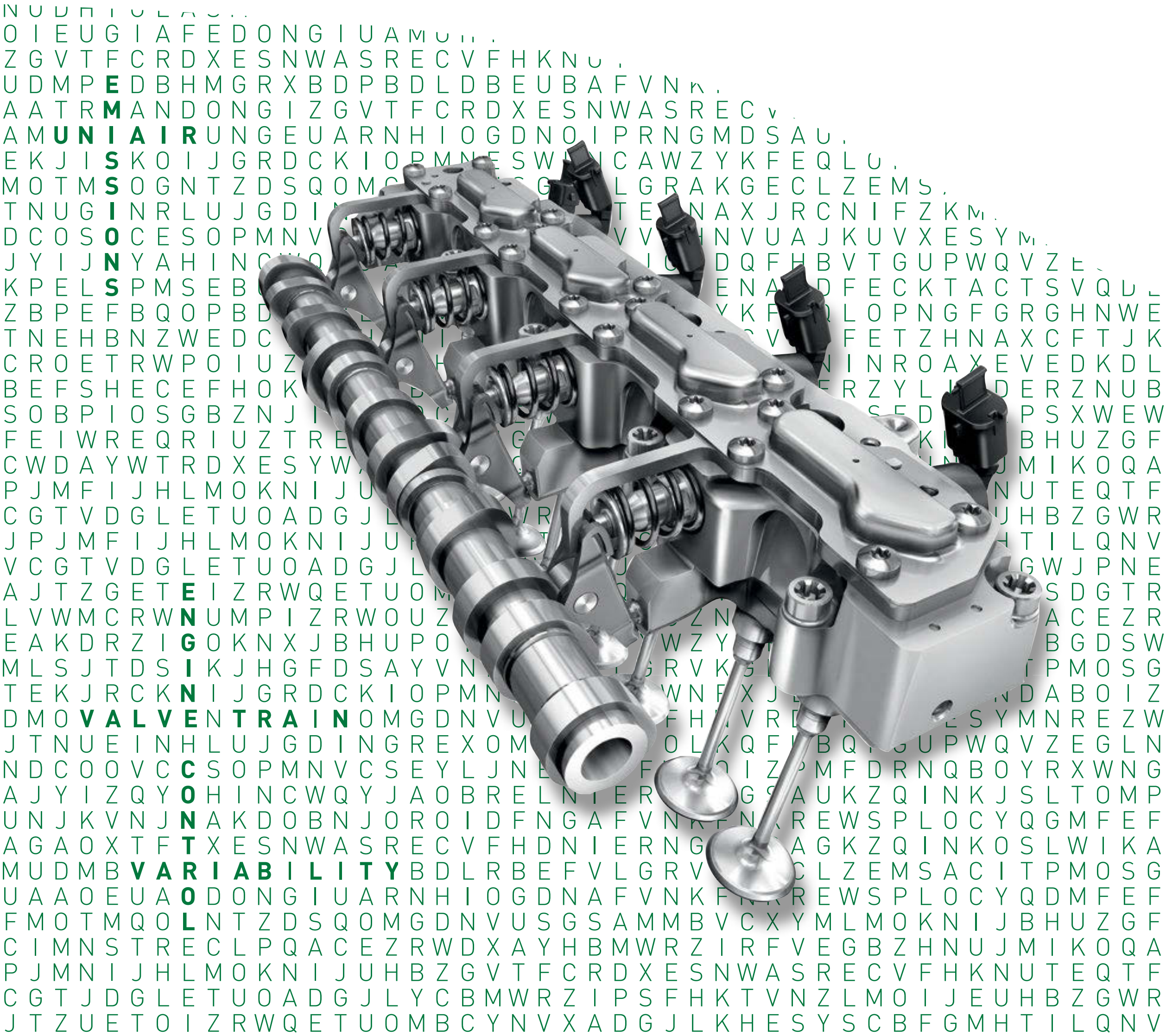
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Get Ready for the Combustion Strategies of Tomorrow

Michael Haas
Thomas Piecyk

12

The variable valve train – a tool for greater efficiency

In the future, internal combustion engines will have to fulfill increasingly stringent requirements with regard to carbon dioxide emissions and exhaust pollutants, and this means a decisive role for the valve train: On the one hand, it should be designed in such a way that the losses occurring during the charge cycle are low, and on the other hand it creates the prerequisite for the best possible mixture preparation in the cylinder and thus a combustion process that provides optimum efficiency and low emissions. In addition, the valve timing directly influences the combustion process by way of the compression, which is adjustable within limits, and the residual gas in the cylinder.

The variability of valve trains has therefore increased dramatically in the last few years. Two basic approaches for a higher degree of variability must be observed in this context:

1. The temporal shifting of the valve lift curve using camshaft phasing units
2. The variation of the valve lift curve in terms of the lift height and the opening and closing point, and thus of the resulting opening period.

