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Opposed-Piston Heavy-Duty Diesel Engine Performance and Emissions Summary

On the journey to more sustainable transportation, internal combustion engines will continue to play a large role, particularly in long haul transit and off-road applications. Among the most impactful ways to rapidly improve air quality is to substantially reduce criteria emissions from medium- and heavy-duty commercial vehicle engines while also improving efficiency and reducing CO_2.

The Heavy-Duty Diesel Demonstration Program is led by Calstart and is supported by the California Air Resources Board (CARB), the South Coast Air Quality Management District, the San Joaquin Valley Air Pollution Control District, and the Sacramento Metro Air Management District to demonstrate that a heavy-duty diesel engine can reduce tailpipe NO_x by more than 90% while also reducing CO_2 by more than 10%, in conformance with the CARB Omnibus emissions regulations for 2027[1].

For the demonstration program, Achates Power built and tested a 10.6L opposed-piston (OP) engine. The engines were extensively testing on dynamometers at Achates Power in San Diego, CA and by Aramco Services in Novi, MI. In addition, an engine was installed in Peterbilt 579 tractor, and was used in fleet service by Walmart for over six months. After the fleet service was completed, Achates Power continued to optimize the engine design and calibration, both on-road and on the dynamometer, operating on both regulated cycles and on simulated in-service routes.

The engine demonstrated the ability to meet every 2027 NO_x and CO_2 emissions limit from both the U.S. Environmental Protection Agency and CARB in a robust manner, demonstrating more than 90% reduction in tailpipe NO_x when calibrated for the original CARB 2027 regulation.

Summary

- The 10L heavy-duty opposed-piston engine developed and demonstrated by Achates Power shows best-in-class efficiency and emissions.
- Measured fuel consumption shows the opposed-piston diesel engine has 10%+ fuel economy advantage over the best-in-class reference engine.
- The opposed-piston engine also demonstrated the ability to meet 2027 EPA and CARB tailpipe emissions and CO_2 regulations, including low-load cycle and in-use limits.
- An independent cost study shows that the heavy-duty opposed-piston engine will cost less than today's heavy-duty engines – even while meeting future emissions and CO_2 standards that will add substantial cost to conventional engines.
- Achates Power is undertaking tests with an aftertreatment system aged to 435k, 600k, and 800k miles to confirm the ability to comply with fully aged requirements.

[1] CARB originally enacted regulations that required a 90% reduction in tailpipe NO_x by 2027 to 20 mg / bhp-hr on the combined Federal Test Procedure (FTP) cycle. The Demonstration Program was structured to demonstrate the ability to meet this target, and the project team was successful in doing so. CARB later revised the regulation to require an 82.5% reduction, to 35 mg / bhp-hr, to harmonize with Federal EPA standards. The Achates Power OP engine demonstrated the ability to meet the more stringent 20 mg / bhp-hr requirement using only conventional, underfloor aftertreatment systems.

In real-world operation during fleet service and on the simulated routes, the opposed-piston engine showed between 4% better and 21% better fuel economy than the best-in-class conventional engine, depending on the route.

Notably, the engine used only a conventional, commercially available underfloor aftertreatment system. By avoiding additional emissions control devices – required by conventional engines to meet ultralow levels of NO_x emissions – the opposed-piston engine reduces cost, complexity, and compliance risk compared to these alternatives.

Ultra-Low NO_x

The Achates OP engine has inherent features that enable it to achieve ultralow NO_x in an efficient, robust, and cost-effective manner.

One important feature is the ability of the Achates OP engine to dynamically control the scavenging ratio and therefore trapped conditions of the engine. In a four-stroke engine, nearly all the exhaust gas is expelled during the exhaust stroke, and a full charge of new gas is drawn in during the intake stroke.

By contrast, in a uniflow, two-stroke, opposed-piston engine, the engine controller manages how much exhaust gas is expelled and how much new gas is brought into the cylinder by managing the pressure differential between intake and exhaust. At high loads, the engine needs a significant charge of fresh air to combine with a full fuel load. At lower loads, however, since less fuel is injected into the cylinder, less new air is required.

