Turbo matching for a Gasoline engine with Miller combustion and VTG control

H. Björnsson [a,1] L. Johansson [a,2] A. Frosteman [a,3] J. Ohlsson [a,4]

a Powertrain Engineering Sweden AB, UNI3 Pumpgatan 1, 417 55 Gothenburg, Sweden.

Abstract: Aurobay have added a 145kW (LP version) Miller engine to the Aurobay VEA gasoline engine line-up. This new engine shares base technology with the VEP MP engine but uses the Miller cycle and a VTG Turbo in addition to reduce fuel consumption.

The Miller concept that was developed for the VEP LP engine includes increased compression ratio, a short intake valve opening duration, new intake ports as well as new piston design and a new VTG turbo. The Miller concept, together with the integrated exhaust manifold, enables operation in the complete operating range of the engine without the need for fuel enrichment. The VTG turbo, together with an improved intake camshaft phaser provides the torque increase to the same rate as the VEP MP non-Miller engine. Meanwhile, the Miller cycle contributes to significant fuel efficiency improvements in the complete engine map compared to the non-miller derivatives.

Since the fundamental strategy of the Miller cycle leads to a reduction in volumetric efficiency, one of the most critical design aspects is to perfectly match the turbo charger to the combustion

In addition, this Miller engine proves that there’s a high potential to reduce fuel consumption as well for high specific performance engine as the next step in ICE development.

Key Words: VTG; Miller; Fuel consumption;

1 VEA architecture and background

During 2013 to 2015 the VEA engine architecture and first generation of the VEA-family was introduced on the market. This family of engines includes 2.0L, 4 cylinder gasoline (VEP) and diesel (VED) derivatives. In total, total eight engine variants were developed: four diesel engines and four gasoline engines with various power levels and with very high commonality and compactness.

In 2017 an emission upgrade was performed to enable the VEA generation 2 to full fill higher emission requirements. This was done by introducing SRC for diesel and GPF on gasoline. Same year our first 3-cylinder 1,5L engine, called GEP3 was launched. VEA generation 2 and GEP3 introduction was the first step toward VEA generation 3.

In 2019 it was time for a third upgrade of the VEA family and focus was on the high-performance diesel, medium-performance, and high-performance gasoline engines. Project target was to improve fuel consumption, emissions and NVH while maintaining a high commonality between all variants and lower fuel consumption in and outside emissions cycle for all driving conditions.

As one fuel consumption reduction measures, a 48V belt driven integrated started and generator (B-ISG) was introduced on all VEA Gen 3 engines which also improves the transient response. In addition, Lambda 1 performance was improved by using an integrated exhaust manifold on MP engine while adding low pressure EGR on HP variant.

To improve NVH behavior of the VEA the whole base engine was stiffened up and natural frequency for dressed engine was increased. The roots supercharger was replaced on HP variant with an electrical compressor which improved NVH and as well reduced the system weight by 5 kg.

Emission target was set to comply with Euro6d in real driving emissions (RDE). By increasing the fuel pressure, a better mixing and a significant PN reduction could be achieved. Close injection to spark distance gives stable combustion during catalyst heating and split injection in heat mode provides fast heat up.

The response was improved, not only due to the 48V system but also by changing a position of the turbo to a high position and shortening the air paths which gives faster air control and reduced pressure drop.

2 VEP LP main objectives and features

To complete the VEA gen 3 petrol line up a new LP (Low Power) variant has now also been successfully developed. The engine is designed for maximum power level of 145kW at 4750 rpm and max torque of 300 Nm from 1500 rpm. By adding Miller concept and a VTG Turbo the efficiency in the complete engine map has been improved. Project target was a CO_2 reduction in WLTC of 3% vs the MP engine in a reference vehicle and a reduction in real driving fuel consumption. All fuel enrichment has been removed and the engine is running lambda 1 with best emission efficiency in the entire engine map. This was possible to achieved by adding Miller cycle together with a VTG Turbo and the project target was with margin fulfilled.
Mass production of this new engine started in Aurobay engine plant in Sweden in October 2021 and has now also started mass production in our engine plant in China beginning of 2022.

.

Tab. 1 Main characteristics of VEP Gen3

	Unit	VEP LP	VEP MP	VEP HP
Layout and Fuel Type	-	In-line Petrol		
Number of Cylinders	-	4		
Displacement	cm^3	1969		
Stroke	mm	93.2		
Bore	mm	82		
Stroke / Bore Ratio	-	1.14		
Cylinder Pitch	mm	91		
Cylinder Block Height	mm	220.0		
Main Pin Diameter / Width	mm	53/26		
Conrod Pin Diameter / Width	mm	50/22		
Conrod Length	mm	143.8		142.8
Piston Pin Diameter	mm	21		23
Number of Valves per Cylinder	-	4		
Valve Angle	°	39.0		
Intake Valves - Head Diameter	mm	30.5		
Exhaust Valves - Head Diameter	mm	26.5		
Intake Cam - Phaser Range	°CA	70	50	
Exhaust Cam - Phaser Range	°CA	30	42	
Intake Cam Duration @ 1 mm Lift	°CA	140	194	201
Exhaust Cam Duration @ 1 mm lift	°CA	183	183	190
Max. Fuel Injection Pressure	MPa	45		
Fuel Grade		98 RON (EN228)		
Alternative Fuels		E25, M15		
Compression Ratio	-	12.0	10.5	9.0

