Heavy-Duty Diesel Engine In-Use Testing

Summary

- In-use testing with PEMS equipment shows 52%-99% compliance margin to the most stringent proposed EPA in-use NO_x limits.
- Measured fuel consumption shows the opposed-piston diesel engine has 10%+ fuel economy advantage over the best-in-class reference engine with similar routes and loads and the same driver.

University of California Riverside (UC-Riverside) is conducting in-use testing of a heavy-duty diesel opposed-piston (OP) engine, as part of the heavy-duty diesel demonstration program. Initial results show that the OP engine demonstrates exceptionally good NO_X emissions control and provides a significant margin to compliance with the most-stringent proposed in-use EPA NO_X regulation while also providing a fuel economy advantage against a reference truck.

Program Background

The heavy-duty diesel demonstration program is funded by the California Air Resources Board, the South Coast Air Quality Management District, the San Joaquin Valley Air Pollution Control District, and the Sacramento Metro Air Quality Management District. The project is led by CALSTART. The objective of the program is to demonstrate that a diesel engine can meet the stringent 2027 CARB NO_X limit that requires a 90% reduction in tailpipe NO_X required by CARB's Heavy-Duty Engine and Vehicle Omnibus Regulation. The Omnibus regulation also introduces limits on low-load, idle, and in-use NO_X, and is the most stringent NO_X limit for mobile sources anywhere in the world. Achates Power has demonstrated that its OP engine can meet all of the fully implemented Omnibus NO_X limits determined by dynamometer testing.

Moreover, the U.S. Environmental Protection Agency (EPA) recently introduced proposed regulations to reduce commercial vehicle NO_X emissions across the U.S. These proposed rules are similar in some respects to CARB enacted rules.

For the demonstration program, Achates Power developed and demonstrated a 400 hp, 10.6L opposed-piston. The engine has been installed in a Peterbilt 579 tractor and is in fleet service with WALMART Corporation.

"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
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In-Use Testing

Historically, emissions limits for commercial vehicles have been measured on an engine dynamometer against a defined test cycle. In the United States, the test cycles are the Federal Test Procedure and the Supplemental Emissions Test.

More recently, regulators have started adding in-use testing requirements so that real world emissions can be assessed and limited. 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 OP engine for the project.

The EPA and CARB use similar schemes to assess in-use emissions, with slightly different stringency levels. Each scheme has three bins.

Bin 1 covers idle conditions, when the engine load is less than or equal to 6% of its rated load.

Bin 2 covers low load conditions (typically of driving in urban and other congested areas), when the engine load is greater than 6% and less than or equal to 20% of its rated load.

Bin 3 covers medium- to high-load conditions, when the engine load is greater than 20% of its rated load. Of the three, Bin 3 most closely matches the regulator dynamometer-based regulatory cycle.

Since at medium- to high-loads diesel engines generate sufficient heat for effective light-off (for optimal conversion efficiency) of the aftertreatment catalysts, Bin 3 is generally the easiest to meet. Bins 1 and 2 are more challenging.

EPA and CARB in-use limits vary based on year (they get more difficult as time goes on) and EPA proposed two different proposals for stringency. The table below shows the limits for CARB in 2030 and beyond, and in EPA for 2031 and beyond in the most stringent proposal:

	NO_X	CARB Omnibus Limit 2030+	EPA Proposed Low Limit 2031+
Bin 1	g/hr	7.5	11
Bin 2	g/bhp-hr	0.075	0.105
Bin 3	g/bhp-hr	0.030	0.042

Engine Configuration and Test Set Up

As noted above, the engine Achates Power developed for the project is a 400 hp, 10.6L 3-cylinder (6 piston) opposed-piston engine. The engine installed in the Peterbilt truck and operated for the demonstration is a Gen1 design. Achates Power is also testing a Gen2 design on its transient dynamometer.