Camshaft phase adjustment

Ever-increasing numbers of gasoline engines have a camshaft phasing system – either on the intake side only or on the intake and exhaust side – and a volume-produced diesel engine recently went into production with a phasing system on one camshaft for the first time. Systems with hydraulically-actuated swivel motors have become established. The trend towards downsizing and downspeeding will increase the rate with which these systems are fitted because power and torque can be increased and raw emissions reduced by changing the relative angle between the camshaft and the crankshaft.

Electric phasing units are the optimum solution from a technical perspective. An electric system allows the greatest degree of freedom when selecting the timing for starting. It offers higher rigidity when torque is applied to the camshaft via the crankshaft and therefore achieves the highest adjustment accuracy. The adjustment speed is also higher compared with the best hydraulic systems. The electric system is also the only system to offer the option of free selection of the timing when the engine is started. Such a system will go into volume production for the first time at Schaeffler in 2015. It is designed so that no modifications to the cylinder head are required.

The high performance of electric phasing units is also associated with a higher outlay, however. This is why it is advisable to further optimize the systems currently used. Further development of these systems must be focused on meeting increasing requirements at comparatively low oil pressures. How this can be done is described in a separate article [1].

Variable valve lift curves

In gasoline engines, incrementally variable valve trains on the intake and exhaust side have been known for many years, and a diesel engine with cam profile shifting implemented on the exhaust side went into volume production a few months ago.

When an incrementally variable valve train system is designed to act on the cam, this is referred to as a “shifting cam”. In this type of system, an electromagnetically op-

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erated actuator axially shifts a cam assembly that is mounted on the camshaft. An advantage here is the independence from the engine's hydraulic circuit with its dependency on temperature and viscosity.

There are many known variants of valve lift curve shifting on the cam contact partner or the hydraulic pivot element, in which the task of switching between the valve lift curves is performed by a hydraulically-actuated locking piston.

Partially-variable valve trains allow both valve lift curve shifting and valve/cylinder deactivation to be implemented. These systems are attractive in that they offer significant benefits in terms of fuel consumption with only a moderate cost outlay.

Engine designers have been looking for a way to regulate the lift of both intake and exhaust valves for a long time. The ideal situation would be to have a valve lift curve that is adjusted to suit the engine's current operating point and condition and can be defined as desired, which would make it possible to set the timing in such a way that it is not a compromise between the diverse requirements of individual sub-targets.

In 2009, Schaeffler and Fiat collaborated to put the UniAir electrohydraulic valve train system, the design and function of which has been described multiple times [2-4] into volume production. The scope of delivery from Schaeffler comprises the following:

- The electrohydraulic actuator module
- The software required for controlling the valve control system, which is integrated into the customer's engine control system
- A calibration data set for the relevant application

This system has since been adapted for a range of volume-production engines with capacities ranging from 0.9 to 2.4 liters and more than 500,000 units have been delivered to customers in Europe and in North and South America.

Development level of UniAir

The basic function of the UniAir valve train has not changed since its market launch. Figure 1 shows a typical assembly. The camshaft acts on a finger follower, which drives the pump (4) that fills a high-pressure chamber (6). Depending on the position of the solenoid valve (5), the oil pressure acts on the engine valve via a piston or is reduced via outflow into the medium-pressure chamber (3) and pressure accumulator (1). By adjusting the solenoid valve – temporarily decoupled from the camshaft position – various pressure levels in the high pressure chamber and thus variable engine valve lifts can be achieved. In today's applications, the maximum pressure in the high-pressure chamber is approx. 150 bar in continuous

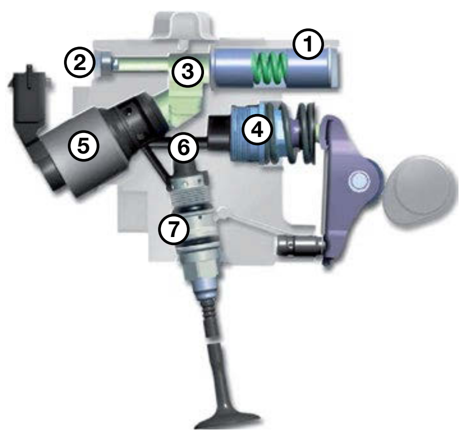

Figure 1 Typical setup of a UniAir actuator with the components:
1 – Pressure accumulator
2 – Oil supply
3 – Medium-pressure chamber
4 – Oil pump
5 – Solenoid valve
6 – High-pressure chamber
7 – Valve brake

operation. The peak pressures that are acceptable for short periods are as high as 200 bar. For energy reasons, a portion of the oil flows from the medium-pressure chamber into a pressure accumulator (1). The oil supply (2) is provided by the engine oil circuit.

