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Achieving Bharat Stage VI Emissions Regulations While Improving Fuel Economy with the Opposed-Piston Engine

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ABSTRACT

The government of India has decided to implement Bharat Stage VI (BS-VI) emissions standards from April 2020. This requires OEMs to equip their diesel engines with costly after-treatment, EGR systems and higher rail pressure fuel systems. By one estimate, BS-VI engines are expected to be 15 to 20% more expensive than BS-IV engines, while also suffering with 2 to 3 % lower fuel economy. OEMs are looking for solutions to meet the BS-VI emissions standards while still keeping the upfront and operating costs low enough for their products to attract customers; however traditional engine technologies seem to have exhausted the possibilities. Fuel economy improvement technologies applied to traditional 4-stroke engines bring small benefits with large cost penalties.

One promising solution to meet both current, and future, emissions standards with much improved fuel economy at lower cost is the Opposed Piston (OP) engine. Recently, there has been surge in developing highly efficient OP engine architecture to modernize it using today's analytical tools, high pressure fuel system and manufacturing technologies to meet emissions, while reaping the fuel economy advantage.

As the company pioneering the OP engine technology, Achates Power Inc. (API) has been publishing technical papers in recent years, including a paper describing inherent efficiency benefits of OP engines, multi-cylinder steady state and transient results for medium duty truck and light duty applications. This technical paper provides detailed performance and emissions results measured on API's 4.9L multi-cylinder OP 2-stroke diesel engine configured specifically to meet BS-VI emissions standards for commercial truck application. The results include:

- Measured performance and emissions data for emissions test cycles.
- After-treatment details and confirmation to meet tailpipe emissions for BS-VI standards.
- Details of API's multi-cylinder test engine's indicated thermal efficiency, friction and pumping losses.
- Comparison with 4-stroke diesel engine.

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INTRODUCTION

The Indian government is introducing Bharat Stage VI (BS-VI) emissions standards (equivalent to Euro VI standards) from 2020, completely by-passing Stage V standards. For commercial vehicles with diesel engines, these standards will reduce the NOx emissions by 88% and Particulate Matter (PM) emissions by 66% from current BS IV standards. Table 1 shows tailpipe emissions and test cycles for BS IV and BS VI emissions standards [1].

Table 1. Tailpipe emissions standards for India.

Standard	Test Cycles	CO	HC	NOx	PM
		g/kWh			
BS IV	European Steady-state Cycle (ESC)	1.5	0.46	3.50	0.02
	European Transient Cycle (ETC)	4.0	0.55	3.50	0.03
BS VI	World Harmonized Steady-state Cycle (WHSC)	1.5	0.13	0.40	0.01
	World Harmonized Transient Cycle (WHTC)	4.0	0.16	0.46	0.01

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While these steps will help reducing pollution from vehicles, it will require costly additional after-treatment devices such as Diesel Particulate Filters (DPF) for trapping exhaust particulate matters and Selective Catalytic Reduction (SCR) for treating engine-out NOx with aqueous urea solution. Additionally, the engine will require Exhaust Gas Recirculation (EGR) system (EGR valve, cooler etc.) for reducing engine-out NOx with upgraded turbocharger. The Diesel fuel system will also have to be upgraded for higher injection pressures to reduce engine out particulates. As per one estimate done by International Council for Clean Transportation, the additional hardware required to upgrade 2.5 L 4-cylinder light duty diesel engines from Euro IV to Euro VI is expected to increase the cost of the engine by $1134 [2]. For 12 L truck engine, this expected cost is $2740 [3]. Even with all cost cutting measures, this increased cost translates into 15 to 20% more expensive engines for BS VI vehicles.

Not only the costs of the engines will increase significantly for meeting BS VI emissions, the fuel consumption will also get adversely affected because of the following reasons:

- Increased exhaust back pressure resulting from more restrictive after-treatment system together with high intake manifold pressure requirements for BS VI engine increase pumping losses.
- Higher EGR requirements also increase pumping losses especially as the recirculated exhaust gas has to pass through restrictive coolers.
- Higher fuel injection pressure requirements result in increased power loss to the fuel pump.
- Increased Peak Cylinder Pressures (PCP) due to higher air and EGR requirements increase friction penalties.

Because of the above mentioned reasons, the BSFC is expected to increase at least 2 to 3% without using additional fuel-saving technologies for BS VI engines in comparison to BS IV engines [4]. With 4-stroke fuel saving technologies proving to be less cost effective in providing improved fuel economy [3][4], there is a serious need for the industry to search for fundamentally better engines. Opposed Piston (OP) engines have been historically more fuel efficient and have potential for reducing engine cost because of simpler architecture and less number of parts [5][8]. These engines are now being investigated by major OEMs around the world as a solution for reducing fuel consumption at lower cost for modern vehicles [6].

Achates Power, Inc. (API), a US based company has been working since 2004 towards developing OP engine technology using today's analytical and manufacturing technologies. Through numerous technical papers, API has explained advantages of its OP engines such as reduced heat losses; leaner, faster and earlier combustion; and higher turbulent kinetic energy at the start of injection with its proprietary piston bowl and two opposing injectors in each cylinder [7][8][10]. API has also explained practical considerations for various applications [8] and demonstrated improved fuel economy while meeting strict engine-out emissions on steady state basis on its multi-cylinder OP 2-stroke research engine [9][10]. This paper describes further investigations on API's multi-cylinder research engine for BS VI emission standards.