Max. Power	kW	145	184	220
-At Speed	rpm	4750	5400	5400
Max. Torque	Nm	300	350	420
-At Speed	rpm	1500	1800	2100
Emission Compliance		EU6d ULEV70 J-SULEV Ch6b Brazil		
48V B-ISG Max. Regen. Power	kW	12		
48V B-ISG Max. torque @ Crank	Nm	130		
Weight (DIN 70020-GZ)	kg	139.8	141.4	152.0

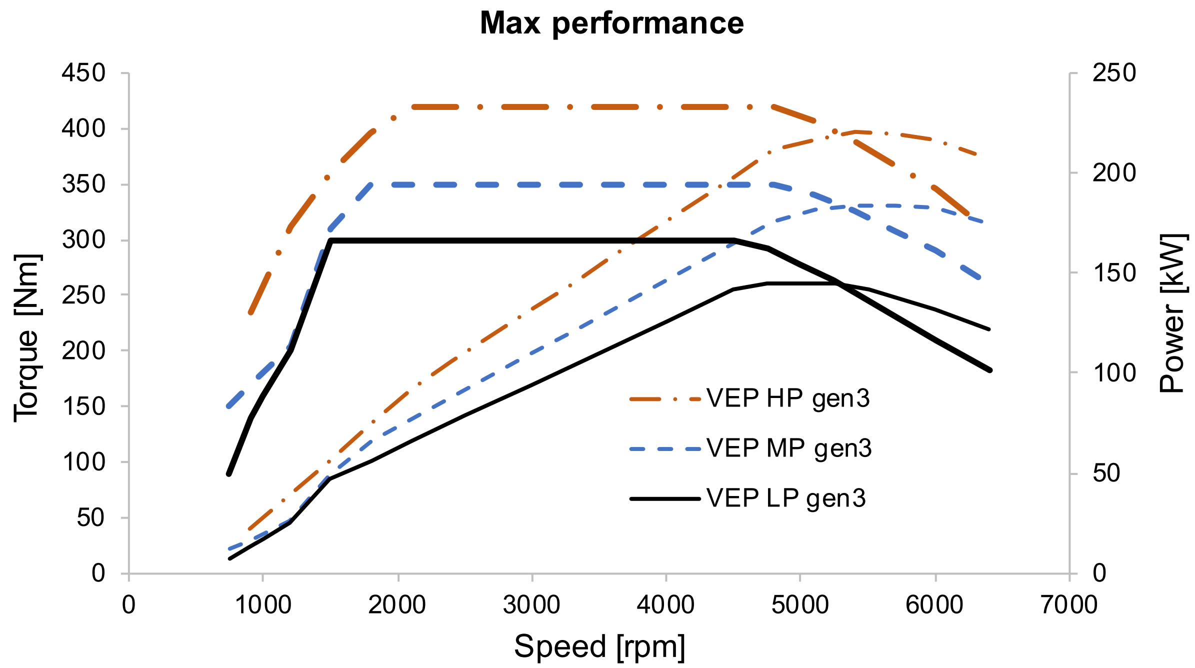


Fig. 1 Max torque and power of VEP Gen 3 LP, MP and HP.

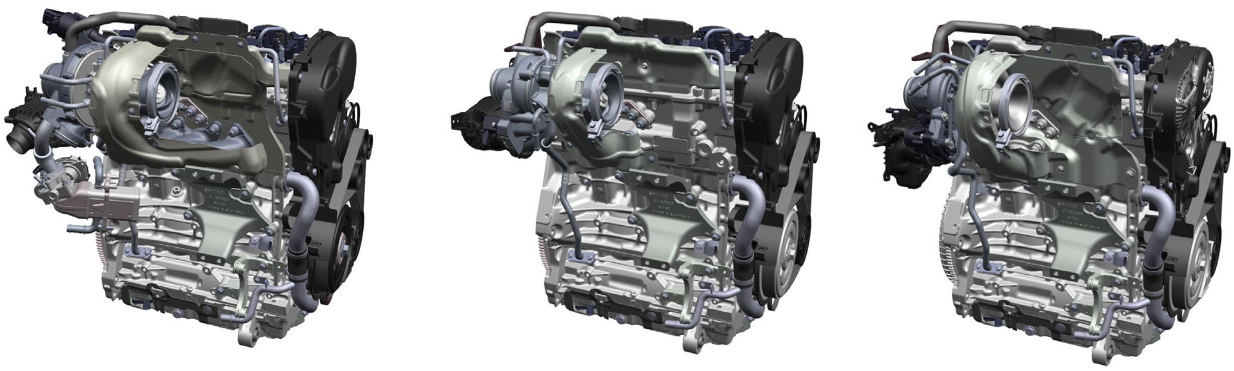


Fig. 2 VEP Gen3: HP (left), MP (middle) and LP (right).

