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# The best of both worlds combined

## The continuously variable cam shifting valve train


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# Initial situation

From an engineering perspective, the transition from internal combustion engines via hybrids to electric drives requires modifications to the vehicle due to the future lower energy storage capacity of energy stores (conventional tanks). The drive of the future will be accompanied by a reduction in the weight of the vehicle, be it due to further developments in lightweight vehicles or due to the increased use of smaller “city vehicles”. Downsizing will be the most important measure for cutting fuel consumption in the near future and very small engines will be the outcome.

From a global perspective, gasoline engines dominate the world passenger vehicle drive market today. Fully-variable valve trains in conjunction with turbochargers and direct injection systems as well as the inclusion of biogenic components in fuel are regarded as necessary in order to facilitate high downsizing rates and to achieve the best $CO_2$ values. This high integration of modern technologies not only creates increased costs but also significant outlay in terms of control in the engine, which is integrated in an even more complex overall drive concept.

Up to now, fully-variable valve control systems have only been able to establish themselves on the market to a limited extent due to the manufacturing outlay involved and the complexity of the control system. The situation regarding costs will escalate further with increasing hybridization and electrification of passenger vehicle drives.

By selectively coupling and specifying the characteristics of variable valve trains during development, it is possible to produce variable valve trains that are cost-effective in terms of manufacturing and complexity of the control system, which can be installed in small, cost-effective engines with high $CO_2$ potential without making any significant changes to the engine design. This paper shows which combinations of characteristics in the valve train determine the $CO_2$ potential of highly-charged gasoline engines.

The new generation of fuel-saving engines require mechanically variable valve trains with the degrees of freedom of conventional continuously variable valve lift (CVVL) systems and the simplicity of a mechanical switching system such as the Audi two-stage cam shifting system.

# Current requirements and potentials of variable valve trains

Variable valve trains facilitate the adjustment of the valve lift function to match the operating condition of the engine.

The pressure on the market continues to rise and is focusing on the global requirements that automobile manufacturers are placing on variable valve train systems:

- Maximum utilization of the maximum theoretical $CO_2$ potential
- Very cost-effective to manufacture
- Lowest loss of the $CO_2$ potential in the vehicle application while considering drivability
- Minimal modifications in the engine design
- Low system complexity
- Compatibility with engine designs that are becoming more compact

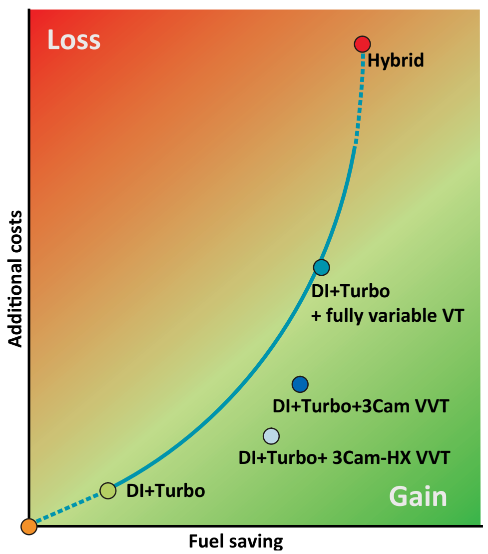


**Figure 1** Fuel consumption potential of internal combustion engines and hybrids

- Usability in a scalable drive concept, e.g. sustainability of the concept, even if components in the drive train are increasingly replaced by electrical systems

Along with the requirements placed on the valve lift function for controlling a single cylinder, other requirements that must be considered originate from the overall drive system:

- Equal distribution between cylinders
- Sensitivity of the settings with regards to tolerances
- Requirements in terms of precision placed on the actuator, coordination of the actuators in terms of time in transient driving operation
- Switching between various setting strategies due to various operating requirements → hysteresis
- Specific requirements in terms of control, sensors, on board diagnosis (OBD), communication with other systems
- Impact on emissions
- Requirements in terms of engine start and emergency running
- Other requirements such as design space, manufacturing requirements, oil pressure requirements, applied electrical loads, costs, development outlay, development risks, etc.

# The concept

The basic element of a continuously variable cam shifting system, 3Cam below, comprises a cam with a contour that can be continuously axially adjusted and provides a solution to the stated requirements for modern valve train systems. The cam, which can be moved axially in addition to rotation, is combined with a rocker arm unit to the cylinder head in order to generate the various valve lifts and valve opening times.