In the Achates Power design, exhaust and intake ports are open when pistons travel towards the outboard ends of the cylinder. Usually, the exhaust piston has a slight lead on the intake piston and the exhaust ports are taller, so that the exhaust ports open first to start the blowdown process. When the intake ports are exposed – assuming the intake manifold pressure exceeds that of the exhaust manifold – scavenging begins. When the intake and exhaust ports are covered as the pistons reciprocate back towards minimum volume, scavenging ceases and compression begins. How much gas is exchanged during the scavenging period is determined by the pressure differential between the intake and exhaust manifolds (higher pressure differential results in more gas exchange) which is controlled by the engine's air handling system.

To create the necessary intake manifold pressure and manage combustion airflow, the Achates OP engine employs actively controlled boosting devices. The current version of the heavy-duty Achates OP engine uses a mechanically driven turbocharger from SuperTurbo. Other Achates Power engine designs use an e-turbo. The combination of the uniflow two-stroke engine architecture coupled with an active air handling system creates valuable flexibility in combustion optimization and exhaust temperature control, enabling much simpler emissions control and exhaust aftertreatment compared to conventional four-stroke engines, especially for maintaining engine efficiency and low greenhouse gas emissions (GHG) at ultra-low NO_x and protecting aftertreatment system components from degradation due to excessive temperatures at high power.

At low- and mid-loads the intake manifold pressure is only boosted to a level that provides partial scavenging, adding enough new gas to achieve the proper air-fuel ratio for clean and efficient combustion, but also leaving residual exhaust gas in the cylinder. Partial scavenging has numerous advantages:

1. It reduces the amount of work required to exchange gases, improving low-load efficiency. As a two-stroke engine, the Achates OP engine does not have a pumping loop; the only pumping loss is to the energy required to boost the intake manifold pressure to enable gas exchange.

2. The residual exhaust gas inhibits NO_x formation. Exhaust gas recirculation is a well-known and common way to reduce NO_x formation. Exhaust gas in the combustion chamber reduces combustion temperatures and NO_x formation by diluting the oxygen concentration. Leaving exhaust gas in the cylinder achieves an EGR effect but avoids the work to expel and then draw in the exhaust gas.

3. It keeps low-load exhaust gas temperatures high relative to four-stroke engines.

4. Similarly, the combination of the uniflow two-stroke engine architecture and an active air handling system has advantages at higher loads and at lower temperature operation. The Achates OP engine has low high-load exhaust gas temperatures relative to four-stroke engines. When selective catalyst reduction (SCR) catalysts are between about 250° – 400° C they are highly effective in converting NO_x into nitrogen and water. Higher low-load temperatures and lower high-load temperatures means the exhaust gas temperature of the Achates OP engine are in the optimally effective range over most of the operating (speed and load) range of the engine, a much broader range than conventional engines.

5. It enables a catalyst light-off mode (CLO) when operating at light load and low ambient temperatures that generates high exhaust enthalpy to heat the SCR catalyst into the effective temperature range while simultaneously generating very low engine-out NO_x . The latter feature is important because until the catalyst is sufficiently hot it is not very effective at NO_x conversion.

This combination of fundamental advantages of the uniflow two-stroke engine architecture and active air handling makes the Achates OP engine ideal for low NO_x operation with high efficiency and low GHG emissions.

During the Federal Test Procedure (FTP) cycle, most NO_x emission occurs in the first 240 seconds after a cold start, before the SCR catalyst is sufficiently warm for effective NOx conversion. The catalyst light off capability of the Achates OP engine substantially reduces both the time to activate the SCR and the cumulative engine-out NO_x during the warmup period.