MULTI-CYLINDER OP 2-STROKE RESEARCH ENGINE

Details of API's 4.9 L 3-cylinder OP 2-Stroke engine are shown in Table 2 below.

Table 2. Multi-cylinder Achates Power OP 2-Stroke engine specification.

Displacement	4.9 L
Cylinders	3
Bore	98.4 mm
Stroke	215.9 mm
Compression Ratio	15.4:1
Rated Power (kW @ rpm)	205 @ 2200
Max. Torque (Nm @ rpm)	1100 Nm @ 1200-1600

API's 4.9 L 3-cylinder engine has been designed and developed internally for carrying out research and developing OP engine technology before developing production engines with customers. Therefore, it is designed with higher safety margin components to allow investigations for different applications. It is also designed to disassemble quickly and is built with modular components that are switchable. Moreover, this engine has off-the-shelf components without customization, primarily because this engine is not production intent and parts customization costs were unnecessary. All of these factors however, result in higher friction and pumping loss penalties than will be measured on optimized and customized production OP engines.

The air system layout together with on-engine measurement sensors for this particular configuration of the API multi-cylinder engine is described in figure 1.

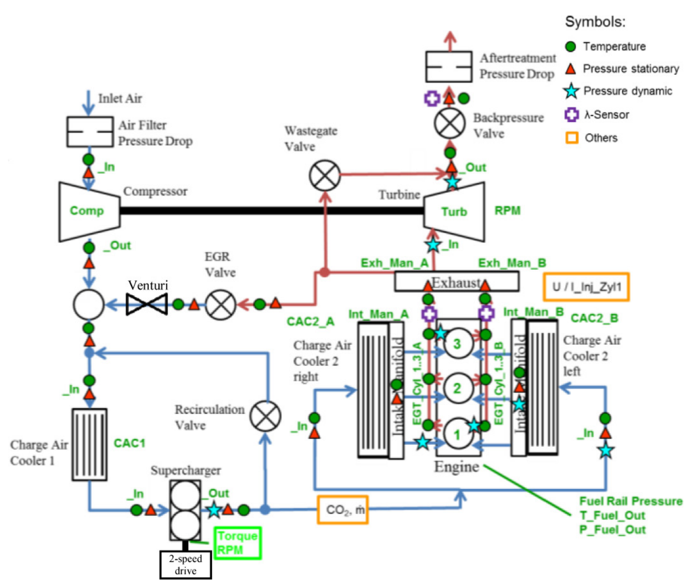

Figure 1. API 4.9L research engine air system configuration & sensor layout.

As seen from the figure 1, API's 3-cylinder inline OP 2-Stroke engine research has turbocharger and a supercharger. It has high pressure EGR system with one intercooler between turbo and supercharger,

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and two small air coolers downstream of supercharger. There are also provisions for supercharger recirculation, 2-speed supercharger drive and wastegate for the fixed geometry turbocharger. Main advantage of this air system include lower pumping losses, faster transient response and improved cold start & warm-up performance [8][10].

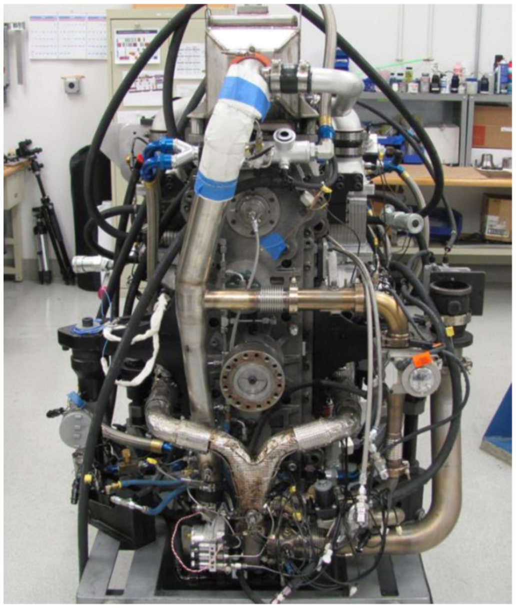

Figure 2. Rear view of API 4.9L research engine on cart.

Figure 2 shows the rear view of API's 4.9 L research engine on the cart ready to be tested on engine dynamometer. More details of the API OP research engine hardware and test cell configuration has been published before in literature [9].

A standard diesel after-treatment system for heavy duty engine with Diesel Oxidation Catalyst (DOC), Diesel Particulate Filters (DPF), Selective Catalytic Reduction (SCR) and Ammonia Slip Catalyst (ASC) has been assumed for meeting BSVI emissions standards. The SCR is assumed to have NOx conversion efficiency of 90% and therefore the engine out NOx target for WHSC is less than 4 g/kWh. The engine out soot target for WHSC cycle is set to be less than 0.025 g/kWh to allow for passive regen of particulate filter during real world driving with low pressure drop. It is assumed that BSIV engine may only have Particulate Oxidation Catalyst (POC) like device in the after-treatment and therefore the engine out NOx for ESC cycle is same as vehicle out (less than 3.5 g/kWh) - which turns out to be only slightly lower to engine out NOx requirements for BSVI engine with full after-treatment.