After the pressure in the high-pressure chamber drops, the engine valve is closed by the valve spring. The guide for the piston that is responsible for opening the valve has small bores that allow the oil to flow out in a controlled manner and thereby act as a brake (7).

In addition, a temperature sensor is also required in order to compensate for the hydraulic effects produced by the temperature-dependent viscosity of the oil. All other parameters required for controlling the UniAir system – such as the camshaft speed – are provided by sensors that are already employed.

The UniAir system is not restricted to application in engines with one intake valve per cylinder, however. Two intake valves of the same cylinder can be operated using either individual activation or with a hydraulic or mechanical bridge (Figure 2). For cost reasons, only the variant with a hydraulic bridge is currently in volume production. Individual activation would, however, provide an even higher degree of flexibility.

The systems that are already installed in volume-production applications today allow a significant degree of variability to be achieved in both the valve lift and the opening times (Figure 3). The maximum lift and the earliest opening point are specified by the envelope curve of the cam that is used to drive the system. The same applies for the latest possible closing point. Within these limits, regulation is carried out exclusively via the current controlling the solenoid valve.

The overall result is that the valve opening and closing times and the valve lifts can be optimally adjusted for all engine operating points (Figure 4).

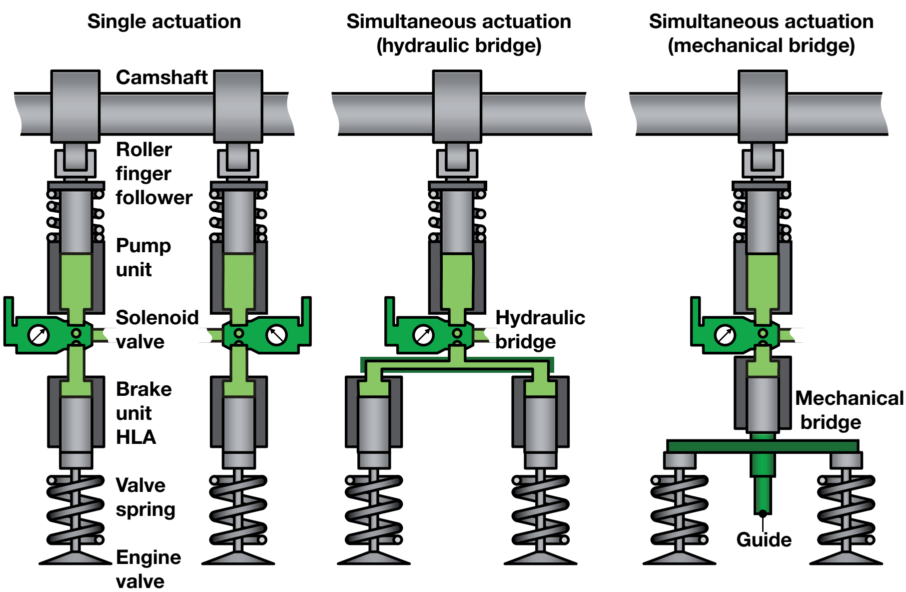

Figure 2 Alternative solutions for operating two intake valves

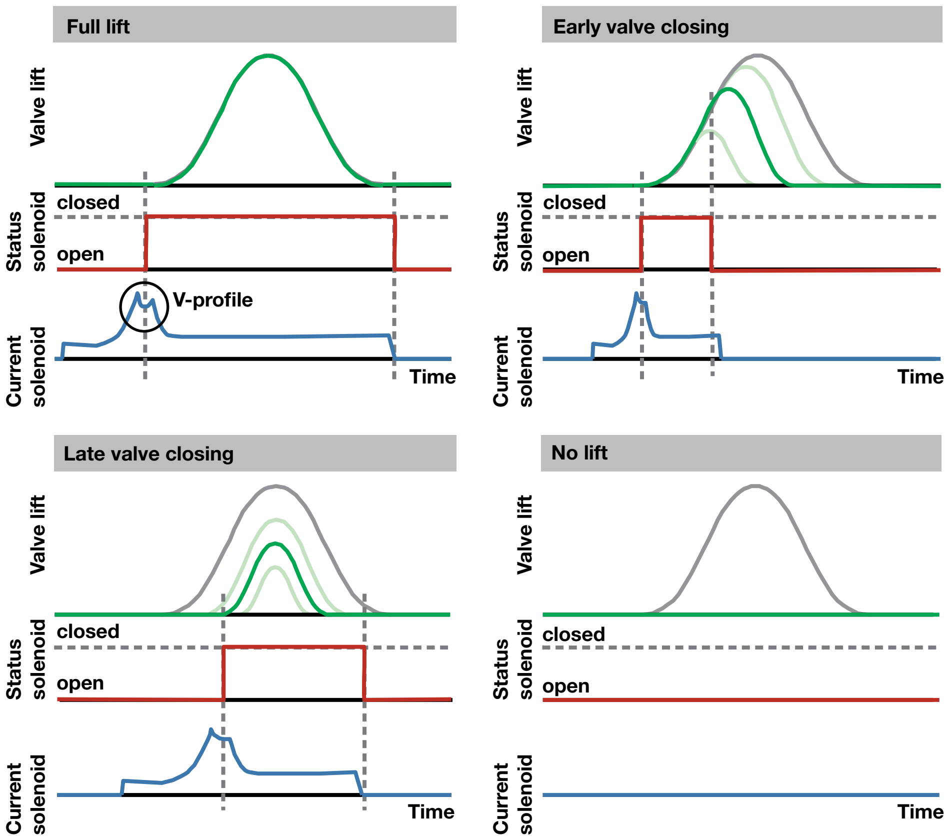

Figure 3 Variability of valve lift and opening/closing point with the current UniAir system