The Gen1 engine uses only an underfloor aftertreatment system. No other emissions control devices (such as a close coupled SCR) are required for the OP engine to achieve ultralow NO_X compliance. The Gen2 engine uses an

even simpler aftertreatment system, a MY2021 one-box, underfloor system with a typical DOC-DPF-SCR-ASC[1] configuration. Like with Gen1, no other emissions control devices are used.

WALMART utilized the demonstration truck in the San Joaquin Air Pollution Control District, a project sponsor. PEMS testing was conducted in December, and ambient temperature during the test was in the mid-40s °F, a fairly challenging temperature for NO_X control (the catalysts in the SCR need to be about 250°C or higher to be most effective in converting NO_X; low ambient temperatures make it more difficult to achieve and maintain this temperature, particularly at low load and idle).

In-Use NO_X Results:

UC-Riverside used a PEM system to measure in-use NO_X emissions during three different periods with the Gen1 engine (labeled D1, D2, and D3 below). *All the tests showed results well below (providing 52%-99% margin) the most stringent EPA proposed limit as well as below the most stringent CARB limit*.

	NO_X	Achates_D1	Achates_D2	Achates_D3	Average	EPA 2031+ limit	Margin
Bin 1	g/hp	0.25	0.05	0.15	0.15	11	99%
Bin 2	g/bhp-hr	0.048	0.039	0.039	0.042	0.105	60%
Bin 3	b/bhp-hr	0.024	0.015	0.022	0.020	0.042	52%

It is important to note that Achates Power implemented only rudimentary controls for in-use compliance, making it likely that performance and emissions will improve with additional controls refinement.

Particulate Matter Results:

The criteria emissions most challenging and troublesome in diesel engines are typically NO_X and particulate matter (PM). In addition to reducing NO_X limits by 90%, the CARB Omnibus rule also reduces PM limits from commercial vehicle diesel engines by 50% from today's EPA limits. The Achates Power OP engine has no problem meeting these more stringent limits.

CO_2 and Fuel Consumption:

During vehicle demonstration, WALMART recorded the fuel consumption of the demonstration truck with the Achates Power OP engine as well as with a reference truck with a DD15 diesel engine from Detroit Diesel. As much as practical, the two trucks drove similar routes and loads with the same driver, though naturally some factors (e.g. wind direction and intensity, traffic) will vary by trip. The demonstration vehicle, with the Achates Power OP engine, consistently achieved 10%+ better fuel economy than the reference truck.

As noted above, Achates Power is testing the Gen2 version of the engine on its transient dynamometers. That testing shows that the Gen2 engine is about 7% more efficient than the Gen1 engine, making it likely that the OP engine performance advantage will increase with the latest design. In addition, the exhaust energy required for aftertreatment catalyst light-off increased, potentially increasing the NO_X compliance margin. Additional

[1] DOC: Diesel Oxidation Catlalyst; DPF: Diesel Particulate Filter; SCR: Selective Catalyst Reduction; ASC: Ammonia Slip Catalyst

refinement – including calibrating the transmission shift schedule, friction reduction, matched component selection, and overall calibration improvement - will likely yield additional performance improvement.

Summary:

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

- The opposed-piston heavy-duty diesel engine can meet all current, future, and proposed regulations for tailpipe NO_X and PM emissions, including idle, low-load, and in-use, with robust compliance margins.
- The OP engine only required a conventional under-floor aftertreatment system to comply with these stringent standards, substantially reducing the cost and complexity of compliance.
- CARB and SCAQMD have extended the project with CALSTART and Achates Power to test the OP engine with a fully aged, 800,000 mile aftertreatment system. Results of those tests will be available later in 2022, and are expected to show that OP engine also offers a substantial reduction in compliance risk even to the most stringent regulations.
- The OP engine has substantial full economy and CO_2 benefits of 10% or more.
- A cost study from FEV shows that in volume production the OP engine – compliant with future stringent emissions regulations – will cost no more than and probably less than current engines.

The 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 a superior solution for today and tomorrow.

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