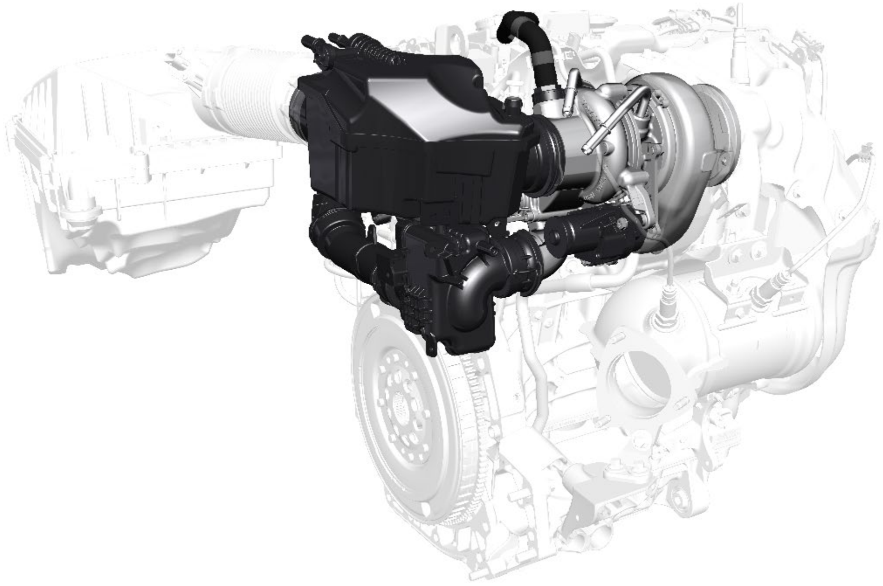


Fig. 3 Hot side of VEP LP with VTG Turbo and air routing and resonators.

3 The Miller Concept

With a Miller concept the geometrical compression ratio is increased while the effective compression ratio, compression experienced by the gas in the cylinder, is controlled by intake valve closing and the intention is to increase the power density. For the LP engine Miller this technology has been used to improve the fuel efficiency in the complete engine map and eliminate all fuel enrichment while keeping low exhaust gas temperature.

The VEA MP engine was used as base, while the compression ratio was increased from 10,5:1 to 12:1. To keep the commonality with MP engine this was achieved by re-designing the top of the piston. An intake camshaft with shorter opening duration was implemented. The intake duration was shortened from 194 CAD@ 1 mm lift to 140 CAD@ 1 mm lift. The stroke of the intake cam phaser increased from 50 to 70 CAD to provide increased control over the volumetric efficiency also considering robustness to meet torque target at high ambient temperature and with low octane fuel. The exhaust cam profile is identical to the one on MP engine (183 CAD@ 1 mm lift) but the cam phaser stroke was reduced from 42 to 30 crank angle degrees (CAD). A faster and more robust intake cam phaser together with a new trigger wheel design was implemented to provide faster and more robust cam phaser control.

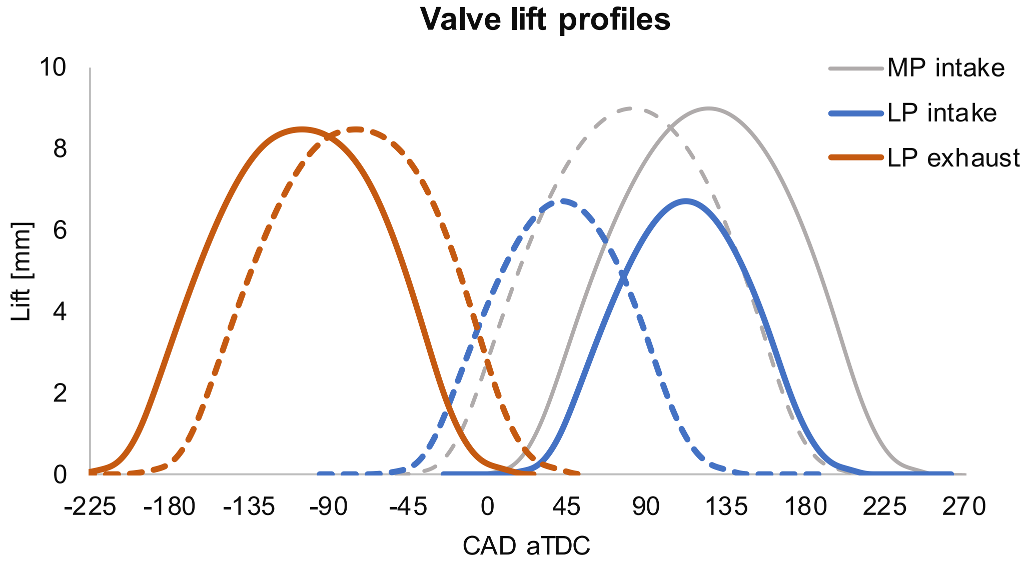


Fig. 4 Intake and exhaust valve lift profiles for MP and LP engine. Solid curves are cam phaser in base position and dotted curves its max position.

To get best fuel efficiency the intake camshaft is phased early in almost the whole engine operation map. Exceptions are at low engine speed, high torque where the turbocharger efficiency is limiting and at low torque where an early intake valve closing causes combustion stability issues.

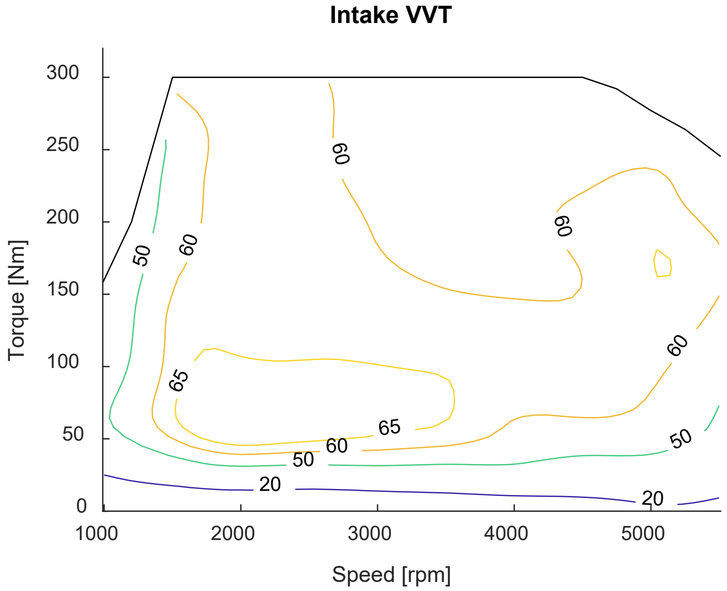


Fig. 5 Intake cam phaser position of VEP LP in steady state operation.