STEADY STATE TEST RESULTS

The API 3-cylinder research engine torque curve for truck application together with ESC and WHSC points are shown in the figure 3.

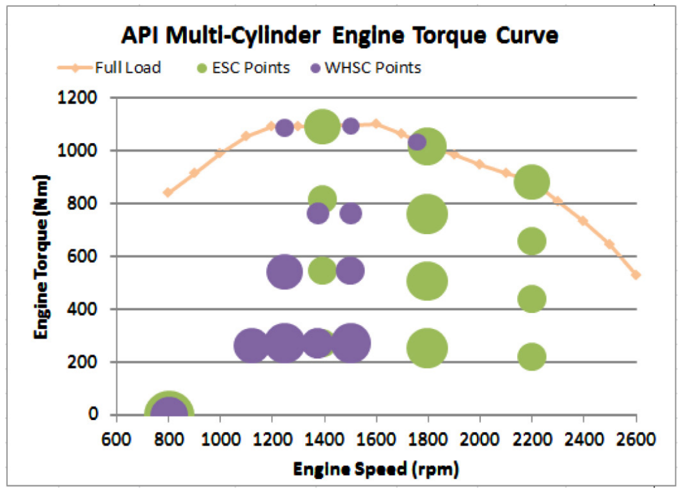

Figure 3. API 4.9L research engine torque curve for truck application with ESC and WHSC points.

As seen from figure 3, the WHSC cycle points are heavily weighted in the low speed and low load region of the torque curve compared to the ESC points. This justifies using of different turbocharger to improve BSFC at lower load and lower speed region for BS VI emissions. However, the engine data was measured for both ESC 13 mode and WHSC points on same air system described earlier.

API has developed control strategy for addressing the challenges of the OP 2-stroke engines. As seen from figure 1, supercharger 2-speed drive and supercharger recirculation valve are two main actuators for controlling air flow; while EGR valve is used for controlling EGR flow. Air massflow is accurately measured with MAF sensor located upstream of the compressor, while EGR massflow is measured with venturi and deltaP sensor in the EGR path. The M470 rapid prototyping open ECU from Pi Innovo has been programmed to allow for firing two injectors simultaneously in one cylinder.

The detailed results of the steady state measurements are shown in the Appendix A. The results show OP engine's high indicated thermal efficiency over the entire engine map. The friction loss for the 4.9L research engine is higher than production version engines as explained earlier. Pumping losses over the engine map are reasonable even with off-the-shelf air system components.

Summary of steady state cycle averaged results are shown in table 3 below. With optimized air system for better BSFC at lower load and speed operating conditions - as required for the WHSC cycle - the cycle averaged BSFC can be reduced about 2 to 4 g/kWh.

Table 3. Summary of ESC and WHSC cycle results.

		ESC	WHSC
BSFC	g/kWh	200	207
BSNOx	g/kWh	3.47	3.62
BSSoot	g/kWh	0.021	0.022
BSCO	g/kWh	1.3	1.5
BSHC	g/kWh	0.10	0.12

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Figure 4 shows BSFC map of API's 4.9 L research engine from these steady state measured results.

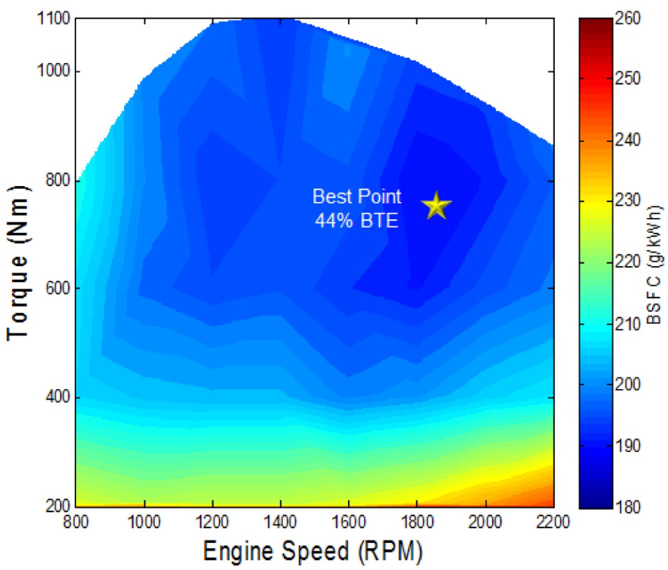

Figure 4. BSFC map from steady state measured data on API research engine.

TRANSIENT CONTROLS AND TEST RESULTS

Compared to the controls software for steady state calibration, the transient operation of the engine need strategy for limiting smoke during acceleration; and for faster actuator response for driving air and EGR. The 4.9L research engine controls strategy was improved with a smoke limiter algorithm and feed-forward controllers for air and EGR actuators.