In contrast to discrete cam shifting systems, all cams of a cylinder head are fixed on a camshaft in this system. The axial movement of the camshaft is only achieved by means of an electromechanical phasing system. The variant known as 3Cam-HX has a rigid linking of lift and phasing. This means that lift and phasing are controlled by a single actuator.

A gas exchange study was used to design the system presented in this paper and to determine the shown potential of the variable valve control system. Calculations were carried out using the GT Power program on the basis of an adjusted model of a turbocharged in-line 4-cylinder gasoline engine with around 1.5 liter capacity. The potential for saving fuel by cutting charge cycle operations at constant combustion is shown. The gas exchange system was not modified except for the valve lift function and was taken from a throttle-controlled basic engine. The valve lift func-

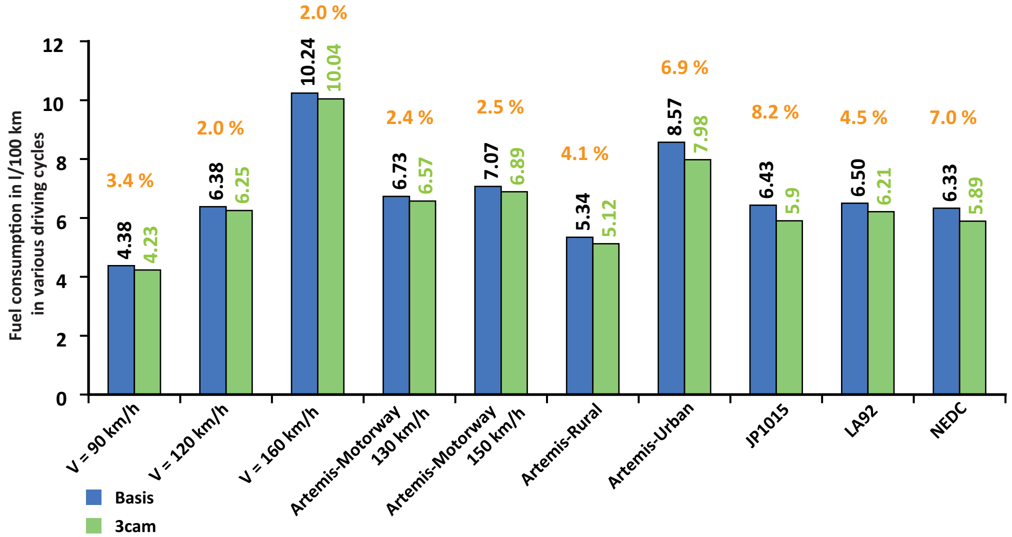


**Figure 2** Fuel consumption in l/100 km in various driving cycles, scope involves the advantage in the charge cycle consumption

tions are selected from a set of valve lifts that are actually implemented with the variable valve train system described in this paper. This method enabled us to determine mechanically feasible lift functions which have been optimized in terms of lift and phasing. At the same time, the potential for fuel consumption of a valve control system that is able to set these lift functions was determined.

The calculated stationary results were extrapolated for fuel consumption in various driving cycles for a vehicle from the compact class with 1300 kg vehicle weight and manual transmission (Figure 2).

The advantages calculated from the stationary results in the charge cycle lead to an advantage of 7.0 % in the NEDC. Comparing various cycles shows that advantages of around 2 % in a further area of the data map exist for the continuously variable system at full load.

Continuously variable valve train systems compete on a technical level or also complement other measures on the valve train side for reducing fuel consumption such as phase adjustment units, 2-stage lift actuators with and without cylinder deactivation or 3-stage lift actuators with cylinder deactivation

| | | Basis | 3Cam | 3Cam-HX | CPS | CDA intake | CDA i + e | CDA Evo |
|---|---|---|---|---|---|---|---|---|
| Configuration | 3Cam | | x | x | | | | |
| | VCT int. | x | x | | x | x | x | x |
| | VCT exh. | x | x | x | x | x | x | x |
| | 2-step CPS | | | | x | | | x |
| | CDA intake | | | | | x | x | x |
| | CDA exhaust | | | | | | x | x |
| Additional characteristics | Application | Base | o | ++ | + | o | o | -- |
| | System costs | Base | | | | | | |
| | Peripheral costs | Base | masking only | masking only | | Vibration and oscillation damping, exhaust system | Vibration and oscillation damping, exhaust system | Vibration and oscillation damping, exhaust system |
| | Total costs | Base | | | | | | |
| Fuel consumption potential | Additional potential from combustion | Base | 1-2 % | 0-1 % | 0 %-0.5 % | 0% included in charge exchange | 0% included in charge exchange | 0 %-0.5 % |
| | Additional potential for optimization (friction, intake and exhaust system) | Base | 0-1 % | 0-1 % | 0.5 % | 0.5 % | 0-1 % | 0-1 % |
| | NEDC, calculated potential from gas exchange | Base | 7.0 % | 6.0 % | 3.8 % | 1.5 % | 5.1 % | 6.1 % |
| | Total potential NEDC | Base | 9.0 % | 7.0 % | 4.5 % | 2.0 % | 5.6 % / 7.1 %* | 6.9 %/8.4 %* |
| | Compatibility with future technologies (lean direct injection turbocharging, EGR, 3 cylinders | | ++ | ++ | + | - | - | o |
| | Total rating | | + | ++ | o | -- | o | - |