The intake port for LP engine was redesigned for higher tumble to maintain the combustion speed with the shorter intake cam duration.

A completely new Turbo charger with variable turbine geometry was matched and tailormade for the LP engine. To keep the commonality between these engines, all interfaces around the turbo charger was kept the same between VEA non-Miller and Miller application.

The combination of all these modifications provides a significant fuel efficiency improvement compared to the existing MP engine.

When developing and optimizing the engine hardware for best efficiency, 1D and 3D system simulations was combined with single- and multi-cylinder testing. This strategy follows a long tradition of CAE and test correlation at Aurobay.

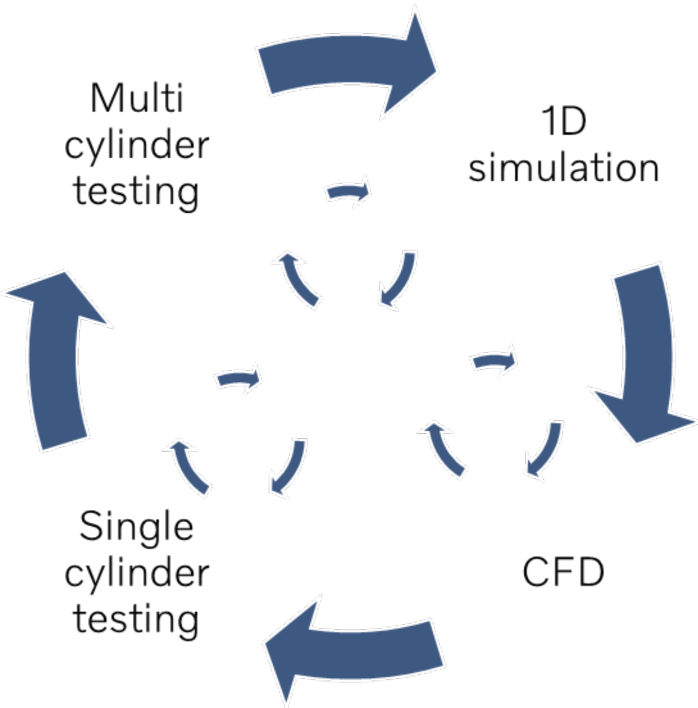


Fig. 6 Schematic description of iteration loops in CAE and testing.

4 Simulation work in 1D

One of Aurobay standard procedure is to perform several pre studies of different concepts using 1D in early project phases. Based on these studies a VTG Turbo together with Miller combustion was chosen.
A shorter Miller intake cam was chosen to enable earlier combustion phasing and togetherer with a VTG Turbo the pressure before turbine could be significantly lowered. The lower backpressure also reduces residual gases in cylinder which helps to reduce residual gases to the combustion and lower temperature into turbine.

With the Miller concept, part of the compression work is moved from the cylinder to the compressor and hence the compressor need to perform at higher pressure ratios. At first, a basic turbo matching was caried out to establish a full load operation line according to targets. The aim was to have good compressor surge margin and to get maxi-mum compressor efficiency at the peak power point while not exceeding the compressor outlet temperature limit.

Design of Experiment (DoE) studies of intake cam duration and compression ratio (CR) for complete VVT-sweeps at all relevant load points was conducted. Sensitivity analysis for the intake valve lift, exhaust cam duration, compressor efficiency, and pressure drops were conducted to make sure margin to the project targets. These studies proved that the concept was solid even before engine tests started

As soon as the first engine results was available the 1D model was calibrated correlation testing was performed to understand the engine characteristic and hence broaden the picture and understand if testing data was sufficient. After this proof-of-concept studies was complete, detailed turbo matching, camshaft strategy and compression ratio studies could be done.

5 Specific fuel consumption

VEA LP engine sweet spot BSFC is @3000rpm/240Nm area. At this point 218 g/kWh was reached. Which means 39,3% in thermal efficiency.

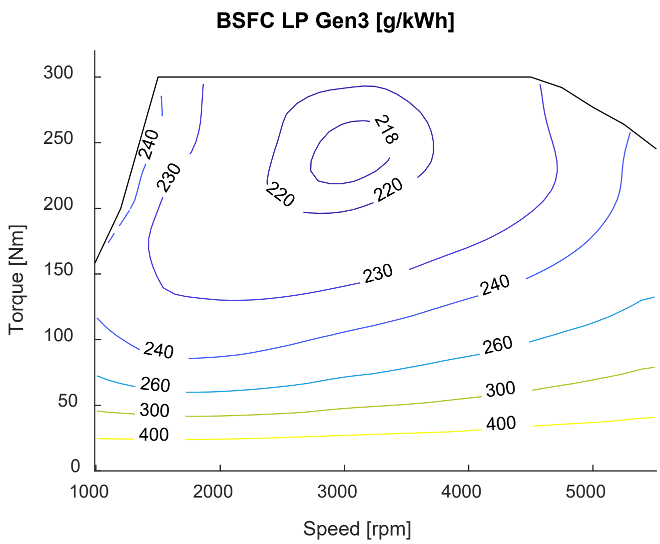


Fig. 7 BSFC VEP LP Gen 3 Miller.