When the catalyst is in the optimal temperature range (250° – 400° C) it has a 99.7%+ conversion efficiency – the engine can have engine-out NO_x as high 4 - 5 g / bhp-hr for higher combustion efficiency and still meet ultralow NO_x emissions requirements. The airflow management flexibility of the Achates OP engine enables combustion air chemistry and exhaust gas temperatures to be maintained in the optimum range across the operating range of the engine and enables attainment of the ultra-low NO_x goals while operating at high efficiency.

Duty Cycle	EPA 2027 NO_x Limit	Achates Power Result	Compliance Margin
	mg / bhp-hr	*mg / bhp-hr*	*%*
RMC/SET	35	24	31%
FTP	35	28	20%
LLC	50	43	14%

Table 1: Robust dynamometer test cycle NO_x compliance

When the engine is operating in low-loads or at idle, the Achates OP engine can generate high exhaust enthalpy when needed to boost catalyst temperature while also generating low engine-out NO_x. As shown in Table 1, the Achates OP engine has demonstrated the ability to meet all the 2027 ultralow NO_x requirements of the EPA and CARB, including the low-load cycle, and all in-use restrictions[2].

In-Use NO_x Limits

University of California Riverside (UC-Riverside) conducted in-use testing of the Achates heavy-duty diesel opposed-piston engine, as part of the CARB Heavy-Duty Diesel Demonstration Program. The results show that the Achates OP engine demonstrates in-use NO_X emissions control with a significant margin below the compliance limit of the most-stringent future in-use EPA NO_X regulation while also providing a fuel economy advantage against a comparable commercial reference truck.

The EPA introduced in-use NO_x limits, starting in 2027. A recent study, for example, shows that at low speeds, typical of urban driving, heavy duty vehicles can emit five times the certification limit.

To assess in-use emissions, a heavy-duty vehicle is equipped with a Portable Emissions Measurement System (PEMS). UC-Riverside, a leader in PEMS development and use, was selected by CALSTART to conduct the in-use measurements of the heavy-duty Achates OP engine for the project. Replicating the three operating cycles encountered during the field test and PEMS measurement, Achates Power continued to develop and refine calibration and design on its dynamometer to meet all future U.S. tailpipe emissions standards while optimizing efficiency.

The EPA has two in-use (or off-cycle) bins, using moving average window methodologies. Bin 1 covers idle conditions, when the engine load is less than or equal to 6% of its normalized average CO_2 rate. Bin 2 covers non-idle conditions.

NO_x	EPA 2027 Limit	LA Grocery Distribution	Ontario to Blythe	Porterville to Santa Maria
Driving condition		Downtown city and freeway mixed cycle	Highway	Steady vehicle speed on mostly secondary roads
Bin 1: idle (g / hr)	10	0.25	0.13	0.14
Bin2: non-idle (g / bhr-hr)	58	28	35	31

Table 2: Robust in-use NO_x *compliance*

The results of off-cycle (in-use) NO_x testing, using both the PEMS and the dynamometer measurements on replicated operating cycles, shows robust NO_x control on all tested routes in both idle and non-idle conditions.

Aftertreatment System Configuration

[2] The EPA also restricts emission of hydrocarbons, particulate matter, and carbon monoxide. The Achates OP engine demonstrated the ability to meet all 2027 emissions regulations with a wide compliance margin. The focus here is on NOx because it is most challenging criteria emissions for diesel engines, and the one subject to most severe new tailpipe restrictions, requiring an 82.5% reduction by 2027.

The results presented here were achieved with conventional, commercially available, underfloor aftertreatment system consisting of a one box design, using a diesel oxidation catalyst, diesel particulate filter, selective catalyst reduction, and ammonia slip catalyst.

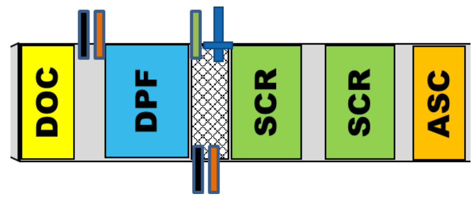

Figure 1: Aftertreatment system configuration of the Achates OP engine. The figure on the left is an image of the one-box aftertreatment system (ATS). The diagram on the right shows the configuration of the ATS components.