During the closing time, the current curve required to close the solenoid valve – i.e. to open the engine valve – displays the typical V-shape that is caused by the valve reaching its end stop position. The position of the turning point in the V-profile indicates the extent to which the desired lift was achieved by the solenoid valve. The reproducibility can be traced by making a comparison of several consecutive events. If deviations occur here that are not within the tolerance limits, e.g. due to aging components, these can be compensated by changing the current curve.

Experience with volume-production engines to date has shown that UniAir displays very good values, both in terms of reproducibility – i.e. deviations from cycle to cycle in one cylinder – and of the system's precision – i.e. the spread across several engines. UniAir thus achieves a repeat accuracy of 0.4 crankshaft degrees at 3,000 rpm and a system temperature of 120 °C for the "early intake closure" function. The opening angle during "late intake valve opening" – which is decisive for cylinder balancing – also achieves a precision of 0.4 crankshaft degrees. Under the conditions described, the deviations between various volume-pro-

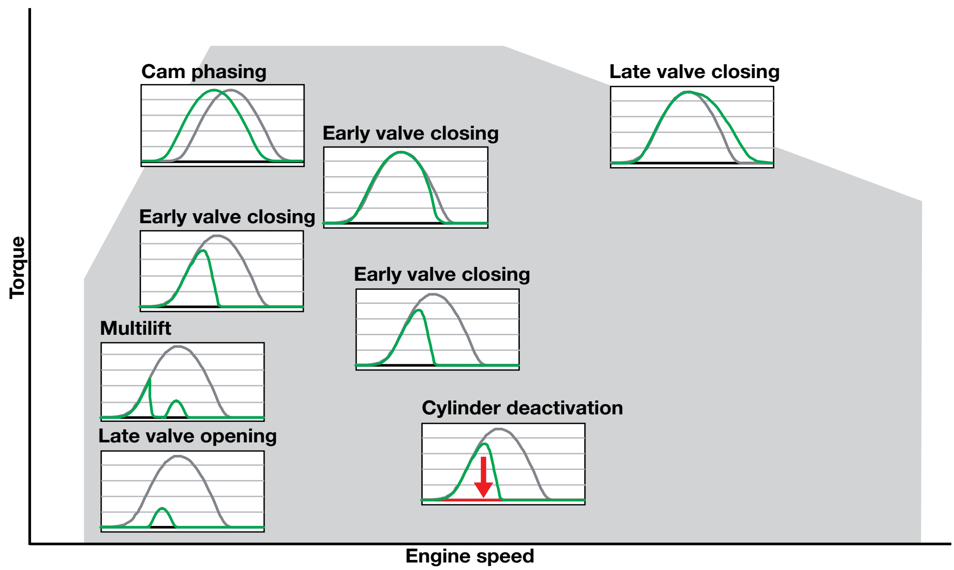

Figure 4 Valve lift curves within the engine map

duction engines are at a slightly higher level for "early intake valve closure" than for individual cylinder actuation. A compensation function that is integrated into the UniAir software also ensures that the cylinders of the respective engine are correctly balanced here, however.

The market launch of UniAir has proved that the system can be applied in such a way that no changes to the design envelope are required. The prerequisite for this is that the UniAir system and the remaining standard valve train are both driven by a common camshaft that is still installed. In the case of a direct injection gasoline engine with centrally-positioned injectors, the injector and spark plug must be arranged perpendicular to the camshaft assembly. If this is carried out, the intake camshaft (for example) can be omitted, which means that the additional costs of the UniAir system can be partially compensated. In the future, however, there will also be applications in which both camshafts are retained.