Compared to the non-Miller MP engine, which has been the reference for this paper, the relative fuel consumption reduction is up to 8% in average and 4-5% in the WLTC area. While it is reaching substantial part fuel consumption reduction, the VEA LP engine still manage to achieve the same BSFC as non-Miller VEA MP at max torque, low speed. This is in an area the VTG turbo cannot compensate for the low volumetric efficiency.

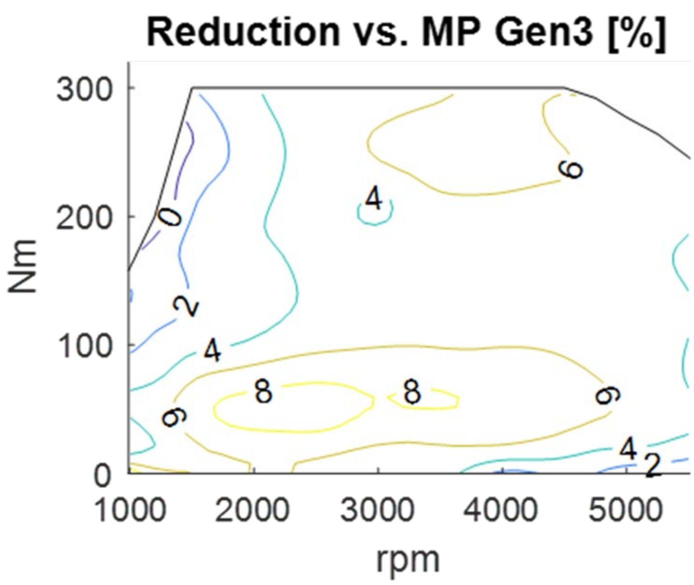


Fig. 8 BSFC reduction compared to VEP MP Gen 3.

Compared to the LP engines predecessor VEP LP Gen2, which has the same displacement but conventional valve timing, equally high compression ratio (11,3:1) and waste gate turbocharger, the fuel consumption of the new LP engine was significantly reduced, especially at higher power level.

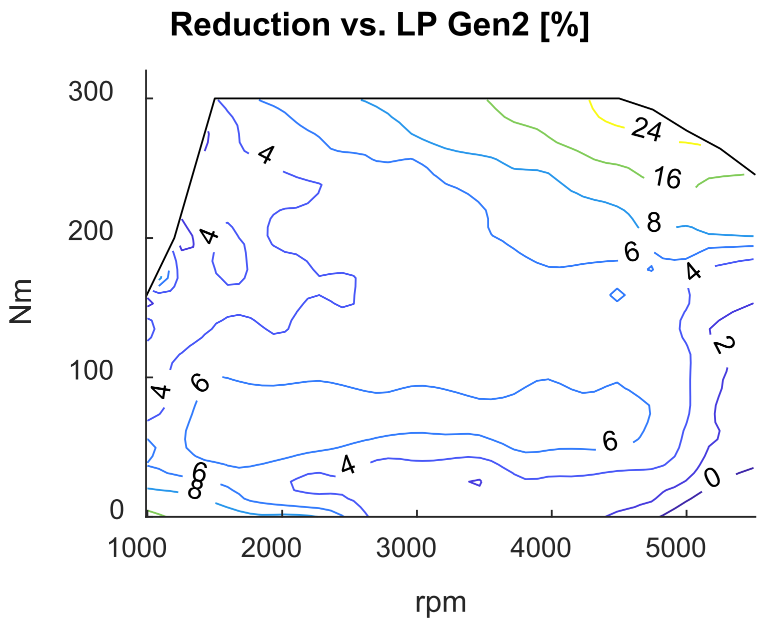


Fig. 9 BSFC reduction compared to VEP LP Gen 2.

6 Transient performance with VTG turbo

Project target was to keep same response time and torque build up as existing non-Miller, MP VEA Gen 3 engine. However, since the Miller concept, with shorter intake cam duration and early intake valve closing, reduces the air to engine transient performance of the engine is challenging.

A VTG Turbo with Variable turbine technology was selected since this technology provides a more exponential pressure build up compared to a wastegate turbine and the dynamic turbine behavior provides necessary volumetric efficiency to fulfill torque response without impacting fuel consumption strategy.

