

Comparative Investigation of Throttle-free Load Control on a 2.0 l Four Cylinder Turbocharged Gasoline Engine with Port and Direct Fuel Injection

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ABSTRACT

A 2.0 l turbocharged gasoline engine with port injection and a comparable turbocharged gasoline engine with direct injection have been investigated on a test bench at Kaiserslautern Technical University. Both engines were driven with throttle-free load control by fully mechanically variable valve actuation (CVVL). The basic series-production turbocharged engine in this comparison is the version with direct injection without the fully variable valve train. The focuses of the fired tests were investigation of the fuel consumption at part load and of maximum torque behavior at low engine speeds at full load. In both engine modes, use of fully variable valve actuation shows improvements compared with the turbocharged engine versions without CVVL. Better turbocharger response enabled the torque behavior to be optimized. The turbocharged engine with port injection and CVVL matches the torque of the basic turbocharged engine with direct injection and at low engine speeds exceeds the torque of the basic engine. The highest torque at full load and low engine speeds can be obtained with the CVVL turbocharged engine in the direct injection mode. The CVVL turbocharged gasoline engine with port injection shows the highest potential to reduce fuel consumption in this comparative investigation.

INTRODUCTION

If we examine vehicle production volumes worldwide, we can identify two significant trends that aim to reduce the fuel

consumption of spark-ignition gasoline engines and therefore motor vehicles' CO₂ emissions. On the one hand, these emissions are being reduced by engine downsizing and repositioning of the internal load point. Comparable torque and power output are obtained from an engine of smaller swept volume displacement or with fewer cylinders. Many automobile manufacturers are currently developing three-cylinder or even two-cylinder engines. These concepts maintain or boost power output by means of forced aspiration. To improve the drive-off response of these downsized forced-aspiration engines, they are operated with direct fuel injection at $\lambda = 1$.

The other means of improving gasoline engine efficiency is to minimize internal friction as much as possible and to adopt throttle-free load control with full mechanically variable valve lift. This trend was pioneered in 2001 by BMW with the introduction of its Valvetronic system and also adopted in Europe by PSA. In recent years Toyota, Mitsubishi and Nissan have also introduced valve lift systems of their own on production vehicles, [1] [2], [3], [4], [5], [6], [7]. Toyota has for example announced that it will be converting its complete program of engines to full mechanically variable valve lift.

Fig. 1 is an overview of the fully variable valve lift systems currently available in series-production vehicles. The Nissan company's VEL system is based on a bucket-tappet design, the MIVEC system from the Mitsubishi company on a rocker

arm principle with only a camshaft in the cylinder head. The various Valvetronic systems from BMW and PSA and the Toyota Valvematic system make use of friction-optimized roller cam follower designs. All these solutions are generally referred to worldwide as CVVL (Continuously Variable Valve Lift) systems. It is in the nature of these systems that varying the valve lift also varies the valve opening period.

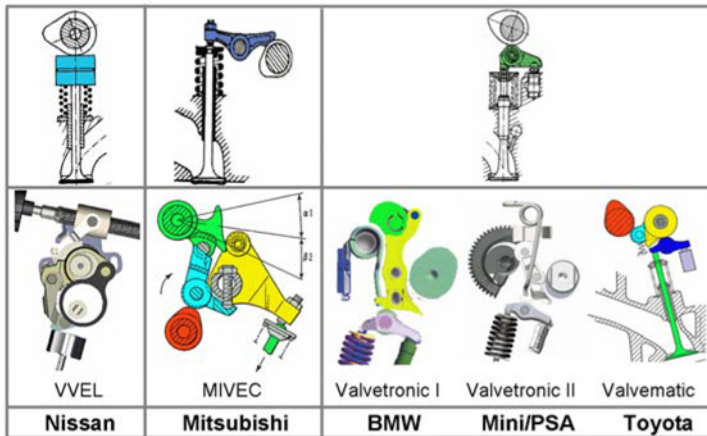


Fig. 1. Overview of current mechanical CVVL systems in series production

If we deliberately disregard the two additional development trends in modern gasoline engine design, namely stratified direct injection with piezo injectors and hybrid or even electric drive as methods of reducing CO₂ emissions, it is only to be expected that in future the downsizing and direct injection at $\lambda = 1$ trends will also be combined with throttle-free load control by means of fully variable valve lift. As a pioneer of full mechanically variable valve lift systems, the BMW company has already announced a combination of turbocharging with variable valve lift and $\lambda = 1$ direct injection; in this connection see Fig. 2. Of interest with this combination are the amounts contributed by the individual technologies to low-end torque or drive-off behavior, to maximum power and to reduce fuel consumption at part load - or to put this question another way, whether the benefits of the individual technologies can simply be added together.

This gives rise to the question of which advantages derive from the combination of direct injection at $\lambda = 1$ and fully variable valve lift. Direct injection on throttle controlled turbocharged engines has in the final analysis made the turbocharging of gasoline engines “socially acceptable”. Direct fuel injection enabled torque to be increased by about 10 % at very low engine speeds (below $n = 1500$ 1/min).