Expansion of the scope of functions

Applications for gasoline engines

The trend for low-consumption gasoline engines with direct-injection and increasingly small engine capacities is continuing unchecked. The introduction of new standard cycles for measuring fuel consumption, particularly the WLTP, mean that operating points with higher loads are being achieved at the same time, in which the benefits provided by the combination of downsizing and turbocharging cannot be exploited to the same degree. When combined with turbocharging, a fully variable valve train can therefore contribute towards reducing fuel consumption even further.

In turbocharged engines, the flushing of the cylinder with fresh air ("scavenging") provides significantly faster response times at low speeds and high loads. The valve overlap that this requires is conventionally achieved through the use of camshaft phasing units. This type of camshaft phasing unit, which is characterized by its high adjustment speed, is available from Schaeffler [4]. When designed correctly, UniAir can partially replace camshaft phasing units of this type. Although it is not possible for this system to influence the point at which the valve's envelope curve begins, the variation of the opening point together with a special lift curve (see Figure 8) can be used to only activate valve overlap when it is required.

Dethrottling at low speeds is known to have a very positive effect on the fuel consumption. It is important that the smaller valve lifts are not designed in such a way that a vacuum that could cause load cycle losses occurs in the cylinder during the intake stroke. This is an argument in favor of systems in which the lift height and lift duration can be varied to the same extent (Figure 5). Compared with an engine operated with a standard valve train and camshaft phasing units, an 8.4 % reduction in the specific fuel consumption that has been measured and verified is achieved at the operating point of 2,000 rpm and 2 bar.

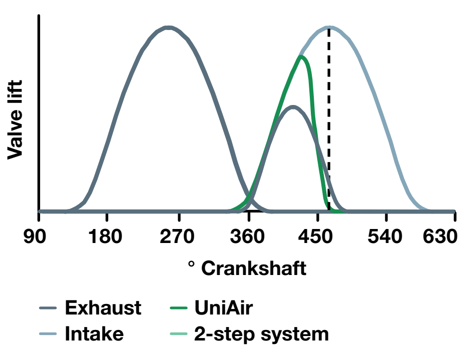

Figure 5 Lift curves for dethrottling at low speeds: UniAir compared with a two-stage cam profile

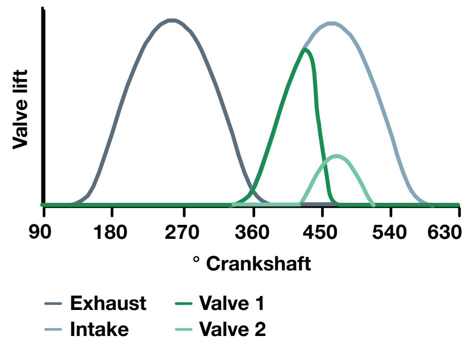

Figure 6 Lift curves of two intake valves of a cylinder when operated individually

An increase in the charge motion in the cylinder ("swirl") can contribute to improving the formation of the mixture and thus making the combustion process more efficient, especially with low loads of the kind typically found in city traffic. If both of a cylinder's intake valves are individually operated by a UniAir system, individual lift profiles for the valves can be illustrated (Figure 6).

Valve lift curves for city traffic/operation under low load conditions are also being developed (Figure 7) that can only be illustrated with UniAir and not with mechanical solutions for a fully variable valve train. The "hybrid lift" function combines late opening of the intake valve with early closure, a pro-

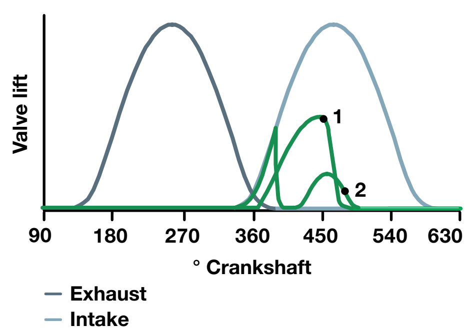

Figure 7 Special valve lift curves: 1) Hybrid lift and 2) Multilift

cess in which the ramps are not symmetrical with one another.

The "multilift" function opens and closes the intake valve twice within the intake stroke, which produces an optimum combustion process and low pumping losses at low speeds and under low to medium load conditions, and is therefore particularly suitable for optimizing fuel consumption in city traffic.

Under medium load conditions, operation using the Miller cycle – i.e. rapid and premature closing of the intake valve – is a good option. The improved expansion ratio improves the engine's degree of efficiency. The Miller cycle can easily be implemented with the UniAir system. The same applies for operation with the Atkinson cycle under high load conditions, during which the intake valve is opened for longer. This provides the desired reduction in compression without the charge motion in the cylinder being destroyed. The lower degree of compression in the high load range reduces the tendency towards knocking, which is of relevance for modern, supercharged gasoline engines.

