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The Third Generation of Valvetrains – New Fully Variable Valvetrains for Throttle-Free Load Control

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ABSTRACT

The SI-engine has a disadvantage in fuel economy compared with a DI-Diesel engine. One of the major effects is the throttle-driven load control with its pumping losses. The main target is to reduce these losses in the thermodynamic process with a throttle-free load control. BMW has developed fully variable valve trains as a possible technical solution to realise a load control by regulating the valve lift and the closing time of the inlet valve. The essential variability can be achieved by fully variable mechanical valve trains or mechatronic systems both showing a robust running behavior in emissions and cyclic fluctuations.

The camshaft driven mechanical system is based on the technology of the BMW Double-VANOS system. An additional variability makes it possible to shift the valve lift continuously in order to control the valve closing.

The highest variability is given by a system with each valve being controlled seperatly. The electromechanical valve train enables the optimised timing of the individual valve offering a reduction in fuel consumption by about 10 per cent and a additional peak torque of 5 per cent. The required energy is supplied by an Starter/Alternator with high efficiency mounted directly on the crankshaft.

Fully variable valve train systems provide significantly better fuel consumption without major compromises in emissions and performance – a promising concept for future engine development

1. INTRODUCTION

Modern forced-induction diesel engines with direct injection are “high-tech” units capable of reducing fuel consumption still further and, simultaneously through forced induction, reach performance levels that were previously the domain of spark-ignition SI engines (Fig. 1). In the past the spark-ignition engine has seen the introduction of multiple-valve technology, reduction in valvetrain frictional losses, variable camshaft timing (VANOS), intake-manifold injection and electronic engine management, enabling high power-output levels to be reached, but in turn reducing fuel consumption by 10% while simultaneously achieving emissions levels. In spite of this, the difference in fuel consumption between SI and diesel engines has increased. Concepts such as gasoline direct injection, throttle-less load control with fully variable valvetrain and the combination of the two demonstrate that the inherent potential of the spark-ignition engine is so great that one should at least be able to get close to the part-load fuel consumption values for diesel engines.

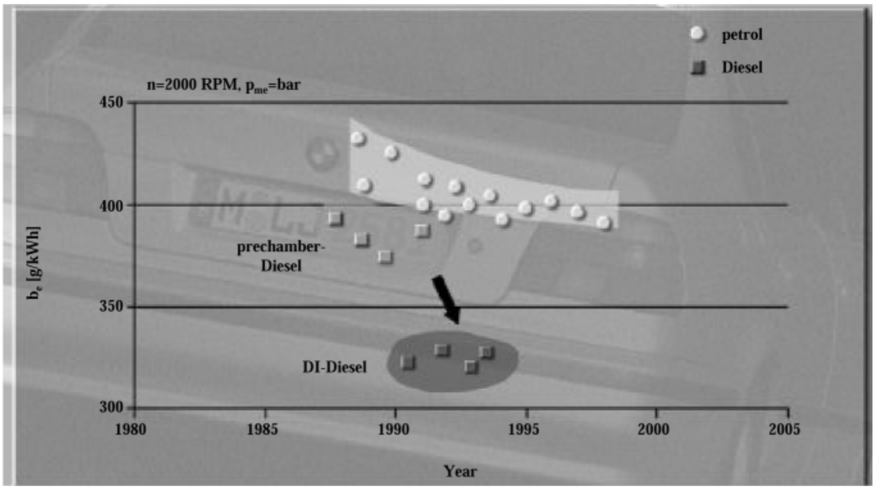

Figure 1. Trend in specific fuel consumption

2. DEMANDS TO BE SATISFIED BY FUTURE ENGINE CONCEPTS

As in the past, demands on new engine developments in the future will be greatly influenced by customer requirements and the need to comply with statutory exhaust emission limits. Development targets such as:

- reducing fuel consumption levels
- improving performance and dynamics
- improving refinement
- reducing emissions
- will continue to exist.

If we analyse specific fuel consumption trends for SI engines in stoichiometric operation at an operating point of 2000 rpm and 0.2kJ/dm^3 during the last 15 years (Fig. 2), a wide spread is detected at 400 g/kWh. Top values for modern engines are expected to be in the region of 385 g/kWh. Sobering though this stagnation may be, these spreads indicate that a 10 % improvement has been achieved on comparable engines during the last 15 years. Bearing this in mind, an engine concept that in the early 1980s had a specific fuel-consumption of 425 g/kWh would be expected to achieve approximately 385 g/kWh at the end of the 90’s, thanks to the many technical advances already mentioned.

The engine designer is faced with the difficulty of finding an approach that promises a significant reduction in fuel consumption, without having to make compromises in respect of other features. Further detail improvements alone will not suffice to achieve this target.

A technical advance must be found that can intervene in the control of the 4-stroke cycle in a suitable manner and thereby bring about a sustainable improvement in the efficiency chain.

3. ASSESSMENT OF ENGINE MEASURES

The Sankey diagram (Fig. 3) illustrates the proportion of unused energy from the chemical energy available in the fuel of a conventional spark-ignition engine.

