

Class 8 Heavy-Duty Opposed-Piston Engine Demonstration

Final Report



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List of Acronyms

Acronym	Definition
AMOX	Ammonia oxidation
APU	Auxiliary power unit
AQIP	Air Quality Improvement Program
ASC	Ammonia slip catalyst
ATS	Aftertreatment system
bhp-hr	Brake horsepower-hour
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CAC	Charge air cooler
CARB	California Air Resources Board
CE-CERT	College of Engineering–Center for Environmental Research and Technology
CLO	Catalyst light-off
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DC	Distribution center
DEF	Diesel exhaust fluid
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECM	Engine control module
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
FSN	Filter smoke number

FTP	Federal Test Procedure
g	Grams
g/bhp-hr	Grams per brake horsepower-hour
g/hr	Grams per hour
g/hp-hr	Grams per horsepower-hour
g/kWh	Grams per kilowatt-hour
GCVW	Gross Combined Vehicle Weight
GHG	Greenhouse Gas
HD	Heavy-Duty
hp	Horsepower
HP-EGR	High-pressure exhaust gas recirculation
HSS	Hot Steady State
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ITE	Indicated thermal efficiency
kg	Kilogram
kW	Kilowatt
KPI	Key Performance Indicator
L	liter
lb-ft	Pound-foot
lbs	Pounds
LCFS	Low Carbon Fuel Standard
LLC	Low-load cycle
LO-SCR	Light-off selective catalyst reduction
LP-EGR	Low-pressure exhaust gas recirculation
MHD	Medium- and heavy-duty
mg/m ³	Milligram per cubic meter

mm	millimeter
NH ₃	Ammonia
NO _x	Nitrogen Oxides
Nm	Newton-meter
OEM	Original Equipment Manufacturer
OPE	Opposed-piston engine
PEMS	Portable Emissions Measurement Systems
PM	Particulate Matter
PPM	Parts per million
RMC	Ramped Modal Cycle
rpm	Revolutions per minute
SCAQMD	South Coast Air Quality Management District
SCR	Selective catalyst reduction
SCRF	Selective catalytic reduction filter
SCROF	Selective catalytic reduction on filter
SJVAPCD	San Joaquin Valley Air Pollution Control District
SWRI	Southwest Research Institute
UCR	University of California at Riverside
ULN	Ultra-low NO _x

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Executive Summary

The opposed-piston engine (OPE) promises a practical and economically viable solution for the reduction of nitrous oxide (NO_x) emissions and carbon dioxide (CO₂) as mandated by the California Air Resources Board (CARB) Heavy-Duty Engine and Vehicle Omnibus Regulation. The OPE resolves one of the conundrums of emissions reduction: achieving ultra-low NO_x emissions without increasing CO₂ and without costly additional emissions technology. Conventional four-stroke engines induct a full cylinder of air during the intake stroke that dilutes the engine's exhaust heat; high exhaust enthalpy is necessary to enable rapid catalyst light-off and maintain the catalyst temperature required to achieve lower NO_x and CO₂ emissions. OPEs, by contrast, utilize scavenging to reduce the amount of additional exhaust enthalpy required to maintain catalyst temperature while undertaking less gas exchange work to achieve simultaneous reductions in NO_x and CO₂ emissions.

This demonstration sought to investigate the application of OPE technology in heavy-duty (HD) trucking operations. OPEs were first designed in the late 1800s and have been used in various applications, including in ships, airplanes, submarines, trains, and other modes of transportation. Gas exchange and combustion are one continuous cycle for OPEs and other two-stroke engines; this connectedness posed a challenge when changing one part of the system since it affected every other. Improvements to the OPE were made by trial and error—an expensive and time-consuming endeavor. OPEs fell out of favor in emissions-regulated applications like cars and trucks because meeting those emissions requirements was more difficult to achieve. However, with the advent of supercomputers and sophisticated chemically reactive computation fluid dynamics, design changes could be evaluated electronically, and millions of iterations could be evaluated to find the right combination of features. Promising OPE design candidates could be evaluated and refined experimentally, and the computer models could be correlated with measured results to make the models more effective at predicting real world results. Combined with a matured, HD truck market with an existing supply chain of widely available components and auxiliary systems, as well as the growing amount of research and data collection on the HD truck sector on fuel consumption, fuel efficiency, and emissions controls, these tools and processes have made it feasible to achieve ultra-low NO_x and GHG reductions with an OPE HD truck. The funding provided by CARB enabled Achatas' development of an OPE HD truck through design, assembly, engine testing, and vehicle installation to its first demonstration and in-use testing as part of Walmart Inc.'s fleet.

In the first two months of demonstration, this OPE HD truck ably performed the same duty cycle as the conventional trucks operating out of Walmart's distribution center in Porterville, California. Monitoring and testing showed the OPE HD truck used 10% less fuel than a conventional baseline truck, and NO_x emissions were in compliance with the CARB OMNIBUS in-use NO_x emission limit by at least 30%. The tables below demonstrate project results from on-road fleet testing and portable emissions measurement system (PEMS) testing.

Table 1: OPE Truck vs Baseline Truck Performance Metrics

Performance Metric	OPE Truck	Baseline Truck
Total Days Operated	32	7
Average Distance Driven per Day (mi)	320	268
Maximum Distance Driven per Day (mi)	390	366
Average Daily Fuel Consumption (gal)	41	39
Average GCVW (lb)	66,703	65,537
Average Fuel Economy (mpg)	7.7	6.9
Maximum Fuel Economy (mpg)	10.8	7.7

Table 2: Porterville PEMS Test Results

Vehicle and Test Day	NO_x (g)	NO_x (g/bhp-hr)	NO_x (g/mile)	NO_x (g/hr)
Baseline (12/14/2021)	26.779	0.030	0.071	2.846
OPE (12/15/2021)	12.791	0.031	0.075	1.288
OPE (12/16/2021)	10.791	0.021	0.049	1.692
OPE (12/17/2021)	8.673	0.031	0.060	1.239

In the demonstration's third and final month operating out of Fontana, California, issues with the OPE's emissions controls caused high NO_x output. Table 3 below demonstrates these results.

Table 3: Fontana PEMS Test Results

Vehicle and Test Day	NO_x (g)	NO_x (g/bhp-hr)	NO_x (g/mile)	NO_x (g/hr)
OPE (04/16/2022)	82.224	0.257	0.702	22.403
OPE (04/19/2022)	85.374	0.237	0.734	20.556
Baseline (04/20/2022)	15.386	0.038	0.127	3.821
Baseline (04/21/2022)	16.309	0.041	0.142	3.596

Investigation of root causes revealed that, due to erroneous mass flow rate signals at high loads, calibration of the engine's aftertreatment system (ATS) was not robust enough for the higher average loads and more aggressive pedal usage in the Fontana fleet. This proved to be invaluable feedback and, to resolve this issue, Achatas performed an extensive selective catalytic reduction (SCR) recalibration and overhaul of the engine and its systems. These updates were validated through engine dyno testing, using parameters that replicated the Fontana drive cycle. Results from the dyno testing showed that the SCR recalibration did resolve limitations encountered in the Fontana testing NO_x emissions and were low enough to comply with the most stringent CARB in-use limits.

This project demonstrated the potential of the OPE to reduce NO_x while improving efficiency in HD trucks; however, there is very limited, real-world data to support that the OPE can achieve these reductions during commercial operations. With more time to fully optimize the engine and develop a path to market, OPEs have the potential to play a significant role in addressing areas that zero-emission technologies will have difficulty covering. Issues that arose during the demonstration provided information that can propel the OPE HD truck along its ultimate path to market.

Project Overview

Background

The movement of freight within and through California's regional centers relies predominantly on the use of HD diesel-fueled trucks. These trucks are a large source of greenhouse gas (GHG), criteria pollutant, and toxic air-contaminant emissions. Since these vehicles tend to frequent ports, railyards, and warehouse districts as part of their normal activities, large amounts of NO_x and diesel particulate matter (PM) emissions significantly impact nearby communities. Reducing emissions from these trucks is not only necessary to meet federally imposed clean-air standards but also to reduce adverse health effects from their emissions—especially in disadvantaged communities.

The continued development and demonstration of advanced technologies (zero-emission and near zero-emission) is necessary to meet California's long-term GHG emissions reduction goals, protect public health, and reach attainment with increasingly stringent federal air quality standards. Therefore, as part of the 2016-2017 Funding Plan for Low Carbon Transportation Investments and the Air Quality Improvement Program (AQIP), CARB announced funding for the On-Road Advanced Technology Demonstrations and Pilot Projects. The primary aim of these projects was to incentivize advanced technology within the freight sector that reduces GHG, criteria pollutant, and toxic air contaminant emissions to disadvantaged communities.

In May 2017, the solicitation period for the On-Road Advanced Technology program began with available funding of \$17 million in grants for pre-commercial technology demonstrations. Five projects were awarded: two hydrogen fuel cell projects; a natural gas near-zero engine; a port congestion emissions reduction plan; and this project, a demonstration of an HD OPE.

Introduction

Engine Design, Assembly, Testing, and Installation

Achates led the effort to design, assemble and test the OPE for the demonstration project, as outlined in more detail below. Southwest Research Institute (SWRI) led the aftertreatment design team. The engine and ATS were initially tested at an Aramco Services Co. facility in Michigan. Integration of the engine into a Peterbilt 579 tractor commenced at the Peterbilt facility in Texas.

Vehicle Testing

Peterbilt installed the new OPE and ATS in an HD truck, then assessed performance with private- and open-road testing. Achates performed a second round of open-road testing following the testing conducted at Peterbilt. The tests demonstrated that the newly installed OPE functioned safely and efficiently with ultra-low emissions. The truck was ready for the next phase of evaluation—revenue-generating service for retailing giant, Walmart Corp.

On-Road Fleet Testing

The OPE truck was put in revenue-generating service and was operated by Walmart for a three-month on-road demonstration period. The OPE truck was tested at two distribution centers (DCs) in Porterville and Fontana, California.

Under CALSTART's direction, Walmart collected the vehicle's operations data over an eight-week period. In addition, Walmart and CALSTART gathered similar data on a conventional HD truck using a 2022 model year truck with equivalent specifications to the OPE truck and driving comparable routes. Though data collection was limited, this data permitted direct comparison between the performance of the OPE demonstration truck and a non-OPE vehicle.

PEMS Analysis

To calculate and validate the emissions savings of the OPE demonstration vehicle, in-use emissions testing was conducted at both demonstration sites. CALSTART contracted University of California, Riverside's (UCR) College of Engineering–Center for Environmental Research and Technology (CE-CERT) to conduct the testing. CE-CERT conducted gaseous and PM Portable Emissions Measurement System (PEMS) testing utilizing AVL's state-of-the-art, ultra-low NOx PEMS prototype unit. CE-CERT captured the actual in-use emissions by installing the lab-grade equipment on the baseline diesel and OPE truck and having both vehicles perform similar duty cycles.

Project Goals

The overarching goal of this project was to develop, test, and demonstrate an OPE for deployment in an on-road Class 8 HD truck used in a regional long-haul application. In-use performance data was captured and analyzed to validate and quantify OPE technology benefits compared to conventional and commercially available diesel engines. The bullet points below describe the goals of this report.





- Detail the demonstration of the industry's first high-efficiency, ultra-low NOx engine for the medium- and heavy-duty (MHD) truck sectors.





- Summarize the performance of the OPE truck in Walmart's operations and identify ideal uses and remaining barriers.
- Monitor NO_x and CO₂ reduction of the OPE truck relative to a conventional diesel truck.
- Document evidence of a minimum 15% fuel reduction and ultra-low NO_x emissions while maintaining or exceeding performance expectations.
- Increase end-user acceptance and optimism for the technology by conducting in-field demonstrations with Walmart, one of the largest freight operators in the country.

Project Team

Table 4: Project Stakeholders and Partners

Organization Logo	Description and Role
	<p>CARB funded the project as part of its On-Road Advanced Technology Demonstration project under AB 118's AQIP. CARB developed a basic data collection framework required from all projects funded under the AQIP which served as this project's primary data collection. In addition to funding, CARB contributed high-level project guidance and monitored ongoing project progress via periodic reports.</p>
	<p>SCAQMD is the air-pollution-control agency for over 16.8 million people, covering Orange County and the urban portions of Los Angeles, Riverside, and San Bernardino counties. SCAQMD provided cash match funding to the project and guidance on the technology implementation plan and final report.</p>
	<p>SJVAPCD is the air pollution control agency for approximately 4.3 million people, covering the San Joaquin Valley from San Joaquin County to Kern County. SJVAPCD provided cash match funding to the project and guidance on the final report.</p>
	<p>CALSTART is a nation-wide, non-profit organization accelerating clean transportation by connecting stakeholders across the industry and creating green jobs. CALSTART, the primary grantee, had the responsibility of collecting data, executing the data analysis, and completing the final report. The data collection process included test plan development, ongoing vehicle metric monitoring, PEMS testing, and in-house data analysis.</p>
	<p>Achates Power, Inc. (Achates) is a San Diego-based developer of opposed-piston internal combustion engines designed for use in MHD vehicle applications. Achates supports original equipment manufacturer (OEM) development and commercialization of OPEs via engineering services and technology licenses and has ten global OEMs among its customers. Achates has 97 employees, primarily at its San Diego headquarters. Achates was the overall leader for project planning, engine development, integration, and testing. Achates also had the responsibility of providing the database container file for telematic translations and reporting basic powertrain characteristics and maintenance costs.</p>
	<p>Walmart Inc. is the world's largest retailer and currently operates approximately 6,000 trucks in its U.S. fleet. Walmart operated the demonstration vehicle as part of its overall operations for a minimum, cumulative period of three months. The vehicle operated out of the Walmart DCs in Porterville, Apple Valley, and</p>

	<p>Fontana on routes passing through several disadvantaged communities. Walmart reported vehicle usage characteristics not captured by dataloggers, such as specific fleet usage, load, and route data.</p>
	<p>CE-CERT is the largest research center at UCR, bringing together researchers from multiple disciplines to address society's most pressing challenges in air quality, climate change, energy, and transportation. CE-CERT analyzed the trucks' performance and modeled the trucks' life-cycle emissions.</p>
	<p>PETERBILT, a subsidiary of Paccar, is an American manufacturer of MHD commercial vehicles; Paccar manufactures approximately 75,000 commercial vehicle engines each year. Peterbilt supplied a 579-truck and provided integration and engineering services as well as testing support. Peterbilt was also responsible for reporting basic vehicle characteristics like fuel tank capacity, chassis weight, etc.</p>
	<p>SOUTHWEST RESEARCH INSTITUTE (SWRI) is a science and engineering non-profit organization with significant capability in engine design, development, and analysis. For this project, SWRI was contracted by Achates to utilize its expertise in low- NO_x aftertreatment design and calibration technology to help design two commercial vehicle engines.</p>
	<p>ARAMCO SERVICES COMPANY, the U.S. subsidiary of Saudi Aramco, is dedicated to the development and demonstration of high-efficiency and low-emission engine and vehicle technologies. The company's research center in Detroit, Michigan operates a state-of-the-art laboratory which houses performance and emissions test cells capable of handling engines from 10 to 1,000 HP, single cylinder research engines for fundamental combustion work, and four-wheel drive chassis dynamometers with temperature capabilities ranging from 20 to 140°F. The Aramco facility and staff were utilized for much of the engine optimization and calibration.</p>
	<p>DELPHI, then Borg Warner now Phinia is a leading supplier of technologies for the automotive and commercial vehicle market. Delphi engineered and supplied the truck's fuel system, which includes state-of-the-art injection components (pump, rail, and injector) that were customized for the engine.</p>
	<p>EATON provides energy-efficient solutions that enable its customers to effectively manage electrical, hydraulic, and mechanical power more efficiently, safely, and sustainably. Eaton engineered and supplied advanced technology, including custom-designed intake air handling components (superchargers, etc.) for the engines.</p>

	<p>Formed in 2017, Eaton Cummins Automated Transmission Technologies (Eaton Cummins) is a 50/50 joint venture between Eaton and Cummins Inc. The global joint venture produces and markets industry-leading MHD automated transmission technologies. Eaton Cummins supplied the transmission for the OPE truck in this project.</p>
	<p>FAURECIA now Forvia is a leader in supplying OEM and engine manufacturers with forward-looking solutions in exhaust emissions control—oxidation catalyst, regenerative PM filters, and selective catalyst reduction systems—to mitigate PM and NO_x emissions from diesel engines. Faurecia engineered and supplied aftertreatment solutions for the demonstration.</p>
	<p>CORNING develops emissions control products for major vehicle and engine manufacturers. Its ceramic substrates and particulate filters form the core of world-class pollution control systems, making them a leader in clean-air technologies for over 40 years. Corning provided flow through and wall flow substrates as building blocks to the aftertreatment system for this demonstration project to achieve ultra-low emissions.</p>
	<p>BASF is a leading supplier of aftertreatment catalyst coatings; for this project, the company applied this expertise to configure and supply catalyst coatings for the ATS.</p>
	<p>FEDERAL MOGUL now Tenneco is a leading supplier of pistons, rings, bearings, and other engine components. The company assisted in engineering the pistons and rings for the demonstration engines.</p>

Engine Design, Assembly, Testing, and Installation

Introduction

The purpose of the OPE design was to create an HD diesel truck engine with increased fuel efficiency, lowered emissions, and ultra-low NO_x emissions by combining Achatés OPE technology with the ATS pioneered by Southwest Research Institute (SWRI). Achieving ultra-low NO_x operation typically causes a penalty in fuel consumption and CO₂ emissions. The heat required to light off the catalyst and maintain adequate temperature comes from diesel fuel combusted in the engine, in an ATS afterburner, from electrically operated heaters, or a combination thereof. This inevitably increases fuel consumption and CO₂ emissions compared to engines that do not seek ultra-low NO_x operation. The first phase of the program was to develop a version of Achatés' pre-existing OPE with the right displacement and power characteristics to fulfill the needs of an HD, on-road Class 8 truck while simultaneously reducing CO₂ and NO_x emissions.

Design

The focus of the main engine design was to meet the requirements of an HD Class 8 truck with an opposed-piston engine. The final specifications are listed in the table below.

Table 5: OPE Specifications

Specification	OPE Truck
Swept Displacement	10.6 L
Number of cylinders	3
Total Stroke	312 mm
Bore	120 mm
Stroke/Bore	2.6
Peak Power	300 kW (400 hp) @ 1700 rpm
Peak Torque	2237 Nm (1650 lb-ft) @ 950-1300 rpm
Emissions Level	California ultra-low NO _x : 0.02 g/bhp-hr
EGR	Yes

Specification	OPE Truck
Fuel	Diesel
Aftertreatment	Includes DOC, DPF and SCR

This rendering was developed to speed design and enable modular modification with colored components. A production design will have a single cast block. For the OPE demonstrated in this project, the main structure of the engine—the block—was composed of three main parts bolted together; this design was selected to make part hardware iteration easier. The cylinder liners are held by the block upper structure.

