



Cold-Start WHTC and WHSC Testing Results on Multi-Cylinder Opposed-Piston Engine Demonstrating Low CO₂ Emissions while Meeting BS-VI Emissions and Enabling Aftertreatment Downsizing

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Citation: Patil, S., Sahasrabudhe, A., Youngren, D., Redon, F. et al., "Cold-Start WHTC and WHSC Testing Results on Multi-Cylinder Opposed-Piston Engine Demonstrating Low CO₂ Emissions while Meeting BS-VI Emissions and Enabling Aftertreatment Downsizing," SAE Technical Paper 2019-26-0029, 2019, doi:10.4271/2019-26-0029.

Abstract

Reducing the greenhouse emissions from on-road freight vehicles to meet the climate change mitigation objectives, has become a prime focus of regulatory authorities all over the world. Besides India, the United States, the European Union, Canada, Japan, and China have already established or planned heavy-duty vehicle efficiency regulations addressing CO₂ and NO_x emissions. In addition, Argentina, Brazil, Mexico, and South Korea are all in various stages of developing policies to improve the efficiency of their commercial vehicle fleets. For CO₂ emissions reduction standards, the U.S. mandates 27% reduction by 2027, EU is calling for 15% reduction by 2025, China for 27% by 2019 over 2012 levels, and India is mandating 10%-15% reduction by 2021 for phase 2 of the new standard. There has also been considerable focus on further reduction in NO_x emissions from current levels (0.2 g/hp-hr), to the proposed ultra-low NO_x standards (0.02 g/hp-hr) in the U.S. for heavy duty engines by 2024.

Given these planned and proposed regulatory standards being implemented around the globe, there have been substantial studies and publications focusing on exploring and evaluating technologies that can help deliver the lower tailpipe NO_x targets and understand the CO₂ impact associated with it. Majority of the NO_x emissions from engine, occur during the cold-start portion of the transient regulatory cycles, like HD FTP and WHTC. This is because, a typical heavy-duty diesel aftertreatment system does not achieve substantial NO_x reduction until approximately 400-500 seconds into the cold-start cycle due to lack of heat from the engine. The result is untreated NO_x escaping through to tailpipe. To achieve low NO_x emission levels over the composite transient cycles, the engine must provide rapid exhaust heat energy, during the cold-start portion, to reduce the time required by the SCR catalyst to reach catalyst light-off temperature, while controlling the

NO_x emissions. Moreover, high NO_x conversion efficiency must be maintained during the hot-start portion of cycle. For a conventional heavy-duty engine, providing rapid exhaust heat while controlling NO_x emissions has been a challenge, because these are competing demands. Implementing secondary or auxiliary heat sources downstream in the exhaust after treatment system (ATS) comes at CO₂ penalty and adds significant cost and complexity. This has been established in recent publications by organization like SwRI [1], CARB and Bosch [2].

Achates Power Opposed Piston (OP) engine technology provides ideal solution to this challenge. The opposed-piston engine has several inherent advantages over conventional four-stroke engines, like higher BTE (15-30% higher), higher power density, an air-system that results in reduced pumping work, the ability to control residual combustion gases, two fuel injectors per cylinder providing greater timing flexibility, and the ability to provide rapid engine out heat and temperature rise for the exhaust emission system while maintaining low engine out NO_x.

This paper demonstrates results from cold and hot start transient WHTC testing and WHSC testing, conducted at Achates Power, on a three-cylinder opposed-piston engine. Results show that the Achates Power OP Engine can deliver engine out heat and temperature rise that exceeded and sustained catalyst light-off temperature thresholds (250°C) within the first 60-100 seconds in the cold start cycle, while controlling engine out NO_x to lower levels when compared to a conventional four-stroke heavy-duty diesel engine. As a result, the OP Engine not only meets current BS-VI and future regulatory emissions requirements but is also able to do so with a significant CO₂ emissions advantage. Furthermore, the inherent advantages of the OP Engine offer unique aftertreatment optimization and downsizing opportunities thereby enabling cost reduction.

Introduction

The growing global challenges of greenhouse gases (GHG) and NO_x emissions has led to the adoption of stringent regulations for these emissions in several countries [3]. As a significant step in this direction, India decided to transition directly to BS-VI emission regulation standards from the current BS-IV standards. Furthermore, GHG regulations for CO₂ all over the world call for a significant improvement in the engine and vehicle fuel economy. For example, the United States has mandated CO₂ emissions improvement of over 10% for MHD engines from 2014 to 2027. Government of India has also published fuel efficiency standards for commercial heavy-duty vehicles that require an average of 10.4% fuel economy/CO₂ reduction from phase 1 (2018) to phase 2 (April 2021). This has put a substantial onus on original equipment manufacturers (OEM) in India and the world to comply to the new stringent emission standards at minimal cost and at minimal fuel consumption impact.

In India, another change made is the certification test cycles. The European Stationary Cycle (ESC) and European Transient Cycle (ETC) are replaced with the World Harmonized Steady-State Cycle (WHSC) and World Harmonized Transient Cycle (WHTC). These new cycles (WHTC and WHSC) are more representative of real-world driving conditions and are therefore more appropriate for evaluating the emission performance of the regulated vehicles [4]. The regulatory emissions limits on WHSC and WHTC emission cycles are specified in Table 1 [4]. Learning from the success in US 2010 and Euro VI applications, China NS VI/India BS VI solutions will also use the 4-way emission control systems with DOC, DPF, SCR and ASC technologies [4]. This will not only add substantially to aftertreatment cost but also add to engine backpressure leading to a CO₂ emissions' penalty. An EGR system if used to control NO_x will also come at added engine system cost and a CO₂ emissions' penalty.

To achieve low NO_x emissions over a composite WHTC cycle, rapid heat energy must be provided to the diesel exhaust after-treatment system during the cold start portion of the cycle to light off the catalyst as fast as possible and peak NO_x reduction efficiency must be maintained during the hot start portion of the cycle [5]. This is usually addressed on a typical four-stroke engine via thermal management which comes with a significant fuel economy and CO₂ emissions penalty. In addition to engine thermal management, some NO_x system solutions also involve implementation of supplemental heat sources in the exhaust system which also comes at CO₂ penalty and adds significant cost and complexity. Therefore, conventional four-stroke engines are faced with a substantial challenge of competing demands of meeting emissions while achieving good fuel economy and CO₂ emissions both of which are also now subject to stringent regulations all over the world.

Advances in conventional four-stroke engines to address this challenge are approaching a state of saturation and a point of diminishing returns. As a result, in certain circumstances OEM's are required to down size, down speed or de-rate the engine to meet competing targets of fuel economy and emissions/aftertreatment cost. Yet another alternative that is often adopted in the industry is that of mild electrification which also adds substantial cost.

On the other hand, the Achates Power Opposed-Piston (OP) Engine design provides an ideal solution to this challenge. The OP Engine has several inherent advantages over conventional four-stroke engines, like higher BTE, low BMEP, rapid exhaust temperature rise and internal EGR. This facilitates excellent fuel economy/CO₂ emissions while keeping low engine out NO_x along with the ability to provide rapid engine out temperature rise for the aftertreatment system while maintaining low engine out NO_x [5].

This paper highlights the results from cold-start and hot-start WHTC testing and steady state WHSC testing with a 4.9L Opposed Piston engine which demonstrate the ability of the OP Engine to meet stringent CO₂ (GHG) emission levels while

TABLE 1 Emissions regulatory limits in India for steady state (ESC, WHSC) and transient testing (ETC, WHTC)
Steady State Testing

Regulation	Test Cycle	CO g/kWh	THC	NO _x	PM	PN 1/kWh
Euro IV	ESC	1.5	0.46	3.5	0.02	
Euro V	ESC	1.5	0.46	2.0	0.02	
Euro VI	WHSC	1.5	0.13	0.40	0.01	8.0×10 ¹¹
NS VI						
BS VI						

Transient Testing

Regulation	Test Cycle	CO g/kWh	THC	NO _x	PM	PN 1/kWh
Euro IV	ETC	4.0	0.55 (NMHC)	3.5	0.03	
Euro V	ETC	4.0	0.55 (NMHC)	2.0	0.03	
Euro VI	WHTC Cold (14%) + Hot (86%)	4.0	0.16 (THC)	0.46	0.01	6.0×10 ¹¹
NS VI						
BS VI						

meeting BS-VI emission regulations at competitive cost without any added engine or aftertreatment complexity. Furthermore, opportunities offered by the OP Engine to optimize and downsize a current production BS-VI aftertreatment, with respect to size, weight, volume and cost, have also been presented.