The smoke limiter algorithm essentially is limiting the amount of fuel that can be injected in the cylinder during acceleration as the air handling devices (turbocharger and supercharger) respond slower than the fuel system. Rail pressure modifier was also implemented for increasing rail pressure during transient.

For increasing airflow during acceleration, EGR valve is closed to allow for more massflow through turbine for reducing turbo lag. For supercharger, first the recirculation valve is closed; if the airflow demand is still not met (or in conditions where the recirculation valve is already fully closed for the starting point), the supercharger 2-speed drive is switched to higher drive ratio. With smoke limiter implemented and higher supercharger drive ratio, the engine was able to achieve the full load torque from 25% load at constant speed within 1.5 seconds with minimal NOx and soot spikes. The torque response time and emissions results for different supercharger drive ratios for OP engine have been discussed in detailed earlier [13].

The 4.9 L research engine was also investigated for transient response with Variable Turbine Geometry (VTG) turbocharger and single gear ratio supercharger. A comparison of VTG turbo with single drive supercharger and fixed geometry turbo with 2-speed supercharger for transient response for 1 second torque ramps at two different engine speeds is shown in table 4 below.

Table 4. Transient response comparison of VTG turbocharger and single speed supercharger Vs FG turbocharger and 2-speed supercharger.

	1400 rpm		1800 rpm	
	Torque response time (s)	Soot (mg/m3)	Torque response time (s)	Soot (mg/m3)
FG turbocharger with supercharger speed ratio of 3.2 and 4.6	1.75	6	1.65	1
VTG turbocharger with supercharger speed ratio of 3.4	7.8	301	4.5	98

As seen from the results, the supercharger 2-speed drive is improving the transient response of the OP 2-stroke engine significantly. With developed transient controls, the 4.9 L research engine was put on test for transient emissions cycle.

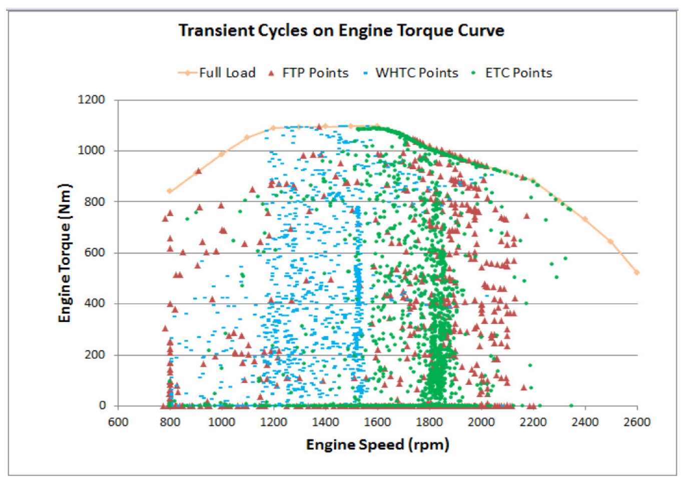

Figure 5. US heavy-duty FTP together with European ETC and WHTC cycles operating points on API 4.9L research engine torque curve.

Figure 5 shows engine operating conditions for three transient cycles - US heavy duty FTP, WHTC and ETC plotted with the torque curve.

As seen from the figure 5, the ETC cycle operates heavily around 1800 rpm for API 4.9L engine (on the higher engine speed region similar to ESC cycle), while the WHTC cycle is weighted more in the region of 1500 rpm (relatively lower engine speed region similar to WHSC cycle). Though the engine operates more in the speed range of 1700 to 2200 rpm for the heavy duty FTP cycle for US 2010 emissions, this transient cycle has wider speed range and larger speed gradients. Also, it is designed for both city as well as highway driving conditions as seen in the figure 6 with New-York Non-Freeway (NYNF), Los Angeles Non-Freeway (LANF) and Los Angeles Freeway (LAFY) segments. Therefore heavy duty FTP was selected for testing transient capabilities of the 4.9 L research engine.

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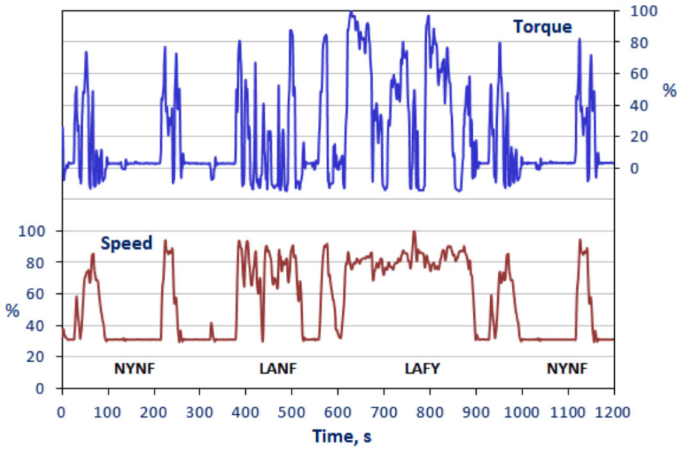

Figure 6. US heavy-duty FTP cycle with NYNF, LANF and LAFY segments [16].

