

Valve-Event Modulated Boost System: Fuel Consumption and Performance with Scavenge-Sourced EGR

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ABSTRACT

In our introductory paper on the VEMB system (SAE 2010-01-1222) we discussed the concept of a divided exhaust period turbocharging system controlled by a concentric cam system, and we presented several fixed speed/load point sets of results that demonstrated the expected BSFC benefits. The BSFC reductions (2.5% to 4%) correlated to reduction in pumping work and to improvement in combustion phasing at knock-limited points from substantial reductions in Residual Gas Fraction compared to the conventionally-boosted baseline engine. In this paper we present additional results from engine tests in the areas of full-load performance and emissions with and without Scavenge-sourced EGR.

To demonstrate the WOT performance potential of a VEMB engine, we show the effect of turbocharger matching steps, with results that exceed the baseline engine output across the engine speed range. In addition we explore the unique aspects of the EGR system of a divided exhaust period engine, for which we can take advantage of the large differentiation in enthalpy and chemistry between the Blowdown and Scavenge manifolds. The Scavenge-sourced EGR has lower temperature and pressure than the Blowdown manifold or the baseline conventionally-boosted engine. In addition, the Scavenge manifold has 3 to 5 times the HC concentration of the Blowdown manifold. Results of this investigation are presented that show significant advantages to Scavenge-Port-sourced EGR.

Finally, to complete the BSFC and emissions benefits picture, sufficient additional speed and load points have been run with and without external EGR, across the speed and load range to enable mapping the BSFC benefits across the speed and load range of a boosted GDI engine.

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INTRODUCTION

In our introductory paper on the VEMB system [5], we demonstrated that a boost system based on a divided exhaust period turbocharging system and controlled by a concentric-cam system on the exhaust side of the cylinder head, could deliver significantly improved BSFC at several speed/load points through significant reductions in PMEP at all test points measured. At knock-limited test points, additional efficiency improvements were demonstrated due to significant RGF reductions attributed to improved pressure drop across the head which allowed us to avoid or reduce retarded combustion phasing. Demonstrated BSFC improvements were up to 4% compared to the base engine at fixed part-load speed/load points. In this follow-up paper we will further explore the VEMB system benefits in these areas:

- Additional BSFC mapping throughout engine speed/load range
- Full-load capability and efficiency improvements

- Cooled EGR results across the speed/load range

VEMB CONCEPT REVIEW

SYSTEM PRINCIPLES

The Divided Exhaust Period method of turbocharging an internal combustion engine has been previously disclosed in SAE paper 2005-01-1150 [1], and patents by General Motors, Mazda (Japan), Lotus, Fleming Thermodynamics (1986) and in a 1924 British patent. The basic principle is to separate the 2 exhaust valve flow paths from each cylinder into separate exhaust manifolds, where only one manifold is attached to the turbocharger turbine inlet. The valve events for the manifold to the turbine inlet are biased towards the Blowdown phase of the exhaust process. The Blowdown phase of the exhaust process is defined as the initial portion of the exhaust process that occurs directly after the opening of the exhaust valve(s) where the process is primarily driven by the pressure difference between the residual cylinder and exhaust

manifold. This occurs in the vicinity of Bottom dead Center (BDC) where the piston velocity and change in piston displacement is low.

The second exhaust manifold is connected directly to the vehicle's exhaust system which includes catalytic converter(s). The valve events for this manifold's exhaust valves are biased towards the displacement (scavenging) phase of the exhaust process. The Scavenge phase of the exhaust process is defined as the latter portion, where the exhaust flow is primarily driven by the displacement of the piston, ending in the vicinity of Top Dead Center (TDC) as the exhaust valve(s) close.

By connecting a turbocharger to a divided exhaust period engine in this manner, the high backpressure between the turbine inlet and the exhaust port is isolated from the engine piston during most of the exhaust stroke, resulting in lower PMEP (and therefore better engine efficiency). If the timing of the blowdown exhaust valve event and the scavenging exhaust valve events are varied, the turbocharger boost level can be varied without the use of a wastegate or variable turbine geometry system.