The paper starts with discussing the fundamental benefits of an OP Engine architecture. This is followed by a discussion of the multi-cylinder OP Engine test set up, the engine controls and operating modes used for transient WHTC testing. Details of WHSC and WHTC testing on a three-cylinder OP Engine are then summarized followed by a summary of measured engine out GHG and emission results. Finally, the engine out composite WHTC results are provided as an input for BS-VI aftertreatment simulation (BASF proprietary modeling software) to evaluate tailpipe compliance, catalyst sizing, as well as potential aftertreatment system optimization and downsizing opportunities.

Advantages of the Opposed-Piston Engine

The inherent advantages of the Achates Power Opposed-Piston Engine over the conventional four-stroke engine are summarized below:

Combustion System

Reduced heat losses: The Opposed-Piston Engine, which includes two pistons facing each other in the same cylinder, offers the opportunity to combine the stroke of both pistons and increase the effective stroke-to-bore ratio of the cylinder, leading to lower area-to-volume of the combustion chamber. This results in reduction in heat transfer or loss from combustion to cylinder head. Additional benefit is that smaller heat rejection packaging or radiator can be used, as well as fan power consumption can be reduced to lower speeds contributing to lower fuel consumption.

Leaner combustion: When configuring an opposed-piston two-stroke engine of the same displacement as a conventional four-stroke engine, for example, converting a six-cylinder conventional engine into a three-cylinder opposed-piston engine, the power that each cylinder must deliver is the same. The opposed-piston engine fires each of the three cylinders in each revolution while the four-stroke engine fires each of its six cylinders in one out of two revolutions. Therefore, the amount of fuel injected for each combustion event is similar, but the cylinder volume is 60% greater for the opposed-piston engine. So, for the same boost conditions, the opposed-piston engine will achieve leaner combustion, which increases the ratio of specific heat. Increasing the ratio of specific heat increases the work extraction per unit of volume expansion during the expansion stroke.

The above mentioned fundamental thermal efficiency advantages [6] are amplified by:

- Lower heat loss due to higher wall temperature of the two piston crowns compared to a cylinder head (reduced temperature difference).

- Reduced pumping work due to uniflow scavenging resulting in higher effective flow area than a comparable four-stroke or a single-piston two-stroke uniflow or loop-scavenged engine.
- Decoupling of pumping process from the piston motion because of the two-stroke architecture allows alignment of the engine operation with a maximum compressor efficiency line.

Air-System

To provide enough air for combustion, Opposed-Piston Engines need to maintain an appropriate pressure difference between the intake and exhaust ports. In addition, the air demand and delivery during transient operation have greater impact on the engine performance and emissions. The advantages of such an air-systems are:

- The compressor provides high pressure ahead of the supercharger, which then further boosts intake flows resulting in low supercharger pressure ratios sufficient for high intake manifold density, reducing pumping work.
- The maximum required compressor pressure ratio is lower compared to turbocharger-only air systems of four-stroke engines.
- The use of a supercharger recirculation valve allows greater control of the flow through the engine, thus providing flexibility for precise control of boost, scavenging ratio, and trapped residuals to minimize pumping work and NO_x formation across the engine map
- Lowering the flow through the engine by decreasing the pressure difference across the engine reduces the pumping penalty at low load points. This, together with having no dedicated intake and exhaust stroke for moving mass to and from the cylinders improves BSFC.
- The supercharger recirculation valve improves transient response. Facilitating EGR with a supercharger reduces the required pumping work.
- Accurate control of the engine pressure differential provides good cold start and catalyst light off capabilities. Low-speed torque is increased by selecting the appropriate gear ratios on the supercharger.

Multi-Cylinder OP Engine Test Bed Description

Table 2 shows the specifications for the multi-cylinder Opposed-Piston Engine used for transient WHTC testing and steady state WHSC testing. This OP Engine was conceived as a research engine and therefore encompasses a modular architecture for flexibility, oversized components to explore capabilities of the engine and a conservative design to facilitate a robust development platform. As a result, the research engine size and its frictional losses are much greater than that of an optimized production OP design.

TABLE 2 Multi-cylinder Achatas Power opposed-piston engine specification

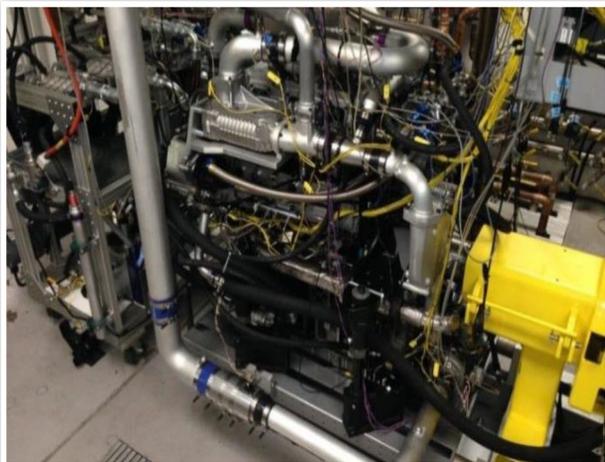
Displacement	4.9 L
Arrangement, number of cylinders.	Inline 3
Bore	98.4 mm
Total Stroke	215.9 mm
Stroke-to-Bore Ratio	2.2
Compression Ratio	15.4:1
Nominal Power (kW @ rpm)	205 @ 2200
Max. Torque (Nm @ rpm)	1100 @ 1200-1600

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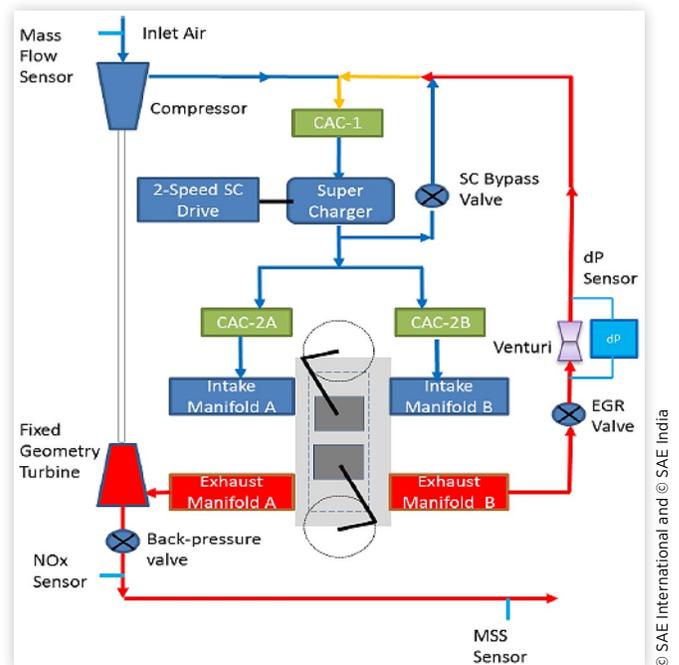
Despite being a research design, the engine powers all accessories coupled to the cranks such as supercharger, fuel pump, oil pump and water pumps. Since, the engine does not have a full aftertreatment system, the exhaust backpressure seen by the engine from a typical BS-VI aftertreatment system (like the one in Figure 9 and Table 6) is simulated in hardware by using an exhaust backpressure valve to set and modify the backpressure in real-time

Figure 1 shows the 4.9L three-cylinder Opposed-Piston Engine in the test cell, for the transient cold-start WHTC testing at the Achatas Power facility in San Diego, California.