During the transient testing, engine speed, torque and power requirements were appropriately matched with the targets to meet the heavy duty FTP cycle requirements. Statistically, the R^2 values of the measured speed, torque and power compared to the targets were 0.97, 0.94 and 0.98 respectively - within the range specified by the regulations. The heavy duty transient cycle averaged values of BSFC, BSNOx and BSSoot were measured to be 217.3 g/kWh, 4.3 g/kWh and 0.056 g/kWh respectively. When compared with the BSFC map data generated from the steady state measurements, the transient BSFC is only 2.1 g/kWh higher - suggesting that the controls strategies are working decently as required for such application. Detailed description and results of the US 2010 heavy duty transient test for API's 4.9L engine have been published in 2016 SAE paper [11].

Additional to transient controls, API has also developed warm-up strategies for catalyst light off, details of which have been published in other papers [10][13].

CONFIRMING TAILPIPE EMISSIONS

API teamed up with Johnson Matthey - a leading after-treatment supplier to check if the tailpipe emissions of its 4.9L OP engine meet stringent BSVI standards. Johnson Matthey has developed a patented SCRT® aftertreatment system (ATS) which allows for passive regeneration of particulate filter using higher engine out NOx, and SCR to reduce the NOx [12].

The system has DOC with platinum group metals (PGM) as first component to oxidize HC and CO, also to convert NO to NO_2 that helps with passive regen of particulate filter. Second component is Catalyst Soot Filter (CSF) for removing PM. Urea is injected after CSF and before SCR to remove NOx emissions. And finally, ASC is used to oxidize access NH_3. Figure 7 shows schematic of Johnson Matthey's patented SCRT® aftertreatment system.

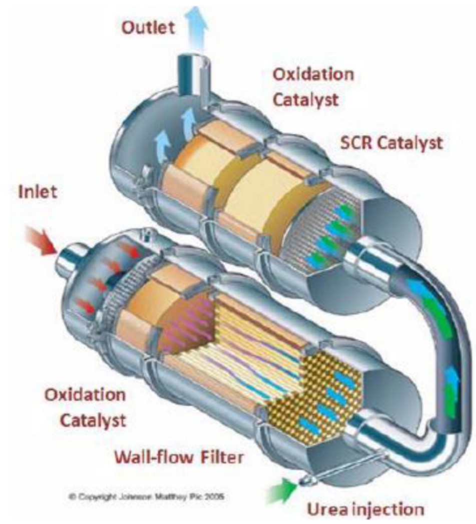

Figure 7. Johnson Matthey's SCRT® aftertreatment system [12].

This system was sized for reasonable space velocities through its components and simulated with chemistry models by Johnson Matthey engineers to check its performance for 13 mode steady state engine out exhaust from API's 4.9L research engine. Full details of the study have been published in 2016 emissions conference paper [12]. The details of the various ATS components size and structure are shown below in figure 8.

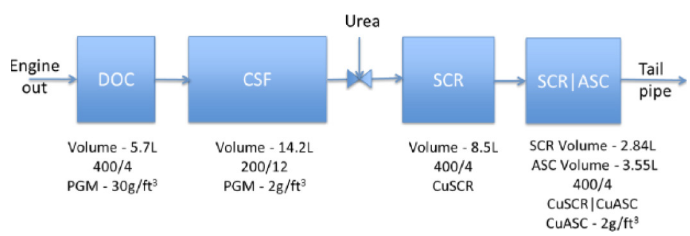

Figure 8. Simulated ATS components volume, CPSI/wall thickness and PGM loading [12].

To check for possibilities of passive regeneration of CSF, the DOC was simulated for two cases -

Case 1. Low Pt:Pd (2:1) ratio aged at 780^0C/10h and

Case 2. High Pt:Pd (5:1) ratio aged at 780^0C/100h [12].

The 100 repetitions of 13 mode steady state cycle results show that for case 2, the DOC would remove THC and CO 92 and 100% respectively [12]. CSF would go through sufficient passive regeneration to stabilize at 1.3 g/L soot loading after 100 ESC tests [12]. The NOx conversion efficiency of 96% can be achieved with the SCR [12]. The maximum pressure drop through this ATS for the steady state cycle simulations is 15 kPa for 0 g/l soot in CSF and 16.5 kPa for 3 g/l soot loading in CSF. Table 5 below show cycle averaged tailpipe emissions for 13 points of the ESC test [12].

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Table 5. Summary of Johnson Matthey ATS simulation results on API's 4.9L engine out cycle-averaged emissions for 13 points of ESC cycle [12].

	Engine out (g/kWh)	Tailpipe (g/kWh)	
		Case 1	Case 2
CO	1.264	0	0
THC	0.102	0.011	0.008
NOx	3.47	0.138	0.120
N_2O	0	0.103	0.112

Results of steady state cycles operating points listed in Appendix A show that the turbine out temperatures of the exhaust for all of the WHSC points except idle range between 250 to 368^{0}C which is similar to the range of 236 to 357^{0}C seen on the ESC cycle points. Therefore, even though the aftertreatment simulations were carried out on 100 cycles of the 13-modes of ESC test, simulating the WHSC operating points with after-treatment should also be able to meet the tailpipe emissions targets.