Fig. 2. The new BMW six-cylinder engine concept with turbocharging and the Valvetronic CVVL system [8]

Improved internal cooling and multiple fuel injection permit higher compression ratios at more satisfactory ignition angles, which also increase torque. At the same time, the adoption of shorter valve opening times has reduced reverse airflow from the cylinders, in other words increased the charge level and therefore full-load torque at very low engine speeds. Shorter inlet valve opening times also reduce residual gas content at lower engine speeds, lower mixture temperature and enhance the internal cooling effect.

Since fuel is injected into the cylinders only after the inlet and exhaust valves have closed, a controlled degree of excess flow or airflow into the exhaust port (scavenging) can expel the residual gas and fill the cylinders with a fresh charge at a lower temperature. The higher fresh charge volume in the combustion chamber results in higher torque and a higher volumetric exhaust gas flow, and thus improves turbocharger response, so that the forced aspiration effect sets in at lower engine speeds.

IMPLEMENTATION OF THE INVESTIGATIONS INTO THE RUNNING RESEARCH PROGRAM

In the past five years an extensive test program has been carried out on a 2.0-liter four-cylinder gasoline engine with double overhead camshafts. The aim of these investigations is to compare the valve operating concept with an identical basic engine in the part-load area and determine the reasons for the results. The principal aim is to achieve throttle-free load control and compare this with conventional throttle butterfly control. The identical basic engine was operated

initially in naturally aspirated form, then with a turbocharger both with and without fully variable mechanical valve lift. A particular aim was to establish the fuel-saving potential. The results of these investigations have already been presented, [9], [10], [11] [12]. The investigations described here were intended to compare the turbocharged engine with a CVVL system for MPI and DI operation at $\lambda = 1$. For improved clarity, Fig. 3 shows the extent of the research project as a table, with reference to the corresponding published sources. The comparison has so far been limited to fully variable lift on the engine's inlet valves.

All engine modes of Fig. 3 were driven at part load with $\lambda = 1$ and at full load with $\lambda < 1$. An inlet cam phaser was installed. The outlet phasing was simulated by turning the outlet chain sprocket. For that no controlled scavenging was investigated.

Concept 2.0 l four-cylinder test engine	Throttled mode	CVVL mode	Reference
Naturally aspirated MPI engine	x	x	[9], [11]
Turbocharged MPI engine	x	x	[10], [11]
Turbocharged DI engine	x	x	new
Turbocharged DI engine with CVVL on inlet and exhaust valve side	-	-	in 2010

Fig. 3. CVVL test program matrix with references

The relevant investigations were carried out at Kaiserslautern Technical University on a 2.0-liter engine manufactured by the Audi company. This engine can easily be converted to the various concepts. It is in series production in both naturally aspirated and turbocharged versions, so that an adequate basis for comparison is available. The UniValve fully mechanically variable valve lift system used on this engine was further developed at the Technical University Kaiserslautern, [9], [10], [11]. Comparison of both turbo charged concepts was commissioned by the enTec CONSULTING GmbH company.



Fig. 4. Test rig application with the 2.0l Audi engine and UniValve

THE UNIVALVE SYSTEM

The UniValve CVVL system used for the investigations has been described on several occasions [9], [10], [11], [12]. Fig. 5 shows the basic layout and components as used in this specific experimental engine. Possible valve lift variations are shown in Fig. 6.