Figure 2 shows the schematic of the air path on the three-cylinder OP Engine used for transient testing. Inlet air flows from the compressor of the turbocharger into the supercharger through charge air cooler 1 (CAC-1). The supercharger is driven using a 2-speed drive which is used to control the drive ratio between the engine crank and the supercharger input shaft. The supercharger also acts as a pump to pull the EGR from the exhaust manifold through an EGR valve. The air flows through the supercharger into engine intake manifold through charge air cooler 2. The supercharger bypass valve allows to accurately control the flow going into the engine. It should be noted that in an OP Engine all the pumping work is provided by turbocharger and supercharger. Pistons do not contribute to pumping. During motoring when the exhaust

FIGURE 1 Achatas Power 4.9L three-cylinder research engine in test cell

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FIGURE 2 Opposed-Piston Engine air system schematic

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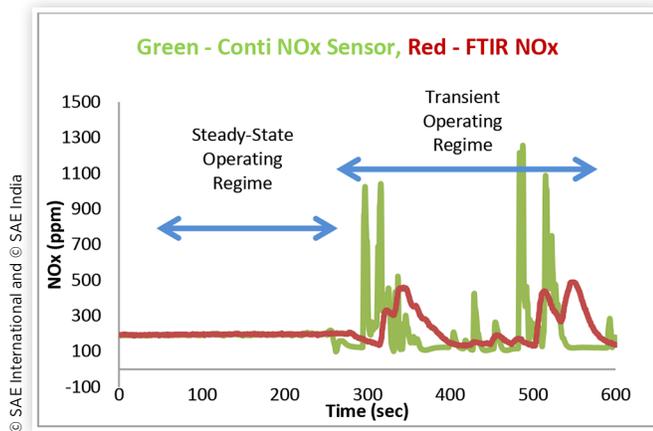
enthalpy is negligible only the supercharger provides all pumping. As a result, during motoring, it is possible to significantly reduce the cold air flow going into the exhaust system through the engine by controlling the position of the supercharger bypass valve. This avoidance of cold air flow through the exhaust aftertreatment system during motoring on OP Engines, helps with keeping the aftertreatment system warm during motoring unlike four-stroke engines in which piston motion continues to pump cold air through the aftertreatment system during motoring.

Engine-Out NOx Measurement

Engine out NO_x was measured in real-time using a Continental NO_x sensor and a FTIR-based gas-analyzer. During steady-state operations, both FTIR and Continental's NO_x sensor indicate similar measurement results. But during transient operations, the FTIR based analyzer system installed in the Achatas Power test-cell exhibits a temporal delay. The difference in performance between the two sensors can be attributed to both response time of the sensors and the transport delay. The Continental's NO_x sensor is located immediately downstream of the back-pressure valve as shown in Figure 3, whereas the FTIR sample lines are located further downstream along the exhaust line.

Figure 3 shows the difference in measurement between the continental NO_x sensor and the FTIR sensor. Since the continental NO_x sensor can record the NO_x spikes during transient events, this sensor was used for NO_x measurement over the transient WHTC cycle.

FIGURE 3 Comparison between FTIR NOx and Continental NOx sensor during steady-state and transient operations



Engine Controls and Operating Mode

Achates Power has developed proprietary controls software to control air handling, EGR and fueling for its Opposed-Piston Engine. For air-handling, control strategies were developed to control airflow using the supercharger recirculation valve and a two-speed drive, whereas EGR is controlled by the EGR valve. For the airflow controller, air mass-flow feedback is provided by a MAF sensor mounted before the compressor [5]. For the EGR control, EGR mass flow feedback is provided by a sensor (measuring delta Pressure), which is mounted across the venturi along the EGR loop shown in Figure 2. Achates Power has developed and implemented controls strategies for controlling rail-pressure for the common rail system, which allows it to utilize two injectors per cylinder to inject the fuel [5]. For the WHTC transient cycle testing, a smoke-limiter, a transient modifier and feed-forward controllers for air-handling and EGR were integrated into the control software. Transient air handling controls implemented for this engine are discussed in greater detail in a prior publication by Achates Power [7].

Fast Catalyst Light-Off Mode (CLO)

With conventional diesel engines, the limited ability to modify trapped conditions, along with the need for stable combustion limit the potential for achieving high exhaust temperatures. This is evidenced by strategies in use for the latest heavy-duty emissions certifications, where manufacturers have implemented fuel injection directly into the exhaust stream to warm diesel oxidation catalysts or used electrical heating elements upstream of the catalysts.

In contrast, the opposed-piston engine can generate trapped conditions to achieve stable combustion (COV of IMEP <5%) and high exhaust temperatures simultaneously. Running the engine at low modified delivery ratios yields

significant internal residuals, which in turn increases the trapped temperature of the charge. In this operating mode, a sufficiently high intake manifold pressure is required to achieve an adequate air-fuel ratio and good combustion stability during light-load operation, low ambient temperature operation and extreme cold starts. When coupled with a series of split and late fuel injection events, it creates a significant temperature rise in the exhaust for thermal management.

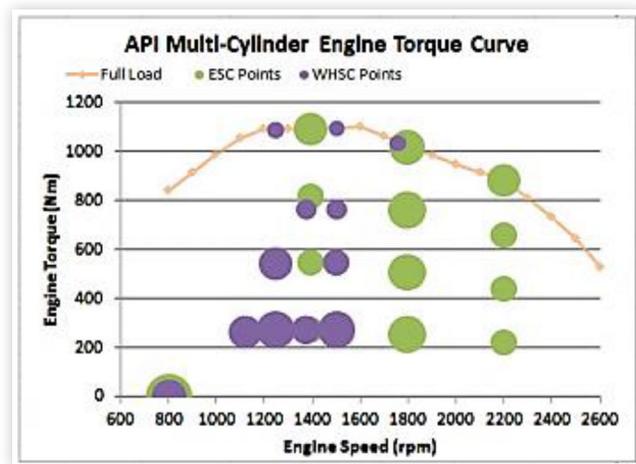
The Achates Power catalyst light-off (CLO) control scheme, designed to activate during cold starts, seeks to maximize exhaust enthalpy while retaining good combustion stability. Controlling NOx emissions during this operating mode are critical as the aftertreatment system will not yet be functioning. The NOx production needs to be minimized after a cold start while the SCR aftertreatment is getting warmed up. Hence the operating mode strategy seeks to absorb crankshaft energy with the supercharger, which also provides high boost pressure, enabling beneficial scavenging characteristics. In a vehicle application, additional energy also could be absorbed by fully engaging the vehicle's charging system, storing some of this energy for later re-use. By creating the heat within the combustion cycle, any number of crankshaft driven accessories can be used to absorb additional energy, increasing the amount of enthalpy available for warming the emissions aftertreatment equipment.

By using the variable geometric turbo, backpressure valve and the supercharger, the scavenging and trapping characteristics of the engine at idle can be altered significantly, such that majority of the fuel injected is converted into exhaust enthalpy, providing rapid temperature rise during idle and low speed & load operating points. The catalyst light-off mode (CLO) offers significant advantages that can be activated almost immediately after startup or during any extended idle where it is necessary to maintain the optimum temperatures in the aftertreatment system. In previous publications [8], it was demonstrated that turbo-out temperatures reaching 400°C were achieved during the elevated idle implemented in Catalyst light off operating mode.

Steady-State (WHSC) and Cold-Start Transient (WHTC) Testing

The fuel economy and GHG emission standards on medium and heavy-duty applications are typically measured over the steady state regulatory cycles. In India the World Harmonized Steady-state Cycle (WHSC) is used for fuel economy assessment and is expected to be used for assessing GHG emissions. The WHSC cycle comprises multiple steady state speed load points or modes with ramps in between to transition between the modes. In a January 2015 paper [9] published at the SAE SIAT in India, Achates Power presented results showing the fuel economy of the opposed-piston multi-cylinder engine over a WHSC cycle. In this paper the three-cylinder OP research engine was run through the WHSC cycle, like the one shown in the Figure 4 (purple points), to measure the cycle

FIGURE 4 WHSC points on Achates Power Multi-cylinder OP Engine



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averaged CO₂ (GHG) emissions from the research engine as well as to forecast the cycle average CO₂ emissions from a low friction, fully optimized and production ready OP Engine design. The engine out CO₂ levels are compared to the current and future regulatory CO₂ / GHG requirements.

The WHTC transient cycle is used for BS-VI regulatory emission testing. The WHTC transient cycle has a duration of 1800 seconds and has both cold and hot start requirements. The WHTC regulatory cycle also has a “motoring” segment that typically requires a DC or AC electric dynamometer capable of both absorbing and supplying power. Since the Achates Power test cell is equipped with an eddy-current dynamometer unit, motoring is not possible. During the motoring portion of the cycle, very light fueling is commanded to maintain engine speed. Such an arrangement allows for generation of power during the motoring segment, but it also results in an emissions’ penalty during those segments. Furthermore, it may be noted that the goal of this transient test for this paper is not to achieve certification but to demonstrate capabilities of the OP Engine to efficiently handle WHTC transients while producing emissions that are compatible with BS-VI requirements. Nonetheless, it is of the interest to observe how closely the WHTC cycle target speed and torque (Table 3) can be followed.

Both cold and hot start WHTC transient tests were conducted on our three-cylinder OP Engine. The regression requirements for the WHTC regulatory cycle are summarized in Table 3. The torque, power and speed regression fits that were achieved on our multi-cylinder OP Engine are shown in the Figure 5.

