Sustainable Now: Opposed Piston Engine Operating on Renewable Diesel

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. The opposed-piston (OP) engine developed by Achates Power has demonstrated the ability to meet the most stringent ultralow NO_x emissions requirements using only a conventional, underfloor aftertreatment system, offering reduced cost, complexity and compliance risk compared to other diesel engines while at same time demonstrating as much as 22% improvement in fuel economy (and commensurate reduction in fuel consumption and CO_2 emissions).

Summary

- An Achates Power opposed-piston engine operating on NESTE MY Renewable Diesel can reduced lifecycle GHG emissions by 77%-96%
- While also reducing tailpipe NO_x by more than 80%
- Without any increase in cost or complexity compared to today's engines
- Enabling a fleet operator to meet its sustainability goals without an increase in cost, additional infrastructure, or performance compromises.

Among the most impactful ways to reduce CO_2 emissions is to use renewable diesel. Neste MY Renewable Diesel™ is a hydrotreated vegetable oil, produced from renewal sources that has a 75-95% reduction in life cycle greenhouse gas (GHG) emissions compared to petroleum diesel.

The combination of the Achates Power OP engine operating on Neste My Renewable Diesel is practical, cost-effective, meaningful, and immediate way to meet sustainability goals:

- Lower cost to purchase
- Lower cost to operate
- Lower compliance risk
- No new infrastructure required
- No performance compromises

The Opposed-Piston Engine

A 10L heavy-duty OP engine was developed and demonstrated by Achates Power in the Heavy-Duty Diesel Demonstration Program, led by Calstart and 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.

Demonstration engines were extensively tested on dynamometers using standard #2 diesel fuel 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.

On three different commercial vehicle routes, the opposed-piston engine showed between 4% better and 21% better fuel economy than the best-in-class conventional engine.

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[1], demonstrated on both dynamometer cycles and in off-cycle testing.

Duty Cycle	EPA 2027 NO_x Limit	Achates Power Result	Compliance Margin
	mg / bhp-hr	*mg / bhp-hr*	*%*
RMC/SET	35	21	40%
FTP	35	28	20%
LLC	50	39	22%

Table 1: Robust dynamometer test cycle NO_x compliance

The EPA introduced in-use NO_x limits, starting in 2027. A recent study[2], 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.

[1] https://achatespower.com/wp-content/uploads/2024/05/Heavy-Duty-Diesel-Engine-Performance-and-Emissions-Summary-5.13.2024.pdf

[2] https://theicct.org/publication/current-state-of-nox-emissions-from-in-use-heavy-duty-diesel-vehicles-in-the-united-states/

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	30	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

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.

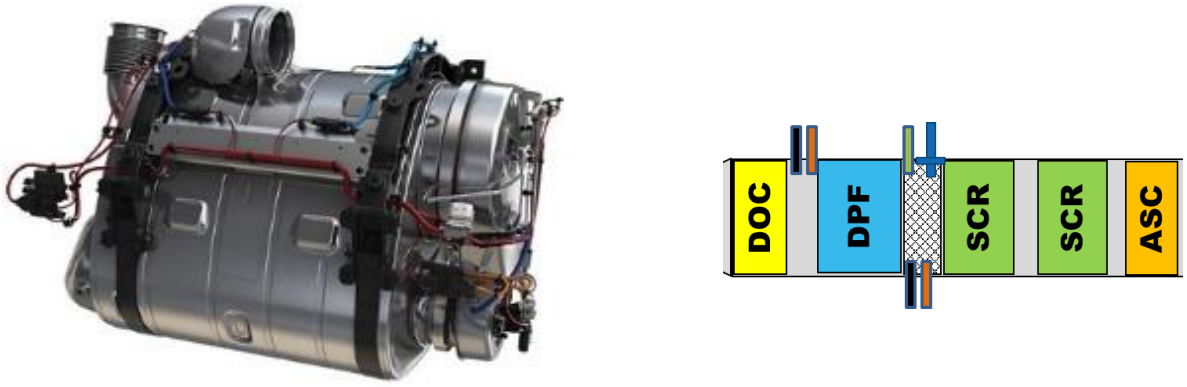

Figure 1: Aftertreatment system configuration of the Achates OP engine. The figure on the left is an image of the one-box aftertreatment system (ATS). The diagram on the right shows the configuration of the ATS components.

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 have fundamental advantages to enable efficient operation. 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.

[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.

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.

CO_2 (g/bhp-hr)	**EPA Limit**	**Achates Power Results**
RMC / SET	432	423
FTP	503	479

Table 3: Dynamometer test cycle CO_2 results

Real world fuel consumption

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.