The same aftertreatment system was also simulated by Johnson Matthey engineers for heavy-duty transient FTP cycle data measured on 4.9 L research engine. Figure 9 below show space velocities through different ATS components and inlet temperature for the heavy-duty FTP cycle.

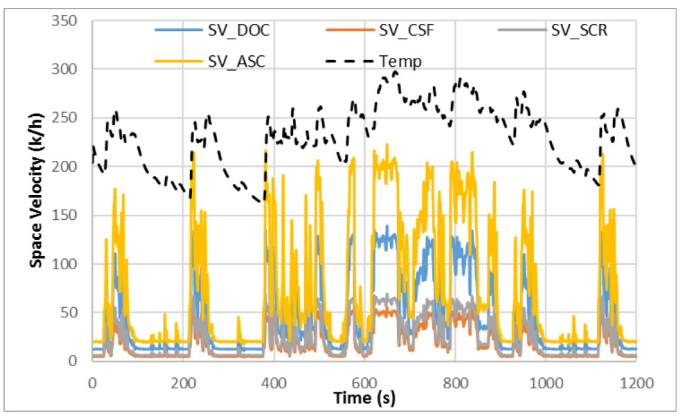

Figure 9. Space velocities through different ATS components and inlet temperature for the heavy-duty FTP cycle.

As seen from figure 9, the ATS inlet gas temperature varies between 160 to 300^{0}C. The maximum pressure drop of the entire ATS for the heavy-duty FTP cycle simulation was 10.4 kPa for 0 g/l soot loading and 12.1 kPa for 3 g/l soot loading. Table 6 below show emissions conversion efficiencies achieved during the heavy-duty FTP cycle simulations.

Table 6. Summary of Johnson Matthey aftertreatment system simulation results on API's 4.9L engine out exhaust for heavy-duty FTP transient cycle.

	Engine out (g/kWh)	Tailpipe (g/kWh)
		Case 2
CO	2.22	0
THC	0.12	0.01
NOx	4.3	0.25
N_2O	0	0129

These ATS system simulations for steady state and transient cycles with measured engine out emissions and exhaust temperatures confirm that API's 4.9 L engine will meet BSVI tailpipe emissions.

COMPARISON WITH 4-STROKE DIESEL ENGINE

The data published in this paper so far is with API's 4.9 L research engine that has high friction penalties as seen in the data table in Appendix A. When the design is optimized for production, API's 4.9 L year 2020 engine has been predicted to achieve best BTE of 48.5% and ESC 12 mode cycle average BTE of 46.6% (180 g/kWh cycle averaged BSFC) [9] while meeting US 2010 emissions (comparable to BSVI emissions standards). These data can be compared with 6.7 L Ford Power-stroke V8 engine [14] and 6.7 L inline 6 Cummins ISB engine (data published in one report by the International Council of Clean Transportation (ICCT) [15] and in another by SouthWest Research Institute (SWRI) [17]). Table 7 below shows comparison of API's 4.9L OP engine with Ford Power-stroke and Cummins ISB specifications.

Table 7. Specifications of comparable 2-stroke OP and 4-stroke engines meeting US 2010 emissions standards (comparable to BSVI) .

	API 4.9 L OP Engine for Medium Duty Truck	Ford Power-stroke for US Pickup Truck [14]	Cummins ISB for US Pickup Truck [17]
Displace-ment	4.9L	6.7L	6.7L
No. of Cylinder	Inline 3	V-8	Inline 6
Stroke	98mm	108mm	124mm
Bore	216mm	99mm	107mm
Rated Power	205 kW, 2200 RPM	300 kW, 2800 RPM	220 kW, 2500 RPM
Peak Torque (PT)	1100 Nm	1085 Nm	900 Nm
PT speed range	1200-1400 RPM	1600-2800 RPM	1600-2200 RPM

The SAE paper with Ford Power-stroke [14] and SWRI report [17] have full steady state BSFC data allowing comparison for steady state cycles. The SWRI report has also predicted the BSFC of improved Cummins ISB engine in year 2019 with reduced friction, improved turbocharger and reduced combustion duration [17]. This data can be compared with API's 4.9L production engine for 2020.

Figure 10 show comparison between various medium duty application engines that meet US 2010 emissions - which are similar to BSVI emissions standards. As seen from the figure 10, API's 4.9 L research engine measured data show 20.7% and 10.7% fuel economy advantage over 2010 Ford Power-stroke and 2012 Cummins ISB engines respectively when compared for 12 operating modes of the ESC cycle excluding idle. With flat fuel map for API's OP engine [8] [9], higher available torque at lower speeds and improved part load fuel economy over 4-stroke engines, the vehicle fuel economy advantage of OP engine in real world driving can be significantly

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higher. When API's production 4.9L engine predicted performance is compared with 2019 Cummins ISB predicted by SWRI [17], the OP engine show 16.2% fuel economy advantage.