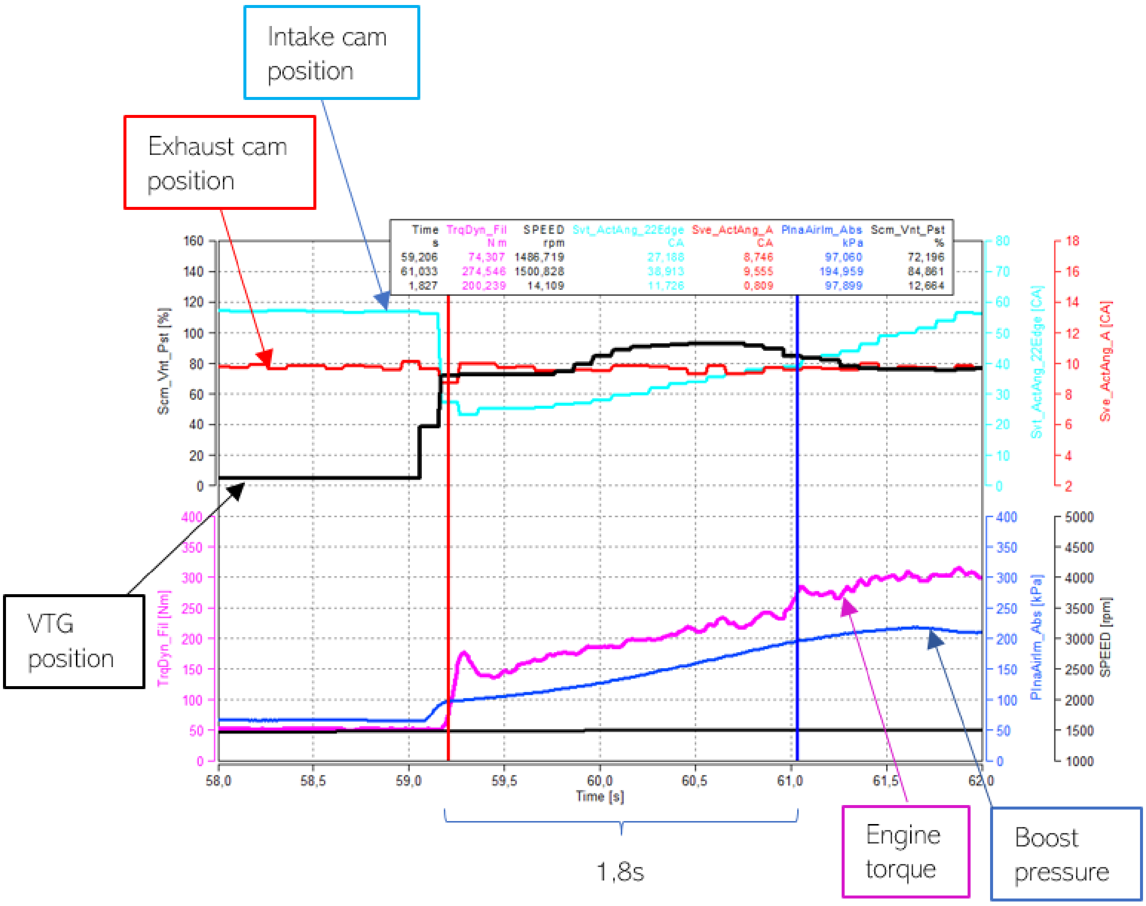
A lot of focus was put in to VTG Turbo optimization combined with the intake cam phasing since these are two important parameters that provides support to mitigate the potential transient response delay.
In addition to VTG control, intake VVT phasing is an important parameter since it has the highest influence on the transient performance.

With a Miller concept the response can be improved by retarding the cam phasing, but this comes with higher knock sensitivity which requires retarded spark timing.

This results in might lead to poor fuel efficiency, which means that the work to optimizing the intake valve phasing to get just enough volumetric efficiency to avoid ignition retardation and knock caused by high volumetric efficiency.

By using the volumetric efficiency as input signal to the charge air control, the best response could be achieved with minimal penalty on BSFC. As soon as the torque target is met the cam shaft setting is advanced back to most efficient point. To avoid mismatch between actual inlet pressure and cam phasing big changes in camshaft phasing and VTG position are avoided. The strategy of optimizing the volumetric efficiency may in extreme situations result in abnormal combustion. Therefore, an octane and temperature dependent limitation was applied.

By estimating the available maximum torque and response, it is possible for the driveline control functions to adjust the shift points and use torque fill from the ISG system to maintain a good transient vehicle response in all boundary conditions.



Time from 5Bar BMEP to 90% of max BMEP

Fig. 10 TTT at 1500 rpm (only combustion engine without B-ISG).

7 Turbo charger specification and design

To reach performance and efficiency targets a completely new VTG Turbo was developed together with Borg Warner Turbo system.

A Miller concept combined with lambda 1 requirement in the whole engine map requires efficient boosting from medium loads to full power.

The turbine and compressor specification were chosen for the lower mass flow and higher boost pressure that is required for a Miller engine. Obviously, it was important to keep commonality with the VEP MP engine and hence all interfaces to engine i.e., air intake and after treatment system are identical. As well the turbo bracket could be reused.

To run lambda 1 and avoid any enrichment, it was important to keep the pressure and temperature before turbine down and hence use a turbine and compressor with high efficiency at higher pressure ratio capacity to compensate for the reduced volumetric efficiency.

Simultaneously, a VTG Turbine provides a more uniform flow into the catalytic converter compared to a turbine with waste gate flow that might create so called hot spots. Hence a VTG turbo prevents aging of the catalyst brick too.

To ensure engine performance and long-term reliability and durability a significant number of tests and calculations was performed on component-, engine- and vehicle level.

When performing hot side durability verification for any modern turbocharged engine, Aurobay standard procedure is to run low cycle fatigue test (LCF- thermo chock) as well as high cycle fatigue test (HCF- Dynamic Cycle Test) and continuously correlate test result with appropriate CAE result. In addition to LCF and HCF verification, potential compressor coking needs to be addressed. This is an even more important topic on Miller engines since the Miller combustion uses a higher average boost pressure more frequently. Coking of the compressor due to carbon deposit will eventually lead to compressor efficiency loss and higher air temperature out from compressor and reduced engine performance. Since this problem is a result of long run time at high temperature and pressure it is generally not a problem for customers or in vehicle durability verification but need to be considered during development.