positive neutral negative

Figure 3 Comparison of fuel consumption potential of various valve train variations (*incl. additional potential with engine shut-off during idling with stop-start systems)





(ZAS-Evo) as the third switching step as well as combinations of these technologies. Various technologies were compared using the same method in order to produce a comparable assessment (Figure 3).

The two-stage lift actuator system under consideration with asymmetrical lift functions achieves a remarkable potential saving of 3.8 % in the NEDC if the lift function is optimized to the cycle. In addition, advantages in mixture formation and combustion are generated that anticipate an overall potential of up to 4.5 %. The area of the data map in which the stage system acts is, of course, smaller than the area in which a continuously variable system can act. However, excellent values very similar to those of continuously variable systems can be achieved in this area and when focusing on this partial load potential.

The continuously variable cam shifting system known as 3Cam-HX does not require a phase adjustment system on the intake side and has a rigid linking of lift and phasing. The system loses only very low levels of performance compared with the 3Cam system with all adjustment options. The advantage in the application due to the rigid linking between valve lift and phasing is reflected in the overall assessment. The low disadvantage in terms of fuel consumption in stationary operation is confronted by significant simplification of the control system and application, which more than compensates for the stationary disadvantage in practice.

Using the increase in load as an example, Figure 4 shows the advantage in the application generated by coupling the lift and phase adjustment units. During the conventional separation of functions, the slower phase adjustment unit determines the maximum useable dynamics of the lift adjustment unit. The throttle valve intervenes during the actuating procedure and corrects it. By linking lift and phasing, the combination defined during development is also present during transient operation. In practice, the advantage in terms of dynamics of a rapid actuator with phase and lift coupling is increased by an advantage in terms of efficiency as maladjustments and ignition-timing interventions are avoided. In the case of turbocharged engines, system design can also incorporate control of the charging pressure.

For these reasons, the continuously variable cam shifting system with phase and lift coupling (3Cam-HX) is a very efficient load control system for cost-effective downsizing internal combustion engines as well as for hybrid drives for which a high

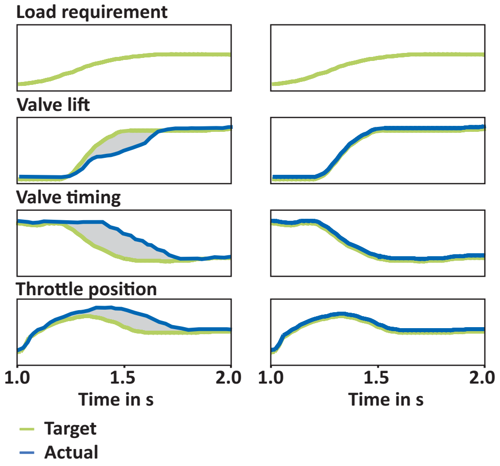


Figure 4 Left-hand side of figure: Increase in load with separate lift and phase adjustment unit, right-hand side of figure: Advantages in the application due to 3Cam-HX

performance range of the internal combustion engine is used to improve drivability.

# The best of both worlds combined



A mechanical solution is to be sought that implements the presented requirements in the best possible way in accordance with the described requirements profile.

The articles about BMW's Valvetronic in [1] and [2] provide an overview of the challenges to be met during development and volume production for a mechanical fully-variable valve train system.

Continuously variable cam shifting valve trains distinguish themselves from classic CVVL systems. Two common characteristics of multi-body CVVL solutions are a complex multi-joint transmission system (sliding block system) as well as the separation of the control shaft and the camshaft (two-shaft design).