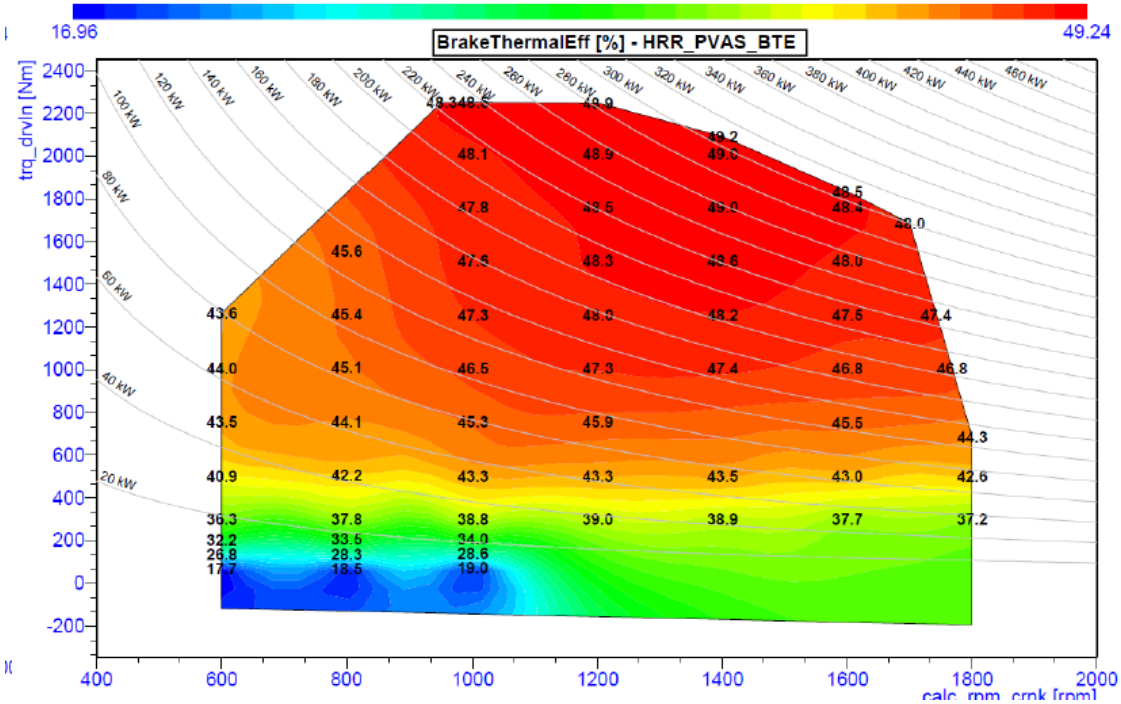

Figure 2: Brake thermal efficiency of 10L ultralow NO_x opposed-piston diesel engine

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), undertook this testing. Using SwRI's Diesel Aftertreatment Accelerated Aging Cycles, the aftertreatment system was aged to 435k and 600k miles. Testing emissions and fuel consumption at each of the aging levels, Achates Power demonstrated the opposed-piston engine is capable of meeting the CARB Omnibus 2027-2030 full useful life requirement while also meeting EPA GHG Phase II regulation at full useful life.

Operating with Neste MY Renewable Diesel

Achates Power ran a series of tests with the Neste MY Renewable Diesel to compare the performance of the engine versus when it ran with standard diesel. The tests primarily consisted of the U.S. EPA cycles – cold / hot Federal Test Procedure, Load Load Cycle, and Ramped Mode Cycle.

		#2 Diesel	Neste Renewable Diesel R100	Difference
	Unit	Avg values - #14	Single Sample	Negative for Neste being lower
Density	**g/ml**	0.8378	0.7807	-7.32%
Cetane number	**(-)**	53.2	81.3	34.62%
LVH	**kJ/kg**	42742	43749	2.30%
Sulfur	**PPM**	4.6457	0.5000	-829.14%
Carbon	**Weight %**	84.77%	84.04%	-0.87%
Hydrogen	**Weight %**	13.24%	14.54%	8.96%

Table 5: Comparison of #2 and Neste Renewable Diesel Properties

The Achates Power OP engine performed well with Neste MY Renewable Diesel.

- The combination achieved the lowest CO_2 emissions ever recorded by Achates Power, between 3% and 5% lower than with #2 diesel, depending on the test cycle. This means combination has compounding CO_2 reduction benefits:

  - The NESTE MY Renewable Diesel has 75% to 95% less CO_2 on a lifecycle basis than petroleum diesel
  - The Achates Power OP engine has 4% to 21% higher efficiency than conventional engines while operating on #2 diesel (and commensurately less fuel consumption and CO_2 emissions)
  - Operating NESTE MY Renewable Diesel on the OP engine results in 3% - 5% less CO^4_2 emissions than #2 diesel
- The combination demonstrated the ability to meet 2027 EPA regulations on all test cycles that were evaluated, with generally favorable characteristics regarding NO_x / soot tradeoffs that can allow greater optimization with further engine calibration.

Summary:

The Achates Power opposed-piston engine operating on NESTE MY Renewable Diesel offers a near-term, practical and cost-effective means to dramatically improve the sustainability of long-haul transportation.

- The combination has the demonstrated ability to reduced tailpipe NO_x by more than 80% while meeting the toughest environmental standards in the world, U.S. and CARB 2027 regulations, without any additional emissions control technology relative to current model year trucks.
- The combination has demonstrated compounding CO_2 benefits so that life-cyle CO_2 emissions are 77% - 96% lower compared to a conventional engine operating with #2 diesel.

This solution has enormous benefits to fleet operators:

- Less expensive to buy than current model year engines. A cost study conducted by FEV shows that because the opposed-piston engine eliminates 260 parts, including the cylinder head and valve train, compared to a conventional engine, it has a lower base engine cost than a conventional engine of the same power and torque. Moreover, because the opposed piston engine does not require additional emissions control technology to meet ultralow level of NO_x, the cost advantage grows as emissions limits become more stringent.
- Less expensive to use than current model year engines. The Achates Power opposed-piston engine reduces fuel consumption by as much as 21%.
- It does not require any additional infrastructure.
- It does not require any performance compromises. Refueling with Neste MY Renewable Diesel is as fast as with #2 diesel, and the range is nearly as long (the slightly lower energy density of the renewal diesel is partially compensated by higher operating efficiency).

In summary, the combination of the Achates Power opposed-piston engine and Neste MY Renewable Diesel offers tremendous sustainability advantages in a practical and cost-effective solution.

Moreover, since the opposed piston engine offers best-in-class efficiency and power density across a range of fuels, including carbon-free hydrogen[5], is it a superior solution for today and tomorrow.

For more information about Achates Power contact
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[4] Measured as g / hp-hr.
[5] https://achatespower.com/wp-content/uploads/2024/02/Achates-Power-SCE-Initial-H2-Test-Results-Report.pdf