Schaeffler and Continental have tested the application suitability of a combination of Miller and Atkinson cycles controlled exclusively by UniAir in a joint advance development project. For this purpose, a 1.4-liter volume-production engine that was already equipped with UniAir was fitted with a different engine control system in order to correspondingly optimize the process control. The results show significant potential with regard to fuel consumption:

- The use of the Miller cycle reduces compression at the operating point of 2,000 rpm and 12 bar, which produces lower final compression temperatures and thus a reduction in the tendency towards knocking. The specific fuel consumption is improved by 4.4 % compared to the volume-production engine.
- If the mean pressure is increased to 15 bar at the same speed, a significantly lower tendency towards knocking is observed due to the closure of the intake valve after the beginning of the compression stroke (Atkinson cycle). The specific fuel consumption is reduced by 4.6 %.
- At a typical full-load point (3,000 rpm and 18 bar), the use of the Atkinson cycle makes it possible to reduce the degree of enrichment that would otherwise be required in order to lower the temperature in the combustion chamber. This leads to a 4.6 % reduction in the specific fuel consumption.

The use of UniAir allows not only the fuel consumption but also the exhaust emissions to be reduced. This particularly applies to nitrogen oxide (NO_x) emissions, as was verified for diesel engines as early as 2008 [6]. Related designs combined internal and external (low-pressure) exhaust gas recirculation in the engine.

With the first-generation UniAir system, it was only possible to adjust the valve lift within the "conventional" envelope curve as specified by the cam. This makes it difficult or even impossible to achieve the kind of large valve overlaps required for high residual gas content. This obstacle has now been overcome thanks to the introduction of a correspondingly designed "two-stage" cam profile for the UniAir system. This is re-

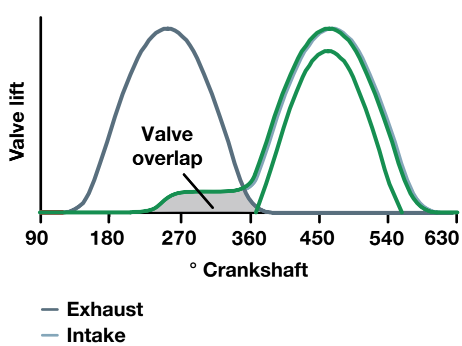

Figure 8 Valve overlap for internal exhaust gas recirculation with a two-stage cam as the UniAir drive

ferred to as a “boot cam” due to its boot-like shape. It is now possible for the first time to achieve a large valve overlap without a significant reduction in the maximum filling level during the intake cycle (Figure 8).

For operating points that do not require internal exhaust gas recirculation (e.g. under full load conditions), no current reaches the solenoid valve that is responsible for the UniAir’s switching until the first stage of the cam has already passed over the contact surface with the high-pressure pump.

UniAir for diesel engines

Over the coming years, the further development of the diesel engine will continue to focus on the reduction of NO_x and soot exhaust emissions. In order to minimize the outlay for costly exhaust gas aftertreatment, especially selective catalytic reduction (SCR), a clean combustion process is of the utmost importance for every engine designer. In addition to other measures such as increasing the injection pressure, combustion with a high rate of exhaust gas recirculation is an important prerequisite for keeping these raw engine emissions to a minimum.

The two-stage cam is not a suitable solution for the diesel engine, because a significant valve overlap is not possible due to the lack of free-running clearance between the piston crown and the engine valve at the top dead center. An alternative concept would be to control the quantity of residual gas remaining in the combustion chamber within wide limits through early closure of the exhaust valve and late opening of the intake valve (Figure 9). The first-generation UniAir system can already provide the lift curve variability that this requires – however, UniAir must also be used on the exhaust side in this case.

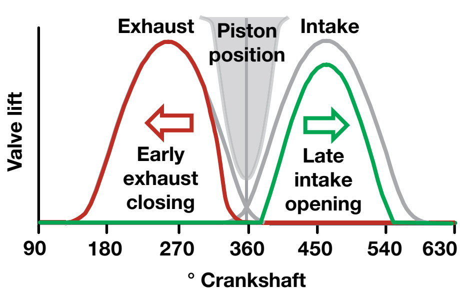

Figure 9 Internal exhaust gas recirculation for diesel engines through early exhaust valve closure and late intake valve opening

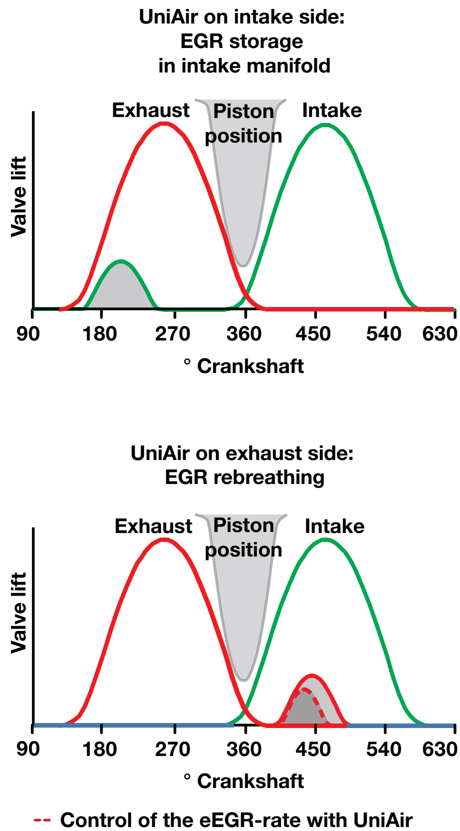

Figure 10 Internal exhaust gas recirculation for diesel engines with double cams for the UniAir drive