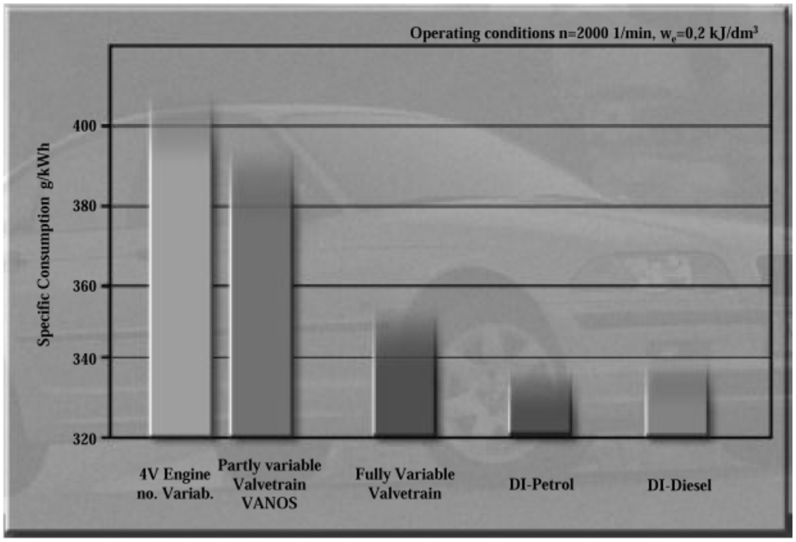

Figure 2. Specific consumption of various engine concepts

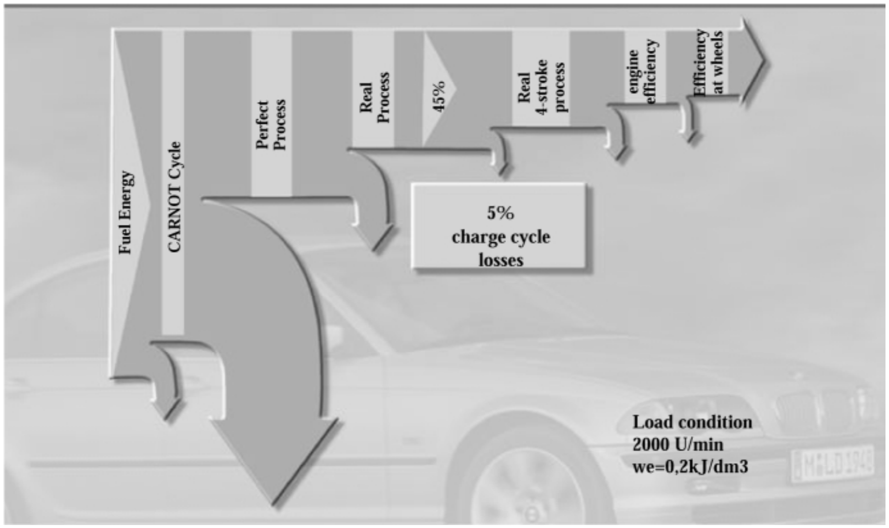

Figure 3. Proportional losses from a conventional spark-ignition engine

In terms of the engine, improving fuel consumption means increasing its efficiency. Principally, the energy conversion process offers only 3 possibilities for technically influenced improvements:

1. Increasing the internal efficiency of the actual engine
2. Reducing frictional losses
3. Preventing gas-flow losses.

Among the means of improving internal efficiency is an increase in the effective compression ratio and the isentropic exponent – in other words, the mixture characteristics. The potential here can – within certain limits – be utilised with a lean mixture in direct injection SI engines. However, the purely constructive approach to the problem, that is to say a variable compression ratio, must be dismissed from further conjecture on account of its low inherent overall potential.

A further significant reduction in frictional losses requires systematic “downsizing”. This solution too must be discarded from further considerations, because of the fact that customers prefer a particular engine size or a certain number of cylinders.

Consequently, the reduction of gas-flow losses represents one of the most promising improvement potentials and, in principle, can be applied to any throttle-controlled engine. There are two possible ways of reducing these losses:

1. For the required load condition, the cylinder is filled with a mixture of the correct calorific value by regulating its quality, in other words by diluting the mixture. The lean-mixture concept is another similarly indirect method of influencing the charge cycle. The direct-injection spark-ignition engine implements the controlled-combustion solution systematically by means of a stratified charge, so that mixture quality can be regulated and the charge-cycle work minimised. At the same time, the large amount of excess air serves to improve high-pressure efficiency. In principle, the direct-injection SI engine also provides a torque advantage because of its charge-air intercooling and intake of `clean´ air, as long as selection of the combustion method does not call for any compromises to be made. However, as well as the high inherent complexity of this technology the greatest handicap is presented by the need for exhaust-emission treatment.The question of whether low-emission concepts can be realised within the short and medium terms is still open.
2. Throttle-less load control with fully variable valvetrain offers potential fuel consumption reductions approaching direct-ignition SI engine levels, without any known fund-amental weaknesses.

4. THROTTLE-LESS LOAD CONTROL

The principle of throttle-less load control operation can best be illustrated by means of a p/V diagram.

Basically, there are different methods of cycle control to obtain the desired load-control effect without any losses. A similar process is “advanced inlet valve closure”. In this process the throttle is fully opened for the induction stroke – the pressure remains at ambient level – and the inlet valve closes during this stroke precisely when the desired mass of mixture has entered the combustion chamber (Fig. 4).

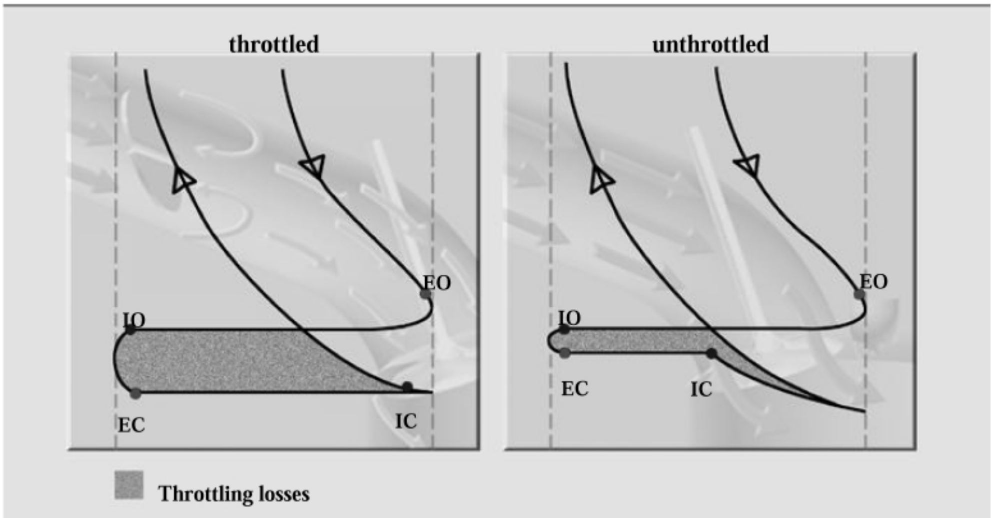

Figure 4. “Throttle-less load control” charge cycle

Further cycle control methods for “throttle-less load control” similar to “advanced inlet valve closure” are:

- Retarded inlet valve opening is a measure that, although it calls a certain amount of charge-cycle work, also offers advantages in the high-pressure process by permitting good mixture preparation, particularly when the engine is cold.
- With the aid of advanced or retarded exhaust valve closure, residual exhaust gas can be accurately controlled and used for dilution or for mixture preparation purposes.