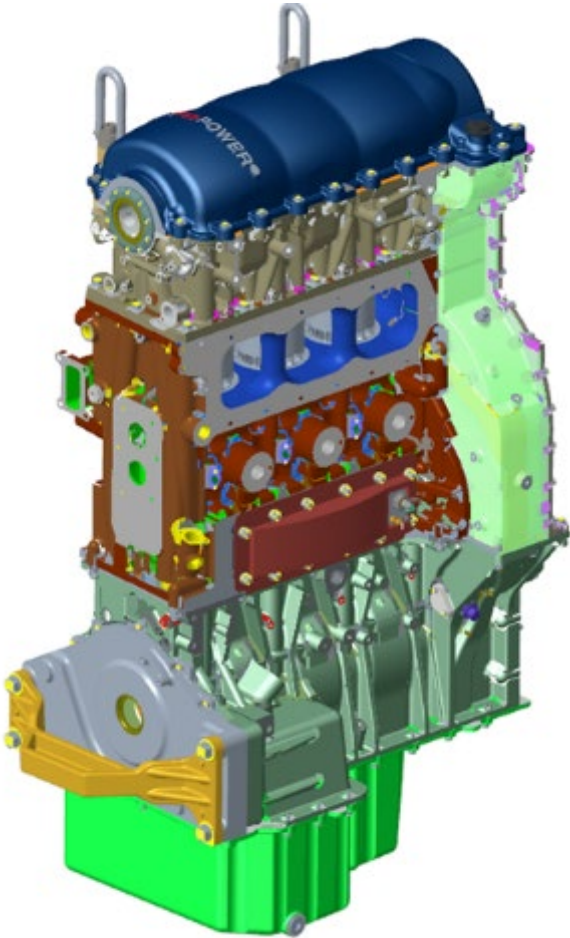


Figure 1: The Main Engine Structure

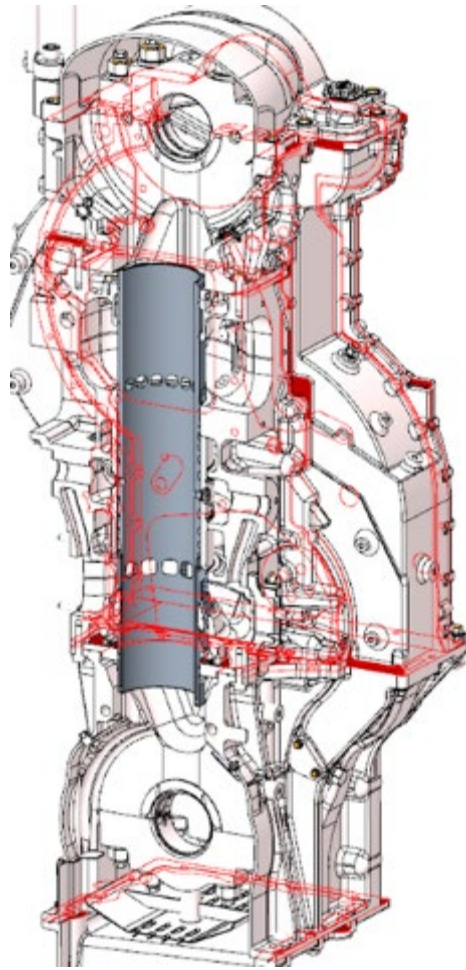


Figure 2: Cylinder Liner

The design uses removable cylinder liners which enables modification during the development process to optimize overall performance.

Because the OPE operates on a two-stroke cycle, a 10.6-L HD engine matches the power and torque of a larger 13-L or 15-L conventional engine for Class 8 trucks. The smaller displacement, along with a reduced part count, can provide a cost advantage for the OPE, everything else being equal. The design of the crank train, crankshafts, connecting rod, and pistons enable a displacement of 10.6 L, smaller than that of a conventional internal combustion engine for a Class 8 truck. A smaller displacement means the engine weighs less, which, in turn, has the potential to use less fuel, reduce emissions, and cost less to produce. The crank train design also combines the stroke of two pistons in the same cylinder for a higher, combined stroke-to-bore ratio of 2.6:1. This provides a favorable surface area-to-volume ratio of the combustion chamber, resulting in less head rejection than conventional engines of the same power and torque. The reduced heat rejection means more of the fuel energy can be converted to useful work and is the main reason OPEs are generally more efficient than conventional engines of the same power and torque.

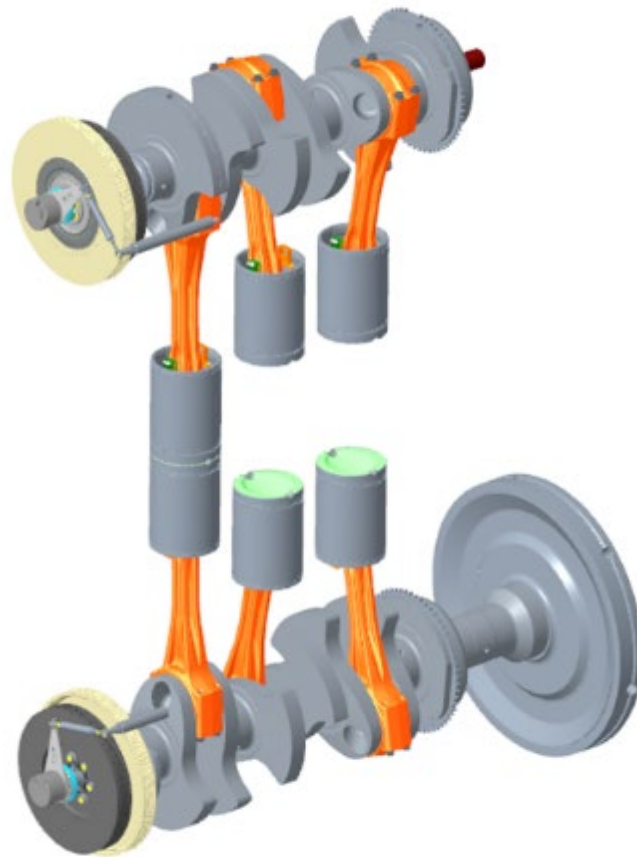


Figure 3: Engine Crank Train

The crankshafts were designed to connect via a four-gear set at the rear of the engine and a smaller geartrain in the front drive with two oil pumps: one for lubrication and one for piston cooling.

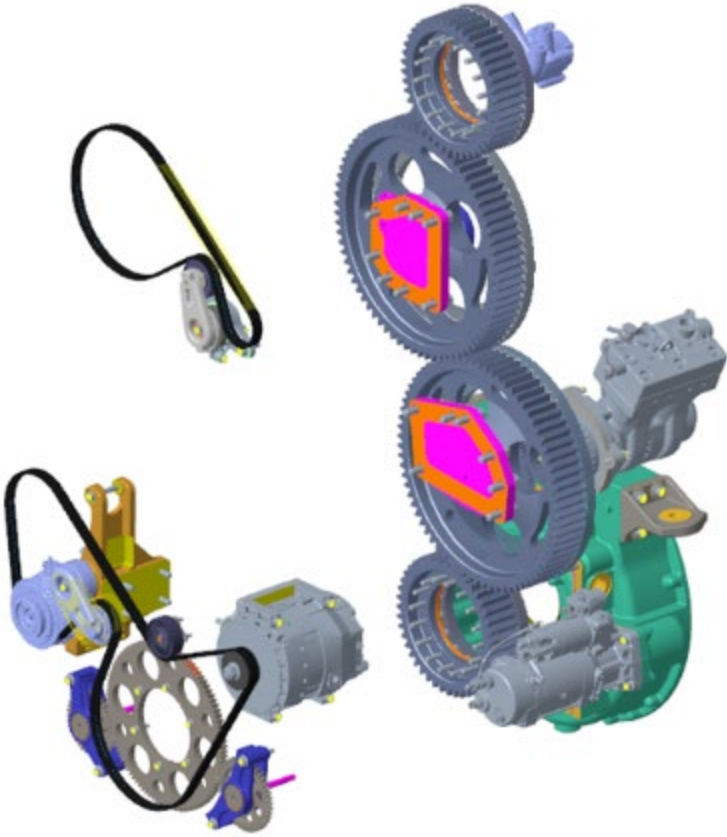


Figure 4: Geartrain Design

The design of the internal engine components, such as the intake and exhaust manifolds and the intake and exhaust ports, was studied extensively using 1D and 3D tools like computational fluid dynamics to optimize overall performance and meet Achates' design guidelines. Figure 5 below captures the activity of the cylinders during operation.

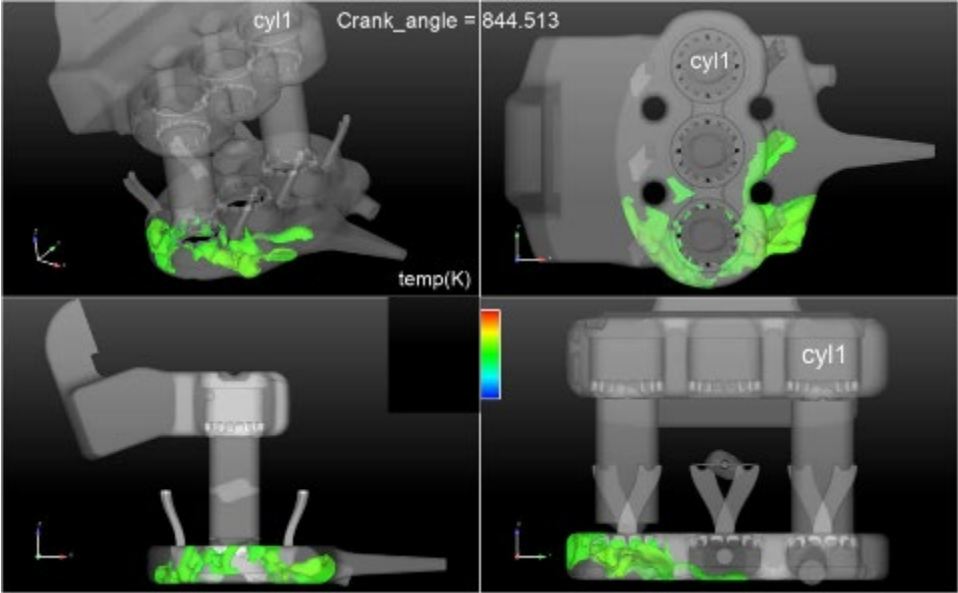


Figure 5: Open Cycle Computational Fluid Dynamics Analysis

The fuel pumps were mounted directly in the upper engine block and driven by cam lobes attached to the upper crankshaft. Two high-pressure fuel rails were mounted on each side of the engine to supply fuel to the injectors on each side. This design provides two fuel injectors per cylinder diametrically opposed.

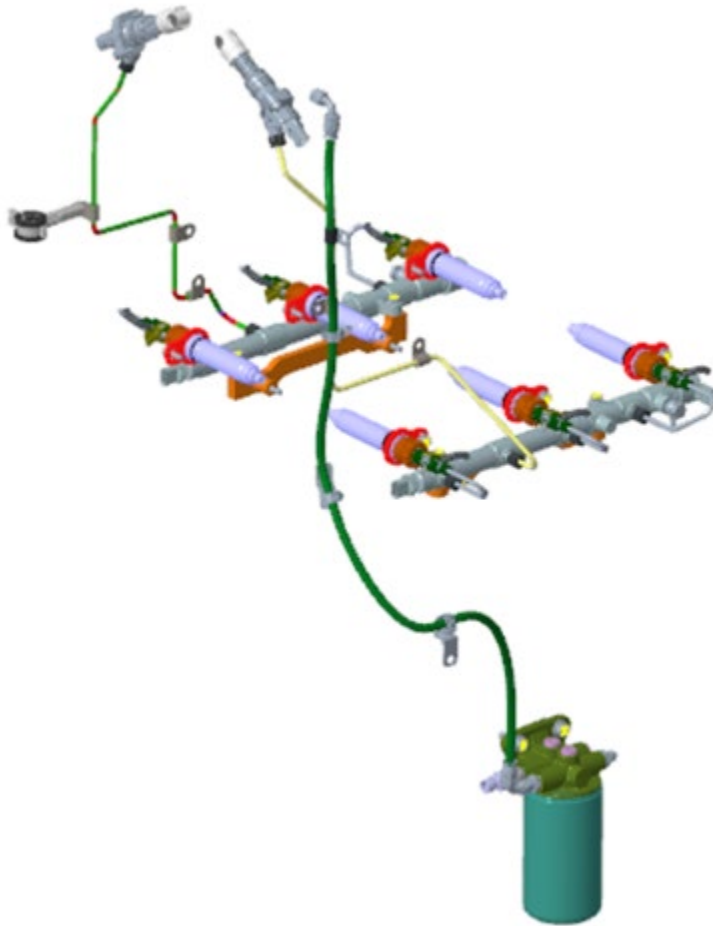


Figure 6: The Fuel System

The air management system, pictured below in Figure 7, is composed of a turbocharger, an engine-driven charge pump with variable speed ratio, charge coolers, and exhaust gas recirculation (EGR). These components were packaged around the top of the engine.



Figure 7: The Engine Air System

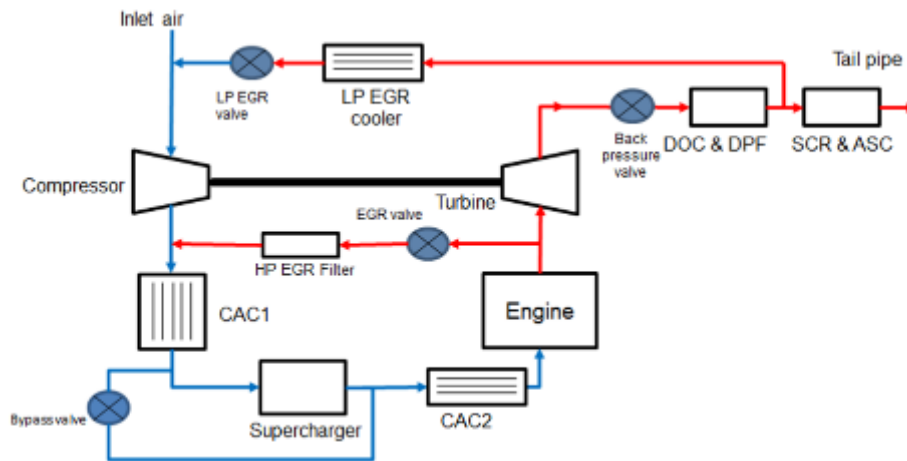


Figure 8: Air System Schematic

The initial ATS selected by the aftertreatment team included a close-couple SCR with its own gaseous ammonia injection system and an underfloor unit with an SCR and particulate filter combination as a selective catalytic reduction filter (SCR) to provide NO_x conversion capability. The close-couple SCR system was eliminated later as unnecessary. See p. 38 in Engine Testing for more details.

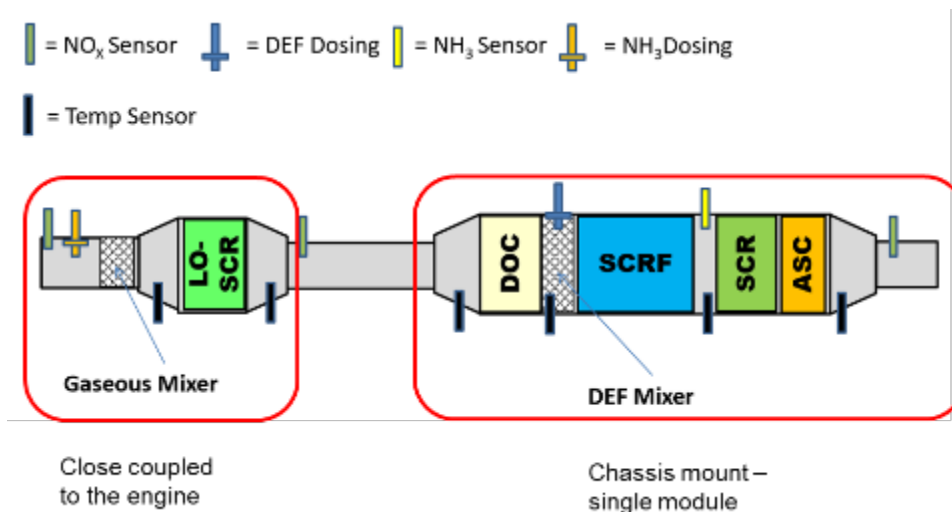


Figure 9: Initial Aftertreatment Configuration

The engine was developed to fit into a 2019 Peterbilt 579. The Peterbilt truck used in the demonstration has a custom hood that creates a slightly larger engine compartment. Because the OPE used in this demonstration program was a prototype unit, it was not yet optimized for size and weight. A production OPE will fit in the standard Peterbilt 579 engine compartment without a custom hood.

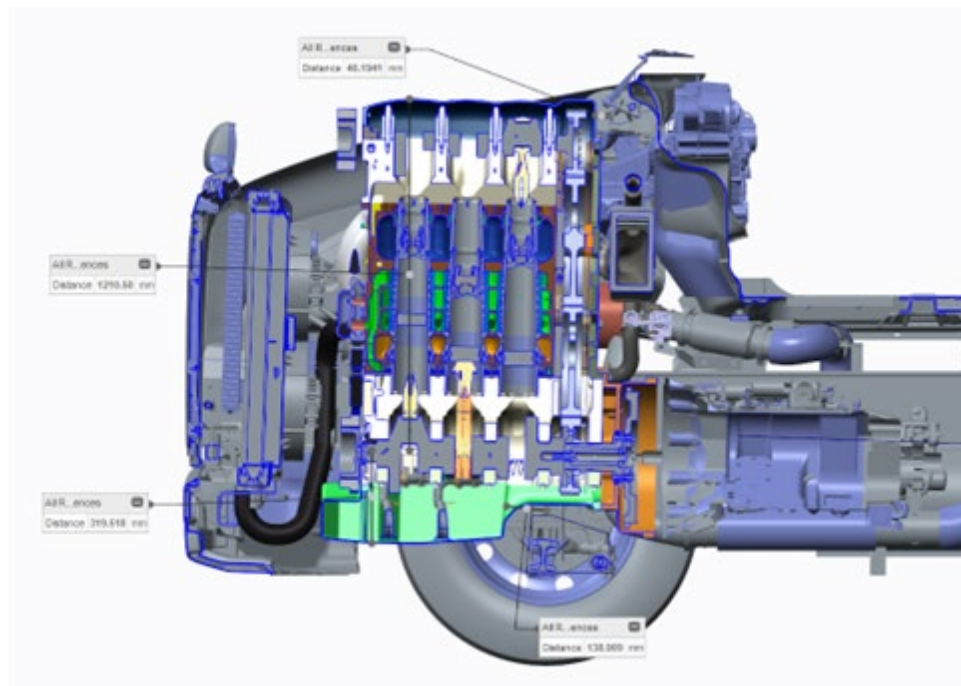


Figure 10: Engine Fit for Peterbilt 579

Assembly

After the design phase was completed and engine parts were manufactured or adapted, assembly began. Both lower and upper crankshafts were assembled along with the pistons and connecting rods. Then, the oil pan and top cover were mounted, and the engine was transferred to the dynamometer cart for assembly of the air and fluid systems. The engine, coolant lines, wiring harness, sensors, including the engine control module (ECM) sensors, and instrumentation were added.

Testing

The first phase of testing sought to verify the engine's mechanical durability. Several minor defects in design, fabrication, and assembly were identified and corrected.

After making these improvements to the engine, the engine was tested for 426 hours and inspected. Figure 11 below shows run time accumulated as a function of speed and load. Out of the 426 hours total run time, for approximately 130 hours, or 31% of the time, the engine ran at 75% and 100%-load.

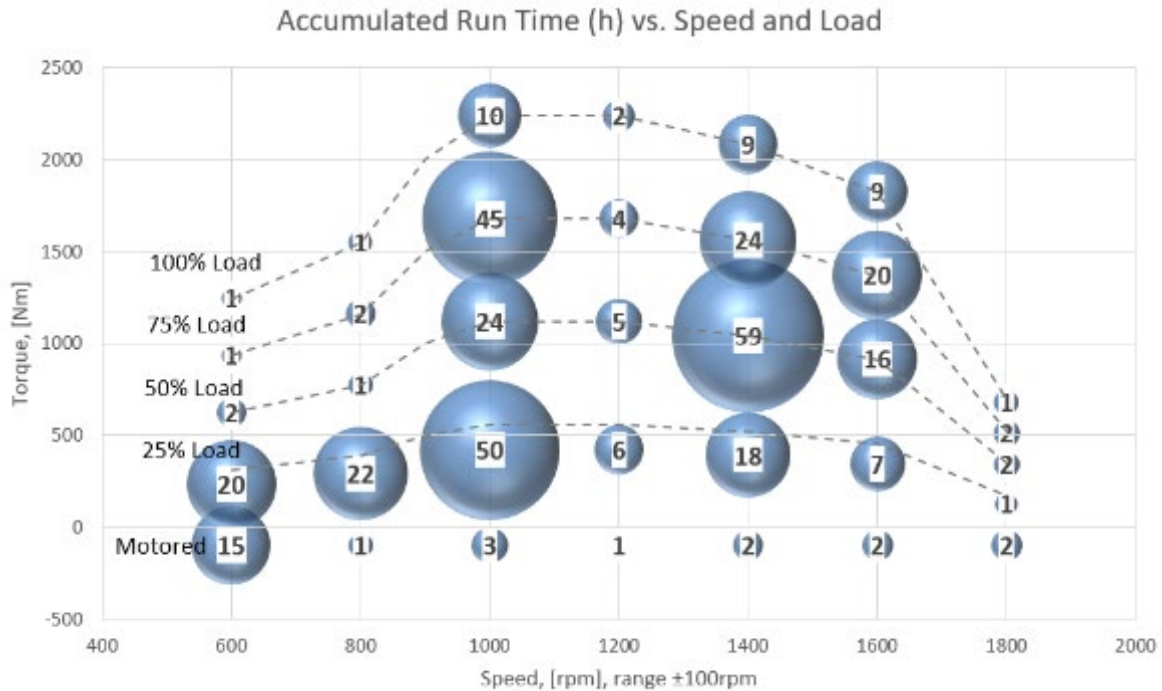


Figure 11: Accumulated Run Time

Before shipping the engine to Aramco for additional performance testing, Achates engineers performed a borescope inspection to check the condition of the OPE's internal components after 426 hours of testing. In addition, Achates developed the base engine calibration and collected performance and emissions steady state engine data. Engine test data for two different operating modes was collected. The first mode, Hot Steady State (HSS), is used for engine operation when the aftertreatment is fully operational and is aimed at minimizing fuel consumption. The second mode is catalyst light-off (CLO), which occurs before the aftertreatment is fully operational so that the engine-out NO_x is minimized while the exhaust enthalpy is maximized. These results meet the program NO_x and CO₂ targets.