By avoiding additional emissions control devices – required by conventional engines to meet ultralow levels of NO_x emissions – the opposed-piston engine reduces cost, complexity, and compliance risk.

CO_2 and Fuel Consumption:

The Achates opposed-piston engine achieved excellent CO_2 and fuel consumption results on regulated dynamometer cycles, and even better results in in-use testing.

The Achates OP engines has fundamental advantages to enable efficient operation. The Achates OP engine eliminates the cylinder head and combines the piston motion of two pistons in each cylinder for a long effective stroke relative to bore at modest piston speed. This results in a reduced surface area/volume ratio of the combustion chamber relative to a conventional engine, leading to reduced heat rejection (on the order of 30% lower) and higher indicated and brake thermal efficiency. Since cylinder heads are cooled to lower maximum temperatures than pistons, the heat transfer benefit of the Achates OP engine arrangement is even greater. An additional efficiency benefit is the reduced parasitic loss to cooling fans.

A second major efficiency is due to more optimally phased combustion timing. Several features enable earlier and faster combustion at the same pressure-rise rate and (as noted above) reduced heat rejection.

Taken together, Warey[3] et al conclude "the opposed-piston diesel engine had about a 13-15% lower CO_2emissions compared to a four-stroke diesel engine", a finding consistent with the results of the demonstration program and subsequent testing.

The demonstration engine showed the ability to meet 2027 EPA CO_2 limits for heavy duty vehicles for both the RMC / SET cycle (for on-road vehicles) and the FTP cycle (for vocational trucks) while also meeting the stringent 2027 EPA NO_X limit of 35 mg / bhp-hr on RMC/SET and FTP cycles.

[3] Warey, A., Gopalakrishnan, V., Potter, M. et al: An Analytical Assessment of the CO_2 Emissions Benefits of Two-Stroke Diesel Engines, SAE International Technical Paper 2016-01-0659, 2016.

CO_2 (g/bhp-hr)	EPA Limit	Achates Power Results
RMC / SET	432	428
FTP	503	479

Table 3: Dynamometer test cycle CO_2 results

<u>Real world fuel consumption</u>

The field testing demonstrated that, as efficient as it is on regulated dynamometer testing, its efficiency advantage grows in real world operation. One reason for this feature is that the engine has both high peak efficiency and very broad islands of high efficiency with peak brake thermal efficiency (BTE) of 49.2 % and large areas of the speed / load map above 44% BTE.