One solution is the continuous 3Cam cam shifting valve train. This system has a simple mechanical layout. It can be integrated in several cylinder heads with only slight modifications to the design space. Small modifications to the basic cylinder head enable this solution to be mounted on existing volume production assembly lines.

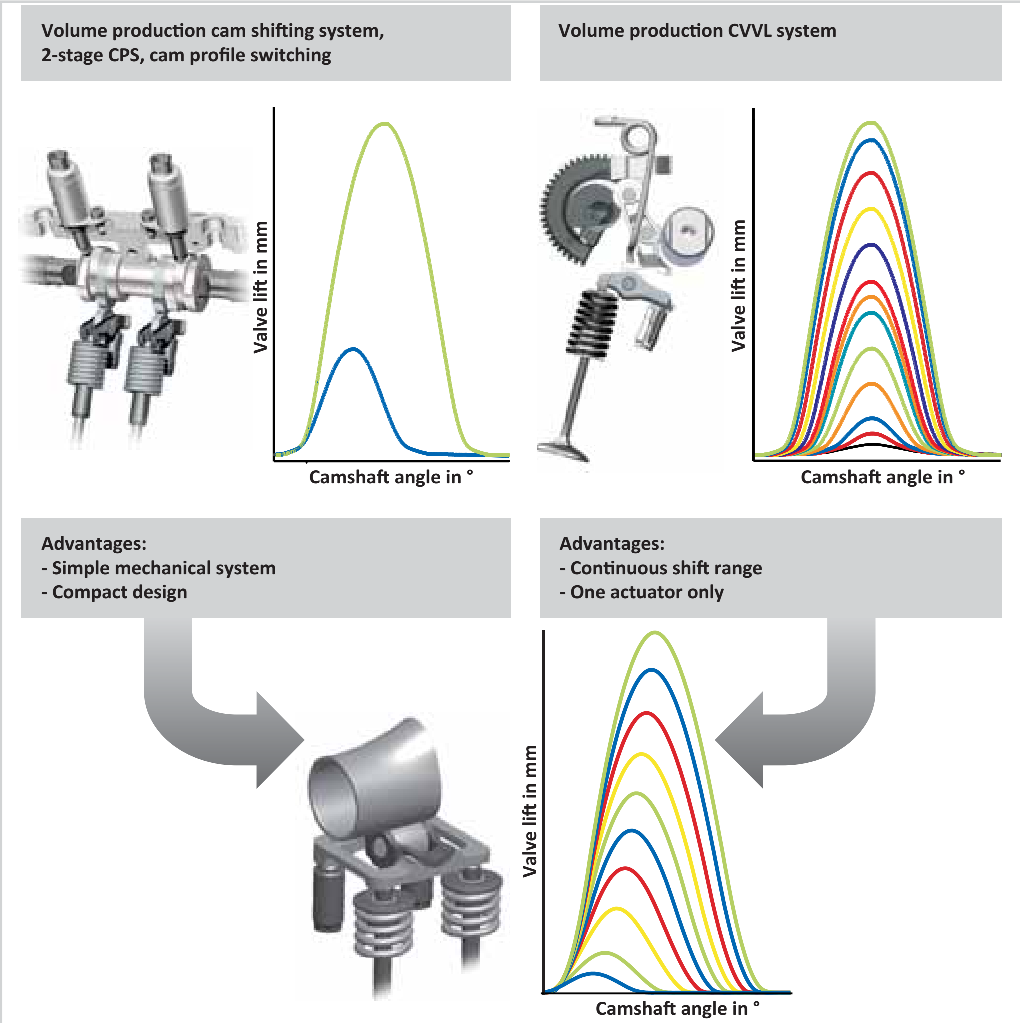


**Figure 5** The best of both worlds combined

The development objective of the continuously variable cam shifting valve train is to merge the positive characteristics of a classic CVVL system and a 2-stage cam shifting system. The 2-stage cam shifting system has a simple mechanical design and can therefore be integrated relatively easily in an existing cylinder head. However, only a few valve lift curves can be generated by switching. In addition, a pair of actuators is required for each cam lobe assembly in order to perform the switching operation for each individual cylinder. Figure 5 shows the relationship of the continuously variable camshaft shifting system with a CVVL and a 2-stage cam shifting system.