From SWRI studies, it was confirmed that once the catalyst is lit, engine-out NO_x emissions ranging from 3-4 g/kWh would allow compliance with the ultralow NO_x limits; Achates' OPE naturally ran at this limit of 3-4 g/kWh, so they focused on optimized calibration for efficiency while making sure engine-out NO_x was within range, which is confirmed by the results in Figure 12.

To verify compliance with the program CO₂ target of 437 grams per horsepower-hours (g/hp-hr) CO₂, the engine was tested on the Ramped Modal cycle Supplemental Emissions Test (RMC SET). The results were 437 g/hp-hr, or 586 grams per kilowatt-hour (g/kWh), as targeted. The results are shown in Figure 12 below.

The RMC SET does not include testing for NO_x emissions during cold starts, low-loads, and idling cycles—conditions that challenge achieving ultra-low NO_x emissions.

Cycle Average Results		STDEV	
BSFC	191.65	0.15	g/kWh
BSNO _x	3.49	0.03	g/kWh
BSSoot	0.041	0.001	g/kWh
BSCO	1.04	0.01	g/kWh
BSHC	0.53	0.01	g/kWh
BSCO₂	586.17	0.45	g/kWh
	437.44	0.33	g/hphr

Figure 12: Ramped Modal Set Cycle Results

This table shows that the engine-out emissions results on the RMC SET cycle were reasonable, meaning that once an aftertreatment system was applied, the engine would be able to meet tailpipe limits on the RMC SET cycle. In the table, “BS” is an abbreviation for brake specific, which indicates that results account for the engine’s operation. Conversions can be made between g/kwh—which is more common globally—and g/hp-hr which is used in the United States.

In addition, the team generated a map of 76 points of engine test data from the HSS and CLO covering operation between 600 to 1800 revolutions per minute (rpm) and 0 to 2200 Newton-meters (Nm) torque. The number of discrete operating points allows more consistency as engine calibration is modified. Figure 13 shows the operating points Achates used, which illustrates good coverage across a full speed and load sweep.

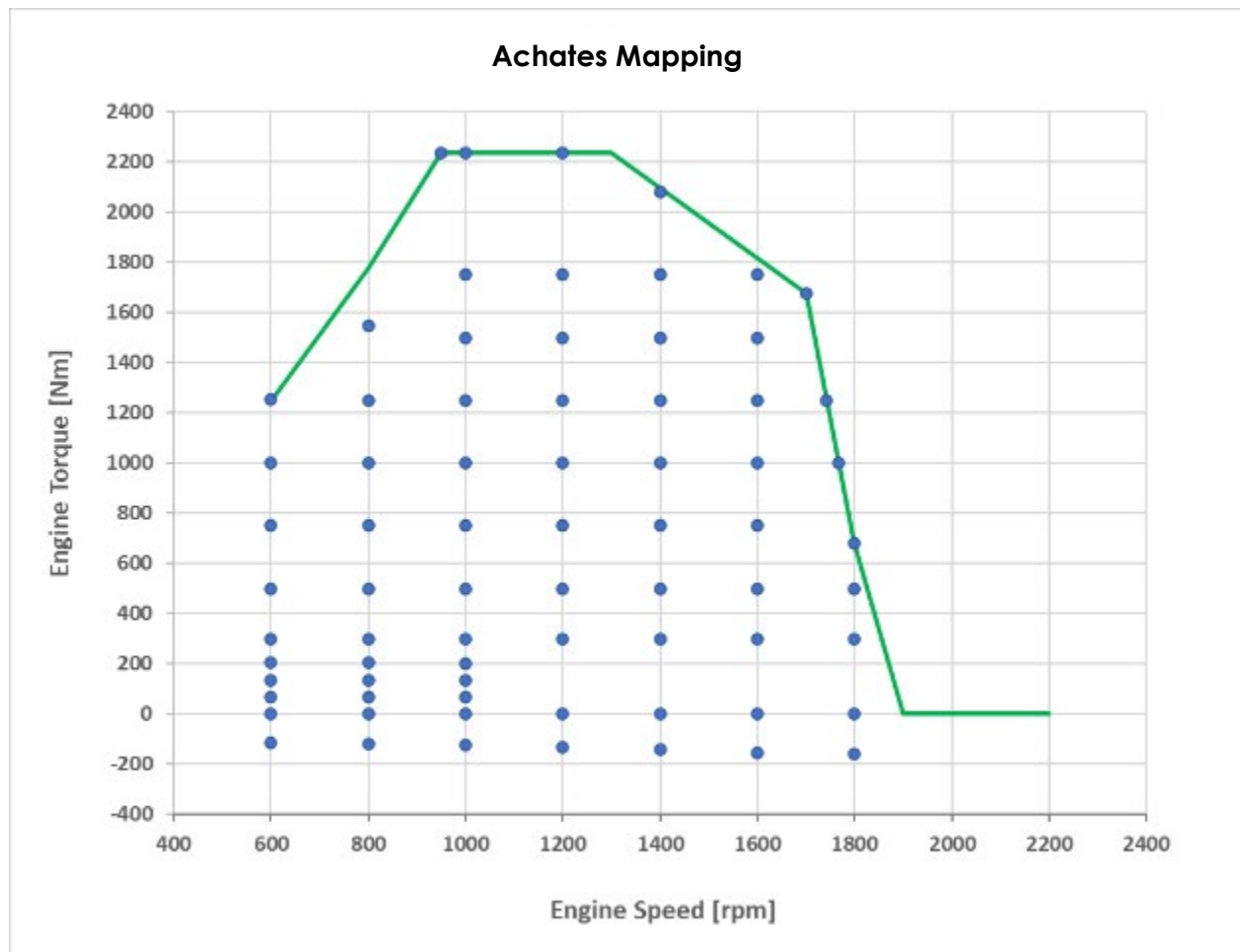


Figure 13: Engine Speed and Torque Data

The team also generated plots to illustrate engine performance for the HSS mode. Figure 14 and Figure 15 below show engine-out emissions of the brake specific NO_x and the CO concentrations, respectively, across speed (x-axis) and engine torque (y-axis). For both criteria emissions, the engine-out levels are low.

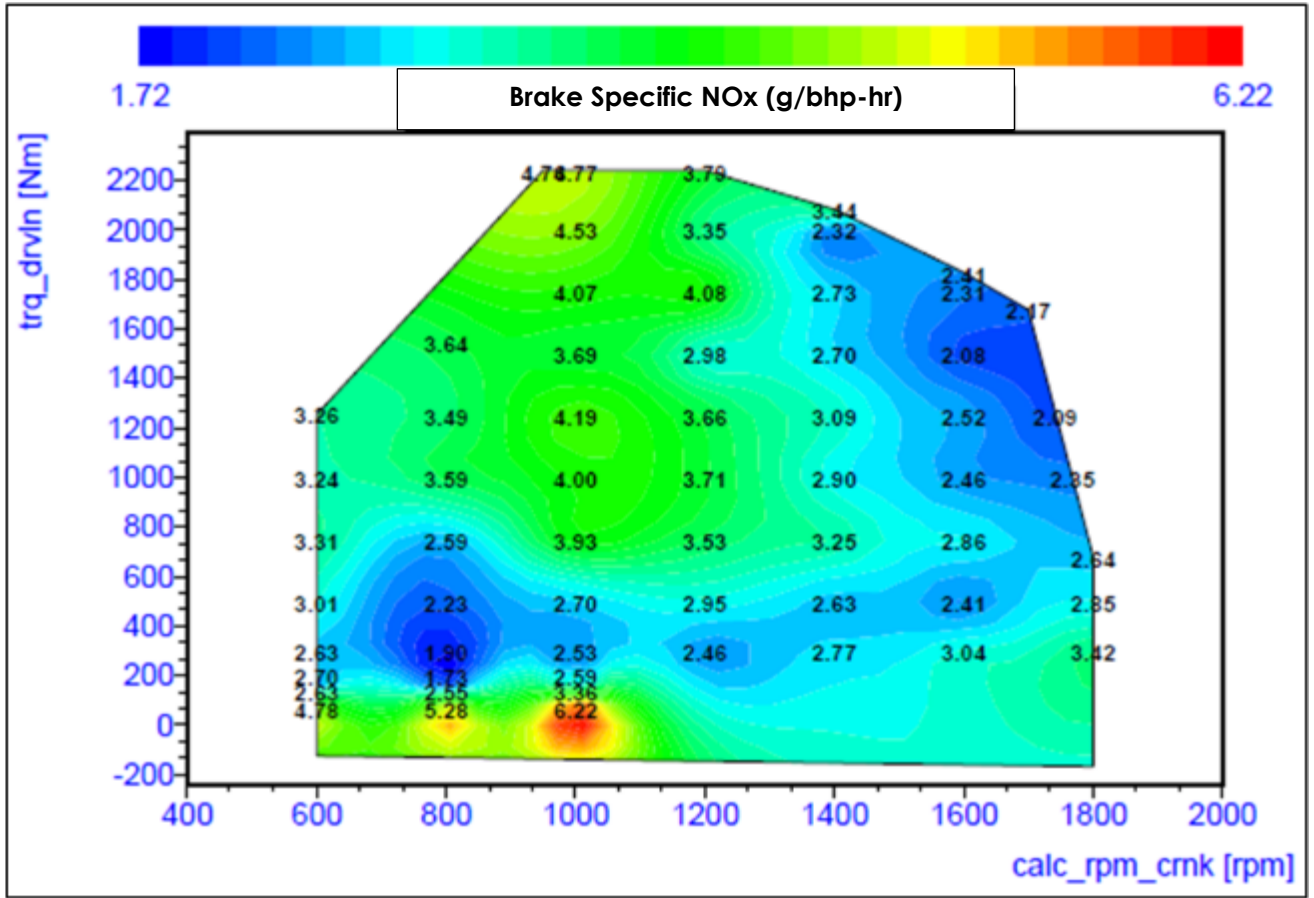


Figure 14: Engine-Out NO_x HSS Mode

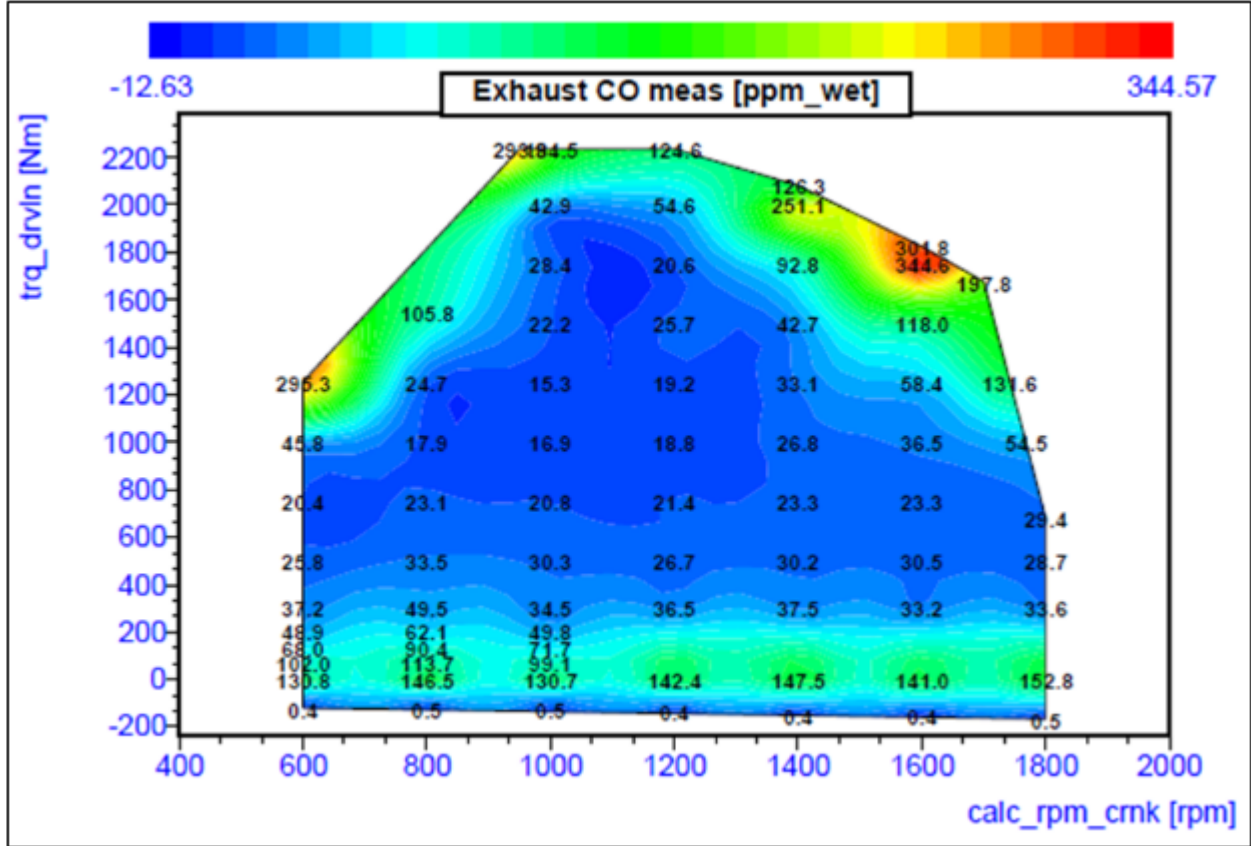


Figure 15: Carbon Monoxide Emissions, HSS Mode

With the ATS configured on the engine, the engine will meet all Omnibus tailpipe limits, as demonstrated during both dynamometer tests; however, additional field testing beyond the scope of this project is needed to prove the engine can meet all Omnibus limits during commercial operations.

Achates used AVL's 415 Smoke Meter equipment to determine the filter smoke number (FSN) and the soot concentration in the engine's exhaust, shown below in Figure 16. FSN is not a criteria emission, however, this data was included to show that the engine-out emissions results were promising—thought not definitive—at this stage before the aftertreatment system was attached and calibrated.

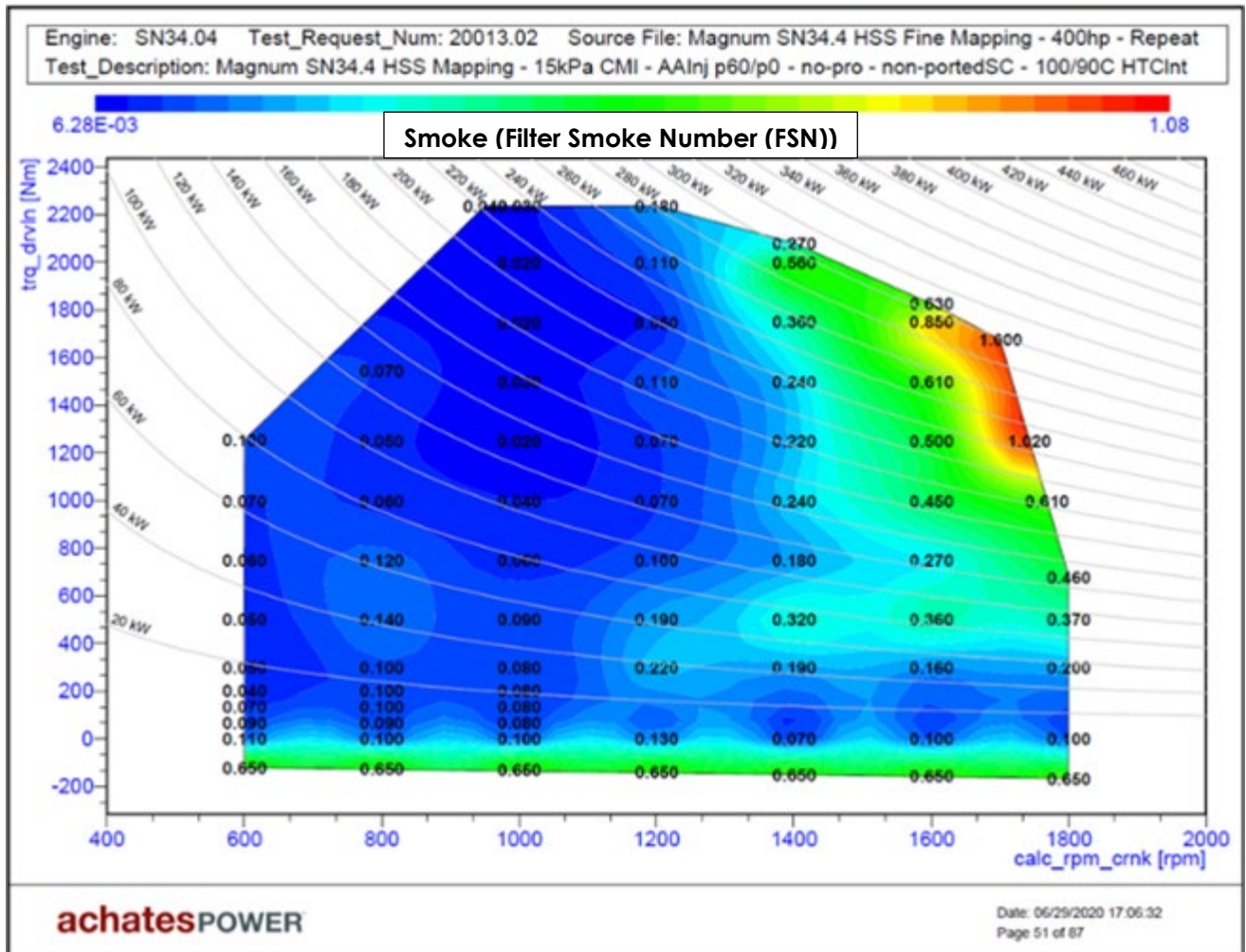


Figure 16: Engine Smoke Level HSS Mode

Several plots were generated to illustrate engine performance for the CLO mode, engine-out NO_x in Figure 17 and exhaust gas temperature in Figure 18. In these figures, the x-axis represents the engine speed in rpm and the y-axis represents the engine torque in Nm. The engine exhibits very low levels of engine-out NO_x during the CLO mode—this is important, because until the catalyst reaches an operative temperature of around 250° C, it will not effectively convert NO_x so much of the engine-out NO_x will exit the tailpipe.