5. CONSUMPTION BENEFITS OF “THROTTLE-LESS LOAD CONTROL”

The improvements in fuel-consumption that can be achieved with “throttle-less load control” are illustrated in the differential consumption map for a four-cylinder engine with the BMW VALVETRONIC, a fully-variable mechanical valve-train mechanism (Fig. 6). The consumption advantages are related to charge-cycle work and, where appropriate, the reduction in mechanical losses in the valve gear, which controls engine load. Discarding the throttle makes itself particularly noticeable at low loads, for which it would have had to be almost fully closed. Here, a fuel saving of up to 20% can be obtained. This potential decreases proportionally with higher loads, but the average saving is 10% in $\lambda = 1$ operation.

6. ACTIVE “THROTTLE-LESS LOAD CONTROL”

“throttle-less load control” is normally obtained by varying the timing of the inlet and exhaust valves. Fully-variable valve timing, that is to say with variable lift and variable inlet valve opening and closing times, is currently being developed by, among others, the following companies:

- BMW,
- Daimler Chrysler,
- Nissan and
- Meta.

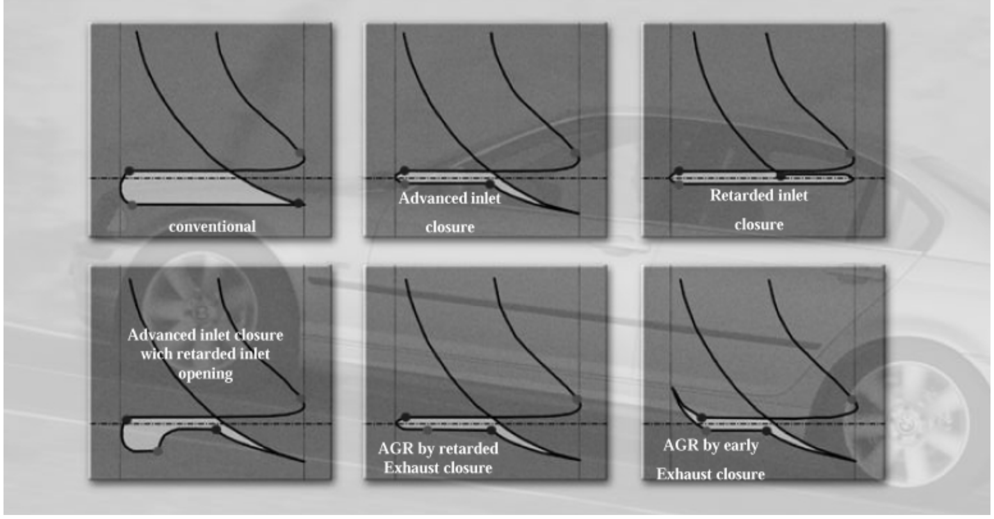

Figure 5. Process control methods

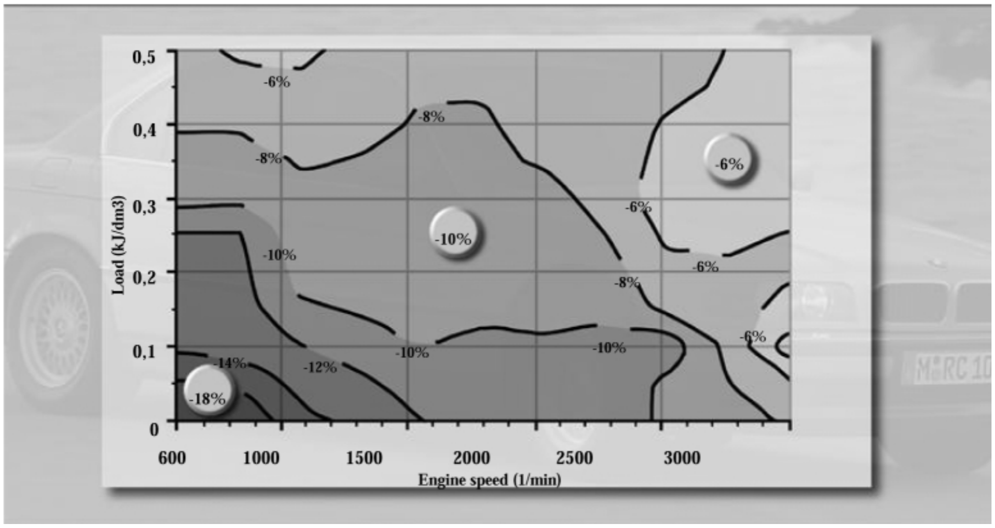

Figure 6. Map-dependent consumption advantages

7. BMW'S VALVETRONIC VALVETRAIN

The mechanical fully variable valve train, Valve Tronic from BMW is based on the infinitely-variable "Double VANOS" camshaft control system used on the latest generation of BMW six-cylinder engines.

The crucial addition to the function of this system is the infinitely adjustable inlet valve lift. Variable lift enables the effective cam profile and therefore the effective opening period to be shortened.

The system achieves this function through an additional intermediate lever.