The significant difference of continuously variable cam shifting valve trains is the design space re-

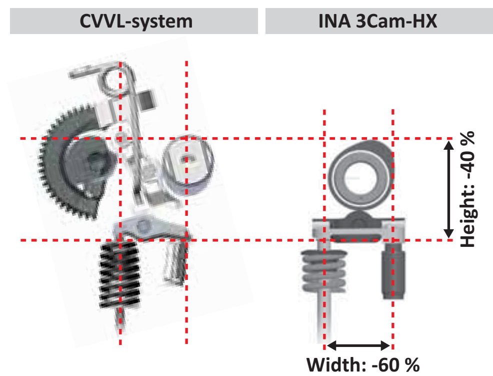


**Figure 6** Comparison of space required for volume production CVVL system according to [1] and continuously variable cam shifting system





quirement. The CVVL system requires a series of additional components, which means the design space requirement in the cylinder head increases. Both concepts are compared without the relevant actuator in Figure 6.

# Old principle, new approach

The idea behind a continuously variable cam shifting valve train has existed for several years. The first designs were conceived by Titolo [5]. Some engine manufacturers have already dealt with the continuously variable cam shifting concept in the past, however, there have not yet been any volume-production applications.

Some significant new developments are being used in the development of the 3Cam valve train due to Schaeffler's expertise in large-scale volume production of high-precision components and rolling bearings. The shortfalls of previous solutions as regards tolerance class, friction, life, and system dynamics have been eliminated:

- Transfer of the entire valve lift data map from zero lift to maximum lift to the cam
- Combining valve groups of a cylinder (intake, exhaust), actuation of both intake or exhaust valves with only one cam
- High transmission ratio of displacement travel to lift for high equal cylinder distribution in idling
- Consistent use of components supported by rolling contact
  - Contact pair between cam and rocker arm unit contour using a roller supported by rolling bearings
  - Variable cam timer supported by rolling bearings (HX characteristic)
- Hydraulic valve lash adjustment
- Linear contact between the cams and the roller
- Support of the axial force of the cam with a rolling bearing that minimizes friction
- Electric axial adjustment with BLDC motor including positioning sensor
- Mechanically-dependent or independent linking between valve lift and phasing that can also be combined with a separate camshaft phasing unit
- Precise adjustment at starter motor speed (engine start) possible

## Complete system

The INA 3Cam-HX valve train comprises the following four assemblies (Figure 7):

- 3D cam shifting shaft
- Rocker arm unit
- Torque transmission unit
- Axial adjustment unit

The torque transmission unit transmits the force from the camshaft drive wheel to the camshaft. The inside of the unit is equipped with rolling elements and it facilitates efficient adjustment of the axial position of the camshaft with low friction. Valve lift and phasing are influenced simultaneously in the HX version due to this control variable.

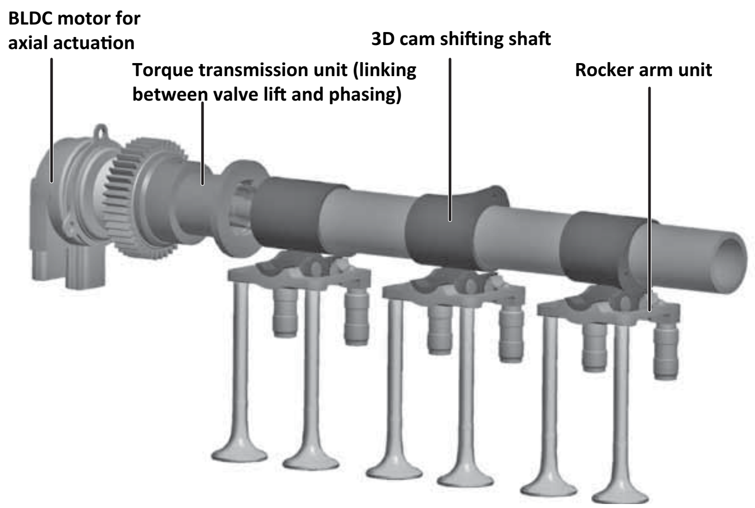


**Figure 7** INA 3Cam-HX valve train on a 3-cylinder engine

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The electrically commutated electric motor is connected to the cam shifting shaft by means of a ball screw drive with optimized friction characteristics. The cam shifting shaft has four cams that each actuate two valves of a cylinder. The 3D rocker arm unit transfers the valve actuation force between the cam and valve. To do so, the internal component, the so-called compensator lever, is supported in the external finger follower and has an angular compensation facility.

Schaeffler's extensive expertise in mechanical systems means the company can manufacture all mechanical components of the 3Cam-HX system very economically. A very economical design and manufacturing process has been specially developed for the complex geometry of the shift cam so as to achieve the typical rating life and tolerance compliance of a conventional valve train in automotive applications.