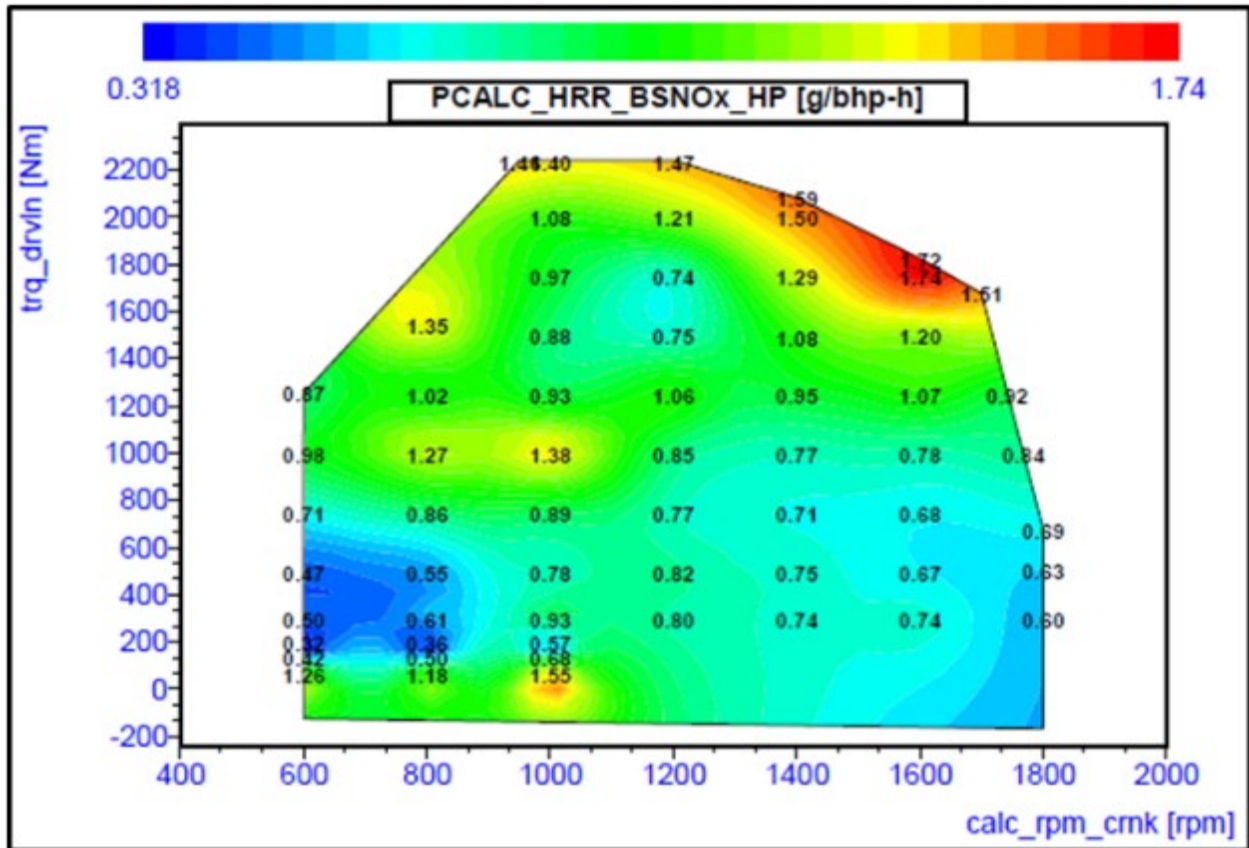


Figure 17: Engine-Out NO_x CLO Mode

Exhaust gas temperature, measured in °C, is a critical parameter for CLO mode because most NO_x emissions occur in the minutes after a cold start before the catalyst warms enough to operate efficiently. High gas temperature heats the catalyst quickly, reducing the warming time and NO_x emissions.

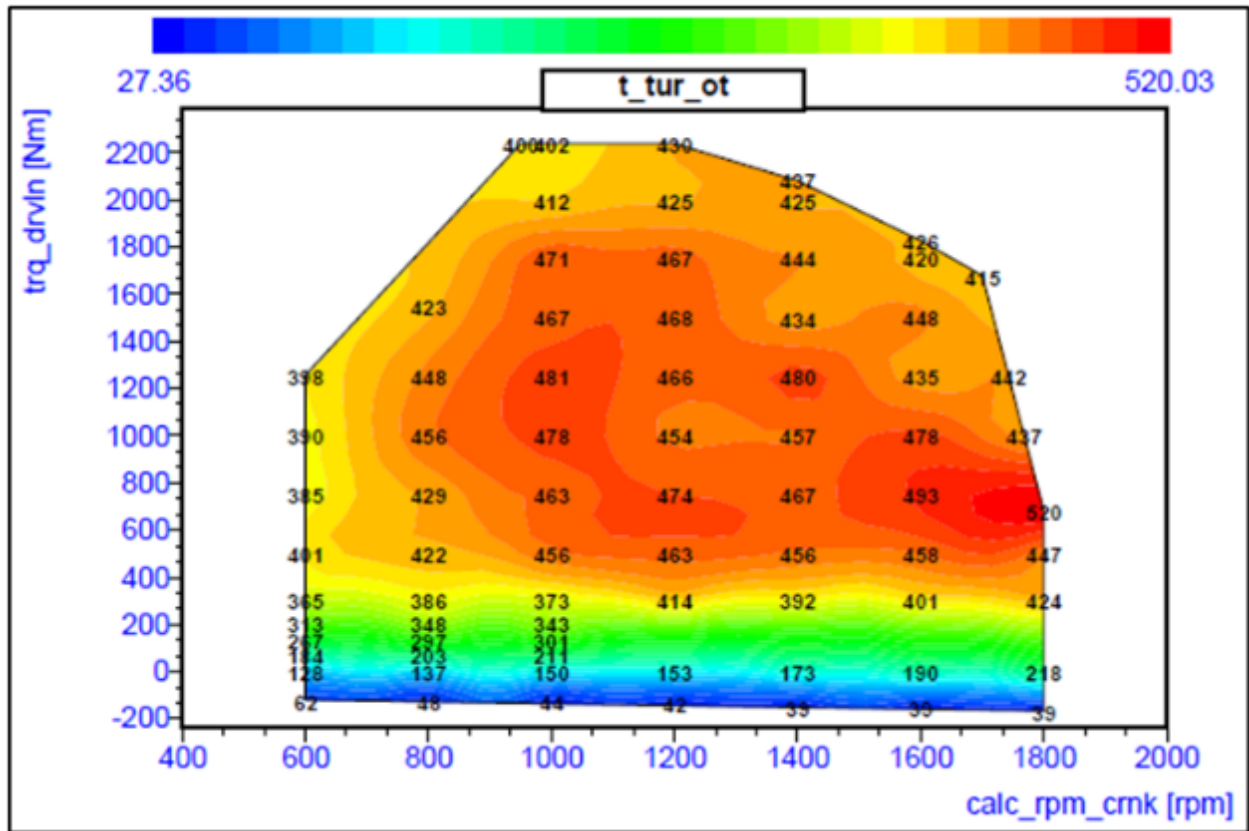


Figure 18: Exhaust Gas Temperature CLO Mode

Next, the assembled OPE was sent to the Aramco Services Co. laboratory for additional testing, calibration, and engine optimization. Initially, Aramco tests sought to reproduce the steady state performance that had been measured at Achates. The laboratory also verified the function of the ATS control before installing it in the test cell. After verification was complete, the ATS was installed on the OPE situated in the Aramco test cell, and an exhaust pipe was connected to the engine to simulate operation in a vehicle.

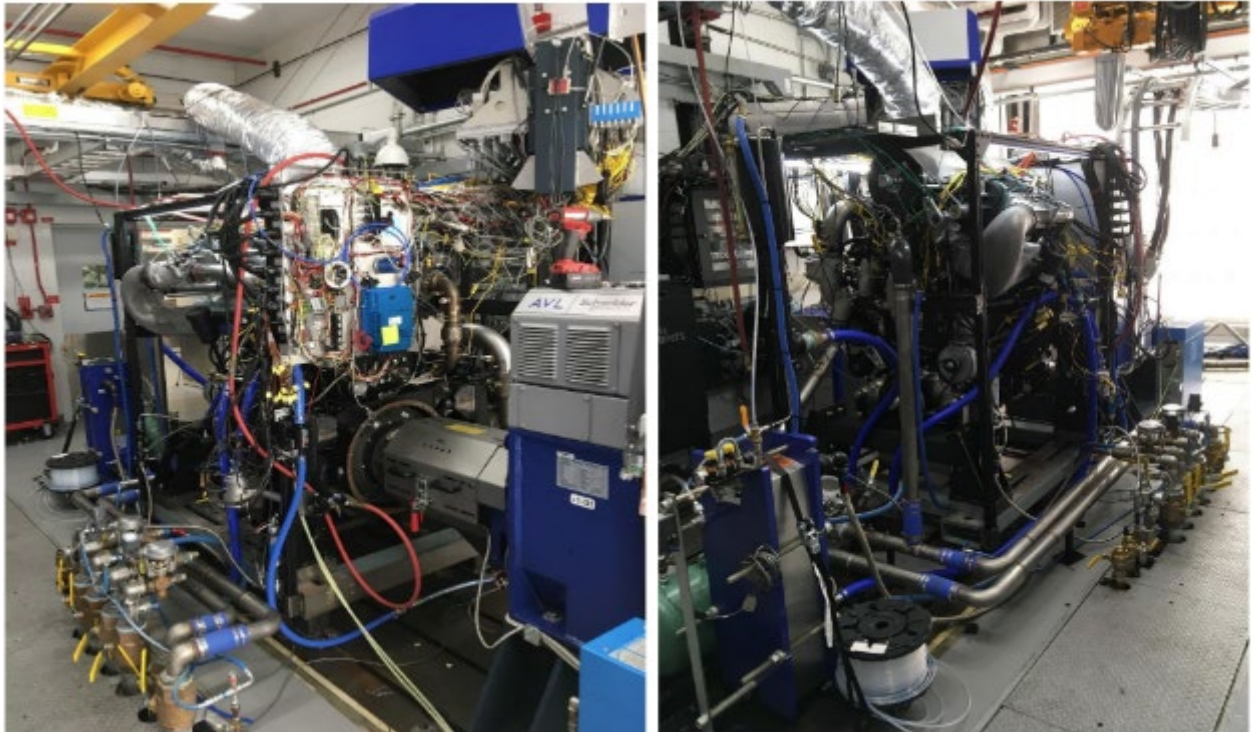


Figure 19: Engine Ready to Run in the Test Cell

Aramco's testing focused on transient engine development and testing of the ATS to demonstrate the tailpipe NO_x targets. Initial transient testing on the Federal Test Procedure (FTP) cycle showed that the OPE's ability to control NO_x emissions was better than expected. At the effective operating temperature of approximately 250°C, the OPE's SCR device was extremely effective at reducing NO_x to diatomic nitrogen and water. The OPE excelled at generating high exhaust enthalpy and low NO_x emissions during the CLO period, which are the two most important factors to meeting mixed FTP NO_x limits.

The results for the combined FTP—for cold start and hot start weightings—was 0.016 g/hp-hr NO_x. The cold FTP was at 0.067 g/hp-hr and the hot FTP at 0.008 g/hp-hr. Thus, the 0.02 g/hp-hr limit on the FTP cycle was met with some margin.

The graphs in Figure 20 below illustrate the variation between the expected performance and measured performance of Achates' OPE compared to other ultra-low NO_x engines previously developed by SWRI. Engine performance was based on exhaust temperature readings and NO_x emission levels after a cold start.

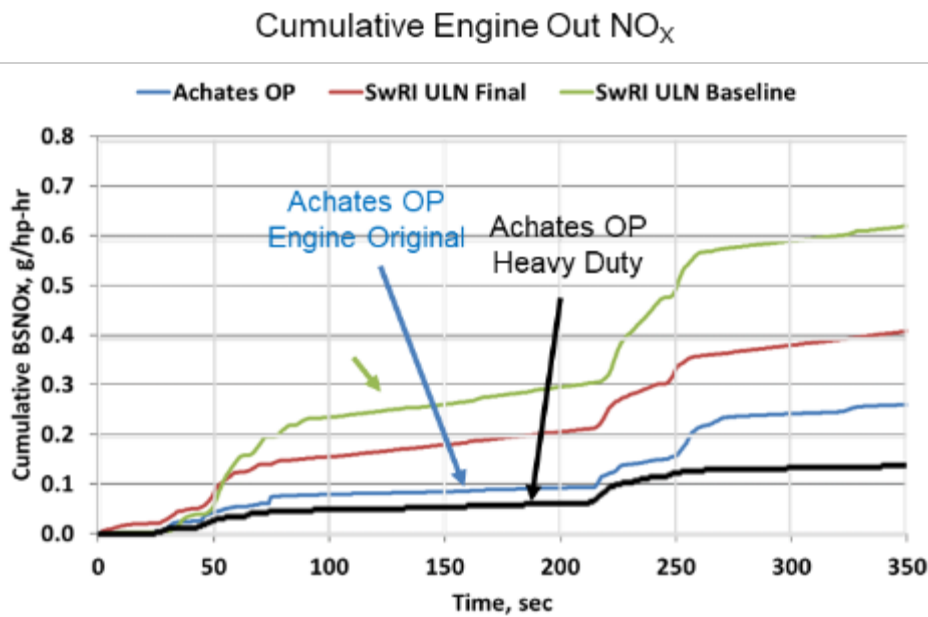
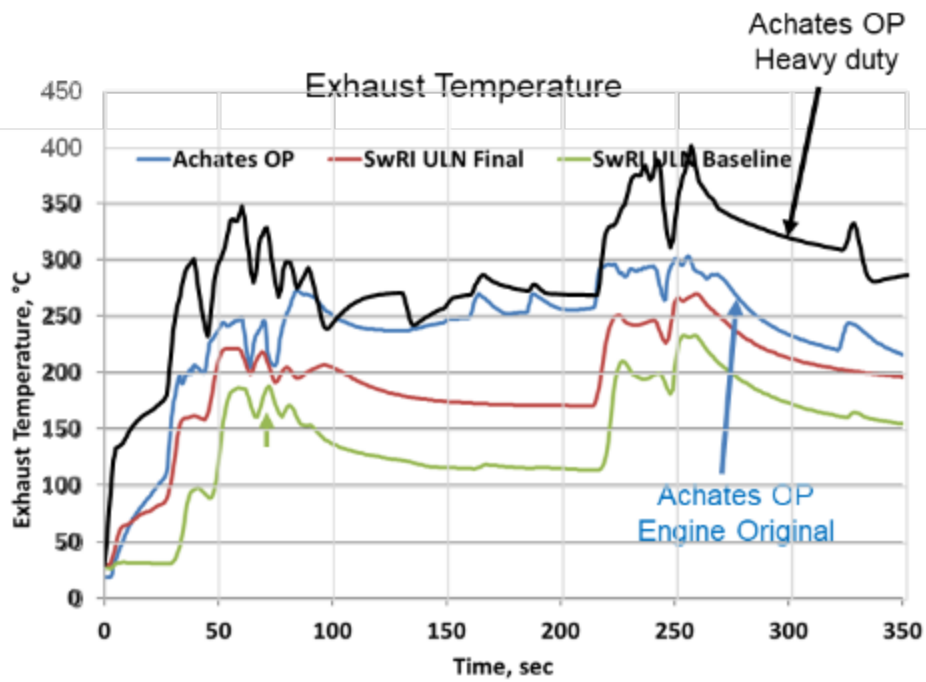


Figure 20: Exhaust Temperature and NO_x

SWRI's baseline engine was a Volvo HD diesel engine as it arrived from the factory; the results from their baseline engine testing are represented by a green line in each graph. SWRI then modified that baseline engine to reduce tailpipe NO_x emissions; the results

from this final engine testing are represented by the red line in each graph. Data for these red and green lines were taken from an SWRI research paper¹.

Achates estimated the performance of their 10.6-L engine based on tests conducted with one of their 5-L engines; the results from this estimation are represented by the blue line in each graph. The black line in each graph represents the actual measured performance of the OPE once it was built and tested. As shown in Figure 20, the Achates OPE for HD trucks demonstrated the highest exhaust temperature and the lowest NO_x emissions of all four.

After seeing this superior performance, the team decided to simplify the ATS by eliminating the close-couple SCR system. This action removed not only the close-couple SCR and ammonia catalyst, but also the complex and expensive gaseous ammonia injection system and one of the NO_x sensors and temperature sensors. This change also eliminated the need for frequent desulfation, which requires high temperatures and ages the system. In addition to enhancing reliability and durability, this simplification will reduce base and warranty production costs. Figure 21 below shows the original ATS layout with the close-couple SCR, followed by the layout of the simplified ATS shown in Figure 22. The ammonia oxidation catalyst (AMOX) is the same as the ammonia slip catalyst (ASC), and the selective catalyst reduction filter (SCRF) is the same as the selective catalyst reduction on filter (SCRoF) in the figures pictured below. The light-off selective catalytic reduction (LO-SCR) is pictured in Figure 21 in the close-coupled unit.

¹ Sharp, C., Henry, C., Yoon, S., Carter, M., and Webb, C. C., "Achieving Ultra Low NOX Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches," SAE Int. J. Engines, vol. 10, no. 4, pp. 1722-1735, Mar. 2017, doi: <https://doi.org/10.4271/2017-01-0956>.

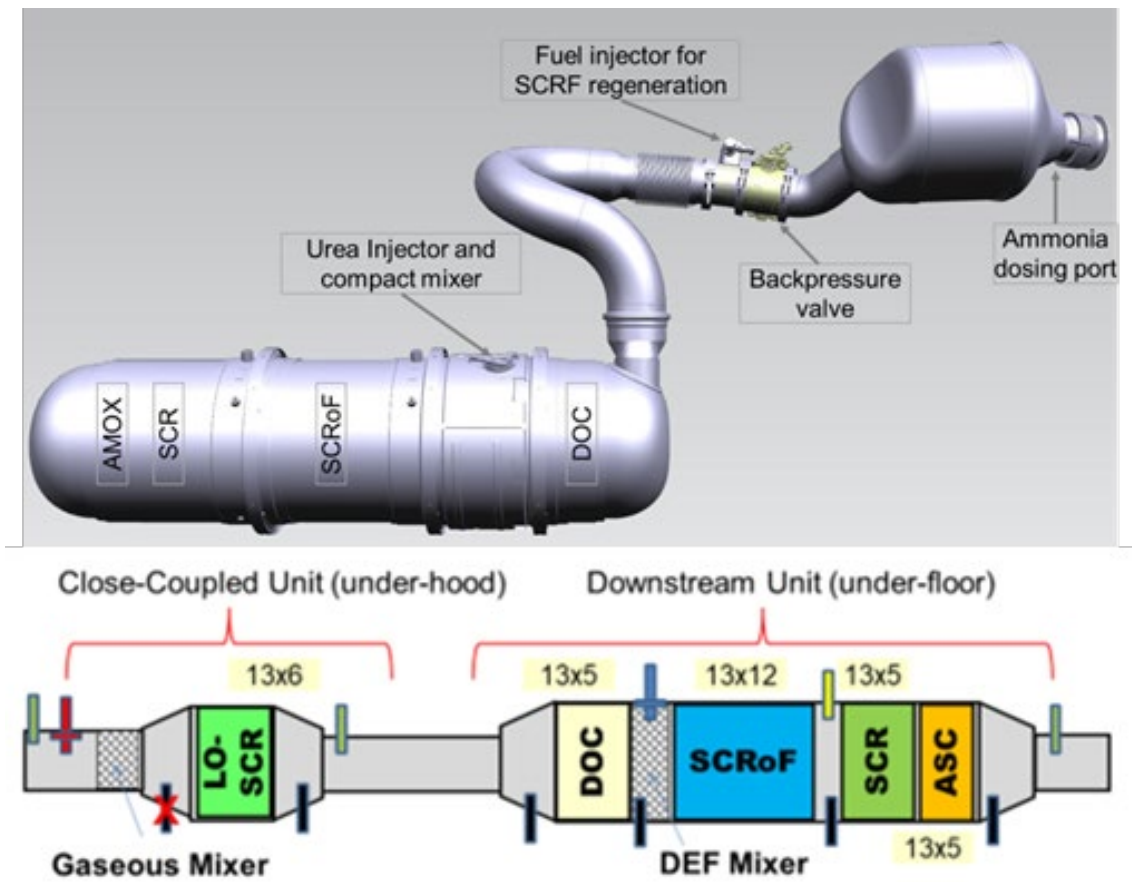


Figure 21: The ATS Layout Before Simplification



Downstream Unit (under-floor)

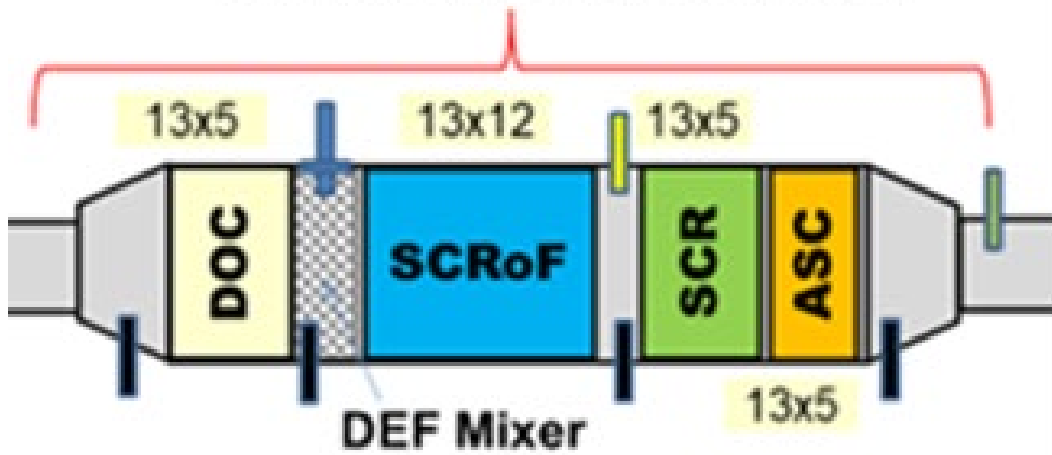


Figure 22: Layout of the Simplified ATS

Vehicle Activities

Vehicle Build



Figure 23: OPE Demonstration Truck

Peterbilt built a dedicated HD truck, the Peterbilt 579, for the OPE demonstration. It was used for the project's vehicle development activities as well as the fleet demonstration.