The intermediate lever is held in position in the cylinder head by an eccentric shaft, the inlet camshaft, the roller cam follower and the return spring. When the inlet camshaft rotates, the lever is turned around the momentary centre M_D by the roller, which runs on an anti-friction bearing and is pressed against the intermediate lever by the return spring. Eccentric shaft rotation shifts the centre between M_{D1} and M_{D2} and, at the same time, the eccentric shaft's position determines on which area of the control contour the roller of the cam follower runs. In the position illustrated in Fig. 8 – the idle position – the intermediate lever rotates about M_{D2}, the roller is in contact with the \`flatter´ region of the control contour and the inlet valve then performs a predetermined minimum lift movement. If the eccentric shaft is turned through approx. 170°, the intermediate lever rotates through $M_{D1}$. In this position the roller is in contact with the \`steep´ region of the control contour and the inlet valve performs its maximum lift. The cluster of curves for inlet valve lift is illustrated in Fig. 9. The eccentric shaft is connected to a high-resolution rotation angle sensor. If the engine management control unit registers a change in load demand, a second control unit is sent a controlled signal determining the electric motor's current ratio.

Figure 7. Double VANOS variable camshaft control on BMW 6-cylinder engines

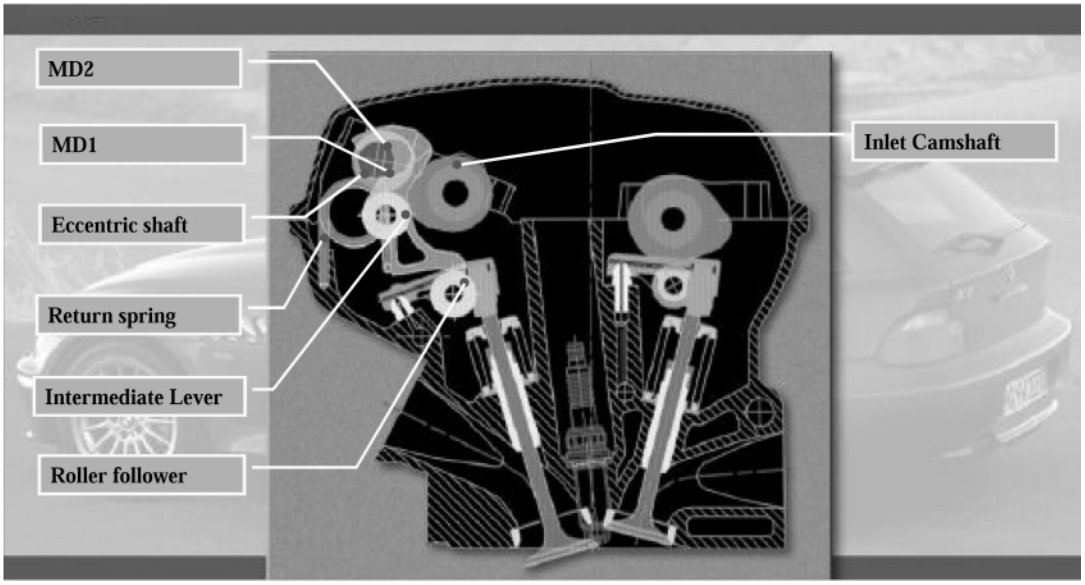

Figure 8. The design of mechanical VALVETRONIC from BMW

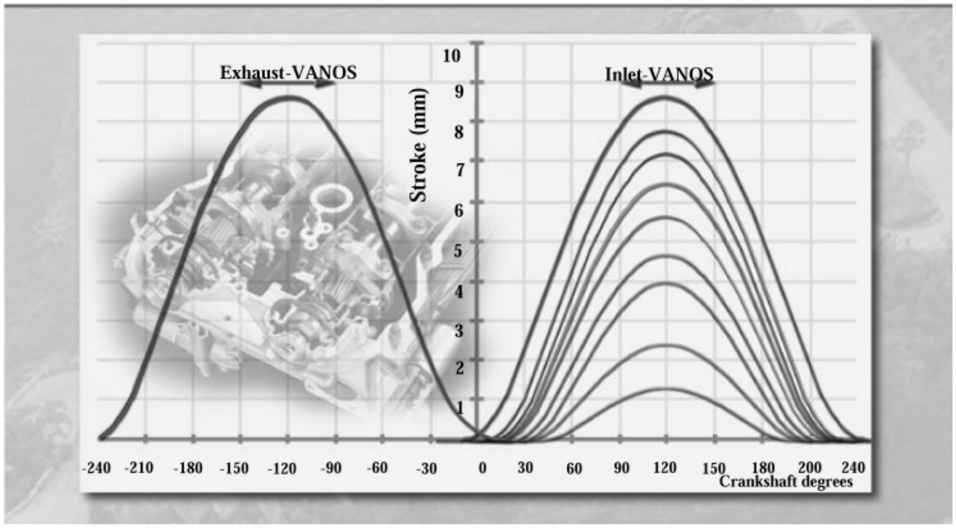

Figure 9. Mechanical fully-variable valvetrain operating principle

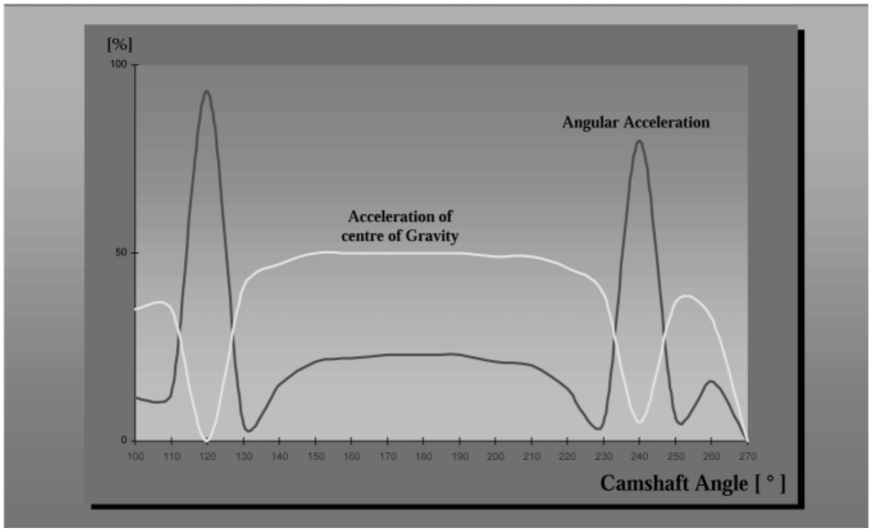

Figure 10. Intermediate lever acceleration

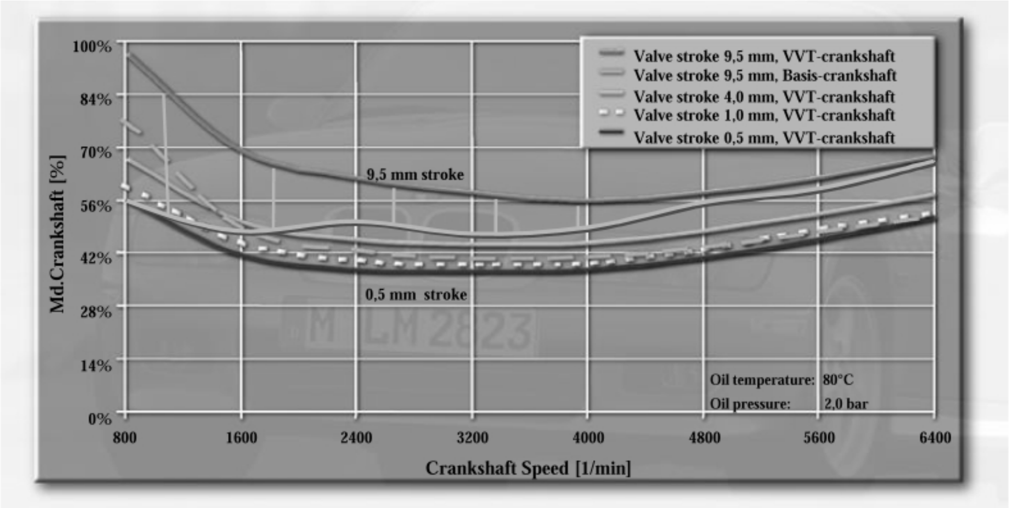

Figure 11. Drive torques of the camshafts of the VALVETRONIC valvetrain

