

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.

CITATION: Naik, S., Johnson, D., Fromm, L., Koszewnik, J. et al., "Achieving Bharat Stage VI Emissions Regulations While Improving Fuel Economy with the Opposed-Piston Engine," *SAE Int. J. Engines* 10(1):2017, doi:10.4271/2017-26-0056.

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

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.

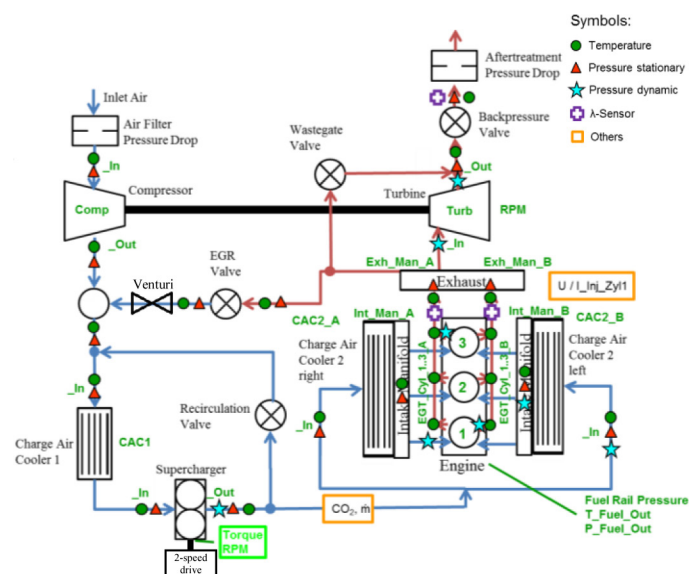


Figure 1. API 4.9L research engine air system configuration & sensor layout.

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.

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].

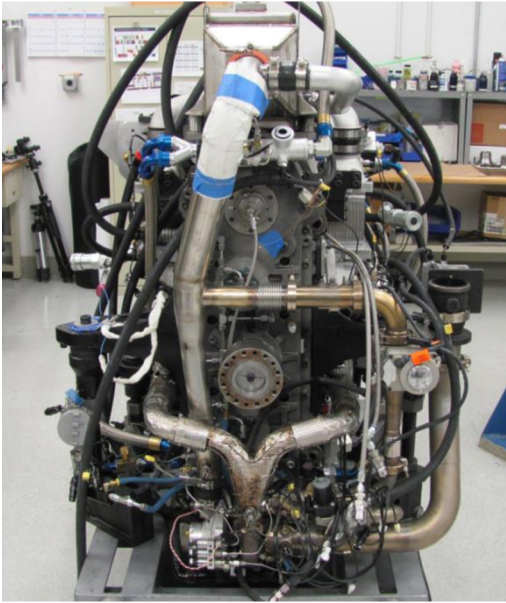


Figure 2. Rear view of API 4.9L research engine on cart.

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 NO_x conversion efficiency of 90% and therefore the engine out NO_x 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 BSVI engine may only have Particulate Oxidation Catalyst (POC) like device in the after-treatment and therefore the engine out NO_x 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 NO_x 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.

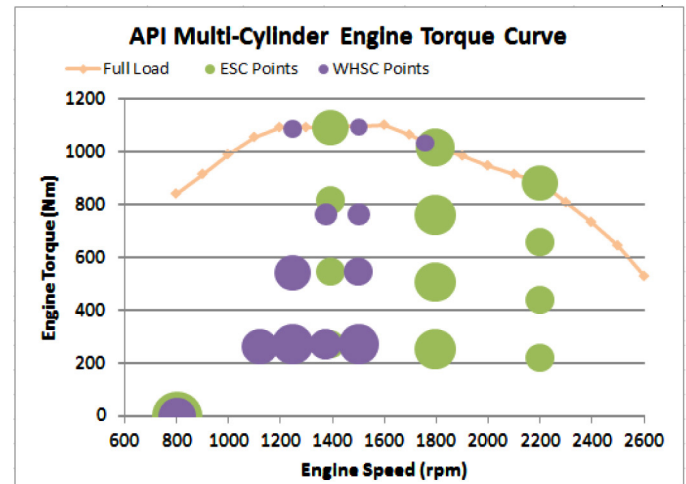


Figure 3. API 4.9L research engine torque curve for truck application with ESC and WHSC points.

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
BSNO _x	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