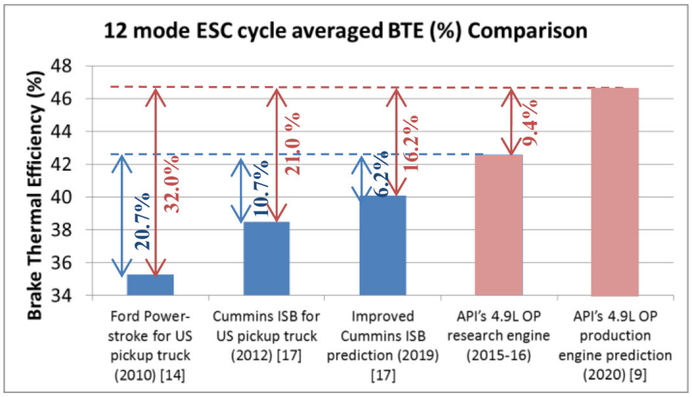

Figure 10. 12 mode cycle averaged BTE results comparison shown together with % improvement with API's OP engines.

The ICCT has published transient heavy duty FTP data for Cummins ISB (year 2011) with calibration that allows for slightly higher torque (1016 Nm) and power (242.5 kW) [15]. The table below show comparison of measured heavy-duty FTP cycle averaged data on API's 4.9L research engine with Cummins ISB MY 2011.

Table 8. Hot start heavy duty FTP cycle results comparison between API's OP engine and Cummins ISB.

	API's 4.9L OP engine (2015-16)	Cummins ISB MY 2011 [15]
Total energy generated over the transient cycle (kWh)	14.7	15.3
Total fuel consumed over the transient cycle (g)	3.2	4.0
Cycle averaged BSFC (g/kWh)	217.3	261.4
Cycle averaged BTE (%)	38.9	31.9
% Improvement	21.9	

As seen from table 8, API's 4.9L OP engine measured data is showing 21.9% fuel economy improvement over Cummins ISB for the heavy-duty FTP cycle. This is substantially higher than 10.7% improvement seen from comparing the steady state data in figure 10. This dataset proves that the flat BSFC map of OP engine helps improve the real world fuel economy almost twice compared to what can be calculated from steady state BSFC map comparison.

SUMMARY

Opposed piston engines have significant fuel economy advantage and potential for lower cost over 4-stroke conventional engines. Achates Power Inc. has pioneered OP engine technology and shown with measured data on its 4.9L research engine that -

- API has successfully developed and implemented controls strategies for the engine to run it effectively on steady state and transient emission cycles.
- When simulated with Johnson Matthey sized conventional diesel after-treatment system, API's OP engine can meet Bharat Stage VI tailpipe emissions standards.
- API's current 4.9L research engine is showing 10 to 21% fuel economy improvement over comparable conventional medium-duty 4-stroke engine. This fuel economy advantage is expected to increase with API's lower friction optimized production engine.

Thus, Opposed Piston engines are capable to address the challenges faced by Indian OEMs to meet Bharat Stage VI emissions standards with reduced cost and offer improved fuel economy to the end users.

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DEFINITIONS/ABBREVIATIONS

API - Achates Power Inc.

OP - Opposed-Piston.