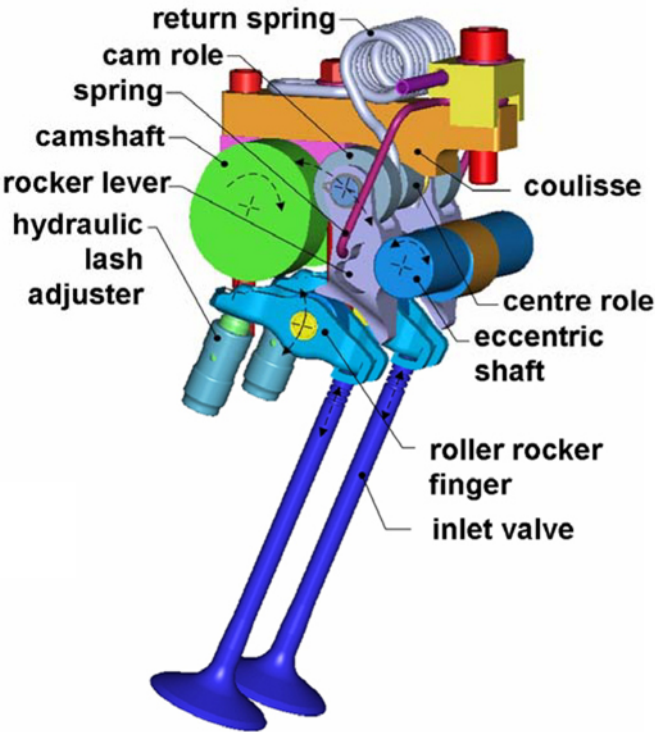


Fig. 5. Functional principle of the UniValve system

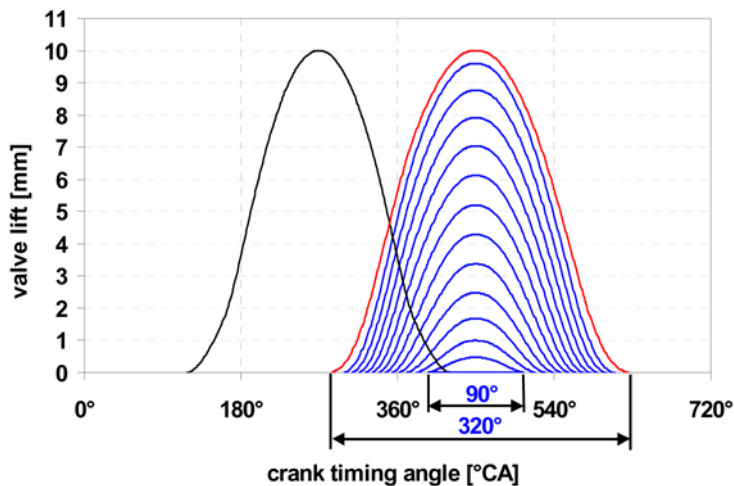


Fig. 6. UniValve system: possible valve curves

This valve operating system permits valve lift to be varied steplessly from 0 degrees to maximum lift. The valve opening period at 1.0 mm lift is in the region of 90 °CA, and it is possible to operate the two inlet or exhaust valves in each cylinder of an engine with four valves per cylinder with different amounts of lift and valve timing. This “valve lift phasing”, as it is called, adds swirl to the airflow inside the cylinder; in this way, the engine's residual gas compatibility can be increased. Fig. 7 shows details of exhaust valve phasing in which the two exhaust valves are operated with different amounts of timing spread (ES = 80 and ES = 135 °CA).

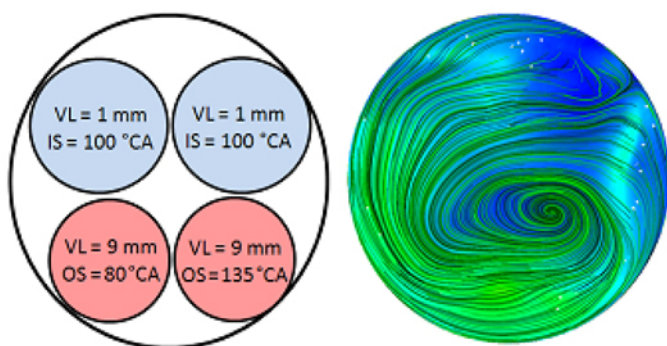


Fig. 7. Swirl effect in the cylinder caused by exhaust valve phasing [10]

FULL-LOAD TEST RESULTS

At very low engine speeds the naturally aspirated CVVL engine achieves the best full-load results at a valve lift of only 5 to 6 mm, whereas the series-production basic engine with fixed valve timing has an inlet valve lift of 10.5 mm. At the UniValve system the correlation of opening duration and valve lift height is fixed. For the increase of torque the valve opening duration is the most important criteria. With the

additional cam phaser that has a spread variation of 40 °CA the total inlet valve closing ranges is at least of about 140 °CA. Since the control timing or opening period of the inlet valve operated by the CVVL system is distinctly shorter than on the naturally aspirated engine with inlet port (MPI) fuel injection, reverse flow of the cylinder charge can be prevented. As a result the CVVL engine yields 20 % higher torque.

On the turbocharged engine too, the torque characteristic in the lower engine speed range can be raised by the use of fully variable valve lift. Fig. 8 shows the differences between the three turbocharged concepts that were investigated:

- 2.0 l turbocharged DI engine with fixed valve lift,
- 2.0 l turbocharged DI engine with CVVL,
- 2.0 l turbocharged MPI engine with CVVL.

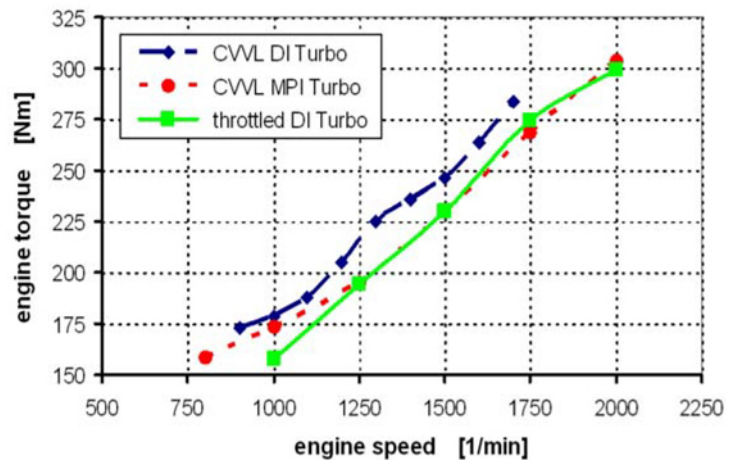


Fig. 8. Low-end torque comparison of three turbocharged engine concepts