Peterbilt started the engine installation in a mock-up chassis to work out all the details of the installation. This allowed an initial fitment check, fabrication of components, and modification of the chassis, which minimized the amount of work necessary once the OPE was installed. The main tasks in the mock-up chassis consisted of: engine placement and clearance checks between engine and frame; fabrication of piping for the fluid systems; mounting off-engine hardware—such as pumps, an electronic control unit, and filters; fitment check of the new cooling module and its shrouding; and the modification of the hood assembly. Engine-to-transmission mating was performed after installation.

Peterbilt installed the coolant pump for the low and high temperature coolant systems. The engine hood was installed on the mockup and small clearances issues were corrected. The cooling system module was fitted along with chassis-mounted pumps. Then, the final vehicle was prepared for the new engine installation.

Vehicle Testing

Vehicle development, testing, and validation were performed on open roads both around Peterbilt's facility in the Denton, Texas area and in the vicinity of the Achates facility in San Diego.

The first round of testing performed in Texas by the Peterbilt team, with the support of Achates, was focused on vehicle functionality and sub-system communication and integration. The testing started in February 2020 with the first run of the truck with the OPE installed. Shortly after that, the activities at Peterbilt were paused because of COVID-19 and resumed only in October 2020. The initial run focused on the transmission integration without the aftertreatment installed and a preliminary engine calibration. Testing was performed to verify the electrical and plumbing configuration for the ATS.

In April 2021, a new OPE, with the identical configuration to the engine tested at Aramco, was retrofitted into the Peterbilt truck. The pipe from the turbo charger to the ATS was insulated to mimic the setup used in the Aramco test cell and to minimize heat losses.

Next, the team drove the vehicle on the roads without a trailer to check the general functionality. They also created a new hood clearance to improve the vehicle's appearance. Lastly, the team installed a complete exhaust system and performed function checks on all actuators and sensors.



Figure 24: Early Test Drive

The image above shows the truck leaving the Peterbilt facility for one of the first test drives.

Eaton Cummins Automated Transmission Technologies (Eaton-Cummins) supplied the truck's transmission, which was made expressly for the OPE demonstration. However, the Eaton-Cummins team calibrated the truck's new transmission to its original engine, an MX 11 engine, not to the OPE even though the original engine was removed and replaced by the OPE a few steps later. The transmission shifts points were never optimized for the OPE because Eaton calibration engineers were not able to finish the calibration in person due to COVID-related travel restrictions. Although the Eaton-Cummins team verified that the various signals necessary for good transmission function were present, the fact remained that the transmission was never calibrated to the OPE, ultimately resulting in problems later, which are detailed in the On-Road Fleet Testing and PEMS Analysis sections later of this report.

At Peterbilt, the vehicle validation continued with trailer towing testing. Then, Peterbilt verified basic functionality of the ATS, and the vehicle was shipped to San Diego for further development.

The second round of testing, performed at Achates in San Diego starting in July 2021, looked at all aspects of vehicle function including engine, clutch transmission, overall performance, and verification of electrical, cooling, and lubrication systems.

A few minor problems were found. The exhaust crankshaft thrust bearing showed damage caused by the pressure from the transmission clutch on the crankshaft, which was only observable after the OPE was installed because the clutch cannot be tested on the engine dynamometer. The clutch problem was visible when the truck was loaded with a trailer and the clutch slipped and overheated. The team resolved the issue after removing the existing clutch and installing a new one.

Several transmission control abnormalities remained, which the team resolved by changing the treatment of messages from the transmission communicated via the controller area network.

The engine was initially tested to make sure everything was installed properly. Next, the data acquisition system was installed, the auxiliary power unit (APU) was repaired, controllers were reprogrammed by the dealership, and some initial drives were performed with the truck unloaded. The aftertreatment functionality was verified and a diesel particulate filter (DPF) regeneration was completed.

The emissions control was validated by looking at the tailpipe NO_x sensor signal and confirming complete SCR conversion. The tailpipe levels remained below 10 ppm NO_x throughout the test drives when the SCR was within the optimal temperature operating range.

Noise abatement was installed on the cab and hood that effectively reduced the noise in the cab and outside the vehicle.

Here is the list of additional items that Achates addressed to improve the vehicle integration:

- Corrected hose clamps in coolant and fuel system on chassis side, or in coolant modules;
- Secured wiring;
- Moved soft lines touching exhaust or EGR components;
- Moved electrical control unit/sensor wiring harness touching exhaust or EGR components;
- Secured fuel pump;
- Resolved clutch overheating issues;
- Resolved wiring harness issues;
- Installed missing capacitor in the ECM;

- Fixed adaptive cruise control and collision mitigation system interference with radar sensor;
- Performed warranty work—HVAC center vents did not direct the flow;
- Enabled the APU as it was left nonoperational after installed at Peterbilt;
- Addressed cruise control related activities;
- Fixed contact vehicle battery draw as ATS system and certain sensors were wired directly to battery so installed switch to power those down once ignition is off;
- Set up the remote monitoring system;
- Performed the truck pre-delivery inspection at local Peterbilt dealership; and
- Installed under-hood fire suppression system.

During this period, a Peterbilt specialist set up the correct transmission calibration for a MX11 Peterbilt engine operating range, although not for the OPE. The team applied vehicle decals and performed several drives around San Diego. On November 4, 2021, the OPE truck was delivered to Walmart to start the vehicle fleet demonstration.

The images on the following pages show the completed OPE truck during a test drive with a trailer attached and loaded to a gross vehicle weight of 78,000 lbs.





On-Road Fleet Testing

Introduction

In November 2021, Achates delivered a Peterbilt Class 8 truck custom-fitted with an OPE to Walmart's Porterville DC, initiating the start of the fleet demonstration. Once delivered, the truck was put into revenue service, transporting goods from Walmart's DC to stores within the San Joaquin Valley. After approximately eight weeks of testing in Porterville, the OPE truck was relocated to serve DCs within the South Coast Air Basin, operating out of Walmart's Apple Valley DC and Fontana DC.

The project team involved in the fleet testing included CALSTART, Achates, Peterbilt, and Walmart. In-use data was collected on the OPE's performance and emissions through vehicle telematics and other diagnostic instruments installed on the truck. The team also collected data on a baseline Class 8 truck with a conventional internal combustion engine. To provide a direct comparison, this conventional truck possessed specifications equivalent to the OPE truck and was operated on the same or similar routes.

The plan was to test the OPE's performance in Walmart fleet operations for a period of at least three months. Achates engineers instructed Walmart drivers in proper maintenance and operation of the vehicle before the demonstration began. The engineers then visited several times once the demonstration was underway to verify that the vehicle was in good working condition. Despite these measures, the OPE frequently malfunctioned, delaying operations significantly. There were several different causes for these malfunctions, including electrical NOx sensor and EGR mass flow sensor failures, engine motor signal issues, high pressure fuel pump failures, and air system component failures. Additionally, the OPE truck had constant battery drain from the datalogging device installed on the vehicle. Eventually, Walmart had to tow the vehicle back to Achates for maintenance and repairs. Achates was unable to resolve the issues causing repeated engine failures, prompting Walmart, CALSTART, and Achates to conclude the OPE demonstration in May 2022. At the end of the fleet testing, the OPE truck had operated across a total of 32 days in revenue service. The conventional truck was tested for a total of seven days across the different Walmart DCs.



Figure 25: OPE Truck Deployed at Walmart

Methodology

With support from Achates, CALSTART used onboard vehicle telematics systems to collect vehicle performance data and assess whether the OPE demonstration technology was able to meet one of Walmart's regional long-haul routes. Onboard telematics were installed on the baseline vehicle, a Freightliner Cascadia DD15 truck, to compare the performance of the technologies. Achates had no access to Walmart's systems monitoring truck performance during the on-road fleet testing and relied on the data collected by Peterbilt loggers installed on the truck. The team later installed a more comprehensive data recording device on the OPE truck to monitor the engine and ATS statuses.

The onboard data loggers recorded trip start and end times, total time spent driving, volume of fuel consumed per day, vehicle fuel economy, and several other parameters. To protect driver anonymity and information confidentiality, data was redacted as the project team saw fit. Walmart provided CALSTART with maintenance and repair data for both the demonstration and baseline vehicles to assess the existing maintenance and repair frequencies, the time out of service for each truck, and the cost of repair if available. Table 6 shows some of the key vehicle performance data parameters collected during the on-road fleet testing. For the complete list of data parameters collected during on-road fleet testing, see the Appendix.

Table 6: Key Vehicle Performance Data Collection Parameters

Metric or Parameter	Unit	Source
Vehicle ID	n/a	Peterbilt Data Logger
Date / Time Trip Beginning	dd/mm/yyyy hh:mm:ss	Peterbilt Data Logger
Date / Time Trip End	dd/mm/yyyy hh:mm:ss	Peterbilt Data Logger
Total Key On Time	hh:mm:ss	Peterbilt Data Logger
Total Time Idle	hh:mm:ss	Peterbilt Data Logger
Total Time Driving	hh:mm:ss	Peterbilt Data Logger
GPS Altitude Min	m	Peterbilt Data Logger
GPS Altitude Max	m	Peterbilt Data Logger
GPS Average Speed	mph	Peterbilt Data Logger

Metric or Parameter	Unit	Source
Average Engine Fuel Rate or Average Fuel Economy	(l/100 km or l/km or offroad l/hr)	Peterbilt Data Logger
Total Fuel Used	gal	Peterbilt Data Logger
Payload	lbs	Walmart

Fleet testing and data collection for the OPE demonstration truck began in November 2021 and concluded in May 2022. For the baseline truck, data collection began in November 2021 and concluded in February 2022. CALSTART worked with Achates and Peterbilt to ensure specific data metrics and parameters were collected and reported during the demonstration period. The specifications of the conventional truck deployed are listed below in Table 7.

Table 7: Class 8 Truck Specifications

Specification	OPE Truck	Baseline Truck
Fuel	Diesel	Diesel
Model Year	2019	2021
Truck OEM	Peterbilt	Freightliner
Engine OEM	Achates	Freightliner
Model Name	579	Cascadia DD15
Data Collection Period	11/29/2021 – 3/2/2022	12/14/2021 – 2/28/2022

Route

Walmart's Porterville DC, located in the San Joaquin Valley, serves the northern section of Southern California, including Oxnard, Visalia, Paso Robles, and Los Angeles. The OPE truck was demonstrated on a 176-mile route from Porterville to Santa Maria, stopping at different Walmart stores along the way. The truck remained in the San Joaquin Valley for approximately eight weeks until late January 2022 when it was moved from Porterville to Walmart's Apple Valley DC, which serves the South Coast Air Basin. The Apple Valley center, located just outside the SCAQMD region, serves as an aggregation point for shipments traveling inbound from railyards in San Bernardino, Los Angeles, and Long Beach. The fleet began operating the OPE truck at the Apple Valley DC in early February on Walmart's La Quinta route, a 230-mile route with four hours and thirty minutes of drive time. However, while operating in Apple Valley, the truck's

supercharger failed and its ATS was damaged; Achates suspected that the truck's engine calibration and DPF regeneration process were not compatible with the high-altitude operating conditions at Apple Valley's as they had never been validated under those conditions. As a result, Achates and Walmart agreed to relocate the truck demonstration to Walmart's Fontana distribution center, at a lower altitude. The switch delayed the demonstration for three weeks while Walmart reorganized the Fontana team. The remainder of the demonstration lasted four weeks in Fontana and concluded in May 2022.

Though the data collected from the demonstration in Apple Valley was not useful in analyzing the performance of the OPE, Achates gained valuable insight from the operational experience and would use their findings to recalibrate the OPE after the demonstration concluded.

The demonstration and baseline trucks traveled on the routes pictured on the maps below under a variety of operating conditions, including travel with loaded and unloaded trailers, with a stop-and-go cycle and with steady-state cruising.



Figure 26: Road Test Routes, Porterville

The Porterville road test routes are listed below marked on the map in Figure 26.

- Santa Maria to Porterville used Highway 101, through Paso Robles.
- Porterville to Paso Robles used Highway 41.
- Porterville to Shafter used Highway 65.
- Shafter to Santa Maria used highways 43 to 119 to 33 to 166.

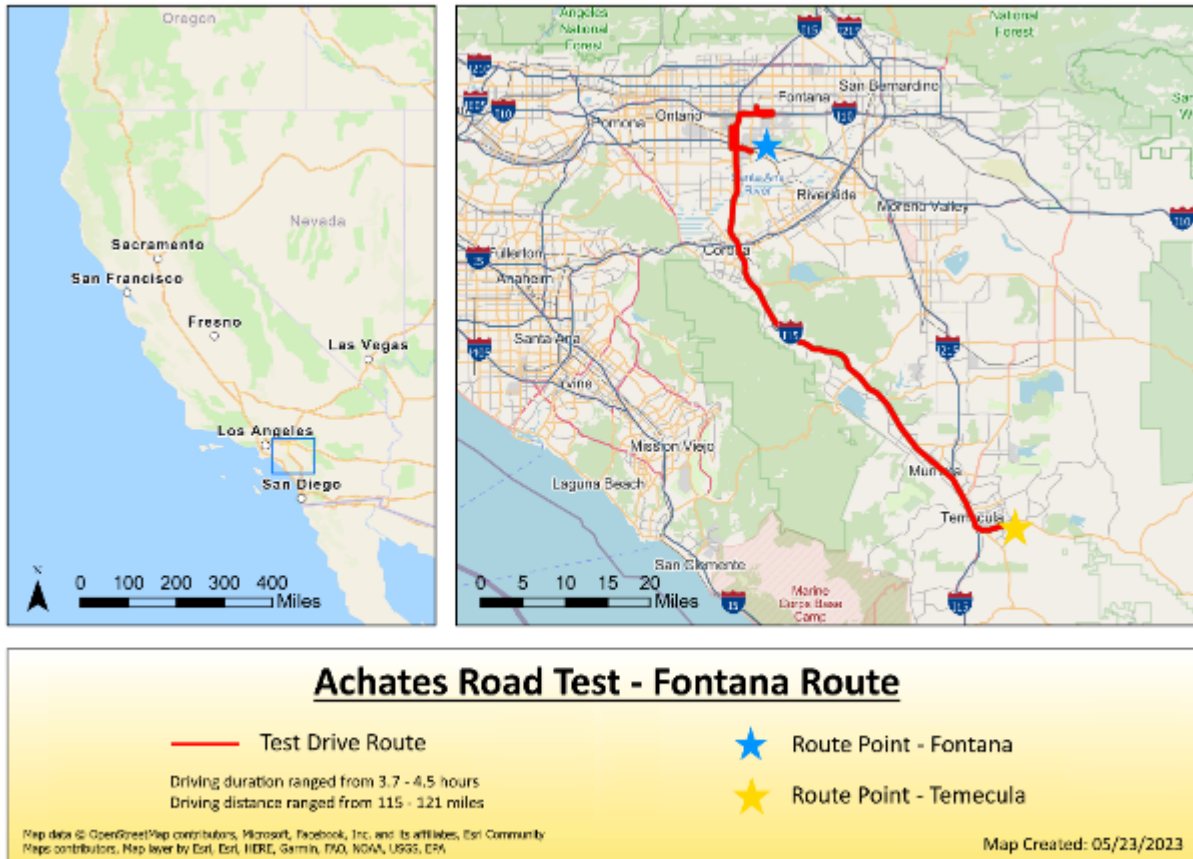


Figure 27: Road Test Routes, Fontana

The Fontana road test route is listed below marked on the map in Figure 27.

- Temecula to Fontana used Highway I-15.

Performance Analysis

Duty Cycle and Performance

During the data collection period, the fleet operated the demonstration OPE truck about two to three days per week. Operations were interrupted frequently for maintenance and repair to various truck parts, putting the truck out of service and preventing data collection. Table 8 below shows both the OPE and baseline trucks' key performance metrics recorded during the demonstration.

Table 8: OPE vs. Baseline Truck Performance Metrics

Performance Metric	OPE Truck	Baseline Truck
Total Days Operated	32	7
Average Distance Driven per Day (mi)	320	268
Maximum Distance Driven per Day (mi)	390	366
Average Daily Fuel Consumption (gal)	41	39
Average GCVW (lb)	66,703	65,537
Average Fuel Economy (mpg)	7.7	6.9
Maximum Fuel Economy (mpg)	10.8	7.7

When the OPE truck was operational, it performed similar duty cycle to the fleet's two baseline vehicles tested at the Porterville and Fontana sites. On average, the OPE truck traveled 320 miles per day and more than 7,000 miles total during the three-month demonstration period. In addition, the OPE truck's average fuel economy was 10% higher than that of the baseline truck.

Achates was unable to collaborate with Peterbilt's transmission manufacturer due to shutdowns caused by the COVID-19 pandemic, so they could not calibrate the OPE truck's transmission to shift for their engine as efficiently as possible to obtain optimal fuel mileage. Additionally, the pedal command rate limiter and vehicle speed limiter, which help achieve better fuel mileage, were inoperable on the OPE truck. Conversations with the fleet's drivers revealed that manually controlling the shifting in the OPE truck to maintain the correct operational speed contributed to greater fuel mileage. The drivers also noted the OPE truck ran very smoothly traveling about 60 mph.

Though able to perform the baseline's duty cycle, the OPE truck experienced repeated auxiliary engine system failures that put the truck out of service. Intermittent electrical issues impacted the truck's injector pumps which stalled the engine, resulting in a loss of power steering and braking. Supercharger and DPF failures interrupted operations as well. Walmart towed the OPE truck back to Achates four times during the demonstration to undergo maintenance and repairs, eventually leading to a premature end to the demonstration.

New engine technology, especially a version of an internal combustion engine, takes years to develop and perfect—considerably more time than the scope of this project allowed. Problems are expected at such an early stage as the OPE HD truck and provide important feedback that can accelerate the path to the commercial market. There are many opportunities for Achates to improve the performance of a second-generation OPE in the future, including optimizing the truck's transmission calibration, cruise control, engine braking, noise control, and DPF active regeneration. Achates has already begun the process as detailed in the Recalibration section later in the report.

PEMS Analysis

Introduction

CALSTART partnered with UCR's CE-CERT to calculate and validate the emissions savings from operating the OPE demonstration vehicle at Walmart's Distribution Center in Porterville and Fontana. CE-CERT conducted gaseous and PM Portable Emissions Measurement System (PEMS) testing utilizing AVL's state-of-the-art, ultra-low NO_x PEMS prototype unit. CE-CERT captured the actual in-use emissions by installing the lab-grade equipment on the baseline diesel and OPE truck. These vehicles then operated their normal duty cycles.

The first round of PEMS testing conducted in Porterville took place in December 2021. The baseline truck was tested for one day, and the OPE truck was tested for three consecutive days. The rest of the on-road fleet testing as well as the PEMS testing was conducted in Fontana, where conditions were similar to those in Porterville. The second round of testing conducted in Fontana took place in May 2022, five months after the first round. In Fontana, the baseline and OPE trucks were both tested for two days. In addition, CE-CERT performed an EPA 3-Bin analysis on the OPE truck's NO_x emissions for both rounds of PEMS tests to determine if the OPE met the most stringent EPA NO_x limit

proposed for 2031 and beyond. NO_x emissions for the baseline truck were analyzed as well for comparison.

PEMS testing focused on CO₂, NO_x, and PM emissions. The specifications of the vehicles tested are shown in Table 9 below. Achatas did not choose the model of the OPE truck to match the technical specifications of the baseline truck directly, as evidenced by the variation in the displacement for each truck. Instead, the focus of their vehicle build was to determine if the OPE truck could meet Walmart's duty cycle needs.

Table 9: PEMS Test Vehicle Specifications

Specification	OPE Truck	Porterville Baseline Truck	Fontana Baseline Truck
Truck OEM (Count)	Peterbilt (1)	Freightliner (1)	Freightliner (1)
Truck Model	579	Cascadia DD15	Cascadia DD15
Engine OEM	Achatas	Daimler Trucks North America	Detroit
Engine Model	Achatas Prototype	PT126064S T	DD15TCO
Engine Model Year	2020	2021	2021
Displacement (L)	10.6	14.8	14.8
Truck Mileage (mi)	32,665	1,989	19,901

Methodology

PEMS testing is normally a two- to three-day process for one unit. PEMS equipment takes about half- to a full day to install, a full day to test, and half- to a full day to uninstall. To ensure the most comparable results, all PEMS testing occurred on units operating similar in-service duty cycles. The equipment was installed on the baseline and demonstration truck at each site. The low NO_x PEMS system recorded GPS data—including route details, vehicle speed, altitude, and acceleration—on a second-by-second basis from the truck's engine control module via an on-board diagnostic connection. In addition, the PEMS analyzers were enclosed inside a temperature-controlled space to ensure stable conditions and high accuracy in changing ambient conditions. CE-CERT processed and analyzed the data collected from the vehicles to compare the

emissions and fuel consumption benefits of the OPE truck to a traditional, diesel-powered truck.