Double cams to actuate the UniAir system on the intake or exhaust side provide a further solution for achieving even higher internal exhaust gas recirculation rates if required. It is ensured here that the valve lift curve of the smaller cam can also be controlled (Figure 10) and that it is thus possible to control the exhaust gas recirculation rate. All of the UniAir system's modes still remain available for the primary/main cam. Operation without exhaust gas recirculation is thus possible at all times, which is important at extremely low temperatures (below -10 °C), for example.

For the sake of completeness, it should be mentioned that this is exactly how the thermodynamically positive effects of an effective compression ratio that has been reduced using the Miller/Atkinson cycles with UniAir can be achieved for diesel engines [5]. However, the objective here is to reduce the final compression temperature and thus the maximum final combustion temperature for emission reasons.

Supporting future combustion processes

Cylinder deactivation

Despite the unmistakable trend towards highly charged low-displacement engines, engines with four cylinders and upwards will continue to be used in large vehicles and those designed with high performance in mind. Engines of this type have to achieve better specific fuel consumption figures, especially under low load conditions and at low to medium speeds, so that the vehicle's overall emissions are reduced in the common standard cycles. A solution for this that has already been put into volume production by manufacturers including Audi, Chrysler,

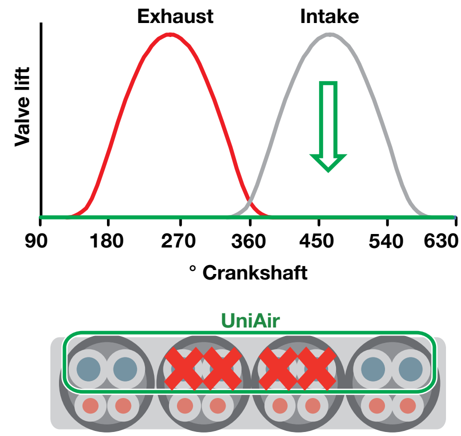

Figure 11 Cylinder deactivated by shutting down the intake valve

GM, Honda, Mercedes, and Volkswagen is cylinder deactivation, which increases the load of the operating point of the cylinders that are not deactivated. The mechanical systems that have been introduced for this purpose require a high level of outlay.

It is already possible to perform simple cylinder deactivation using the current UniAir system (Figure 11). However, this

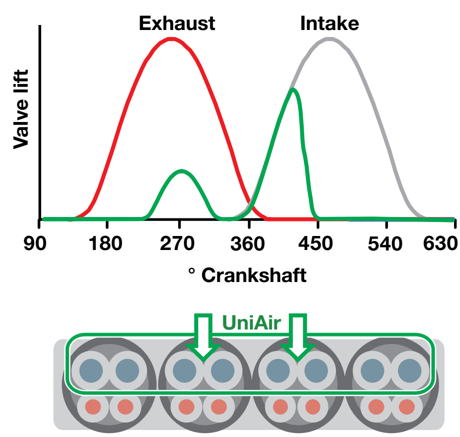

Figure 12 Cylinder deactivation with additional intake valve opening

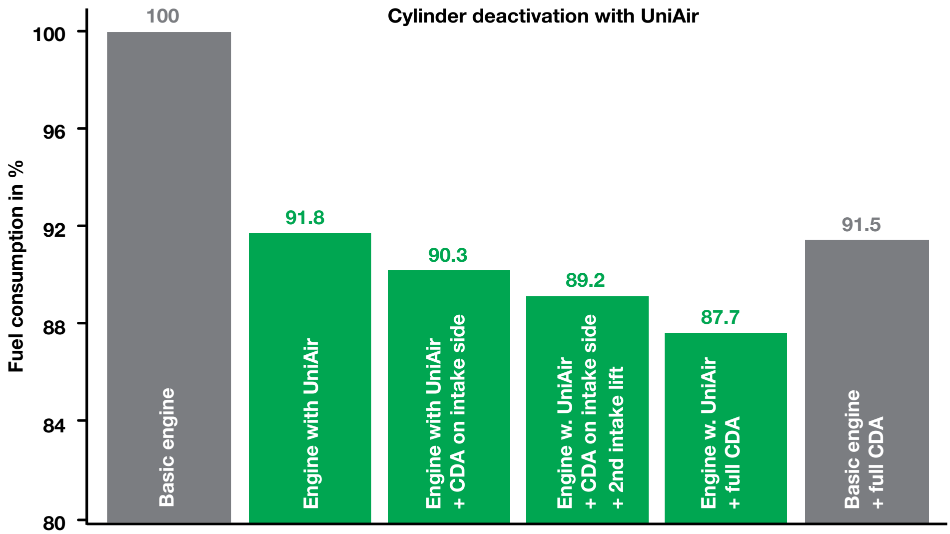

Figure 13 Simulated fuel consumption benefits for different cylinder deactivation strategies