The intermediate lever with return spring represents a separate dynamic vibration system that is not coupled to the inlet valve's spring/mass system. The intermediate lever's oscillatory acceleration is illustrated in Fig. 10.

Initially, movement of the intermediate lever on the intake side results in additional frictional losses, which can be minimised by using rollers. The reduction in the valve lift more than compensates for this additional frictional loss at low speeds and loads, so that in the part-load operating range friction is reduced. (Fig. 11).

The mechanical VALVETRONIC valvetrain alters the valve lift, the opening duration and the valve opening position. To ensure that the valve opens at the correct time, the inlet and exhaust camshafts are turned simultaneously by VANOS units. Fig. 12 illustrates a possible engine map characteristic for inlet valve spread with appropriate valve lift values.

This intervention in the 4-stroke cycle control is naturally not without consequences. On the one hand, the following points must be considered:

- The vacuum which promotes mixture formation in the intake manifold is lost
- An expansion phase occurs before the compression process, with a drop in temperature
- The polytropic rise for the subsequent compression phase starts at a lower temperature.

On the other hand, new mechanisms are present that are highly beneficial to mixture formation and cylinder filling.

An analysis of the process at the valve gap demonstrates that the reduced valve lift which is required for the shorter opening time causes an increase in inflow speed from somewhere in the region of 50 m/s to more than 300 m/s. This speed increase results in high shear stresses with a highly efficient preparation mechanism, as seen in the significantly finer fuel spray in the combustion chamber (Fig. 13).