## 3D cam shifting shaft

The cam of the INA 3Cam-HX system is the central component of the valve train. All valve lift curves are found on the profile of the cam. In conjunction with the cam roller, the contour forms a unit precisely matched during development. This means that the geometry of the roller is taken into consideration when designing the cam. By using a calculation and design process specially developed at Schaeffler it was possible to generate a cam and roller pairing that forms a linear contact between both partners in the lift phase. In the base circle phase where the load on the cams is low a contact ellipse is generated between the cam and the cam roller. The line contact sufficiently accommodates the requirement for a long rating life.

The design process takes the grinding technology used to manufacture the cam into consideration. With a specially developed grinding process for which a patent application has been made, it is possible to manufacture the surfaces of the cams very economically with short cycle times.

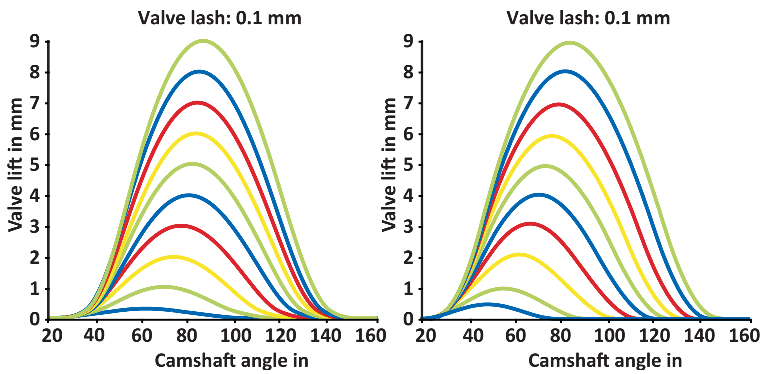


**Figure 9** Two possible groups of valve lift curves in the INA 3Cam cams

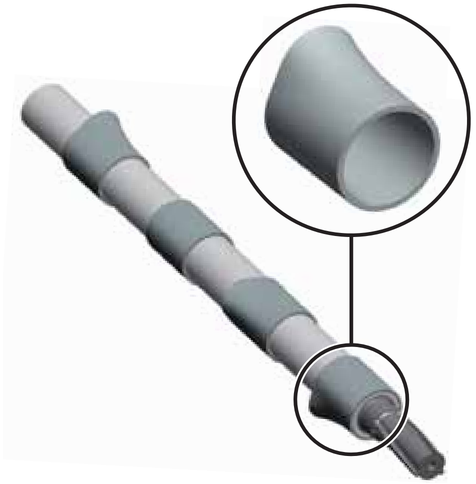

**Figure 8** Camshaft and individual cams

Conventional manufacturing methods can be used to manufacture the camshaft.

By using the design process described above, groups of valve lift curves with a valve lift adjustment range of 0.4 mm to 9 mm and a opening period range of 120° crankshaft up to approximately 260° crankshaft as well as "zero lift" were implemented. The surface pressures in the cam roller contact are kept at a level suitable for the entire rating life due to the linear contact of the contact partners. The largest loads occur at engine speeds of 7000 1/min and maximum valve lift.

The graph on the left-hand side of Figure 9 shows the group of valve lift curves from the test system cam. The cam was designed in a very similar manner to the group of curves of CVVL systems in order to carry out a comparison of the dynamic behavior of the CVVL and shifting cam kinematics during subsequent valve train dynamics tests.

The developed design and grinding technology facilitates an additional reduction of the opening period in the lower valve lift range. The graph on the right-hand side of Figure 9 shows such a cam. However, complete line contact must be avoided in certain contact areas of the cam. The influence of the anticipated increased surface pressures in the cam-roller contact area on the rating life is part of a future investigation.

The cam contours shown above can be applied as required on individual parts or on the entire camshaft with the Schaeffler manufacturing process. For the first internal test camshafts, finished cams were joined to a base shaft to form a four cylinder camshaft. A conventional shaft/hub connection joining method can be used to join the cams to the base shaft. In addition, the camshaft is completed by adding the inner component of the torque transmission unit to form an overall camshaft. The assembled design led to a reduction in weight in comparison to the basic camshaft. The total weight of the complete 3Cam 4-cylinder camshaft is approximately 1.2 kg.

## 3D rocker arm unit

The rocker arm unit comprises a frame-like finger follower with an internal compensator lever and a cam roller based on a needle roller bearing. The end of the finger follower is supported by two hydraulic valve lash adjustment elements.