Since VTG turbos for higher temperatures is available at a reasonable cost, there’s a high potential for as well a high specific performance Miller engines as next step to reduce fuel consumption. Our current MP engine uses a waste gated turbo, which are designed for exhaust gas temperatures up to 1020°C (t3). For the LP Miller engine, selected material specification is D5S for the turbine housing while Inconel 713C is used for the turbine wheel. This choice of material can be regarded as cost efficient.

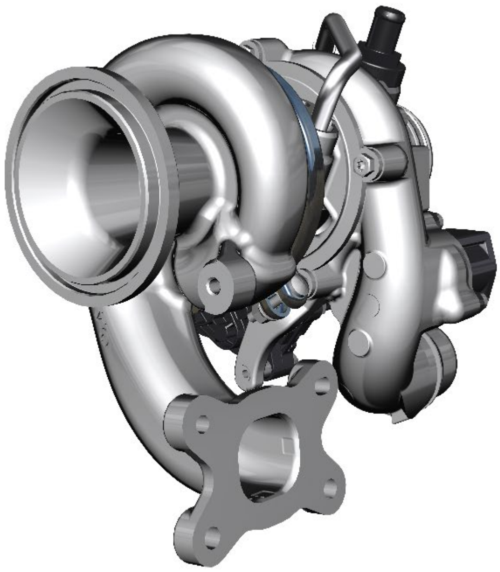


Fig. 11 VEP LP Gen 3 VTG Turbo charger from turbine side.

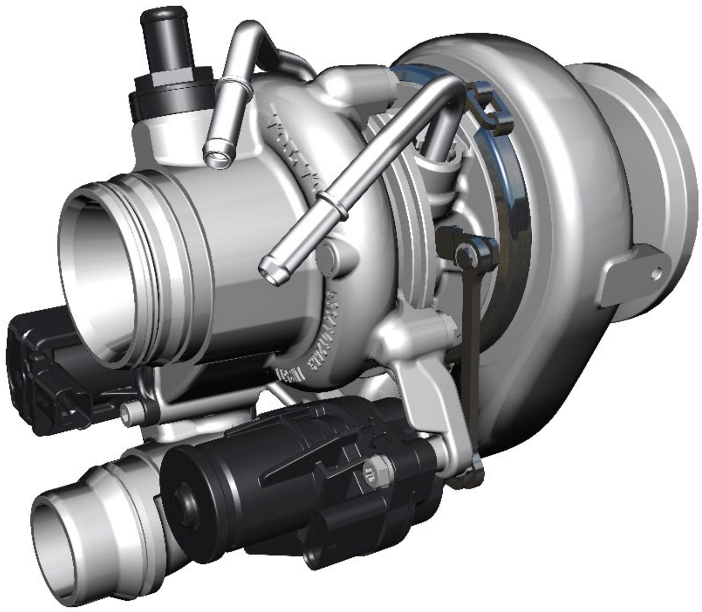


Fig. 12 VEP LP Gen 3 VTG Turbo charger from compressor side.

Technical system specification BV43 VTG Turbo

Turbine
- Control: electrically Variable Turbine Geometry (VTG)
- Turbine wheel diameter: 43mm
- Rotation: Counterclockwise
- Turbine housing type: Mono scroll w/o manifold
- Turbine housing material: D5S
- Turbine wheel material: Inconel 713C
- Turbine wheel type: P91
- Temp limit (t3): 950°C

Core assembly
- Water cooled bearing housing
- K03.3 bearing system

Compressor:
- P241 wheel w/o coating
- Gravity die cast housing
- Integrated crank case ventilation

Controls
- Electrical bypass valve
- Rotatory electrical actuator

Turbo system boundaries
- Max boost pressure:300 kPa (abs)
- Max boost temperature: 200°C