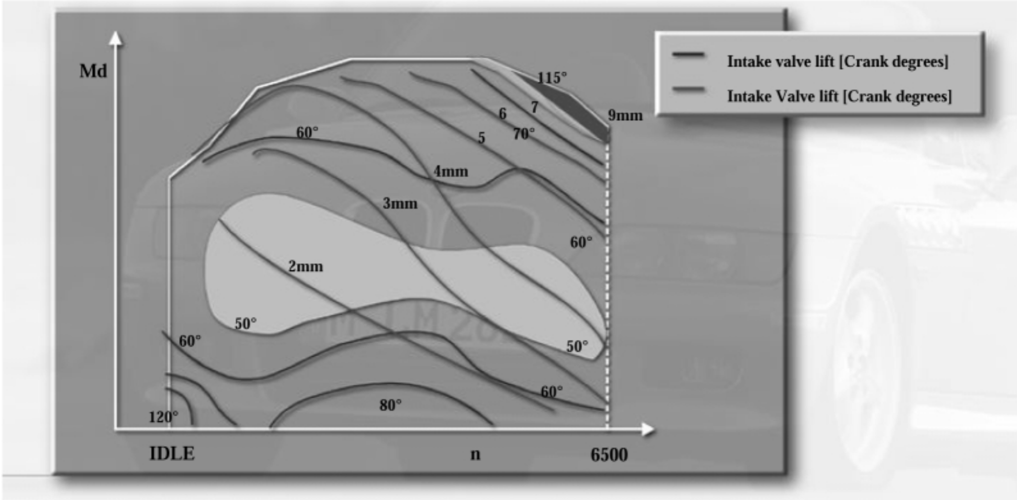

Figure 12. Valve lift and valve spread map

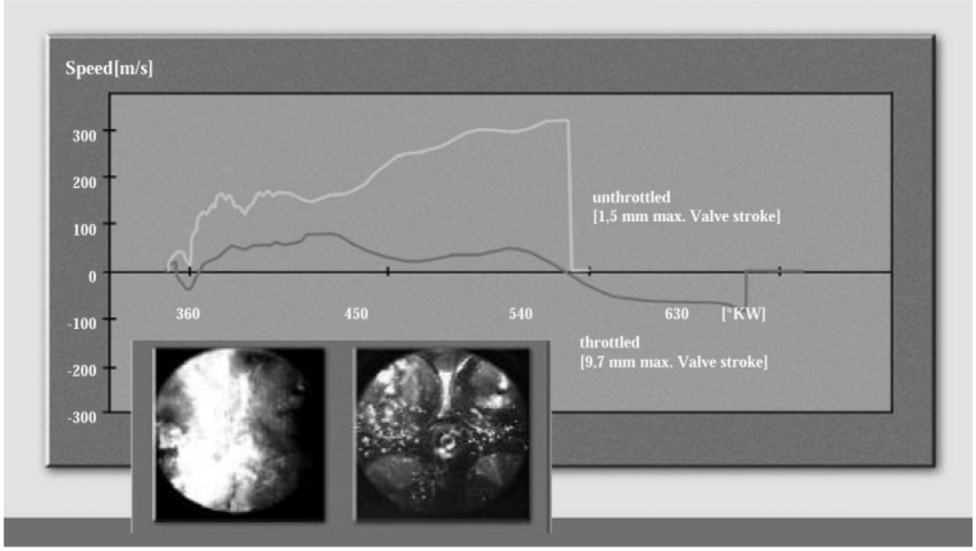

Figure 13. Inflow speeds at the inlet valve gap

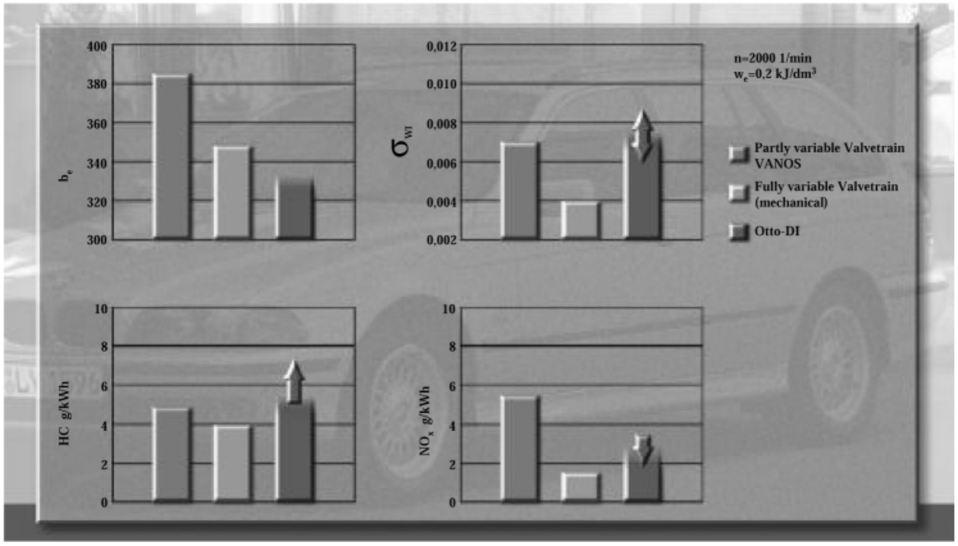

Figure 14. Map of different engine concepts

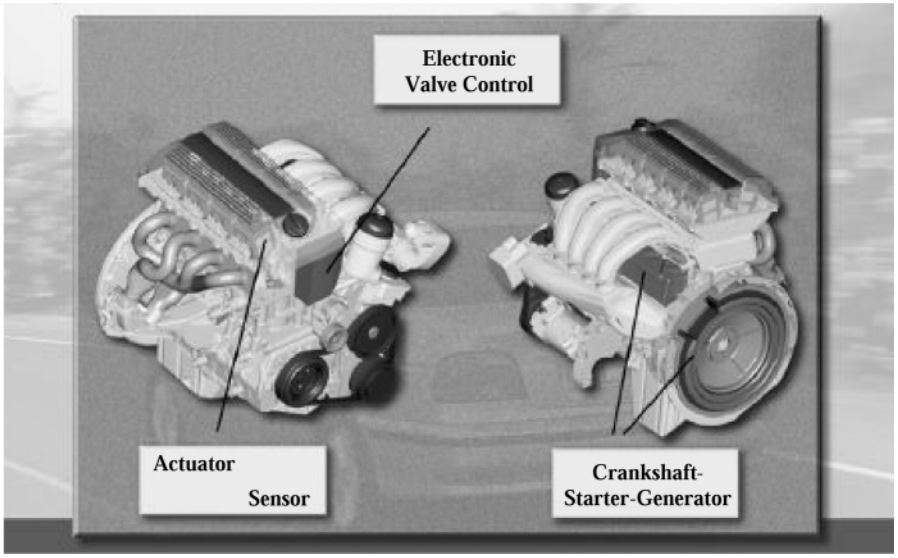

Figure 15. Electro-mechanical valvetrain

The robust operation characteristic of the throttle-less load control system results from the addition of positive characteristics, as clearly shown by comparison of various parameters at the operating point n= 2000/ min and w_e = 0.2 kJ/ dm³. As well as the previously mentioned fuel-consumption advantages, cyclic variations are also minimised as a result of the excellent mixture formation and HC emissions also drop to a desirably low level, with a distinct improvement possible in NO_x emissions. This no-compromise process is currently matched by no other concept (Fig. 14).

The attainable fuel-consumption advantages are illustrated in Fig. 6 in a differential map for a four-cylinder engine with VALVETRONIC.

8. ELECTRO-MECHANICAL VALVE GEAR

Maximised functional efficiency is achieved by BMW's second engine development concept: electro-mechanical valvetrain.

The greatest degree of variability in the valvetrain is achieved when each individual valve has its own timing system, enabling it to be opened and closed as and when required.