Two valves are actuated by one cam so as to provide enough space for a high ratio of displacement travel to valve lift by using only one cam.

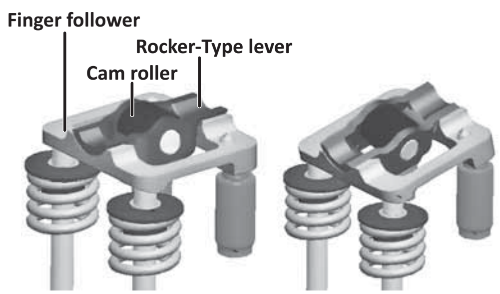


**Figure 10** Rocker arm unit of the continuously variable cam shifting valve train

The cam roller profile facilitates effective adjustment to the cams in the lift range. The generated common line of contact limits the contact pressure. The guidance between the compensator lever and finger follower forms the coupling for the required degree of tilting movement. Axial loads on the cam roller are minimized as the load of the shifting cam always acts vertically to the roller axis.

A force component acts parallel to the camshaft during each cam lift. This force must be transmitted by the rocker arm unit. The valve lash adjustment elements support both the longitudinal forces and the transverse forces from the lift motion. Both valves therefore remain free of transverse forces.

In comparison to the basic type, each compensator lever and finger follower replaces two finger followers. This produces only a slight increase in mass and mass moment of inertia compared with the basic type.

## Torque transmission unit

The torque transmission unit supports the chain sprocket or belt pulley and transfers the introduced torque to the camshaft. In conventional valve trains, the camshaft defines the axial position of the chain sprocket. Since the camshaft in continuously variable cam shifting valve trains can be axially displaced, the drive wheel must be supported axially by a bearing on the outside of the torque transmission unit (bearing sleeve). Rows of balls act as low-friction supports between the outer and inner parts in order to ensure smooth axial displacement under the load of the camshaft drive torque.



In the case of the INA 3Cam-HX valve train, the rows of balls move on helix-shaped counterparts in order to implement the advantageous coupling between lift and phasing mentioned above and to transmit maximum load with minimum friction. The helix angle can be freely selected in accordance with the desired thermodynamic strategy. Conventional rolling bearing balls serve as the coupling body that moves in a special raceway profile so as to transmit maximum load with minimum friction. The balls are paired during manufacturing, which enables quasi clearance-free transfer of torque of the camshaft drive torque.

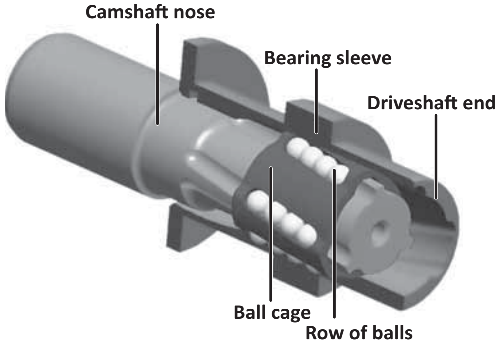


Figure 11 Torque transmission unit and camshaft phasing unit of the 3Cam-HX valve train

In the internal test cylinder head, an adjustment angle of 44° crankshaft in "advanced" direction was realized. Up to 100° crankshaft can also be manufactured.

## Axial adjustment unit

The design of the axial adjustment unit fulfills the following boundary conditions:

- No additional design space requirements in comparison with the volume production cylinder head
- No modifications to the test cylinder head
- High efficiency
- Actuated with an electric motor

A ball screw drive manufactured by forming methods and with optimized friction characteristics converts the rotational motion into linear motion with a high level of efficiency. The electric motor that provides the drive is brushless. The use of rare-earth magnets means the drive motor is particularly compact.

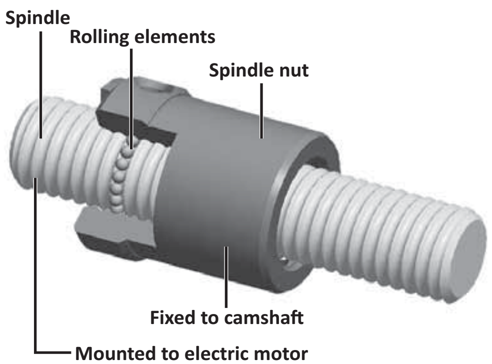


Figure 12 Axial adjustment unit of the 3Cam-HX valve train

The axial adjustment unit of the 3Cam-HX is designed as a co-rotating system. The electric motor therefore permanently rotates at camshaft speed and accelerates or decelerates the threaded spindle for short periods in order to axially position the camshaft. This design produced a very compact axial actuator for the test system with the result that the 3Cam-HX adaptation on the cylinder head reduced the length of the overall base cylinder head by 3 mm compared with the basic system. The basic cylinder head is equipped with a conventional valve train and a hydraulic phasing unit.