For the first day of PEMS testing conducted at the Porterville site, CE-CERT equipped the OPE truck with a standard PEMS unit and the low NO_x PEMS unit. During the test, the low NO_x PEMS unit lost a portion of the data collected during the OPE truck's cold start cycle. CE-CERT used the data from the standard PEMS unit to calculate the cold start data for the low NO_x PEMS unit. CE-CERT derived results on valid tests exclusively. Based on EPA's 3BIN analysis methodology, data where instantaneous ambient air temperatures were below -7° C was excluded from the analysis.

PEMS Results

The results from the first round of PEMS testing conducted in Porterville showed compliance with the CARB OMNIBUS in-use NO_x emission limit by at least 30%. On average, the NO_x emissions from the OPE truck showed an 8% reduction from the baseline truck on a grams per brake horsepower-hour (g/bhp-hr) basis.

Table 10: Porterville PEMS Test Results

Vehicle and Test Day	NO _x (g)	NO _x (g/bhp-hr)	NO _x (g/mile)	NO _x (g/hr)
Baseline (12/14/2021)	26.779	0.030	0.071	2.846
OPE (12/15/2021)	12.791	0.031	0.075	1.288
OPE (12/16/2021)	10.791	0.021	0.049	1.692
OPE (12/17/2021)	8.673	0.031	0.060	1.239

CE-CERT also performed an EPA 3-Bin analysis on the OPE and baseline trucks' NO_x emissions; the results are shown in Table 11 below.

Table 11: Porterville EPA Bin Analysis Results

Bin	Baseline (Day 1)	OPE (Day 1)	OPE (Day 2)	OPE (Day 3)
Bin 1 (g/hr)	3.26	0.25	0.05	0.15
Bin 2 (g/bhp-hr)	0.155	0.048	0.039	0.039
Bin 3(g/bhp-hr)	0.013	0.024	0.015	0.022

Bin 1 represents the NO_x emissions recorded while the trucks idled. Bin 2 represents the NO_x emissions recorded during the truck's low-load cycle, and Bin 3 represents the NO_x emissions recorded during the truck's medium/high load cycle.

The NO_x limit for the OPE truck—as proposed by the EPA for 2031—was 0.02 g/bhp-hr. The three BIN NO_x limits for the baseline truck, as proposed for the CARB Omnibus 2030+ regulation, were 7.5 g/hr (BIN 1), 0.075 g/bhp-hr (BIN 2), and 0.030 g/bhp-hr (BIN 3). The baseline vehicle met the CARB Omnibus NO_x limits for BIN 1 and BIN 3, and even met the 0.02 g/bhp-hr limit proposed by the EPA for BIN 2 and BIN 3, indicating that the that the Porterville Freightliner truck engine and ATS was also efficient at controlling NO_x emissions.

Nevertheless, NO_x emissions for the OPE truck were 95% and 73% lower than those of the baseline truck for Bins 1 and 2, respectively. Though NO_x emissions for the OPE truck showed an increase of 56% compared to the base truck for Bin 3, the Porterville PEMS results demonstrated that the OPE truck met the most stringent EPA-proposed limit for 2031 with a 50+% margin with development-aged catalysts.

The second round of PEMS testing was conducted after the OPE and baseline trucks were moved to Walmart's Fontana distribution center in April 2022. Contrary to expectations, however, in this second round of PEMS tests, the OPE truck demonstrated significantly higher NO_x levels than in the first round. The results from the PEMS tests and EPA 3-Bin analysis are shown in Table 12 and Table 13 below.

Table 12: Fontana PEMS Test Results

Vehicle and Test Day	NO _x (g)	NO _x (g/bhp-hr)	NO _x (g/mile)	NO _x (g/hr)
OPE (04/16/2022)	82.224	0.257	0.702	22.403
OPE (04/19/2022)	85.374	0.237	0.734	20.556
Baseline (04/20/2022)	15.386	0.038	0.127	3.821
Baseline (04/21/2022)	16.309	0.041	0.142	3.596

Table 13: Fontana EPA 3-Bin Analysis Results

Bin	OPE (Day 1)	OPE (Day 2)	Baseline (Day 1)	Baseline (Day 2)
Bin 1 (g/hr)	3.24	1.51	1.38	0.38
Bin 2 (g/bhp-hr)	0.410	0.289	0.149	0.155
Bin 3 (g/bhp-hr)	0.257	0.230	0.025	0.031

The results from the second round of testing in Fontana revealed that the NO_x emissions for the OPE truck were 525% higher compared to the baseline vehicle on a g/bhp-hr basis. The OPE truck's NO_x emissions were on average 170%, 130%, and 770% higher than the baseline truck's for Bins 1, 2, and 3 respectively.

The variation in BIN 1 emissions for the baseline truck could potentially be attributed to the temperature of the catalyst; if in-use results were captured when the catalyst was warm—perhaps from hotter climates or from the engine operating at full load—the tailpipe NO_x would be lower than if the catalyst was cooler.

Achates Recalibration

After CE-CERT concluded their testing, Achates investigated the potential root causes for the higher level of NO_x emissions from the Fontana PEMS test, including engine hardware issues, ATS hardware issues, and steady state drive cycle differences. Achates determined that the calibration of the ATS was the root cause of the high NO_x emission levels. The higher average load and more aggressive pedal operation in Fontana shifted operation to higher fuel flow rates, resulting in high exhaust mass flow rates. The calibration of the ATS was not robust enough for these test conditions.

Though the second round of PEMS testing concluded in May 2022, Achates executed a seven-month ATS recalibration process to achieve the previously recorded NO_x emissions reductions from the OPE truck.

The conditions that the engine was exposed to during the Fontana test cycle gave Achates the opportunity to learn and improve the calibration robustness, not only for the SCR storage and real time dosing settings, but also for the base engine calibration under conditions that caused peak cylinder pressure to exceed the design limit.

For this effort, a “Gen-2” ATS was used to better align with current production equipment, eliminating the SCRF for a conventional DPF that enables passive DPF regeneration.

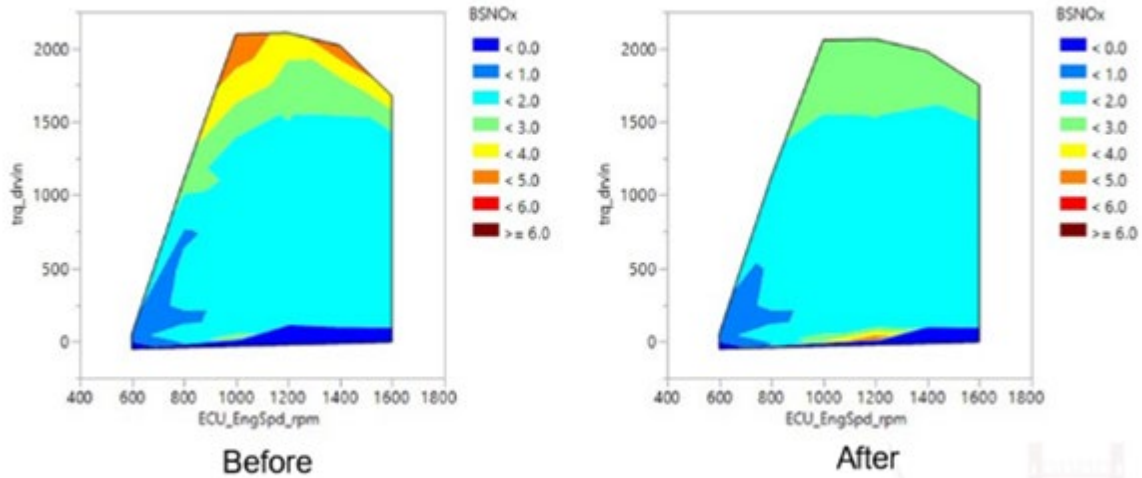
After the recalibration, test results show the engine can comply with all the 2027 CARB limits on combined FTP, RMC, and Low-Load Cycle (LLC) including NO_x, HC, CO, and nitrous oxide (N₂O). PM was not measured directly as part of the current calibration development since DPFs have been shown to deliver PM well below the emission standards. Achates’ immediate development focus was on more robust NO_x control. In addition, simulation of the previously troublesome Fontana cycle on the dynamometer showed compliance with the most stringent CARB in-use limits.

This confirms the potential of the OPE. With a conventional and available commercial underfloor ATS, the OPE can achieve the future CARB emissions requirements.

Base Engine Calibration

The interdependence between the engine and aftertreatment conditions led Achates to revisit and improve the engine calibration. The recalibration focused on the catalyst light-off mode, which is the operation mode used before the aftertreatment is active. The changes reduced the NO_x at higher load, and the soot at mid-loads as can be seen in Figure 28 and Figure 29 below. Achates used AVL’s 483 Micro Soot Sensor equipment to measure the engine exhaust’s soot mass concentration measured in mg/m³ as displayed in Figure 29.

Base Engine Calibration Changes – BSNOx

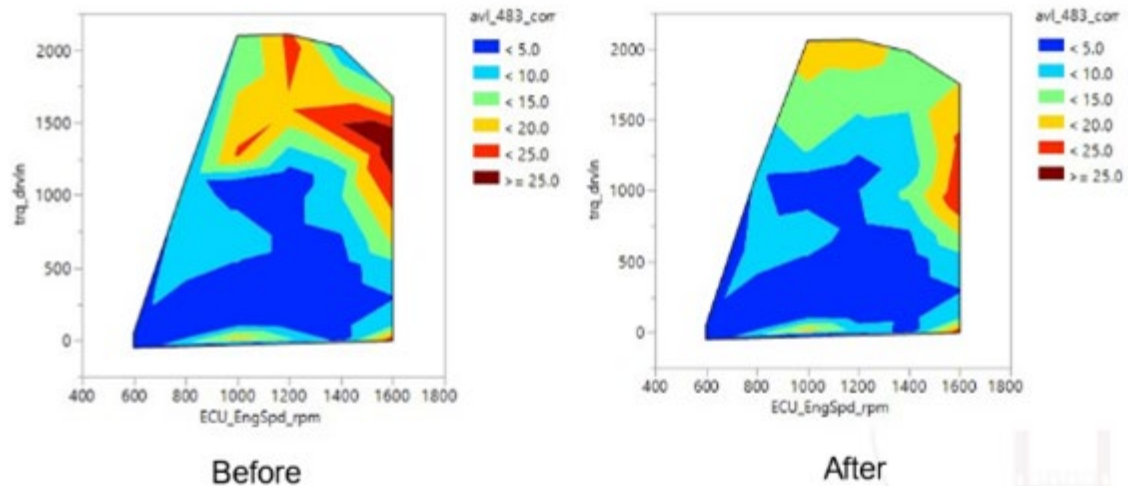


High Nox area at high load has been tuned down to < 3 g/kWh BSNOx.

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Figure 28: Base Engine Calibration Changes BSNO_x

Base Engine Calibration Changes – AVL483



AVL 483 soot (mg/m³) is improved with the changes.

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Figure 29: Base Engine Calibration Changes AVL483

In addition to the NO_x emissions already noted in the field test, replaying the Fontana PEMS cycle on the engine dynamometer showed that frequent and aggressive accelerator pedal dynamics caused the peak cylinder pressure to exceed the 250-bar limit during transmission shifts. To address this, several of the transient correction factors were adjusted to control and limit peak cylinder pressure under these conditions. This also had a beneficial impact on engine-out NO_x, further improving NO_x control.

Aftertreatment Calibration

Regarding the aftertreatment calibration, the exhaust mass flow rate calculation was verified all the way through the aftertreatment controller, and it was confirmed that the signals were matching. Figure 30 below shows the exhaust mass flow signals which are all consistent.

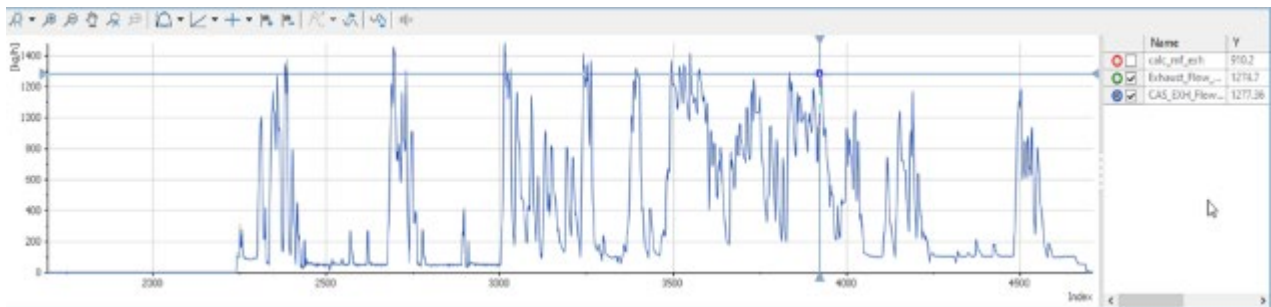


Figure 30: Exhaust Mass Flow Signals

The Diesel Exhaust Fluid (DEF) flow calculation was also verified against test cell flow actual measurements as shown in Figure 31 below.

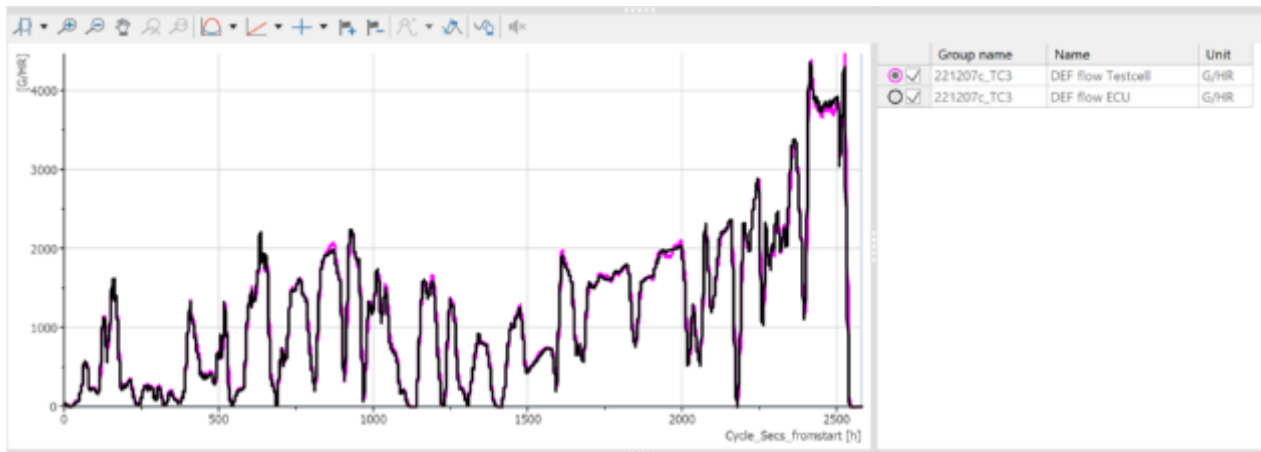


Figure 31: DEF Flow

Once these were confirmed, the storage models were validated with the mid-bed ammonia sensor. A comprehensive, next-step-of-development overall engine and exhaust aftertreatment controls recalibration was undertaken, including specific focus on ammonia storage targets and dosing tables. Temperature thresholds to transition from CLO to high efficiency modes were also tuned, and the keep-warm mode was enabled as a third active mode.

Calibration Results

The results summary can be found in the table below. All the emissions limits were met for all certification cycles with a margin. The LLC and RMC showed especially low numbers with 90% and 75% NO_x margins, respectively.

Table 14: Emissions Results

		NOx	NOx Limit	HC	NMHC Limit	CO	CO Limit	PM	PM Limit	N2O	N2O Limit	CO2
		g/bhp-hr						mg/bhp.hr			g/bhp-hr	
SN3406 - Cold FTP	23/01/23 - c	0.101		0.03		0.84		NA		0.05		567
SN3406 - Hot FTP	23/01/23 - d	0.004		0.02		0.59		NA		0.07		506
SN3406 - Combined FTP	23/01/23 - c/d	0.018	0.020	0.02	0.14	0.62	15.5	NA	5	0.06	0.10	515
SN3406 - RMC -A	23/01/23 - h	0.005	0.020	0.01	0.14	0.00	15.5	NA	5	0.06	0.10	438
SN3406 - LLC	23/01/23 - f	0.004	0.050	0.04	0.14	0.08	15.5	NA	5	0.09	0.10	712

This excellent NO_x control came with very low ammonia (NH₃) emissions.

During the Cold FTP cycle, the tailpipe NO_x characteristic and level were very similar to the Aramco tests; only the first two speed and load increases during the cycles showed any tailpipe NO_x. The hot FTP cycle showed that almost no NO_x emissions were measured at the tailpipe. Similarly, the LLC showed no sign of NO_x at the tailpipe with a 90% margin to the limits, meaning that tailpipe NO_x emission is low throughout the entire cycle due to engine-out NO_x and temperature management, as well as keeping the ATS in good conversion efficiency range. The tailpipe NO_x produced was only 8% of the allowable limit.

The RMC cycle was the only cycle that showed any measurable ammonia at the tailpipe, but that occurred only for a short time and was still well below the 30-ppm limit.

In the replay of the Fontana PEMS cycle after the initial cold-start and a small tailpipe NO_x emissions spike, the NO_x control was excellent with near zero concentration levels. This shows that even with a cycle as aggressive as the Fontana one, the NO_x control is robust with no NH₃ issues (0.4 ppm on average and 3.3 ppm at peak).

The results of the 3-Bin analysis of the Fontana PEMS cycle simulation on the dynamometer confirmed that the NO_x control is excellent with at least a 77% margin to the CARB limit, as shown in Table 15 below.

The margin values are calculated as: $100\% - (\text{measured NO}_x \text{ value} / \text{NO}_x \text{ limit}) * 100$. SWRI performed the binning analysis.

Table 15: SWRI Binning Analysis

	Fontana Dyno Replay	CARB limit	Margin
	NO _x	NO _x	%
Bin 1 - idle (g/hr)	0.10	7.5	99%
Bin 2 - low load (g/bhphr)	0.006	0.075	92%
Bin 3 - med/high load (g/bhphr)	0.007	0.03	77%

The NO_x trace comparison between the original Fontana PEMS measurement and the revised calibration can be seen in Figure 32 below. However, as the results from the recalibration were only tested on the dynamometer and not during on-road field testing, a direct comparison cannot be made between the results. Additional field testing is required to validate the results from the recalibrated engine.

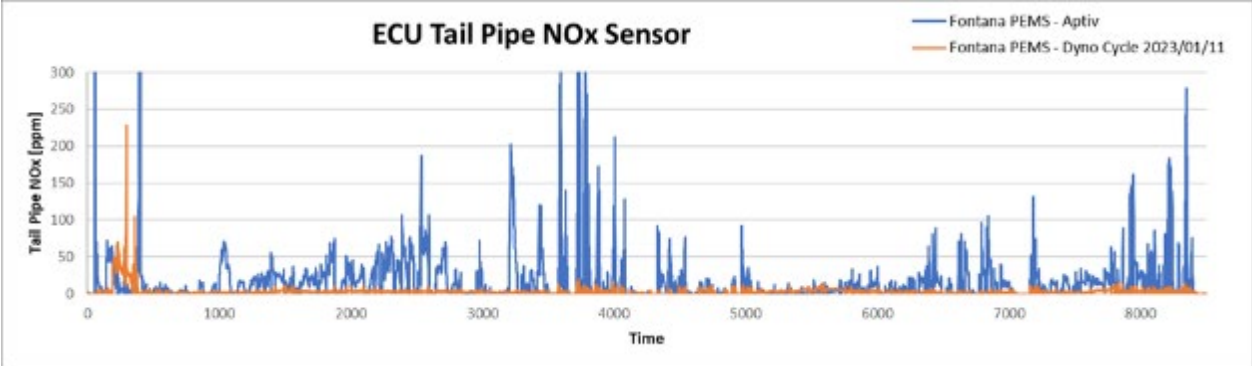


Figure 32: NO_x in Fontana PEMS vs. Recalibration

Lessons Learned

Manufacturing issues and OPE component failures can significantly delay key project milestones and limit the data collection necessary to conclusively assert that the OPE prototype can effectively be used in commercial applications. Supplier delays for block casting, machining, and assembly caused a six-week delay for the first engine assembly, while an issue with the main bearing cap in two of the engine blocks resulted in an additional delay of approximately seven weeks. The COVID-19 pandemic exacerbated manufacturing issues and timeline delays, as Peterbilt engineers could not remain onsite to complete their work.