It may be noted that the slope and COD values for torque and power meet the WHTC regulatory requirements which confirms the ability of our engine to conform to WHTC. The COD values for rpm are slightly lower than the WHTC regulatory requirement as this is a limitation of an eddy current dyno. Nonetheless the conformance of our OP Engine to the WHTC regulatory cycle as shown in Figure 6 is considered good enough to demonstrate transient capability and BS-VI “emission-ability” over the WHTC cycle.

WHSC and WHTC Engine-Out Results

The brake specific CO₂ emissions (GHG) from our three cylinder 4.9L OP research engine are measured over the WHSC cycle. As previously discussed, our research engine has a modular architecture to offer flexibility and has oversized parts to offer a robust development platform. As a result, our research engine exhibits much higher friction than what is expected from a fully optimized and low friction production OP Engine design. Furthermore, the air handling system components such as turbocharger and supercharger on our research engine are off the shelf components. A production design having optimized friction, improved combustion, optimized OP specific air-system components and optimized calibration is expected to demonstrate approximately 7-8% lower CO₂ emissions than our prototype research engine. A prior Achates power publication discusses this roadmap in detail [10]. Further optimization to engine architecture (for example stroke to bore ratio) is expected to lower CO₂ emissions by another 2-3%, as this offers an even lower surface area to volume ratio resulting in lower heat losses and improved efficiency. The measured BSCO₂ results on our OP research engine are thus converted to expected BSCO₂ results for a

TABLE 3 Torque, power and speed regression requirements for the transient WHTC cycle

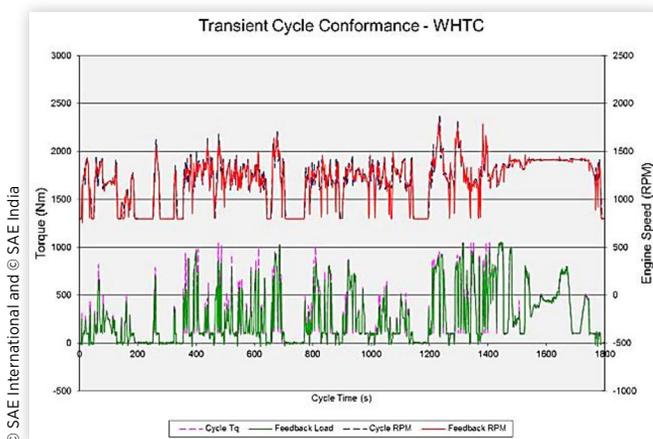
Regression line tolerances			
	Speed	Torque	Power
Standard error of estimate (SE) of Y on X	Max 100 min ⁻¹	Max 13% (15%) (*) of power map maximum engine torque	Max 8% (15%) (*) of power map maximum engine power
Slope of the regression line, m	0,95 to 1,03	0,83-1,03	0,89-1,03 (0,83-1,03) (*)
Coefficient of determination, r ²	min 0,9700 (min 0,9500) (*)	min 0,8800 (min 0,7500) (*)	min 0,9100 (min 0,7500) (*)
Y intercept of the regression line, b	± 50 min ⁻¹	± 20 Nm or ± 2 % (± 20 Nm or ± 3 %) (*) of max torque whichever is greater	± 4 kW or ± 2 % (± 4 kW or ± 3 %) (*) of max power whichever is greater

* Until 1 October 2005, the figures shown in brackets may be used for the type-approval testing of gas engines. The Commission shall report on the development of gas engine technology to confirm or modify the regression line tolerances applicable to gas engines given in this table.

FIGURE 5 WHTC regression fits on Achates Power Multi-cylinder OP Engine



FIGURE 6 Conformance of multi-cylinder OP Engine to WHTC regulatory cycle



production design on the WHSC cycle considering that the production design will be at least 7% better. The forecasted BSCO₂ values of a production multi-cylinder ~4.9L OP Engine are then compared to expected current and future CO₂/GHG emission limits for heavy-duty engines in Europe and India.

The Environmental Protection Agency (EPA) has published US GHG (CO₂) emission standards for medium and heavy-duty engines over US RMC-SET steady state cycle [11]. Typically, the GHG emissions are reported for the highest rated engine in a given engine family. The International Council on clean transportation (ICCT) has published the scaling factors to convert the CO₂ GHG limit on US SET to WHSC in Europe/India [3]. Based on this, it is possible to derive the equivalent current and future CO₂ GHG regulatory limits on the WHSC cycle applicable in Europe and India.

The measured WHSC cycle averaged BSCO₂ on our three-cylinder 4.9L OP research engine was ~ 685 g/kWhr. The production OP design is predicted to demonstrate ~ 637 g/kWhr WHSC cycle average BSCO₂ (at-least 7% lower than our research engine). This is compared to expected current and future CO₂ GHG emission limits in Europe and India in the Table 4.

Furthermore, as discussed in a prior Achates Power publication [12], the Achates Power OP Engine demonstrates transient performance which closely matches steady state performance because of its novel combustion system, flexible air system and corresponding OP specific control strategies. Therefore, WHSC BSCO₂ levels shown in Table 4 closely represent the capabilities of the OP Engine during transient operation.

As shown in Table 4, the Achates Power Opposed-Piston Engine exceeds the 2021 CO₂ emission limit with a margin and meets the 2027 CO₂ emissions standard. The OP Engine is therefore an ideal cost competitive solution to meet the future GHG targets without implementing technology solutions, such as dual stage turbocharging, waste heat recovery, thermal barrier coatings, mild electrification etc. that are considered additive to an efficient base-engine. Based on the roadmap presented by ICCT, conventional four-stroke engines will require additive technologies in the hope of getting closer to meeting future CO₂ emissions standards [3] which will add significant complexity and cost. In a cost -sensitive market like India the OP Engine therefore offers a very compelling value proposition.

The engine out WHSC cycle averaged emissions of the OP Engine over the WHSC cycle are shown in the Table 5. The OP Engine demonstrates acceptable engine out NO_x, THC, CO levels and demonstrates ultra-low soot levels.

To achieve acceptable tail pipe emissions on a composite WHTC transient cycle, it is important to have sufficient engine out exhaust temperature particularly during cold start portion

TABLE 4 OP Engine CO₂ emissions compared to expected current and future CO₂ regulatory limits

OP engine WHSC BSCO ₂ g/kWh	Expected 2021 CO ₂ limit (HD engine EU/India) g/kWh	Expected 2027 CO ₂ limit (HD engine EU/India) g/kWh
637	658	636

TABLE 5 WHSC cycle averaged engine out emissions from Achates Power multi-cylinder OP Engine.

BSNOx	4.16 g/kWh
BSTHC	0.02 g/kWh
BSCO	0.61 g/kWh
BSSoot	0.007 g/kWh

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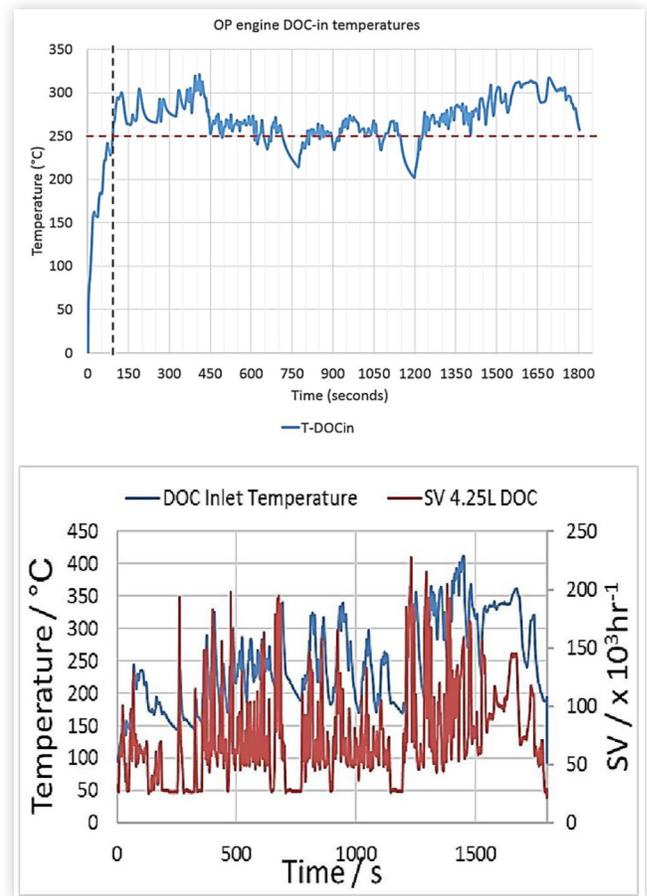
of the WHTC cycle. With sufficient exhaust temperature, early urea dosing can be enabled, as well as NO₂/NO_x ratio can be improved to allow high NO_x conversions [4]. On Achates Power OP Engines, the catalyst light-off (CLO) operating mode, is activated at cold start wherein the engine calibration is modified to rapidly raise the exhaust gas temperature to enable the SCR to reach its light-off temperature as fast as possible. Since we did not have an actual after treatment system in the test cell during this testing, the transition of the engine operating mode, from CLO to normal operation, was activated at 400 seconds into the WHTC cold start transient cycle that was deemed sufficient for the SCR catalyst to reach its light-off temperature. It should be noted that if needed, it is also possible on our OP Engine to activate CLO mode during idle or low-speed and low-load points on the WHTC cycle, when the SCR-bed temperature falls below a certain threshold - a thermal management strategy which helps to keep the SCR temperatures above its light-off requirement throughout WHTC cycle.