An overview of the system shows the essential components in this engine concept. The inlet and exhaust valves are actuated by a single control unit per valve, consisting of the actuator itself and a sensor for registering the operating condition at any given time. The actuator is controlled by a special electronic valve timing system, which determines the required current flow for the control units. The energy requirement is covered by a high-efficiency generator in the form of the crankshaft-mounted starter-generator, which was exhibited at the Geneva Motor Show in 1998.

Fig. 16 illustrates the design principle of an actuator and a typical operating cycle when opening a valve.

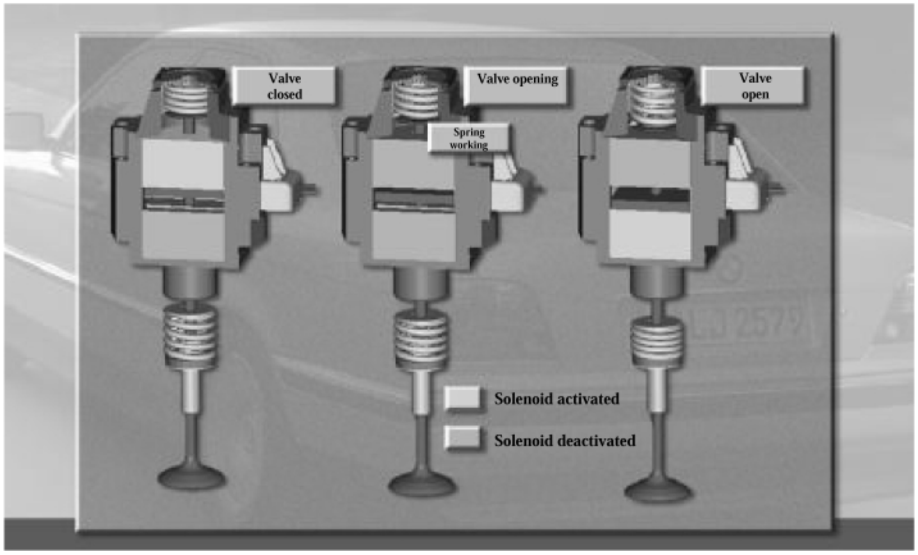

Figure 16. Operating phases when valve is opened

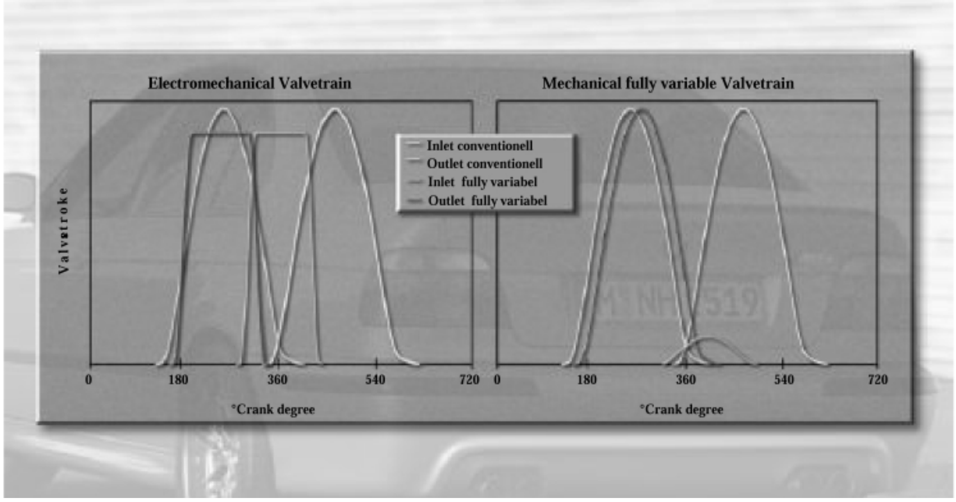

Figure 17. Valve openings with conventional and fully-variable valvetrain

An armature regulated by a spring is moved between two solenoids, which hold it in the fully open / closed positions.

The start of the valve opening process is inizted by a signal from the engine management system for the corresponding valve to be opened.

The electronic valve control system implements this signal by controlling the electrical supply to the two solenoids:

- The upper coil’s holding voltage is switched off
- The compressed spring accelerates the armature
- The valve is opened.

When the armature approaches the maximum open position the lower coil is activated and the armature held in the open position.

When the specified valve opening time has been reached the control unit transmits a corresponding closure command and the valve is closed in a similar manner.

With regard to throttle-less load control and the efficiency advantages resulting from it, similar thermodynamic conditions prevail as with mechanical fully-variable valvetrain systems. Differences exist, however, in terms of the valve opening techniques.

Whereas in the mechanical fully-variable valvetrain the gap exerts a positive influence on the mixture quality in the cylinder, thermally favourable mixture preparation is achieved by utilising the hotter remaining burnt gas resulting from the larger valve overlap phase made possible. (Fig. 17).

One of the major advantages of individual valvetrain actuation lies in its high degree of flexibility.

Depending upon requirements, it is possible to select a suitable process by making use of individual and cycle-consistent control of the valve actuating units:

- Advanced inlet valve closure and retarded inlet valve closure are the most efficient timing procedures for engines at regular operating temperature.

The flexible process method in conjunction with the steep valve-opening ramps means that cylinder filling at low and medium engine speeds can be improved by controlled energising and systematic utilisation of charge-cycle dynamics. The resulting gain in maximum torque is almost 5% compared with the already outstanding value of 100 Nm/dm³ achieved.

Implementation of throttle-less load control using an electro-mechanical valvetrain requires a systematic analysis of the specifications for each part. The necessary operating reliability can only be achieved if every part functions perfectly under the specified engine operating conditions.

The electronic valve control unit is mounted on the engine in order to optimise the system connection and is therefore subject to the prevailing thermal and mechanical conditions. Its primary function is to supply the actuator coils with sufficient voltage so that the target current requirement is generated. Functional requirements are a high degree of efficiency and adequate processor capacity. Also thermally stable and compatible electromagnetic emissions resulting from the high power control units must be assured.