The Achatas team had to continuously adjust the engine development and calibration plan to realign the program objectives to the original timeline. However, subsequent engine failures after the engine installation prompted a halt in engine testing. Though these failures were corrected, and testing was resumed, the three-month on-road fleet testing milestone, initially scheduled for November 2019, was delayed to November 2021. OPE failures during on-road fleet testing prompted a premature end to the demonstration, which limited the data collection period. With limited data from on-road fleet testing, it is not conclusive to state that the OPE will provide emissions and cost reductions during commercial operations.

On-road, in-service demonstrations are significantly more complex than those based on dynamometer testing. Demonstration of an engine in service requires integration with the transmission, vehicle, and ATS. Dynamometer results are brake-specific and only measure engine performance even without the transmission and ATS included. Achatas optimized the performance of the engine operating in isolation, but optimization of the engine integrated with the transmission and ATS was shortchanged because of several issues, including COVID-related restrictions and the limitations inherent in a demonstration of short duration. The time necessary to fully optimize overall systems was beyond the scope of this project. Though it was never within this project scope to fully optimize the OPE systems, it still proved challenging to reach the level of development needed for successful on-road testing. Further development of the engine, transmission, and aftertreatment calibration, as well as the optimization of integration of these three components, will result in improved system performance. Furthermore, adjust calibrations for variations in altitude, temperature, and humidity will also improve system performance and robustness.

Preliminary test results from both on-road and dyno testing demonstrate the potential to meet CARB Omnibus Ultra-Low NO_x regulations can be achieved in a cost-effective and practical manner; however, additional data collection and field testing is required

to validate this claim. No additional specialized equipment was used in the OPE and ATS to achieve ultra-low NO_x emissions. ATS models that account for ATS degradation predict the engine can comply with all Omnibus regulations during the extended warranty and full used-life periods. Further validation will be accomplished with the completion of a fully aged ATS project currently underway.

In both cold start and low-load conditions, the ability of the engine to rapidly generate high exhaust enthalpy proved essential to maintaining low tailpipe NO_x. In cold start conditions, the high exhaust enthalpy resulted in rapid catalyst light-off. The SCR is only effective in eliminating NO_x once it reaches 250°C; getting the catalyst to that temperature as quickly as possible is essential to limiting NO_x emissions. In low-load conditions, the catalyst temperature can drift down. If the engine—or supplemental heat sources—can quickly generate high exhaust enthalpy, sufficient catalyst temperature can be maintained for effective NO_x conversion.

Before the catalyst in the SCR reaches 250°C, however, engine-out NO_x will pass through the ATS and be emitted from the tailpipe. To achieve ultra-low NO_x tailpipe emissions, then, the engine must generate very low levels of NO_x during the light-off period.

Managing air mass flow through the engine is key to ultra-low NO_x. Achieving and maintaining high exhaust temperature and enthalpy is critical to achieving ultra-low NO_x on both regulatory cycles and in real-world operation while optimizing engine efficiency to reduce fuel consumption and CO₂ emissions. Under low-load conditions, the exhaust gas temperatures of all engines decline because not as much fuel is being combusted, which can cause the SCR catalyst temperature to decrease, reducing its NO_x conversion efficiency. Engines can always generate more heat to raise the catalyst temperature by combusting more fuel. The OPE has a key advantage; because it can dynamically control the scavenging ratio, it can minimize engine scavenging during low load operation. This results in an increased, low-load exhaust gas temperature compared to conventional engines, since the heat generated from combustion is not diluted with a full load of fresh air. This reduces the amount of additional enthalpy required to maintain catalyst temperature, reducing fuel consumption and CO₂ emissions during low load, ultra-low NO_x operation compared to conventional engines. While the OPE has some NO_x to CO₂ trade-off like any engine, its superior efficiency and NO_x control allows it to meet the Omnibus ultra-low NO_x limits on all dynamometer conditions. The improvement in fuel economy of the OPE is 10% or more compared to conventional engines and therefore shows great potential.

Eliminating the need for a second ATS substantially reduces cost, complexity, and compliance risk. This makes the OPE a feasible and practical option for meeting the reductions in emissions goals set by the Omnibus regulations. Conventional HD truck engines, on the other hand, are expected to require additional emissions control devices, including some combination of a second close-couple ATS, cylinder deactivation, increased SCR volume, and heat DEF doser. In addition to increasing the cost and complexity of the system, placing a second ATS in the engine compartment may increase the risk of failure since high temperatures degrade ATS components. In its public comment on the CARB Omnibus regulation, the Truck and Engine Manufacturers Association (EMA) stated that meeting the Omnibus regulations would require an extra \$35,000 per truck.² While the OPE will also incur additional costs due to extension of the required warranty, the extra costs are projected to be much lower. The OPE shows the potential to meet ultra-low NO_x regulations without additional emissions control, though additional real-world testing is required to be certain.

OPE Future Development

The HD truck market in North America is approximately 300,000 units per year.³ If a conventional engine costs an extra \$30,000 per truck to meet ultra-low NO_x, compared to an OPE, provisioning OPEs across the North American heavy industry would save \$9 billion per year. Although it takes around \$300 million to release a new HD engine into volume production, in the case of the OPE, this investment would be recouped in just 12 days.

While the EMA labeled the Omnibus regulations as “cost-prohibitive, infeasible, unenforceable, and illegal,”⁴ the OPE demonstration program provides some evidence that the regulations can be met in a practical and cost-effective manner.

² “Comments of the Truck and Engine Manufacturers Association,” <https://www.arb.ca.gov/lists/com-attach/8-hdomnibus2020-1jACGvmafaqDgEIXk.pdf>

³ “Global Truck Players: FY 2022 Review,” <https://www.berylls.com/wp-content/uploads/2023/03/20230315-Global-Truck-Players-FY-2022.pdf>

⁴ “Comments of the Truck and Engine Manufacturers Association,” <https://www.arb.ca.gov/lists/com-attach/8-hdomnibus2020-1jACGvmafaqDgEIXk.pdf>

Commercialization

A typical path for vehicle engine commercialization starts with extensive development and validation during a prototype stage. From there, it takes about six years for a new commercial vehicle engine to enter volume production. This period can be split into two stages, the first of which is focused on creation of a production-intent design, development of the engine, and validation. At this stage, prototype engines are built, deployed, and validated. The second stage consists of industrialization—development of the manufacturing plant, supply chain, and service infrastructure. Regulatory certification is obtained, and vehicle integration is completed. Achates expects the HD OPE to follow this commercialization timeline.

Components, Designs, and Industrialization

A powertrain utilizing an OPE has an advantage over many other new powertrains because it uses common materials, manufacturing tools, and processes. Existing manufacturing machines can be redeployed to make OPE components. Of the big five engine components—crankcase, crankshaft, connecting rod, cylinder head, and camshaft—the OPE eliminates the latter two. Overall, the OPE 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 4 by 40 steel. In addition, conventional manufacturing tools and processes are used to make OPE components.

Moreover, most of the components used by the OPE 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.

Paths to Market

At least two paths to market exist. Commercial vehicle engine manufacturers already have all the necessary capability to develop, manufacture, distribute, and service OPEs. Achates can work with these firms during the development and industrialization process and will earn a royalty for a license to its OPE 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 for the U.S. Army.

Another path to market is for Achates to assemble a team of established organizations to undertake the development, certification, manufacturing, integration, distribution, and support for diesel, HD OPEs. Achates 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 OPE. It is a logical starting place considering that HD vehicles emit 26% of all NO_x emissions in California.

The OPE advantages in low tailpipe emissions and improved fuel efficiency scale into larger and smaller engines and can be applied to off-road applications as well. Combined, off-road and MHD engines emit 67% of all NO_x in California. If the OPE, capable of reducing NO_x emissions by 90%, were put in place in all these applications, California-based NO_x emissions could be reduced by more than 90%.

Conclusion

Though the Class 8 HD OPE Demonstration project ended prematurely due to truck engine and DPF failures, the results from this project have shown that a Class 8 OPE HD truck could perform similar duty cycles of a conventional HD truck used in large-scale, commercial operations while meeting the most stringent enacted and proposed tailpipe and CO₂ emissions regulations in the world⁵. Furthermore, the demonstration showed the potential of the OPE to meet these regulations through at least 2027⁶ in a cost-effective, robust, and practical manner. In addition to its inherent advantages in high-efficiency, low-emissions, and low-complexity, the OPE also has advantages in fuel flexibility, including carbon-free hydrogen combustion and low-carbon combustion of alcohols like ethanol and methanol.

It was not expected that a perfect, OPE HD truck would be implemented within the timeframe and scope of this project, and the issues that arose during the demonstration provided information that can propel the OPE HD truck along its ultimate path to market. In a rapidly expanding zero-emission MHD truck industry, the OPE HD truck is a complementary part of enabling more sustainable transportation. With more time to fully optimize the engine and develop a path to market, OPEs have the potential to play a significant role in addressing areas that zero-emission technologies will have difficulty covering.

⁵ These refer to the CARB Omnibus regulations and the proposed and enacted EPA regulations.

⁶ Since the original draft of this report, the EPA has proposed CO₂ rules beyond 2027 for HD trucks that go beyond what the demo program has demonstrated.

References

“Comments of the Truck and Engine Manufacturers Association,”
<https://www.arb.ca.gov/lists/com-attach/8-hdomnibus2020-1jACGvmafqDgEIXk.pdf>

“Global Truck Players: FY 2022 Review,” <https://www.berylls.com/wp-content/uploads/2023/03/20230315-Global-Truck-Players-FY-2022.pdf>

Sharp, C., Henry, C., Yoon, S., Carter, M., and Webb, C. C., “Achieving Ultra Low NOX Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches,” SAE Int. J. Engines, vol. 10, no. 4, pp. 1722–1735, Mar. 2017, doi: <https://doi.org/10.4271/2017-01-0956>.

Appendix

On-Road Fleet Testing Data Collection

Table 16: Vehicle Performance Data Parameters

Metric or Parameter	Unit	Source
Vehicle ID	n/a	Peterbilt Data Logger
Date / Time Trip Beginning	dd/mm/yyyy hh:mm:ss	Peterbilt Data Logger
Date / Time Trip End	dd/mm/yyyy hh:mm:ss	Peterbilt Data Logger
Total Key On Time	hh:mm:ss	Peterbilt Data Logger
Total Time Idle	hh:mm:ss	Peterbilt Data Logger
Total Time Driving	hh:mm:ss	Peterbilt Data Logger
GPS Latitude Beginning	degrees, minutes	Peterbilt Data Logger
GPS Latitude End	degrees, minutes	Peterbilt Data Logger
GPS Longitude Beginning	degrees, minutes	Peterbilt Data Logger
GPS Longitude End	degrees, minutes	Peterbilt Data Logger
GPS Altitude Min	m	Peterbilt Data Logger
GPS Altitude Max	m	Peterbilt Data Logger
GPS Average Speed	mph	Peterbilt Data Logger
Beginning Odo	mi	Peterbilt Data Logger
End Odo	mi	Peterbilt Data Logger
Average Engine Fuel Rate or Average Fuel Economy	(l/100 km or l/km or offroad l/hr)	Peterbilt Data Logger
Total Fuel Used	gal	Peterbilt Data Logger
Total Fuel Used at Idle	gal	Peterbilt Data Logger
Payload	lbs	Walmart

Table 17: Fueling Data Parameters

Metric or Parameter	Units	Source
Vehicle ID	n/a	Peterbilt Data Logger
Station ID	n/a	Walmart
Date / Time of Fueling	dd/mm/yyyy hh:mm:ss	Walmart
Fuel Source	n/a	Walmart
Gasoline / diesel	gallons	Walmart
Gasoline / diesel, cost	\$	Walmart

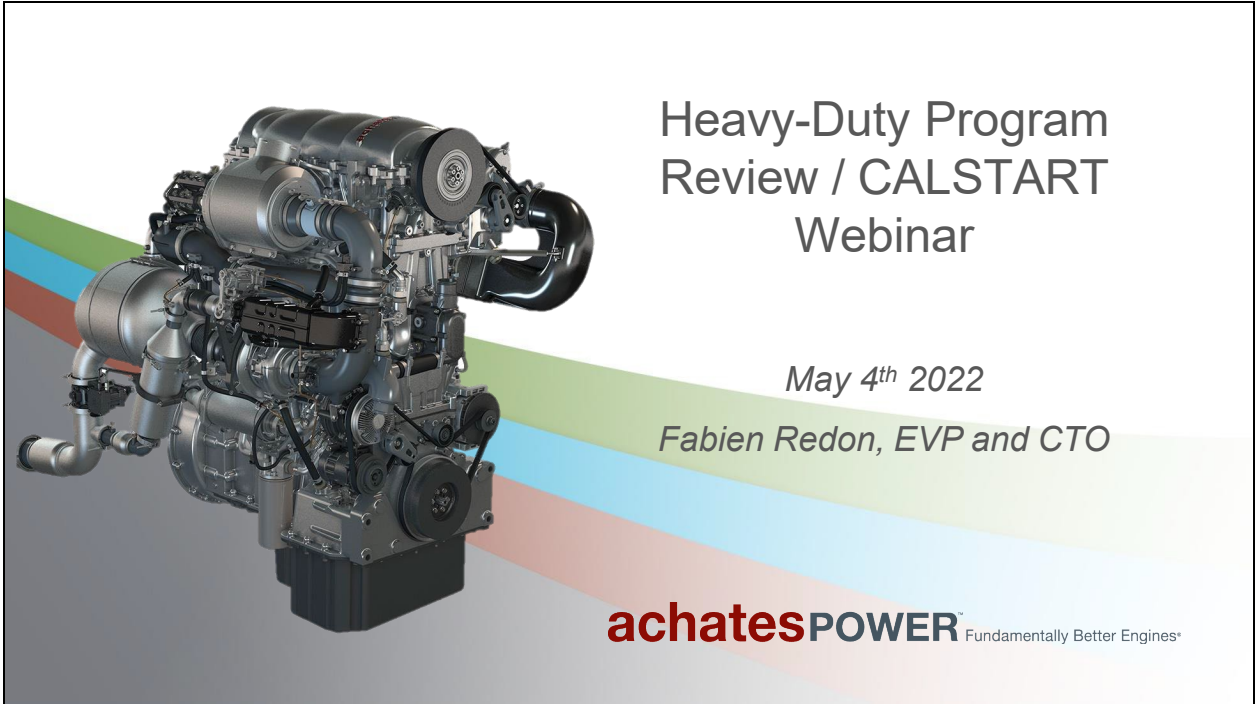
Table 18: Maintenance Data Parameters

Metric or Parameter	Unit	Source
Date of service call	Date	Walmart
Length of repair	Number	Walmart
Description of problem	Description	Walmart
Description of repair	Description	Walmart
Parts replaced	Description	Walmart
Cost of parts replaced	\$	Walmart
Cost of labor	\$	Walmart
Odometer reading at time of service call	Miles	Walmart
Time out of service	Days	Walmart
Service response time to call	Days	Walmart

Project Presentations

After the on-road fleet testing and PEMS testing concluded, CALSTART and the Achates team summarized and presented the test results in several webinars. The slides from two of the presentations are included below to give additional context to the data visualizations and the more technical aspects of this project presented in the main body of this report.

CALSTART Webinar: Heavy-Duty Program Review, May 2022



HD Opposed-Piston Engine

Efficient and Clean

- 10+% fuel economy improvement in fleet service
- 5-8% further improvements with second generation
- Compatible with 2027+ ULNOx

Cost Effective

- Reduced part count and lower manufacturing requirement. No cylinder head or valve train
- Uses common materials, processes, tools, existing supply base
- ULNO_x with conventional underfloor aftertreatment for lower cost and increased robustness



→ Future GHG and ULNOx can be met robustly and economically with the opposed piston engine

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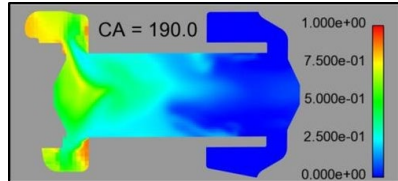
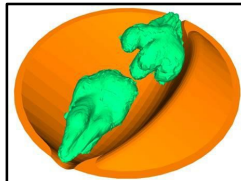
Confidential and proprietary information of Achatés Power, Inc.

High Efficiency and Low Criteria Emissions

Enabled by:

Flexible Charge Control

- Does not use pistons to pump charge
- Engine pressure differential controls internal EGR
- Independent cooled EGR, boost and air mass flow control



Greater Work Extraction

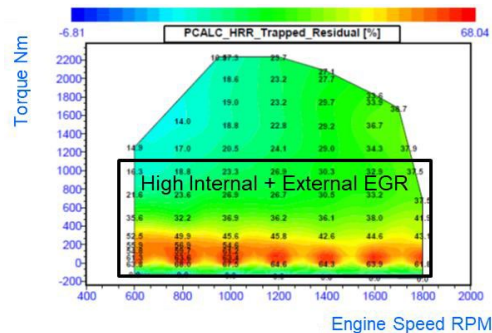
- Low heat loss enables near ideal combustion phasing
- One combustion per cycle enables faster combustion

High Mixing Combustion System

- Preserves good combustion even with late phasing
- Ultra low soot (4X lower than 4S)

→ Very efficient high efficiency mode

→ Very low NOx and high exhaust enthalpy Catalyst Light-Off (CLO) mode



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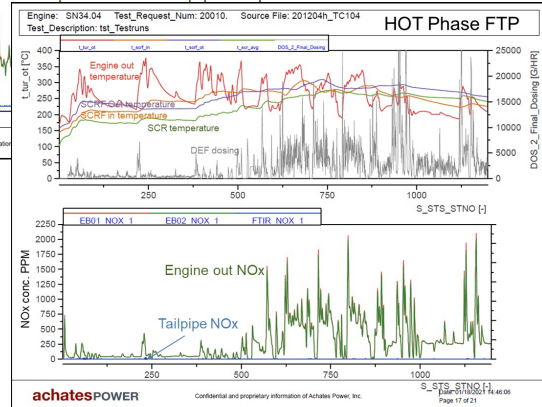
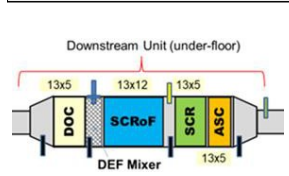
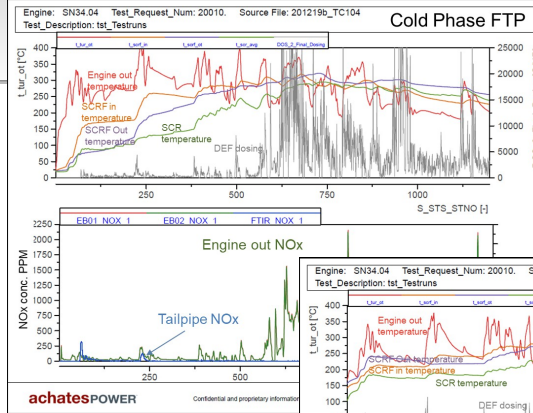
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FTP Test Results

- First generation engine
- Development aged catalyts
- Tested at Aramco services
- Combined 0.016 g/hphr NO_x

→ Meets 0.02 g/hphr NO_x with single SCR

	Cold	Hot	Comb
EO NO _x g/hphr	2.721	3.086	3.032
TP NO _x g/hphr	0.067	0.008	0.016
SCR conv eff %	97.5	99.7	