Engine out (DOC-in) temperature profile of the Achates Power OP Engine during cold start is shown in Figure 7 below. As shown in the Figure 7 the OP Engine demonstrates dramatically fast DOC-in temperature rise during cold start and the temperatures reach 250°C in just 100 seconds into the cold start cycle. Furthermore, the exhaust temperature is maintained over 200°C for the entire duration of the cold-start WHTC. This temperature profile with CLO on OP Engines enables SCR catalyst light off at least ~ 4X faster than the profile on comparable four-stroke, wherein temperature during cold start portion of the WHTC cycle are under 200°C on an average and reaches 250°C (light off requirement) at around 400 seconds into the cycle.

Typical cold-start strategy in conventional four-stroke engines, involves no EGR to generate the required heat, but this comes at the cost of increased engine-out NO_x emissions. The OP Engine architecture avoids this compromise by using its ability to control the internal EGR or residual combustion gas. The ability helps increase the temperature of the exhaust gases while generating low NO_x by using internal EGR. This is evident in the engine-out NO_x comparison shown in Figure 8.

As shown, while the OP Engine generates rapid exhaust temperature rise during cold start, the NO_x emissions from the OP Engine are also noticeably lower during the first 400 seconds into the cold start WHTC cycle as compared to those on a comparable conventional four-stroke engine.

The engine out emissions and temperature profiles from multi-cylinder OP Engine over WHSC and cold start WHTC cycles were used as inputs for aftertreatment system simulations, with different components and configurations to identify a simplified solution that can help meet BS-VI emissions with our OP Engine.

FIGURE 7 DOC-in temperature comparison between OP Engine (top figure) and comparable four-stroke engine (bottom figure [2]) over cold start WHTC

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After-Treatment System Architecture

In this paper, we consider systems that consist of DOC, DPF, Cu-SCR, and AMOx as shown in Figure 9. Table 6 lists the details of different catalyst technologies used in the modeling study and approximate sizing. This aftertreatment system is comparable to a typical exhaust after-treatment system on a comparable commercial HD diesel four-stroke engine meeting BS-VI.

Aftertreatment Simulation Results

The exhaust after-treatment simulation was done using a 2-D simulation tool from BASF, (its proprietary modeling software), for monolithic catalysts and filters. The tool can model any drive cycle including WHTC and WHSC. The tool also accounted for effect of aged catalysts, while solving for energy, species, mass and momentum (including soot)

FIGURE 8 Measured engine out NO_x and THC comparison between OP Engine (top figure) and comparable four-stroke engine (bottom figure [2]) over cold start WHTC

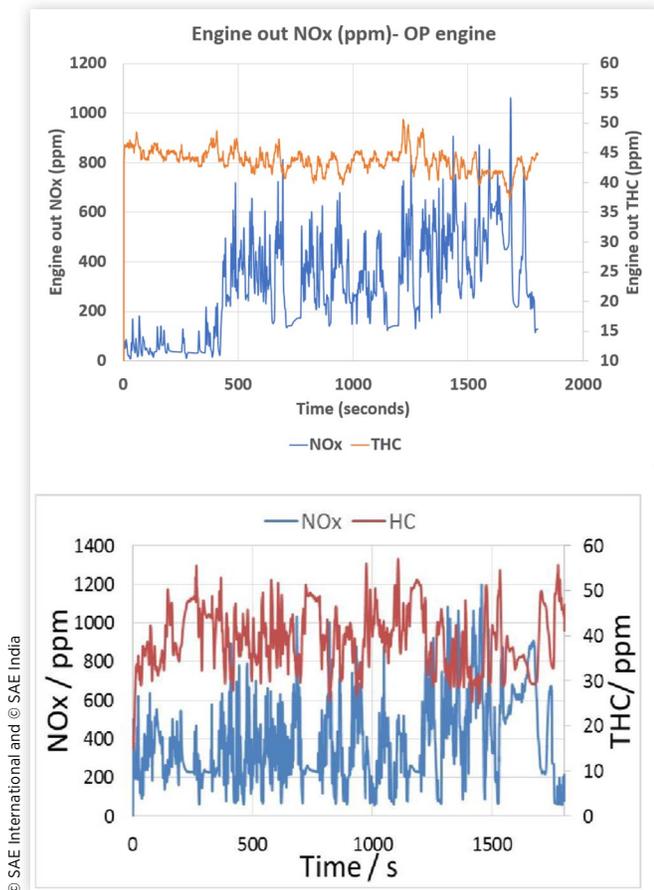


FIGURE 9 BS-VI aftertreatment system architecture considered for OP Engine aftertreatment simulation

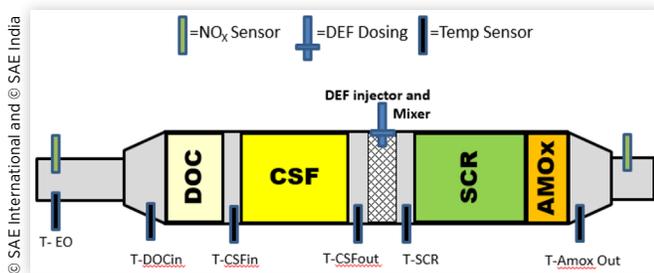


TABLE 6 Catalyst technologies and sizing used in baseline configuration

Component	Substrate CPSI/Wall Thickness (mil)	PGM (g/ft ³)	Aging Condition	Dia. (in)	Length (in)	Volume (L)
DOC	400/4	20-30	650C/50 hr	9.5	3	3.49
CSF	200/12	2.5	650C/50 hr	9.5	7	8.13
CuSCR	600/3	N/A	650C/50 hr	10.5	8	11.35
AMOX	600/3	2.0	650C/50 hr	10.5	2	2.84

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TABLE 7 Different engine management approaches and SCR catalyst lengths evaluated

Scenarios/Cases	SCR length	Engine Operating Mode	
		Cold-start	Hot-Start
1a	8 inches	CLO (400 seconds)	Normal
1b	8 inches	CLO (400 seconds)	CLO (400 seconds)
2a	4 inches	CLO (400 seconds)	CLO (400 seconds)
2b	4 inches	CLO (400 seconds)	Normal

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balance in the catalyst channels. The simulation does assume the single channel performance as representative for the entire catalyst and homogenous gas mixing in front of the catalyst. The tool also provides the ability to model pipes and cones to model the pressure drop and temperature variation through the after-treatment system. Injectors are modelled in BASF proprietary modeling software with feedback control via Matlab and excel. Each catalyst technology is defined by wash coat properties and reaction kinetics. The 2D model also accounts for diffusion through wash coat layers and captures the effects of axial and radial heat transfer. The filter model can capture the effects of soot accumulation and regeneration. The model assumes a homogenous gas mixture to be present in front of the catalyst and the composition downstream of any injectors is uniformly mixed and vaporized. The tool facilitates building of aftertreatment system models using system components and probes (cumulative emissions, pressure, temperature etc.).

The cold-start and hot-start WHTC and WHSC data (engine out mass flow, NO_x, THC, CO, CO₂, O₂, H₂O and engine out temperature) from the Achates Power 4.9L three-cylinder engine was used as input to this simulation exercise. The model conservatively assumes zero NO₂/NO_x ratio for the gas upstream of the exhaust aftertreatment system. NO₂/NO_x ratio of 40% is achieved at light off with the DOC PGM loading used in this simulation (shown in Table 6). DEF injection is activated in simulation as and when the SCR-in temperature exceeds 200°C.