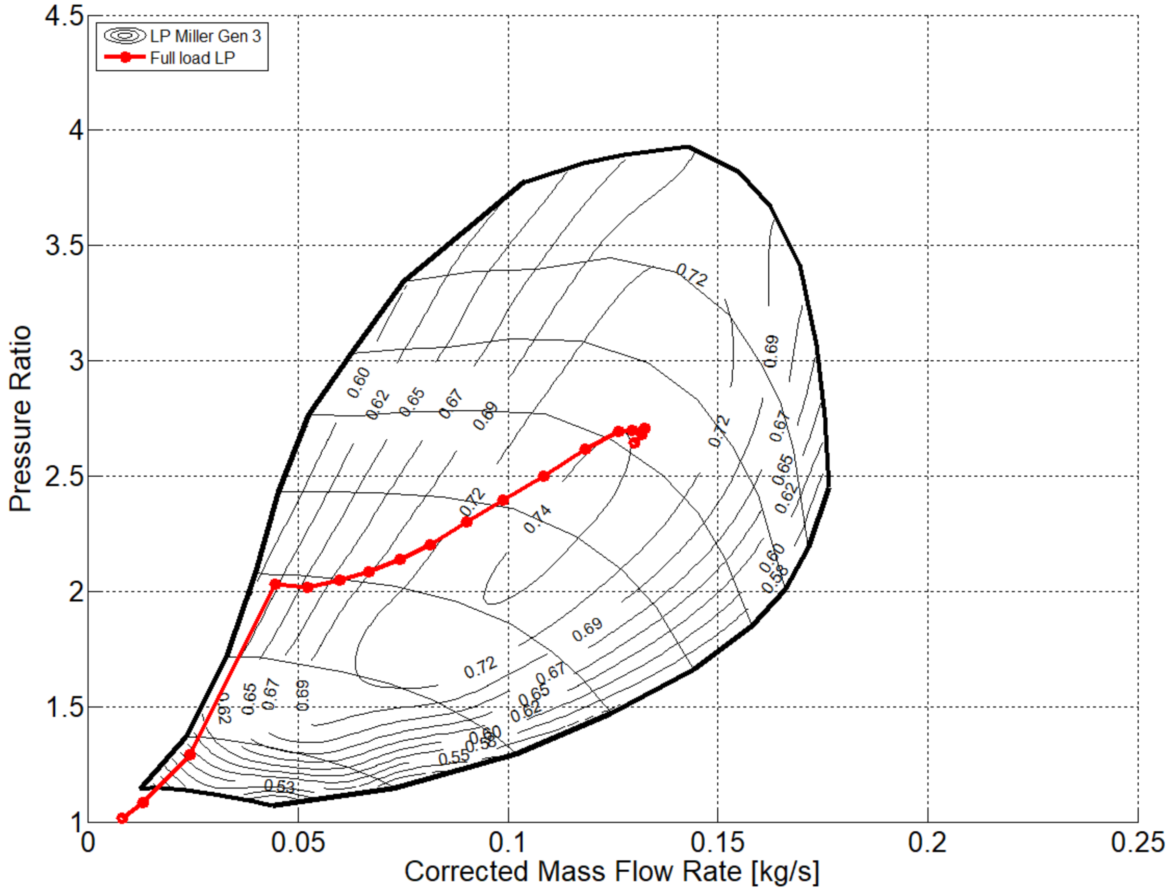


Fig. 13 VEP LP Gen 3 Compressor map including full load operation line.

8 Control Strategy

The control strategy for a VTG turbo needs to consider low flow and transient characteristics. High load at low engine speed, means that the engine is trying to build pressure during low flows. To build pressure the VTG vanes need to be close to fully closed. This result in a situation in which a high exhaust pressure is achieved in an area where the turbine efficiency is low.

As the flow is increasing, the VTG vanes can start to open. If this is done too late, the VTG opening increases the turbine efficiency and the effective power transfer to compressor can increase faster than the actuator can open the vanes and hence result in a boost pressure overshoot.

The larger VTG turbine lowers the back pressure of the engine and reduces pumping losses. As mentioned in earlier it is significant to optimizing the VTG together with intake cam phasing to get best performance with minimal penalty of fuel consumption without unpredictable over- or under-shoots.

During build up at high engine speed and high flow it is still important to keep the VTG position where the pressure build up is enough and keep the turbine efficiency. There is a general maximum for optimal transient control where the VTG is closed enough to created driving pressure at higher efficiency to increase boost pressure. If the VTG is instead closed further, it only gives back pressure and do not improve the transient performance.

9 Summary and Outlook / Zusammenfassung und Ausblick

Our new VEP LP Gen 3 engine with Miller combustion and VTG Turbo has successfully been developed. This engine, that is now available, has the capability to run lambda 1 in the full engine map up to its peak power of 145 kW. This was an important goal since reducing environmental im-pact is of highest priority for Aurobay. Base for the development have been our MP Gen 3 engine with following changes implemented:

- Increased compression ratio (new piston design).
- Intake camshaft with shorter duration intake camshaft for early intake valve closing.
- A new VTG turbo to compensate the reduced volumetric efficiency.
- A faster and more robust intake cam phaser together with a new trigger wheel design to provide faster and more robust cam phaser control.
- Updated engine control software.

This new LP engine shows Aurobay’s ability to develop and produce state of the art engines for the future. The engine is now in production in Aurobay’s engine plants both in Europe and China. Start of production in Europe was end of 2021 and in China beginning of 2022.
As the development of VTG turbo for higher temperature is in progress there is a high potential for as well a high specific performance Miller engines as next step to reduce fuel consumption while still keeping engine price down.

References / Literature

[1] Michael Fleiss, Derek Crabb, Joop Somhorst, Niels Möller, Joachim Kvarfordt, Karl Samuelsson, 2013. VEA – Volvo Engine Architecture Extreme Downsizing and maximum commonality while maintaining highly competitive costumer attributes. In: 22nd Aachen Colloquium Automobile and Engine Technology. Aachen, 2013.

[2] Håkan Björnsson, Paul Adkin, Tomas Johannesson, Kaj Johansson, Göran Josefsson, Lena Johansson, Christer Odenmarck, 2016. The new Volvo Drive-E 3-cylinder Engines. In: 25th Aachen Colloquium Automobile and Engine Technology. Aachen, 2016.

[3] Mats Morén, Ragnar Burenius, Staffan Rengmyr, Daniel Dahl and Daniel Balke, 2019. The new Volvo Mild Hybrid Engine Architecture. In: 28th Aachen Colloquium Automobile and Engine Technology. Aachen, 2019.

[4] Daniel Dahl, Ayolt Helmantel, Fredrik Wemmert, Mats Morén, Staffan Rengmyr, Ali Sahraeian. The New Volvo Mild Hybrid Miller Engine. In: 29th Aachen Colloquium Automobile and Engine Technology. Aachen, 2020.