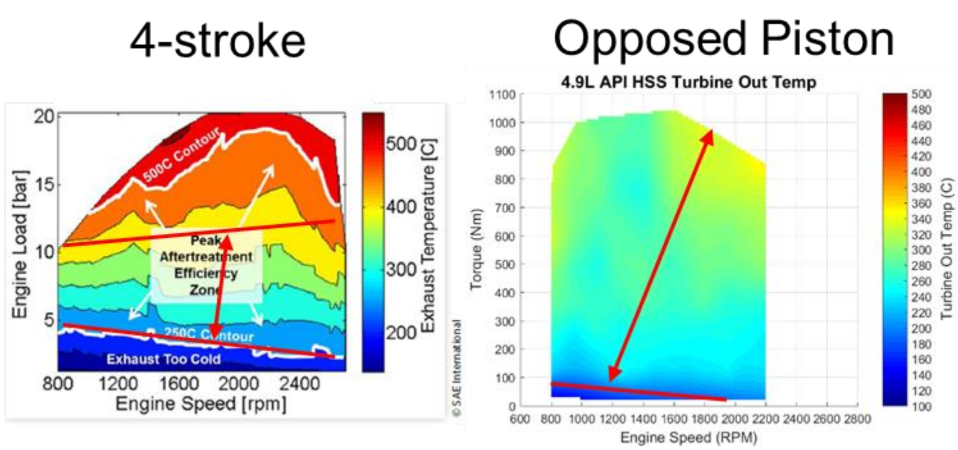


achieve 0.006 g / bhp-h NO_X, using CLO in both hot and cold FTP cycles. Also, because the one-box system has much lower backpressure (15 kPa vs. 35 kPa in the existing system), its adoption will help achieve the lower CO_2 targets suggested in the graph above.

Three features of the new system design have the potential to substantially reduce compliance risk and cost. First, the one-box ATS is much simpler than the existing design and of other designs being pursued to achieve ultralow NO_X that typically include split SCR, heated DEF, and, in the case of conventional engines, cylinder deactivation. None of these technologies are required in the contemplated design, which reduces both cost and opportunity for component failure.

Second, the configuration of OP engine + one-box ATS is expected to substantially reduce the number of active DPF regenerations required, substantially reducing the thermal degradation of the ATS and reducing ATS failures.

Finally, the OP engine operates at nearly ideal temperature range. According to Dave Youngren, Senior Application Engineer at BASF, "Standard calibration is … **ideal for feeding the SCR**. [Its] typical temperatures [are] between 250°C and 400°C for efficient SCR function. [The] high floor [is] ideal for NO_X reduction over proposed Low Load Cycle. Mild thermal exposure is easy on the aftertreatment. [The] temperature range [is] also **ideal for DOC function** with moderate precious metal loadings [for] low cost. [It has] **ideal engine-engine out conditions to reach ULNO$_X$**."



Cost

A recently published[1] cost study bases on analysis FEV concludes that an OP engine costs 11% less than a comparable conventional engine, even while emitting less CO_2 and 90% less NO_X.

Summary:

Based on measured results to date, the demonstration program is on its way to meet its program goal of meeting Class 8 power and torque requirements with less CO_2 and 90% less NO_X. Supporting analysis suggests the engine will also have a substantial cost advantage, and lower compliance cost and risk compared to conventional engines of the same power and torque.

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[1] http://achatespower.com/wp-content/uploads/2020/03/Achates-Power-Cost-Study-White-Paper_March-2020.pdf