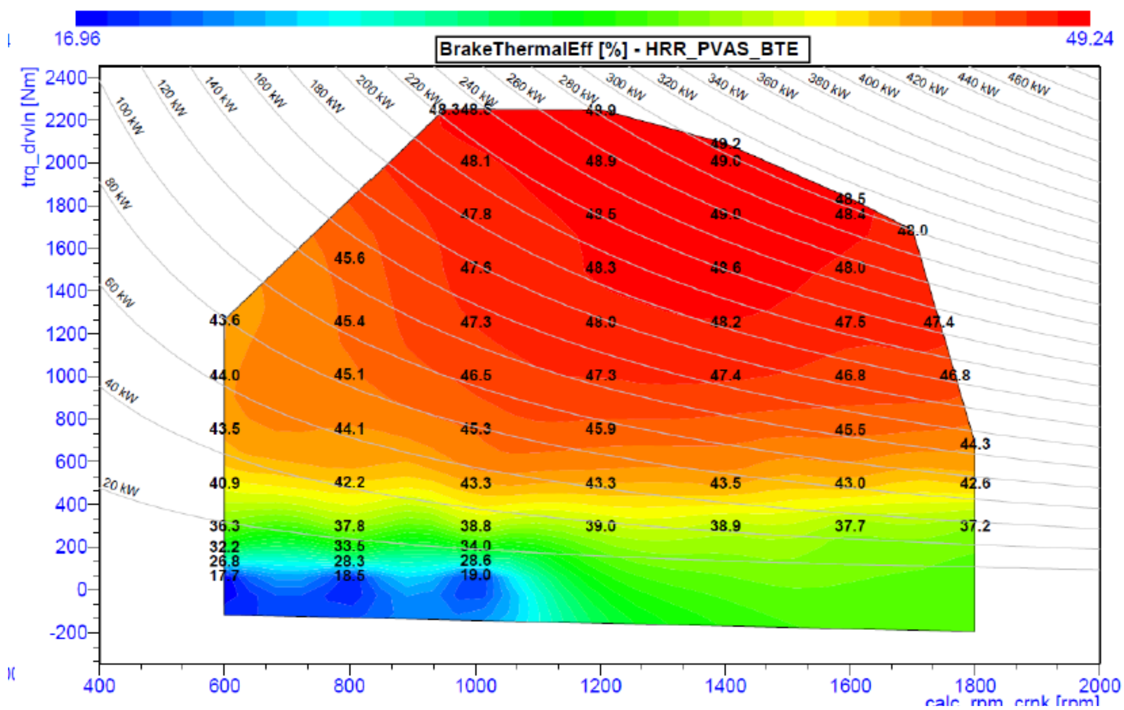

Figure 2: Brake thermal efficiency of 10L ultralow NO_x *opposed-piston diesel engine*

During operational service, Walmart measured the fuel consumption of the Peterbilt 579 with the Achates Power OP engine and that of a Freightliner Cascadia truck with a Detroit Diesel DD15 Gen 5 engine on the same routes with similar loads.

The Peterbilt truck with the Achates OP engine showed a consistent and significant fuel economy advantage. Achates Power continued to develop and refine calibration and design on its dynamometer, replicating the three operating cycles encountered during the field, to ultimately demonstrate a fuel economy advantage between 4% and 21%, depending on the drive cycle while also meeting in-use NO_x restrictions.

Miles Per Gallon	LA Grocery Distribution	Ontario to Blythe	Porterville to Santa Maria
	Downtown city and freeway mixed cycle	Highway	Steady vehicle speed on mostly secondary roads
Cascadia with DD15	5.73	6.93	7.04
Peterbilt with OP Engine	6.63	7.19	8.57
OP Engine Fuel Economy Improvement	16%	4%	21%

Table 4: Fuel economy comparison of heavy-duty trucks with Achates OP engine vs. with a conventional engine

Full Useful Life:

CARB extended the original Heavy Duty Diesel Demonstration Program to add full useful life testing. Achates Power, working with Southwest Research Institute (SwRI), is undertaking this testing. Using SwRI's Diesel Aftertreatment Accelerated Aging Cycles, the aftertreatment system is being aged to 435k, 600k, and 800k miles. Achates Power will conduct CO_2 and tailpipe emissions tests on the regulated cycles at each aging level and expects to demonstrate the opposed-piston engine is capable of meeting all future tailpipe emissions and all CO2 emissions to at least 2027 including at the full useful life.

Summary:

The Heavy-Duty Diesel Demonstration Program has yielded numerous important insights:

- The Achates opposed-piston heavy duty diesel engine can meet all current, future, and proposed U.S. regulations for tailpipe NO_X and PM emissions, including low-load and in-use, with robust compliance margins.
- The Achates OP engine can beat 2027 CO_2 regulations for heavy duty engines and shows 10%+ efficiency advantage vs. benchmark conventional engines in real world operation.
- The Achates OP engine only required a conventional under-floor aftertreatment system to comply with these stringent standards, substantially reducing the cost, complexity, and risk of compliance.
- A cost study conducted by FEV shows that in volume production the Achates OP engine – compliant with future stringent emissions regulations – will cost no more than and probably less than current engines.

The Achates OP engine has proved inherent advantages in high-efficiency, low-emissions, and low-complexity. It also has advantages in fuel flexibility, including carbon-free hydrogen combustion making it a superior solution for today and tomorrow.

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