As part of the simulation exercise, scenarios with different SCR catalyst lengths were evaluated. Table 7 provides detailed information on each case.

Case-1a

The baseline configuration specified in Table 6 was simulated with input data wherein the OP Engine was run in CLO thermal management mode during cold start for the first 400 seconds and in normal operation mode (no thermal management) during hot start. The baseline aftertreatment configuration simulation run with CLO during cold start and normal mode during hot start is hereinafter referred to as 'Case-1a'. The tailpipe simulation (BASF proprietary modeling software) results of Case-1a indicate that the Achates Power OP Engine with the exhaust after-treatment system specified in Table 6, meets BS-VI tailpipe NO_x target with a substantial margin. Tailpipe simulation results of the Case-1a over composite WHTC and WHSC are shown in Table 8.

Figure 10 shows the simulation results of the cold-start temperature plots for Case-1a probed at various locations along the exhaust aftertreatment system. The DOC-in and CSF-in temperatures reach and exceed 250°C within approximately 100 seconds into the cold start WHTC cycle. The SCR-in temperature also reaches 200°C in just 150 seconds into the cycle thereby enabling fast SCR catalyst to light-off and exceeds 250°C in 200 seconds thereby facilitating peak conversion efficiency.

Furthermore, the AMO_x-out temperature exceeds 200°C in less than 275 seconds into the cold-start cycle ensuring an

TABLE 8 Case 1a - Composite WHTC and WHSC tailpipe results

Test Cycle	CO	THC	NO _x
	g/kW-hr		
WHTC	0.167	0.046	0.207
WHSC	0.002	0.001	0.086

NO _x (g/kWh)	WHTC		
	Cold-start	Hot-start	Composite
Engine Out	4.33	4.774	4.711
Tailpipe Out	0.08	0.23	0.207
NO _x Reduction	98.25%	95.22%	95.61%

FIGURE 10 Case 1a - Cold-start temperatures at various locations in the exhaust after treatment system

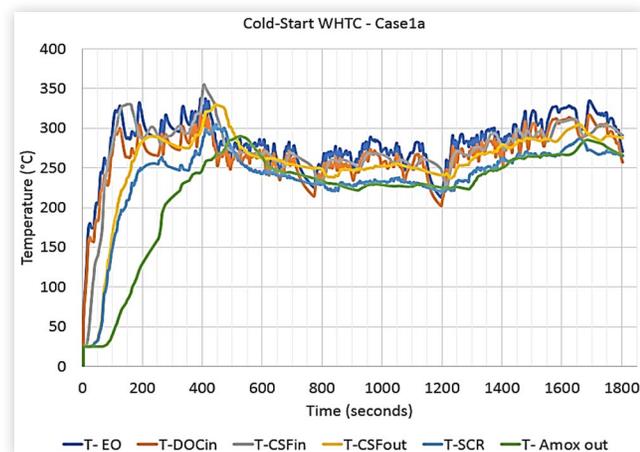
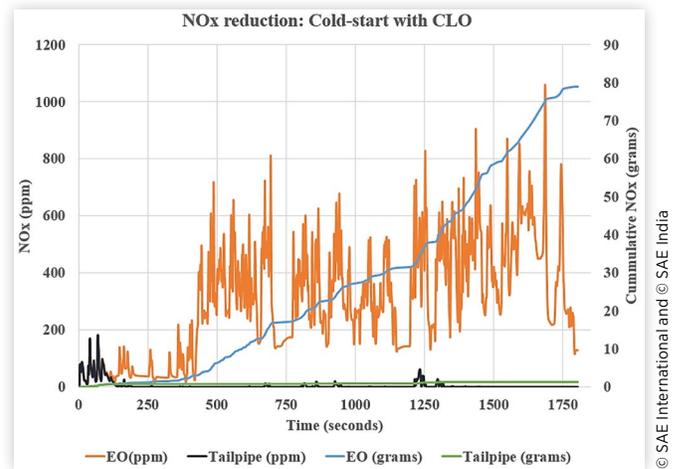


FIGURE 11 Case 1a - Cold-start engine-out and after-treatment system out NO_x

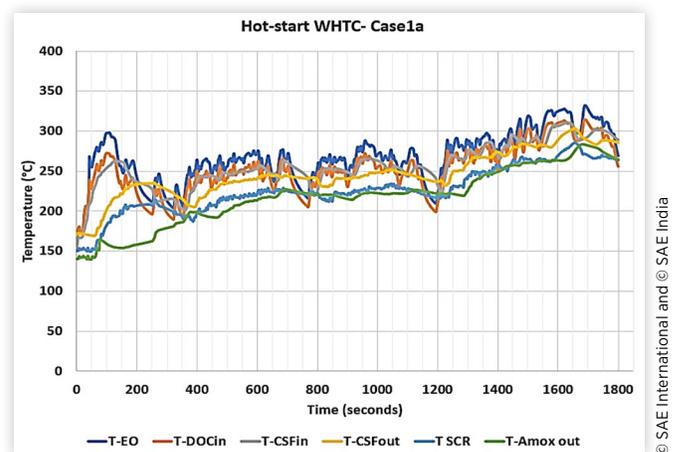


excellent NO_x conversion efficiency of 98.25% on an average over the cold start WHTC cycle as shown in Table 8. This results in cycle average NO_x levels that are substantially under the WHTC regulatory limit.

Figure 11 shows, instantaneous and cumulative NO_x measurements at engine-out and tailpipe out. Moderate NO_x reduction starts very early, approximately 150 seconds, into the cycle. The OP Engine's ability to provide rapid heat enables peak NO_x reduction by less than 300 seconds into the cold-start cycle. For conventional four-stroke engine, moderate NO_x reduction starts around 500-600 seconds into the cold-start.

Figure 12 shows the simulation results of the hot-start temperature plots for Case-1a. As noted earlier, the hot start WHTC cycle is run in normal operation engine mode without any thermal management. The hot-start cycle is executed following a hot soak segment. During the soak segment the catalyst temperatures drop below 175°C as seen from the hot start WHTC temperature plots (at time zero). In the absence of any thermal management the SCR in temperatures exceed 200°C sustainably after about

FIGURE 12 Case 1a - Hot-start temperatures at various locations in the exhaust after treatment system



400 seconds into the hot start cycle and the average NO_x conversion efficiency over the hot start cycle is 95.22%. The resulting cycle average NO_x levels over hot start WHTC are above those of the cold-start cycle but are still well under the WHTC regulatory NO_x limit.

Thus, the tail pipe simulated composite WHTC NO_x emissions, of 0.207 g/kWh, with Case-1a are under the BS-VI regulatory NO_x requirement with a substantial margin.

The baseline catalyst configuration was verified in simulation over the WHSC steady state cycle as well, and the simulated tailpipe results shown in Table 8 demonstrate that the baseline aftertreatment configuration meets the WHSC regulatory emission limits with a substantial margin.

Case-1b

Conventional four-stroke engines typically need to implement thermal management during the hot start portion of WHTC when the system temperatures are cooler than the light off temperature requirements. The need for thermal management to meet BS-VI emissions on conventional four-stroke engines is discussed in elaborate detail in [4]. The thermal management mode in four-strokes is typically enabled as and when the catalyst bed temperature drops below a pre-defined temperature threshold. To understand the effect of thermal management during hot start portion of WHTC cycle with the Achates Power OP Engine and to evaluate associated potential aftertreatment optimization, the baseline aftertreatment configuration was simulated with input data wherein the OP engine was run in CLO thermal management mode (for the first 400 seconds) during both cold start and hot start portions of the WHTC cycle. This scenario is hereinafter referred to as 'Case-1b'.

The tailpipe simulation (BASF proprietary modeling software) results of Case-1b indicate that the Achates Power OP Engine with the exhaust after-treatment system specified in Table 6, meets BS-VI tailpipe NO_x target with a very substantial margin. Tailpipe simulation results of the Case-1b over composite WHTC and WHSC are shown in Table 9.

Figure 13 shows the simulation results of the cold-start temperature plots for Case-1b probed at various locations along the exhaust aftertreatment system.

Figure 14 shows the simulation results of the hot-start temperature plots for Case-1b probed at various locations along the exhaust aftertreatment system.