# Test results

Various measurements to verify the performance of the 3Cam-HX valve train were carried out on the internal test cylinder head. The selected evaluations are as follows:

- Adjustment times
- Control accuracy
- Power requirement in stationary and dynamic operation
- Valve train dynamics

## Power consumption and dynamic positioning

The electrical power requirements of the phasing system were determined by measuring the current drawn by the servomotor. Values were determined for various speeds and increases in valve lift of various sizes.

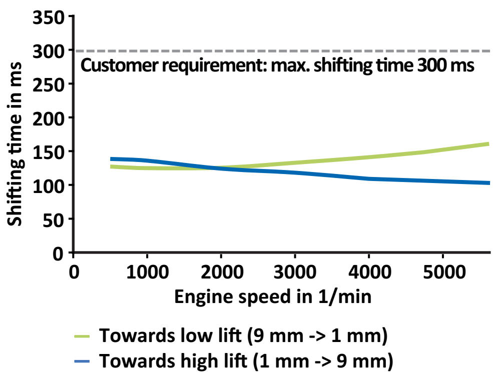


Figure 13 Phasing times of the 3Cam-HX valve train between 1 mm and 9 mm valve lift





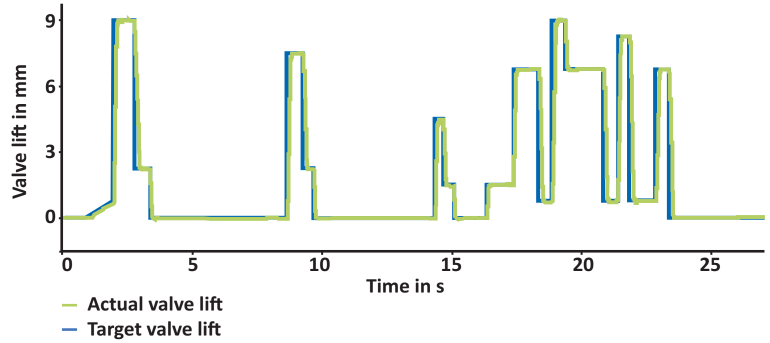


Figure 14 Dynamic adjustment cycle (measurement)

In stationary operation, the electric motor draws on average 0.8 A, depending on the crankshaft speed. This value approximately corresponds to the holding current for the proportional valve of a hydraulic camshaft phasing unit. The peak current for the electric motor was limited to 40 A for dynamic operation. This means that this peak current is half the acceptable value according to [2] and is sufficient to achieve high dynamic positioning.

Figure 13 shows the results of measurements of valve lift jumps on a driven cylinder head between 1 mm and 9 mm valve lift depending on the crankshaft speed in open-loop operation. All increases in phasing times are possible in significantly less than 200 ms.

These phasing times show the performance of the phasing system without the influence of a closed-loop controller. The measured values are significantly lower than the customer acceptance limit [2]. Short phasing times are extremely beneficial when regarding driving dynamics and spontaneity, since lift and phasing can be adjusted simultaneously in the 3Cam-HX during this time.

Figure 14 shows a dynamic phasing cycle on the cylinder head controlled by a closed-loop system. A prototype system with a simple PID controller is used for positional control. The system shows that the high dynamics are mastered by the controller and that the deviations between target and actual position are low. This reflects the very low frictional hysteresis in the mechanical components.

# Summary

The continuously variable cam shifting system 3Cam-HX is an extremely compact, dynamically adjusting variable valve train that combines the advantages of a two-stage cam shifting system with those of a continuously variable mechanical CVVL valve train. Along with the subsequent modification of an existing cylinder head, the simplicity of the actuation system and the feasibility of the very effective linking of lift and phasing must be emphasized. This function simplifies the engine application when integrated in a vehicle and offers a wide range of options for high efficiency in practical transient driving operation. Low system costs, amongst others due to the omission of a separate camshaft phasing unit, provide an attractive cost-benefit ratio.

The very good cost-benefit ratio is particularly attractive for the utilization of the system in economical turbocharged engines with downsizing and drive concepts with hybridization for which a particularly high level of pressure in terms of costs exists for the engine.

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