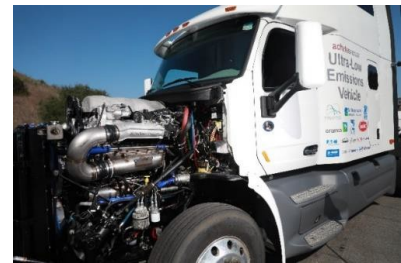


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Vehicle Integration

- Installed in a 2019 Peterbilt 579 with Eaton Cummins Endurant 12 speed automated manual.
- First Generation 10.6L OP HD engine, 400hp 2200Nm
- Mechanical and control integration in collaboration with Peterbilt, Eaton Cummins and Aramco
- Vehicle running in fleet service since November 2021, completed 7000 miles of operation
- Comments from the Walmart drivers:
 - "FYI Truck purrs like a kitten at 60+ mph"
 - "Power curve on uphill grade 6%-8% at 1500RPM in 9th Gear maintained 30-32 MPH"
 - "I controlled the shifting all day to stay in the correct operational speed for optimal shifting I believe this is the reason for the great fuel mileage."
- Still an early prototype, some opportunities for improvements:
 - Transmission calibration not optimized for the engine, using a Paccar MX-11 calibration
 - Cruise control not fully operational
 - Engine brake not implemented
 - Engine noise was not a design consideration so can be improved
 - No automated DPF active regeneration



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Fleet Operation: Walmart Fuel Economy Logging

- 10+% fuel economy advantage over 2021 reference 4-stroke vehicle
- Opportunities with transmission calibration



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Porterville CA to Santa Maria CA

2019 Peterbilt 579 Sleeper, Achates Power 10.6L					2021 Freightliner Cascadia Sleeper, DD15				
Date	Miles	Fuel gal	MPG	GCVW lbs	Date	Miles	Fuel gal	MPG	GCVW lbs
29-Nov	366	38.4	9.53	66120	14-Dec	366	52	7.04	60220
1-Dec	393	51	7.71	62380					
3-Dec	349	48	7.27	63970					
10-Dec	366	45	8.13	61410					
7-Jan	389	44.5	8.74						
10-Jan	389	44	8.84	67080					
11-Jan	389	46	8.46	65290					
14-Jan	389	36	10.81	63300					
21-Jan	389	58	6.71	65780					
24-Jan	389	43	9.05	67860					
25-Jan	383	52	7.37	69850					
26-Jan	383	46	8.33	65770					
Total	4574	Average	8.42	65346					

* Note from the driver: I controlled the shifting all day to stay in the correct operational speed for optimal shifting I believe this is the reason for the great fuel mileage.
 **Run with CLO Threshold for Cold ambient about 0.3MPG penalty

Apple Valley CA to La Quinta CA

2019 Peterbilt 579 Sleeper, Achates Power 10.6L					2021 Freightliner Cascadia Sleeper, DD15				
Date	Miles	Fuel gal	MPG	GCVW lbs	Date	Miles	Fuel gal	MPG	GCVW lbs
10-Feb	230	28	8.21	73595	15-Feb	233	41	5.68	65420
1-Mar	235	29	8.10	68820	16-Feb	235	33	7.12	67260
2-Mar	228	29	7.86	71060	17-Feb	250	36	6.94	66780
					18-Feb	268	35	7.66	66180
					21-Feb	286	44	6.50	66960
					28-Feb	235	31	7.58	65940
Total	693	Average	8.06	71158	Total	1507	Average	6.92	66423

In-use emissions results, EPA 3-Bin Analysis

- San Joaquin Valley CA
- December 2021, mid 40s ambient temperature
- 890 Miles over 3 days in fleet service with Walmart
- PEMS measurement performed by UCR with AVL 494 PM system

EPA 3-Bin Analysis, meets most stringent 2031+ EPA proposed low limit with a 50+% margin with development aged catalysts or CARB OMNIBUS by 30%

“The PEMS measurements conducted by UCR for Calstart on the Peterbilt 579 powered by the Achates Power 10.6L HD opposed piston engine demonstrated NOx 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 while the vehicle was in active fleet operation showed between a 99% and 50% margin to the most stringent in-use EPA 2031+ NOx proposed regulation, which is outstanding.”

Kent Johnson, Ph.D. | Principal Investigator, Emissions and Fuels Research
 College of Engineering - Center for Environmental Research and Technology
 University of California, Riverside

	Achates_ D1	Achates_ D2	Achates_ D3	Average	EPA Low 2031+ IUL	Margin to EPA	CARB 2030+	Margin to CARB
BIN 1	0.25	0.05	0.15	0.15	11	99%	7.5	98%
BIN 2	0.048	0.039	0.039	0.042	0.105	60%	0.075	44%
BIN 3	0.024	0.015	0.022	0.020	0.042	52%	0.030	32%

BIN 1 - idle (g/hr) BIN 2 - low load (g/bhphr) BIN 3 - med/high load (g/bhphr)

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Second Generation Engine Improvements

Air system improvements:

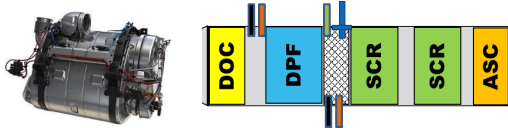
- SuperTurbo driven turbocharger:
- Eaton EGR Pump: Provides independent EGR control

Various Friction improvements:

- Lower friction rings, cylinder material and honing process improvements and lower viscosity oil

Aftertreatment system improvements:

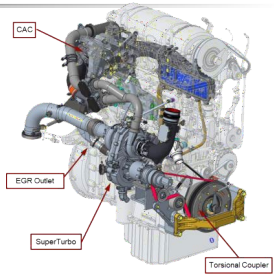
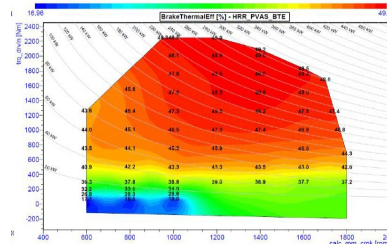
- Conventional DOC, DPF, SCR, still underfloor only
- BASF catalyst formulations, Corning substrates, Eberpaecher insulated can



SUPER TURBO CORNING BASF

EATON TENNECO cerlikon metco Lubrizol

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Second generation testing program:

- Measured results compared to first generation:
 - 49.2% best point BTE vs 47.1%
 - 5% lower CO2 on SET, 8% lower on Hot FTP
 - 30% higher exhaust heat generation for catalyst light-off mode
 - Higher and Narrower exhaust temperature range
- 3 level aging testing program underway:
 - SWRI DAAAC 435, 600 and 800 kMiles

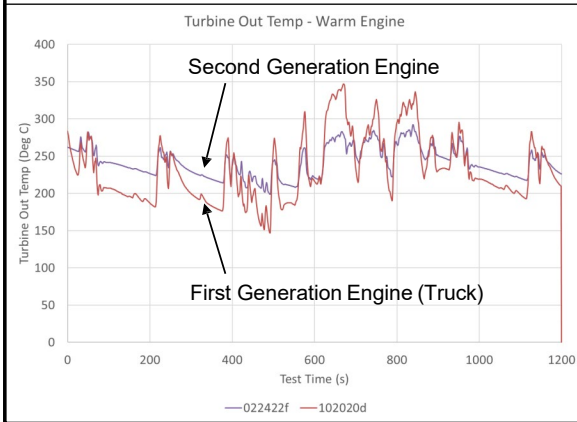


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Second Generation Engine Exhaust Temperatures

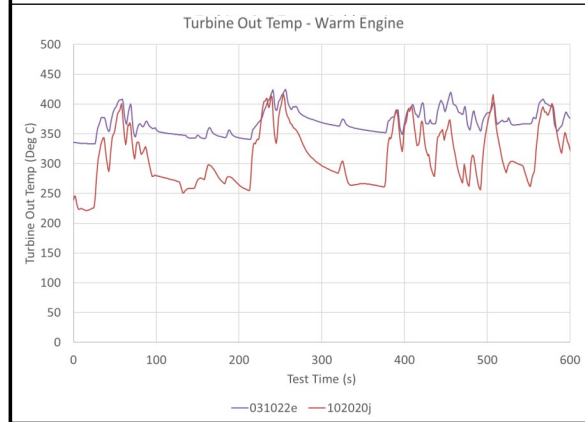
Hot FTP in high efficiency mode:

- Higher and narrower temperature range (200-300C)
- 8% lower CO2



First 600sec of hot FTP in catalyst light-off mode:

- Higher and Narrower temperature range (330C Min)
- 30% higher enthalpy by 380 sec, same NOx



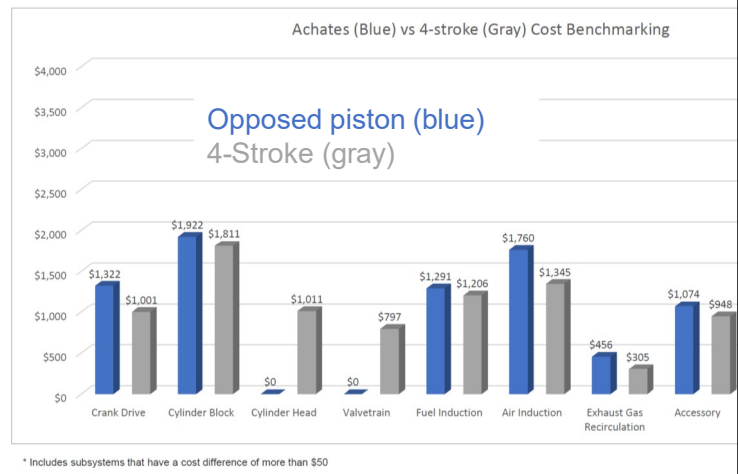
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Engine Cost

- FEV estimated the opposed piston base engine is 7% Lower cost than conventional 4-stroke engines (~260 fewer parts to assemble)
- OP only requires simple conventional aftertreatment systems

SUBSYSTEM COST COMPARISON*



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Conclusion

The Opposed Piston engine enables significant reductions in CO₂ and NO_x without increasing the cost of the powertrain:

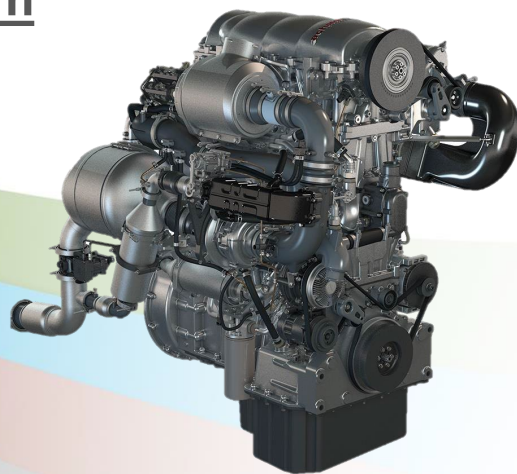
- Demonstrated 10+% fuel economy improvement in fleet service, even more benefits with next generation
- Confirmed capability to meet ULNO_x with single underfloor conventional aftertreatment system
- Lower engine cost

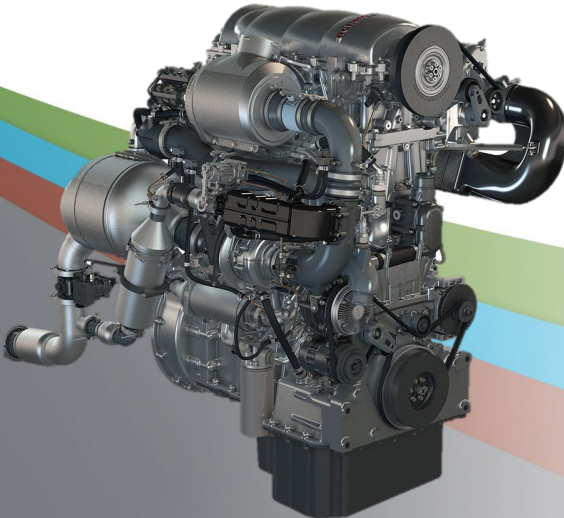
→ An Affordable solution will allow the fastest and greatest penetration for maximum benefit to the air quality

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Thank you
Fabien Redon
redon@achatespower.com





PEMS results and next steps

Zoltan Bako, Fabien Redon
2022 August

achatesPOWER Fundamentally Better Engines®

Program Goals and Execution

Program goal: Develop and demonstrate emission opposed piston (OP) engine technology in Class 8 heavy-duty, line-haul trucks that meet a 0.02 g/bhp-hr NOx target, with concurrent reductions in CO2 emissions.

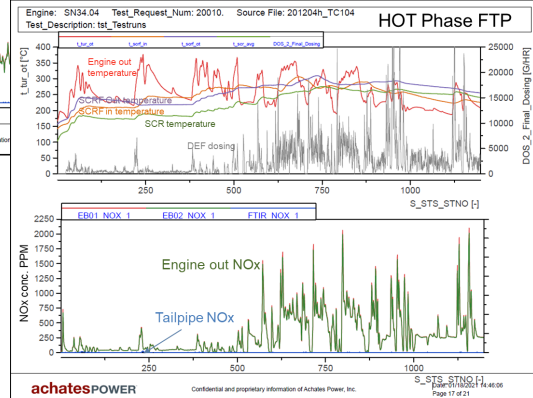
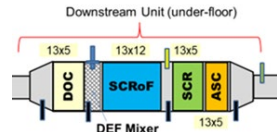
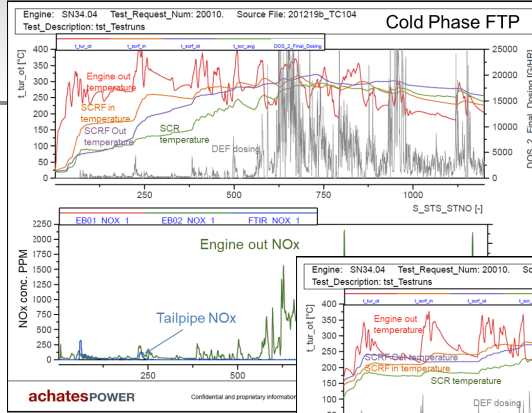
- High risk, aggressive and compressed program aimed at demonstrating the technology potential with a first-generation prototype engine.
- 0.02 g/hphr NOx on FTP was demonstrated on engine dynamometer and calibration was carried over to the truck
- Vehicle emissions control was based on preserving the calibration settings and verifying functionality developed on the FTP cycle. Calibration changes would have required validation on the engine dynamometer which was not in the scope.
- Successful first round of PEMS showed the technology potential even without any in-use development.
- High emissions on second PEMS was a surprise to Achates Power and immediately prompted a root cause analysis and the initiation of SCR recalibration efforts internally to better align with the spirit of the program in good faith.
- Engine and aftertreatment calibration settings were identical between Porterville and Fontana PEMS measurements.

FTP Test Results

- Same as vehicle system and calibration
- Erroneous exhaust mass flow signal was present but compensated for.
- Combined 0.016 g/hphr NO_x
- Below 0.02 g/hphr NO_x with single underfloor SCR

	Cold	Hot	Comb
EO NO _x g/hphr	2.721	3.086	3.032
TP NO _x g/hphr	0.067	0.008	0.016
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Fontana in-use emissions results, EPA 3-Bin Analysis

No change to the calibration but much higher NOx levels than in Porterville

UNIVERSITY OF CALIFORNIA, RIVERSIDE

UC RIVERSIDE

PEMS data - EPA 3 BIN analysis

	THC	CO	Soot (mg)	NOx	CH4	NMHC	Valid Window Count	Avg. Power (hp)	Avg. Exhaust Temp (DegC)	
Achates D1 →	idle (g/hr)	1.931	36.622	0.000378	3.242	0.048	1.892	1239	17.157	151.326
	low load (g/bhphr)	0.137	6.062	0.000059	0.410	0.003	0.134	1826	86.190	228.325
	med/high load (g/bhphr)	0.032	1.543	0.000031	0.257	0.001	0.031	6069	143.193	257.367
Achates D2 →	idle (g/hr)	0.000	0.963	0.003625	1.511	0.000	0.000	37	0.000	235.071
	low load (g/bhphr)	0.389	6.540	0.000210	0.289	0.010	0.381	2826	73.422	233.020
	med/high load (g/bhphr)	0.079	1.951	0.000132	0.230	0.002	0.078	6767	146.178	265.859

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PEMS Testing Results, investigation

- Second round of PEMS testing out of the Fontana Walmart hub showed higher NOx levels than the first round.
- Investigated potential root causes:
 - Engine hardware issues causing higher engine out NOx
 - Steady state NOx production → OK
 - Transient engine out NOx production → Higher NOx spikes, root cause under investigation
 - ATS hardware issues causing lower conversion efficiency
 - New ATS hw / conversion efficiency check. Pre and post ATS replacement check → No issues
 - Drive cycle related issues, transient or SS dosing / calibration → Yes, outstanding controls may have resulted in under dosing especially at higher Nox/exhaust mass flow rates.
 - Steady state drive cycle differences, high avg load, full load performance check
 - Transient drive cycle differences → Higher average Power 86 hp vs 40hp → Higher engine out NOx flow rate
 - Transient acceleration comparison – FTP, Porterville and Fontana drive cycle → More digital driving behavior → Higher engine out NOx flow rate

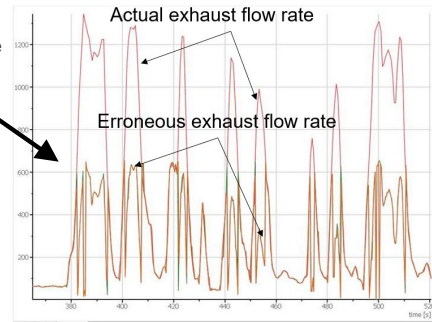
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Fontana Test Results – Learnings & Resolution

- The engine demonstrated excellent NO_x control during FTP testing and in-use testing at Porterville.
- In-use tests results at Fontana were both very disappointing and surprising.
- Conclusion of root cause analysis:
 - Aggressive on/off driver inputs exposed a weakness in our calibration.
 - During engine dyno development at Aramco in 2020, found that aftertreatment exhaust mass flow rate signal was erroneous at high loads, the fix came too late to be carried over and emissions targets were already met anyway without it.
 - From the initial (dual dosing) base calibration from SWRI the following adjustments were made, to adjust to the single dosing system, to offset the exhaust mass flow error and to adapt to real engine conditions.
 - ANR: 25-30% increase across the board up to ~1.3-1.4 ANR
 - SCRF storage: ~35-40% increase across the board
 - Downstream SCR storage: 100% increase across the board (double)
 - This enabled very good NO_x performance on the FTP cycle and Porterville PEMS testing.
 - But did not provide enough robustness for the conditions in Fontana.



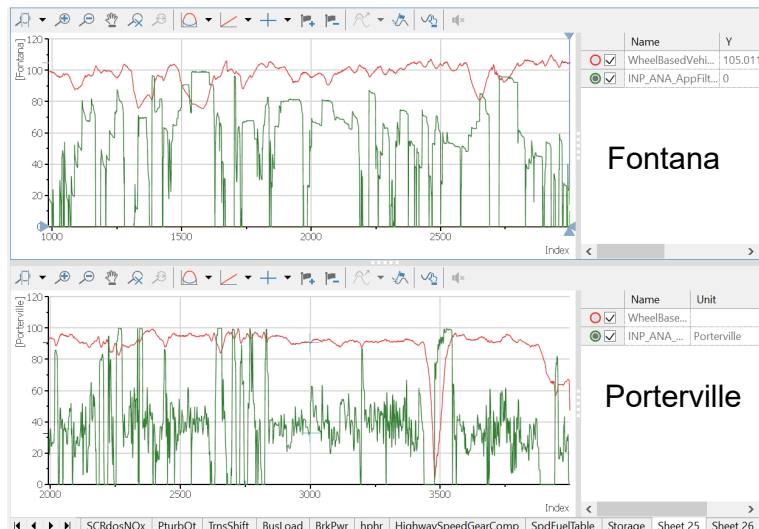
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Pedal input vs vehicle speed

- Red = vehicle speed
 - Steady highway
- Green = pedal position
- Porterville duty cycle is relatively steady at mid-pedal, with some heavy applies mixed in
- Fontana duty cycle seems very on-off, heavy constant pedal followed by no pedal, repeated many times



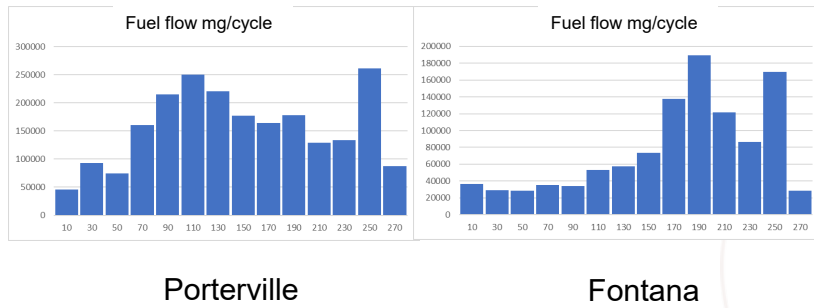
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Engine Fueling Histogram

- Higher average load and more aggressive pedal operation shifts operation to higher fuel flow rates and therefore high exhaust mass flow rates.



Porterville

Fontana

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