BSFC - Brake Specific Fuel Consumption

BSNOx - Brake Specific Nitrogen Oxides

BSHC - Brake Specific Hydrocarbons

BSCO - Brake Specific Carbon Monoxide

PM - Particulate Matter

THC - Total Hydrocarbon

ESC - European Steady-state Cycle

ETC - European Transient Cycle

WHSC - World Harmonized Steady-state Cycle

WHTC - World Harmonized Transient Cycle

BTE - Brake Thermal Efficiency

VTG - Variable Turbine Geometry

ATS - After-treatment System

DOC - Diesel Oxidation Catalyst

DPF - Diesel Particulate Filter

SCR - Selective Catalyst Reduction

ASC - Ammonia Slip Catalyst

CSF - Catalyst Soot Filter

PGM - Platinum Group Metals

CPSI - Cells per square inch

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APPENDIX

Appendix A: Measured steady state data on API's 4.9L OP 2-Stroke research engine

ESC Cycle

Cycle Weight		0.15					0.05	0.05	0.05	0.08	0.1	0.1	0.1	0.09	0.05	0.05	0.05	0.08
Operating Point		IDLE	PT25	PT50	PT75	PT100	A25	A50	A75	A100	B25	B50	B75	B100	C25	C50	C75	C100
Speed	RPM	800	1201	1200	1200	1200	1400	1400	1400	1400	1800	1800	1800	1800	2200	2200	2200	2200
Torque	Nm	8	281	553	842	1093	291	551	824	1091	268	528	782	1019	229	445	665	882
Brake Power	kW	0.7	35.3	69.5	105.8	137.3	42.6	80.7	120.9	159.9	50.4	99.4	147.4	192.0	52.6	102.5	153.3	203.3
ITE	%	33.2	48.2	49.8	48.7	46.7	49.9	50.7	49.4	48.4	51.8	52.0	50.6	49.2	51.5	52.7	52.5	51.5
BTE	%	4.9	39.0	42.5	42.6	41.4	39.9	42.2	42.7	42.5	38.5	43.0	43.6	42.6	35.7	40.7	42.3	42.2
Pumping Loss	%	3.0	1.0	1.9	1.7	1.6	1.3	2.5	2.2	2.3	2.5	1.9	1.8	1.8	3.4	3.4	3.0	2.8
Friction Loss	%	25.3	8.1	5.4	4.4	3.7	8.7	5.9	4.4	3.5	10.8	7.1	5.2	4.8	12.3	8.6	7.3	6.5
BSFC	g/kWh	-	215	197	196	203	210	198	196	197	217	195	192	197	234	206	198	199
BSNOx	g/kWh	34.09	2.44	4.22	5.26	4.75	2.16	3.91	4.15	3.98	2.55	3.85	3.89	4.87	2.02	2.56	2.29	1.98
BSSoot	g/kWh	0.005	0.025	0.023	0.021	0.045	0.033	0.013	0.016	0.023	0.035	0.014	0.011	0.019	0.038	0.024	0.014	0.033
BSCO	g/kWh	23.9	0.5	0.4	2.1	7.6	0.6	0.3	1.1	3.1	0.7	0.2	0.8	2.4	0.7	0.3	0.3	1.3
BSHC	g/kWh	3.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rail Pressure	bar	587	802	615	884	1024	701	818	923	1098	716	845	1136	1291	895	981	1418	1827
Fuel Flow	kg/h	1.1	7.6	13.7	20.8	27.8	9.0	16.0	23.7	31.5	11.0	19.4	28.3	37.8	12.3	21.1	30.4	40.4
AFR	-	101.8	29.4	32.2	27.6	26.0	30.7	32.1	27.6	25.6	34.7	29.3	24.5	22.8	32.5	30.1	25.5	22.5
EGR Rate	%	35.8	29.0	28.7	26.2	20.3	29.4	30.2	28.4	27.5	30.0	26.8	26.3	23.2	31.6	30.7	31.6	30.5
Int. Man. Press.	bar A	1.07	1.22	1.71	2.11	2.59	1.32	1.88	2.33	2.87	1.54	2.05	2.51	3.14	1.60	2.22	2.73	3.29
Exh. Man. Temp	deg C	139	287	334	393	451	291	329	389	433	280	365	437	506	298	337	397	470
Turbine Out Temp	deg C	150	262	272	304	336	260	256	292	312	236	276	321	357	251	253	287	328
Turbine Out Press.	bar A	1.01	1.03	1.06	1.10	1.15	1.03	1.06	1.10	1.14	1.05	1.08	1.11	1.16	1.06	1.09	1.13	1.17

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WHSC Cycle

Cycle Weight		0.17	0.02	0.10	0.03	0.02	0.08	0.03	0.06	0.05	0.02	0.08	0.10
Operating Point		IDLE	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12
Speed	RPM	800	1500	1500	1500	1246	1119	1374	1374	1500	1756	1246	1246
Torque	Nm	8	1076	273	766	1074	269	769	271	553	1023	549	276
Brake Power	kW	0.7	169.0	42.9	120.3	140.2	31.5	110.7	39.0	86.8	188.0	71.6	36.0
ITE	%	33.2	48.6	50.5	50.2	47.8	48.2	49.4	49.8	50.7	48.4	50.0	48.7
BTE	%	4.9	41.8	39.3	42.6	42.2	39.1	42.6	39.4	42.1	42.2	42.4	39.2
Pumping Loss	%	3.0	2.8	1.7	2.5	1.7	1.0	2.1	1.3	2.8	1.4	2.1	1.1
Friction Loss	%	25.3	4.0	9.4	5.1	3.9	8.1	4.7	9.1	5.8	4.7	5.5	8.4
BSFC	g/kWh	-	200	213	197	199	214	197	213	199	198	198	214
BSNOx	g/kWh	34.09	3.76	2.40	3.76	5.40	1.95	4.06	2.16	3.69	4.13	4.36	2.42
BSSoot	g/kWh	0.005	0.021	0.025	0.016	0.023	0.023	0.019	0.024	0.013	0.040	0.019	0.021
BSCO	g/kWh	23.9	2.8	0.6	0.9	4.1	0.5	1.1	0.6	0.3	5.1	0.4	0.5
BSHC	g/kWh	3.6	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Rail Pressure	bar	587	1146	710	999	1044	790	890	708	849	1313	653	782
Fuel Flow	kg/h	1.1	33.8	9.1	23.7	27.9	6.8	21.8	8.3	17.3	37.3	14.2	7.7
AFR	-	101.8	25.2	33.1	27.4	26.6	29.7	27.7	30.9	30.8	22.1	32.6	30.6
EGR Rate	%	35.8	26.8	29.6	28.1	21.0	29.5	28.5	29.3	28.4	23.6	29.0	29.2
Int. Man. Press.	bar A	1.07	3.04	1.37	2.31	2.63	1.19	2.19	1.29	1.95	3.04	1.76	1.25
Exh. Man. Temp	deg C	139	439	284	387	440	279	383	286	345	514	334	305
Turbine Out Temp	deg C	150	311	250	289	324	260	292	258	266	368	269	282
Turbine Out Press.	bar A	1.01	1.15	1.04	1.10	1.13	1.02	1.09	1.03	1.07	1.16	1.06	1.03

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