type of system does not utilize the full potential for reducing CO_2 emissions that is available with the latest mechanical deactivation systems, which is estimated at up to 4 % in addition to the use of the fully variable valve train. This is because of the high level of charge cycle work caused by the exhaust valves that are still being actuated.

If the use of additional measures on the exhaust side, e.g. the use of switchable pivot elements, has to be avoided, there is a further variant that is also based on the use of a double cam. In this case, the cam is used on the intake side to briefly open the intake valve of an unfired cylinder during the exhaust stroke (Figure 12), allowing the exhaust gas to flow into the intake system. The intake valve in turn is then opened and then rapidly re-closed during the intake stroke, so that almost only the "stored" exhaust gas is allowed to flow into the combustion chamber. This alternating effect means that the overall charge cycle work is significantly reduced, and a large proportion of the savings potential available from the complete deactivation of all cylinders can be achieved (Figure 13).

Homogeneous charge compression ignition

Homogeneous charge compression ignition (or HCCI for short) has been undergoing development for volume production for some time . The section of the engine data map in which the thermodynamic benefits of self-ignition can be utilized has been continuously expanded, but still only covers part of the engine data map (up to a maximum of mid-range loads and speeds). This is because charge stratification with precisely defined composition and a high quantity of residual gas is the decisive factor for a stable HCCI combustion process. In addition to injection, the precise guidance of the charge motion combined with precise metering of the exhaust gas recirculation rate and adjusted compression can also have a significant positive effect on the stability of the combustion process [6].

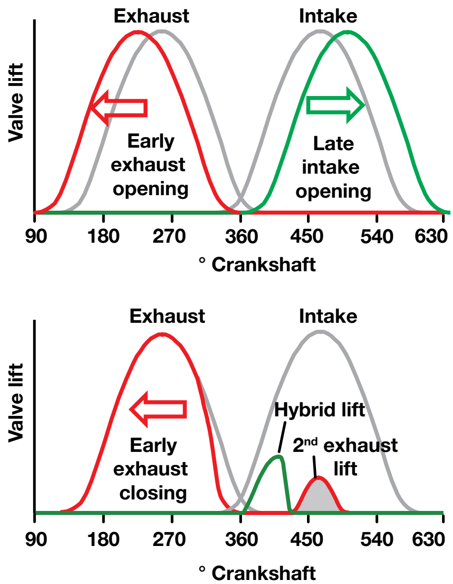

Figure 14 Valve lift curves for an HCCI combustion process: Greater variability through the combination of a phasing unit (left) and UniAir system (right)

In order to ensure the correct charge motion at high speeds and under high load conditions, Schaeffler relies on a combination comprising a camshaft phasing unit (electromechanical or hydraulic) and a UniAir system with a double cam drive (Figure 14). This fast actuator system makes it possible to set the correct compression and mixture ratio for every operating point. Switching between sections of the data map with compression ignition and external ignition can also be achieved in a significantly faster and more reliable way.

Outlook

The UniAir system has firmly established itself on the market. The significantly higher degree of valve lift curve flexibility displayed by an electrohydraulic system compared to mechanical systems, which are also in volume production or development, makes far more dynamic process control possible even today. The second-generation UniAir system also makes additional functions available. The adjustment of the UniAir drive using two-stage or double cams that is required for this purpose has achieved a high level of maturity.

From 2015/16 onwards, UniAir will be used in a range of further passenger car applications, including engines equipped with different numbers of cylinders from those in today's volume-production applications, and it is also set to be put into volume production by more automobile manufacturers. Intensive preproduction testing is currently being carried out on a four-cylinder diesel engine application.

The first motorcycles to be equipped with the UniAir system will also be seen in the near future. In parallel to this, Schaeffler is also collaborating with ABB Turbo Systems on a project to market the UniAir system for use in stationary engines. An area of particular interest here is the use of gas-operated stationary engines for energy generation. Even these engines will have to be controlled with a significantly higher degree of flexibility in the future without their high degree of efficiency being sacrificed. In applications of this kind, the cost savings that are achieved through the targeted improvements in fuel economy are significantly higher than the cost of the variable valve train system.

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