The crankshaft starter-generator control unit is also installed close to the engine and therefore subject to the same environmental conditions as the electronic valve control unit. The generator must be able to supply the required electrical energy with a high degree of efficiency. In order to minimise losses, a 42 V power supply has been adopted.

Above and beyond this, the crankshaft starter-generator's inherent potential includes extremely fast, almost noiseless starting and efficient supply for a constantly increasing number of electrical devices.

If the components for the overall engine system are regarded as a whole, the package and the vehicle's electrical supply system (42 V technology, EMC) take on greater significance.

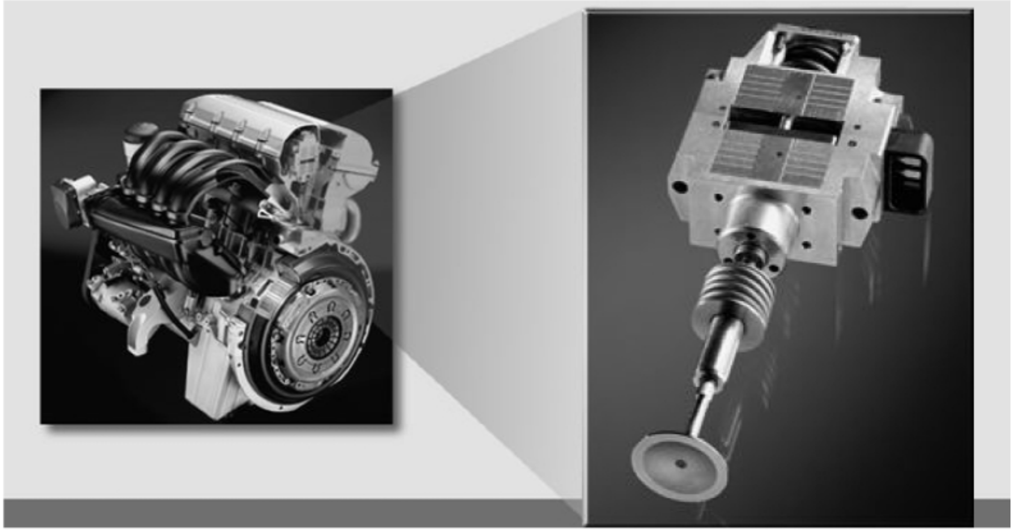

Figure 18. System elements in the electro-mechanical valvetrain

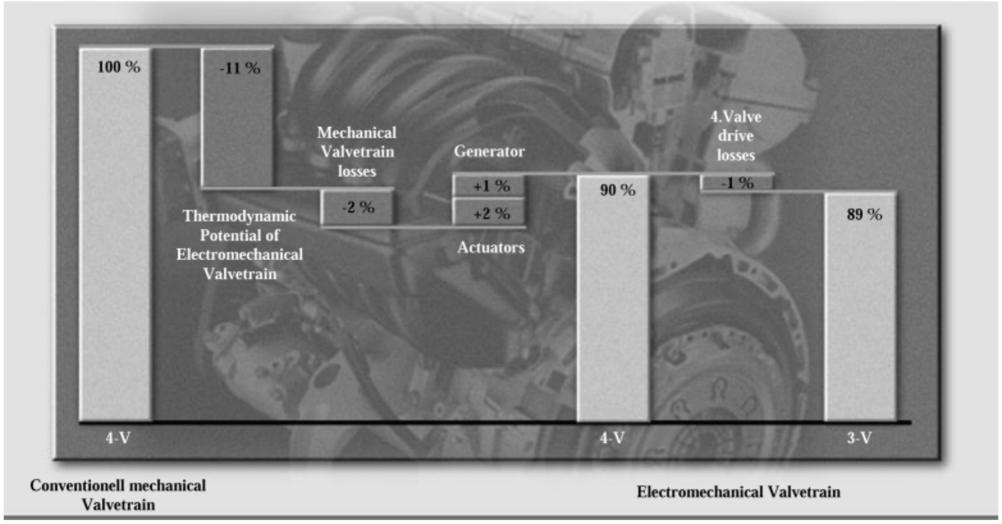

Figure 19. Energy balance for electro-mechanical valvetrain

As with the mechanical energy which conventional camshaft-operated valvetrains requires, the electro-mechanical valvetrain also needs an energy source. A decisive success factor is the overall energy balance.

Taking the specific fuel-consumption of a conventional engine with four valves per cylinder as a starting point, throttle-less load control in conjunction with electro-mechanical valvetrain achieves an indicated consumption bonus of 11%. If one replaces the conventional valvetrain, the frictional saving from the roller-bearing valvetrain achieves a further 2% reduction in fuel consumption. The electro-mechanical valvetrain, including its electronic control system, increases consumption level by 2%, and – assuming a generator efficiency of 75% – another rise of 1% has to be accepted for the electrical energy supply. At part-load, the previously mentioned additional fuel-saving potential is achieved by disabling an exhaust valve, so that an overall improvement in fuel consumption of 11% is achieved (Fig. 19).

CONCLUSION

Throttle-free load control – whether with electromechanical, or mechanical valve train – offers modern motor-vehicle combustion engines a fuel consumption benefit of 10% in costumer consumption cycles.

This consumption benefit does not require special, high quality fuel or newly developed special emission controls and also is not reduced in emissions cycles through the use a Nox-Catalyst, for example.

The exhaust system technology for this concept is well-known and successful.

The system with mechanical valvetrain, relies upon known and successful elements, the control concept is comparable with E-Gas.

From this view, the mechanical VALVETRONIC system from BMW is the next step in modern future development, that will in the foreseeable future be supplemented by an electromechanical valvetrain.

This will offer further consumption benefits through cylinder disablement, cycle disablement and single-valve operation, allowing the fuel consumption gap with modern Diesel engines to be further reduced.