TABLE 9 Case 1b - Composite WHTC and WHSC tailpipe results

Test Cycle	CO	THC	NO _x
	g/kW-hr		
WHTC	0.941	0.1	0.070
WHSC	0.002	0.001	0.086
NO _x (g/kWh)	WHTC		
	Cold-start	Hot-start	Composite
Engine Out	4.33	4.32	4.32
Tailpipe Out	0.08	0.06	0.06
NO _x Reduction	98.25%	98.56%	98.51%

FIGURE 13 Case 1b - Cold-start temperatures at various locations in the exhaust after treatment system

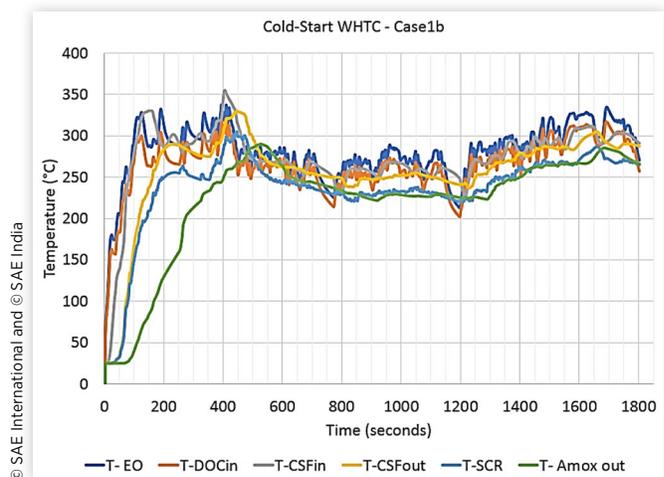
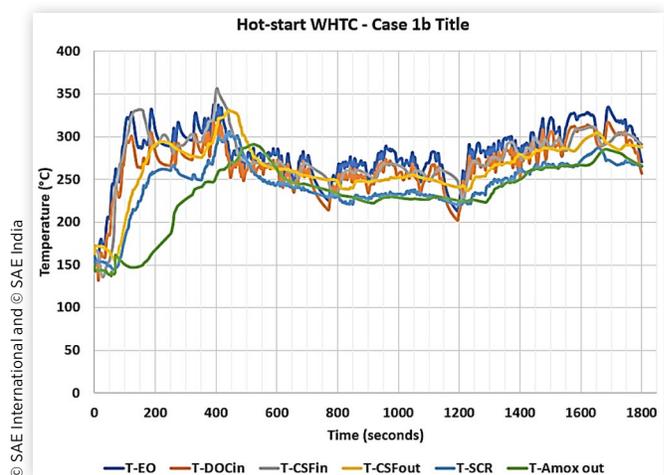


FIGURE 14 Case 1b - Hot-start temperatures at various locations in the exhaust after treatment system



The hot start cycle is executed following a hot soak segment. During the soak segment the catalyst temperatures drop below 175°C as seen from the hot start WHTC temperature plots (at time zero). CLO thermal management mode during hot start portion of WHTC, provides rapid heat to the catalysts. Since thermal management was enabled during hot-start portion of WHTC for Case-1b, the catalyst temperature profiles demonstrate rapid temperature rise and considerably higher temperatures relative to hot start of Case-1a.

The DOC in and CSF (filter) in temperatures reach and exceed 250°C within approximately 100 seconds into the hot start WHTC cycle. The SCR-in temperature also reaches 200°C in just 150 seconds into the cycle thereby enabling fast SCR catalyst light-off and exceeds 250°C in 180 seconds into the hot-start cycle thereby also facilitating peak conversion efficiency.

Activating CLO operating mode, during the first 400 seconds of cold-start and hot-start WHTC, help achieving very low tail pipe composite NO_x emissions in Case-1b relative to Case-1a. The simulated composite WHTC tail pipe NO_x emissions in Case-1b (0.07 g/kWh) are ~1/7th of the regulatory

TABLE 10 Catalyst technologies and sizing used in downsized configuration

Component	Substrate CPSI/Wall Thickness (mil)	PGM (g/ft ³)	Aging Condition	Dia. (in)	Length (in)	Volume (L)
DOC	400/4	20-30	650C/50 hr	9.5	3	3.49
CSF	200/12	2.5	650C/50 hr	9.5	7	8.13
CuSCR	600/3	N/A	650C/50 hr	10.5	4	5.68
AMOX	600/3	2.0	650C/50 hr	10.5	2	2.84

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NO_x requirement of 0.46 g/kWh thereby strongly supporting the catalyst size downsizing argument. This is in accordance with the study published by Johnson Matthey [4] which indicates that higher cold-start and hot start temperatures allow for significant SCR downsizing.

Case 2a

Considering the excellent tail pipe NO_x results from Case-1b, the catalyst downsizing opportunity was evaluated with BASF proprietary modeling software by reducing SCR length by 50 % relative to the baseline SCR length of 8 inches. The optimized catalyst sizing is shown in Table 10.

The downsized catalyst configuration is simulated with input data wherein the engine was run in CLO thermal management mode during cold start and hot start for the first 400 seconds.

The downsized aftertreatment configuration simulation, with CLO during cold start and hot start, is hereinafter referred to as Case-2a. Tailpipe simulation results of Case-2a are shown in Table 11.

The simulated composite WHTC tailpipe NO_x emissions in Case-2a with the downsized SCR (0.16 g/kWh) also meet the WHTC regulatory NO_x requirement with a very substantial margin.

The downsized configuration was then verified in simulation over the WHSC cycle and tailpipe results, shown in Table 11, demonstrate that the downsized configuration also meets the WHSC tailpipe NO_x requirement with a substantial margin.

Considering the significant margins demonstrated by configurations in Case-1b and Case-2a (with thermal management during both cold start and hot start), it was of interest to understand how close to the regulatory emission limits do we get with the downsized aftertreatment configuration on an OP Engine without any thermal management during hot start portion of the WHTC cycle.

TABLE 11 Case 2a - Composite WHTC and WHSC tailpipe results for downsized configuration

Test Cycle	CO	THC	NO _x
	g/kW-hr		
WHTC	0.944	0.1	0.16
WHSC	0.002	0.001	0.128

NO _x (g/kWh)	WHTC		
	Cold-start	Hot-start	Composite WHTC
Engine Out	4.33	4.32	4.33
Tailpipe Out	0.16	0.15	0.16
NO _x Reduction	96.28%	96.41%	96.39%

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Case 2b

The downsized aftertreatment configuration simulation run with CLO during cold start and normal operation during hot start (no thermal management) is hereinafter referred to as "Case-2b". Simulation results of tailpipe emissions, for Case-2b are presented in Table 12.

Table 12, shows that the composite WHTC tail pipe NO_x emissions for Case-2b, with the downsized SCR and without any thermal management during hot start portion of WHTC, also meet the WHTC regulatory NO_x requirement with a margin of ~ 0.04 g/kWh.

The simulation results of tailpipe NO_x emissions, for the various scenarios studied through BASF proprietary modeling software tool, are summarized in Table 13.

These results demonstrate that there exists a significant opportunity for aftertreatment optimization and downsizing with OP Engines. Further system level optimization is possible depending on the needs of the end application within the multiparameter space comprising variables such as thermal management duration during cold and/or hot starts, reduced catalyst PGM loading, reduced aftertreatment size/volume etc.

The baseline and downsized aftertreatment (AT) catalyst sizes for the Achates OP Engine presented above were compared with the BS-VI aftertreatment catalyst sizes of a conventional four-stroke heavy-duty engine [4] of comparable power and torque in the Indian market. Table 14 shows this catalyst sizing comparison and the aftertreatment downsizing opportunity offered by an OP Engine.