In previous Divided Exhaust Period investigations, the phase relationship between the Blowdown and Scavenge cams was fixed, and the energy apportioned to the turbocharger was varied by changing the cam phase of the exhaust camshaft which held the Blowdown and Scavenge cams. In the VEMB system, the phase relationship between the Blowdown and Scavenge valve-events is controlled by a concentric-cam system shown in [Figure 1](#). The concentric-cam system for the exhaust valvetrain is a joint development project between BorgWarner and ThyssenKrupp Presta. The Scavenging camshaft lobes are connected to a BorgWarner cam-phaser by an inner shaft running the length of the camshaft. The actuation authority for the Scavenging lobes for this testing was 60° crank. Further details of this system are in our earlier VEMB paper [5].

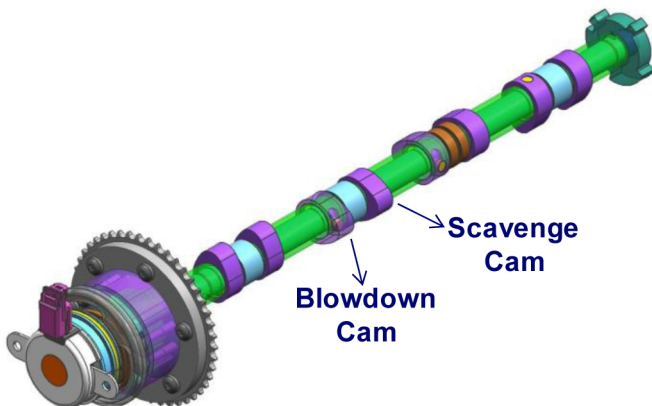


Figure 1. Concentric Cam System

The phase relationship between the Blowdown and Scavenge valve events yields a direct effect on the percentage of exhaust energy delivered to the turbocharger vs. bypassing the turbocharger. If we consider the effect of the concentric-

cam phase setting on the overlap between the 2 cams as shown in [Figure 2](#), and define this as the Blowdown-Scavenge Overlap Area, we can summarize the operation of the concentric cam system operation strategy as follows:

- At any engine speed/load:
 - Smaller Blowdown-Scavenge Overlap Area increases energy to the turbine
 - Accomplished by retarding the Scavenge cam
 - Larger BSOA decreases energy to the turbine
 - Accomplished by advancing Scavenge cam
- At low engine speed:
 - Advancing Blowdown (Exhaust Valve Opening) increases energy to the turbine
 - Best BSFC EVO will be similar to conventional engine (retarded compared to best power)
 - Scavenge valve closing time will effect TDC valve overlap area (along with intake cam phase)
 - Best BSFC Scavenge phase will be minimum retard that attains power target
- At high engine speed:
 - Blowdown timing (EVO) will be similar to conventional engine
 - Best BSFC Scavenge phase will be minimum retard that attains power target

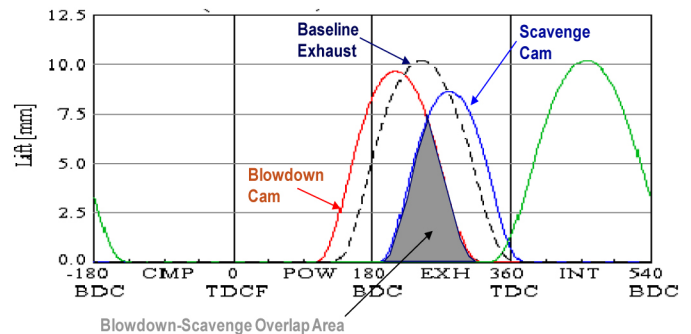


Figure 2. VEMB Operation Principles - Blowdown-Scavenge Overlap Area

VEMB System Differentiation Summary

The BorgWarner VEMB system is an improvement on the basic Divided Exhaust Period turbocharging system by incorporation of the following features:

- Concentric-cam System on Exhaust to control energy delivery to turbine

- Non-wastegate turbocharger (wastegate not required for boost control)
- Scavenge and/or Blowdown side sourced EGR system

The basic architecture of the engine system is shown below in [Figure 3](#) without EGR system and in [Figure 4](#), with 2 Scavenge-sourced EGR paths:

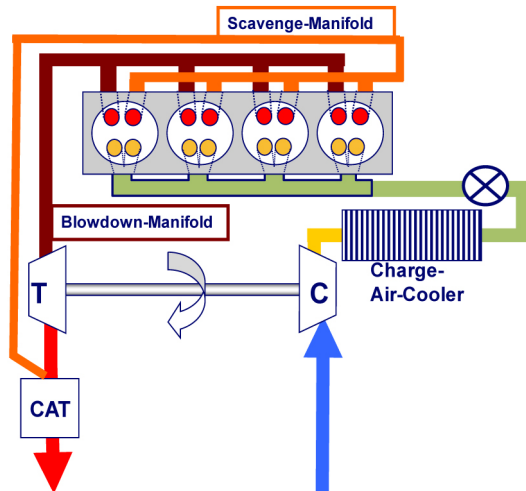


Figure 3. VEMB System Architecture without EGR

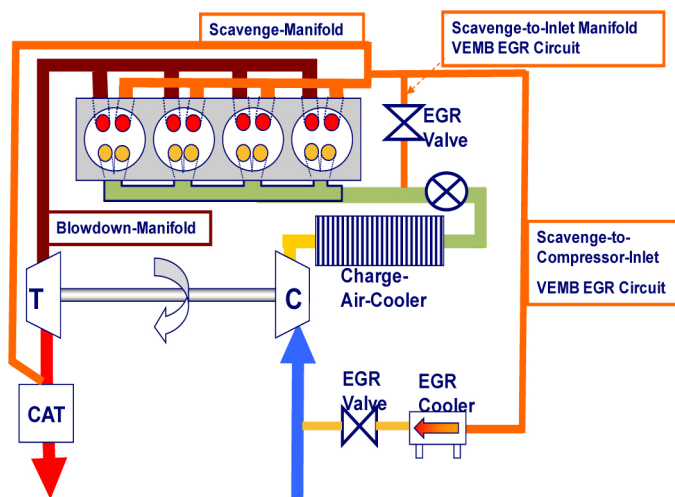


Figure 4. VEMB System Architecture with Scavenge-sourced EGR

VEMB ENGINE FULL-LOAD PERFORMANCE

GOALS

For this project we emphasized exceeding the low and medium-speed full-load performance of the base engine, while matching the rated-speed performance. This goal was chosen because in the original Divided Exhaust Period [1] paper, matching the base engine's low-speed output was

difficult to achieve without the flexibility of the concentric-cam system, though the rated-speed output was readily exceeded with cam-phaser-alone control of the exhaust valve events.

Engine Specifications

The test engine was a side-injector Turbocharged GDI engine rated at peak BMEP of approximately 21 Bar as-equipped with a twin-scroll Turbocharger in current production. It was run with an open-architecture version of the production ECU which allowed us full-control of fuel injection, cam phase, and ignition timing. The engine specifications are listed below in [Table 1](#).

Table 1. Test Engine Specifications

Engine Type	SIDI Turbo
Displacement	1998 cm ³
Valvetrain Type	DOHC w/ roller finger follower, DCP
Valve diameters (mm)	35 intake, 31 Exhaust
Compression Ratio	9.2:1
Max. Torque	350 Nm
@ engine speed	2000 Rpm
Max. Power	194 / 260 kW / HP
@ engine speed	5300 Rpm

TURBOCHARGER MATCH OPTIMIZATION

1-D Simulation

Optimization of the breathing parameters of the VEMB engine generally requires an iterative approach, since the following aspects all effect performance and have strong interactions:

- Exhaust Blowdown Valve-Events
- Exhaust Scavenge Valve-Events
- Exhaust and Intake Port-flow characteristics
- Blowdown and Scavenge manifold tuning
- Turbocharger matching

In our initial report, we set up the test engine based on a GT-Power model built with correlation to only the base engine and a single-optimization of valve-events based on our initial best-guess turbocharger match. For the effort to optimize the turbocharger match we spent considerable effort in correlating the VEMB test engine results to the GT-Power model with particular emphasis on:

- Combustion characteristics
- Turbine inlet Temperature and cycle-resolved Pressure
- All air-path temperatures

As a result of this effort we were able to achieve excellent correlation between the base engine test results and the GT-