As shown in Table 14, with Achates Power OP Engine there is potential of up to 60 % reduction in SCR catalyst size/volume alone, and up to 38 % reduction in the overall aftertreatment system volume/size. This down-sizing also results in optimized packaging and space claim, reduction in weight and reduction in cost of the after-treatment system. Downsized after treatment system (relative to that on a comparable

TABLE 12 Case 2b - Composite WHTC and WHSC tailpipe results for optimized configuration

Test Cycle	CO	THC	NO _x
	g/kW-hr		
WHTC	0.167	0.046	0.421
WHSC	0.002	0.001	0.128

NO _x (g/kWh)	WHTC		
	Cold-start	Hot-start	Composite WHTC
Engine Out	4.33	4.77	4.708
Tailpipe Out	0.16	0.46	0.42
NO _x Reduction	96.28%	90.29%	91.06%

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TABLE 13 Summary of simulation results of NOx emissions for various scenarios (1a, 1b, 2a & 2b)

WHSC		SCR			WHTC			
NOx (g/kWh)		Length		Engine Op Mode	NOx (g/kWh)	Cold-start	Hot-start	Composite
Engine Out	4.16	8" SCR	1a	Cold= CLO	Engine Out	4.33	4.774	4.711
Tailpipe Out	0.086			Hot = Normal	Tailpipe Out	0.076	0.228	0.207
Nox reduction	97.93%				Nox reduction	98.25%	95.22%	95.61%
		4" SCR	1b	Cold = CLO	Engine Out	4.326	4.323	4.324
				Hot = CLO	Tailpipe Out	0.076	0.062	0.064
					Nox reduction	98.25%	98.56%	98.51%
Engine Out	4.16	4" SCR	2a	Cold = CLO	Engine Out	4.328	4.325	4.326
Tailpipe Out	0.128			Hot = CLO	Tailpipe Out	0.161	0.155	0.156
Nox reduction	96.92%				Nox reduction	96.28%	96.41%	96.39%
		4" SCR	2b	Cold= CLO	Engine Out	4.33	4.770	4.708
				Hot = Normal	Tailpipe Out	0.16	0.463	0.421
					Nox reduction	96.28%	90.29%	91.06%

TABLE 14 Catalyst sizing comparison and downsizing opportunity with OP Engine

	Component	Diameter (in)	Length (in)	Volume (L)	Size Reduction Opportunity
Conventional 4-stroke with BS-VI AT	DOC	10.5	3	4.26	
	CSF	10.5	7	9.93	
	CuSCR	10.5	10	14.19	
	AMOX	10.5	3	4.26	
	Total volume(L)	32.64			
OP Engine with Baseline BS-VI AT	DOC	9.5	3	3.49	18.14%
	CSF	9.5	7	8.13	18.14%
	CuSCR	10.5	8	11.35	20.00%
	AMOX	10.5	2	2.84	33.33%
	Total volume(L)	25.81			20.93%
OP Engine with Optimized BS-VI AT	DOC	9.5	3	3.49	
	CSF	9.5	7	8.13	
	CuSCR	10.5	4	5.68	60.00%
	AMOX	10.5	2	2.84	
	Total volume(L)	20.13			38.32%

four-stroke engine) also offers lower exhaust backpressure/restriction, thereby facilitating further fuel economy improvements from the engine.

In addition to higher engine out temperature during cold-start, the OP Engine architecture inherently offers additional after treatment downsizing opportunities by:

- Lower exhaust flow rates, in comparison to conventional four-stroke engine of comparable power and torque.
- Ability to reduce or cut-off engine out exhaust flows, during motoring operation (when the engine is driven by the vehicle), as explained in the "Multi-cylinder OP engine test bed description" section of this paper.

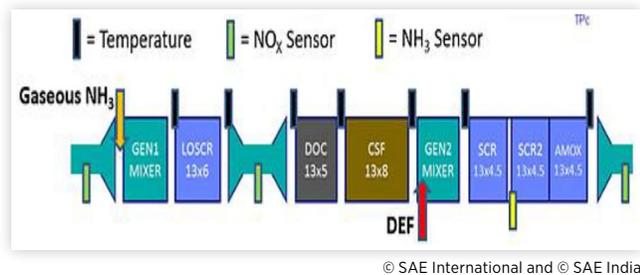
The potential of "reduced-flow during motoring" offered by OP Engines was investigated in BASF proprietary modeling software simulation tool. The simulation results indicate an additional up to 30% opportunity for further

aftertreatment optimization and reduction in PGM metal usage. This is because, the reduced exhaust flow during motoring, prevents or limits cooling of the aftertreatment system and helps to keep the aftertreatment warm and active. It is expected that the benefits of reduced exhaust flow during motoring operation with OP Engines will be even more pronounced on duty cycles wherein the vehicle operates in motoring for extended durations. A resulting additional fuel economy/CO₂ benefit on such motoring-heavy duty cycles is therefore plausible.

Future Proofing: BS-VI and Beyond

In recent years, regulatory bodies in leading emissions regions, are in the process of evaluating and proposing further reduction in criterion emissions and GHG emissions. For example,

FIGURE 15 Ultra Low NO_x solution simulated with the HD 10.6L Opposed-Piston Engine



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TABLE 15 Simulated NO_x performance with the 10.6L OP Engine

10.6L HD OP engine		HD FTP		
with ULNO _x ATS		Cold	Hot	Composite
Engine out	BSNO _x , (g/hp-hr)	3.57	3.75	3.72
Tailpipe Out	BSNO _x , (g/hp-hr)	0.05	0.03	0.03
	Cumulative (grams)	1.44	0.86	
NO _x reduction	% conversion	98.60%	99.20%	99.12%

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the planned 2027 Phase2 GHG emissions standard, the proposed 2024 ultra-low NO_x emission standard by US-EPA [13], and EU proposed GHG reduction plan [14]. Achates Power, publication [5,13] demonstrate that OP Engine can enable meeting these planned and proposed future requirements in a cost competitive way, using the current exhaust after-treatment solutions and a close-coupled SCR catalyst as shown in Figure 15.

In conventional four-stroke engines, for meeting these future NO_x standards, new and advanced emissions solutions are required based on the SwRI ultra-low NO_x study for California ARB [1], adding substantial complexity and cost. Moreover, these emission solutions come at the expense of GHG/fuel economy penalty. Whereas, the Achates Power 10.6L HD OP Engine with ULNO_x ATS was able to deliver ultra-low tailpipe NO_x level, as shown in Table 15.

The Achates Power OP Engine was able to also deliver fuel economy improvement in transient ($\approx 15\%$ less CO₂) and steady state operations ($\approx 12\%$ less CO₂) based on the results

TABLE 16 Overall CO₂/fuel consumption impact to achieve ultra-low NO_x at tailpipe

Engines	BSCO ₂ , g/hp-hr			
	HD FTP			SET
	Cold	Hot	Composite	RMC
13L HD engine (conventional 4 stroke)	574.2	542.6	547.4	457.7
10.6L HD OP Engine with ULNO _x ATS	503.29	454.83	461.7	400.47
Total CO ₂ Reduction with Achates OP Engine			15.70%	12.40%

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shown in Table 16, over the current production 13L HD engine of comparable power and torque meeting 2014 US GHG Phase1 limits.

Conclusion

With respect to meeting the current and future GHG and criterion emissions standards, the conventional four-stroke engines have reached a state of diminishing returns. They present an inevitable trade-off between meeting NO_x emissions and CO₂ emissions. There is a substantial complexity and cost impact, with respect to implementing novel technologies on the conventional four-stroke engines for it to meet future mobility and regulatory needs.

The Achates Power OP Engine provides an ideal solution, as it can meet current BS-VI emission and GHG emission requirements and provides a cost-effective way to meet future planned and proposed regulatory standards. The OP Engine can deliver this without the NO_x vs GHG trade-off that exists with conventional four-stroke engines. Inherent advantages of the OP Engine architecture provide significant opportunities to optimize and downsize the exhaust after-treatment system, offering further cost reduction and performance improvement. There is a considerable merit to also argue for the manufacturing cost reduction opportunity offered by OP Engines because the OP Engine does not require complex engine head sub-system, components like camshafts, valves and because the OP Engine also offers engine cooling package size reduction opportunity due to its inherently lower heat loss.

Thus, the Achates Power OP Engine offers a win-win for transportation, heavy machinery and defense industries, as well as the air quality improvement efforts by regulatory bodies around the world. Therefore, the Achates Power Opposed-Piston Engine design can help encourage wide scale adoption and implementation of the tighter GHG and NO_x emission norms while providing the fuel economy and cost benefits to the end-user.

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Acknowledgments

The authors would like to express their gratitude and sincere thanks to Mr. David Youngren of BASF Corporation for after-treatment simulation analysis support using BASF proprietary modeling software

The authors would also like to thank the leadership team at Achates Power for the support and assistance provided during the WHTC transient testing and simulation phase.

Definitions/Abbreviations

API - Achates Power Inc.

OP - Opposed-Piston Engine

GHG - Green House Gas

EGR - Exhaust Gas Recirculation

BTE - Break Thermal Efficiency

SwRI - Southwest Research Institute

BTE - Break Thermal Efficiency

WHTC - World Harmonized Transient Cycle

WHSC - World Harmonized Steady-state Cycle

EONox - Engine Out NOx emissions

ULNOx - Ultra-low NOx at tailpipe

SCR - Selective catalytic reduction catalyst

DEF - Diesel exhaust fluid.

CLO - Catalyst Light-off

DOC - Diesel Oxidation Catalyst

DPF - Diesel Particular Filter

BS-VI - Bharat Stage VI regulation

ATS - After-Treatment System

Lo-SCR - Light-off SCR (close coupled)