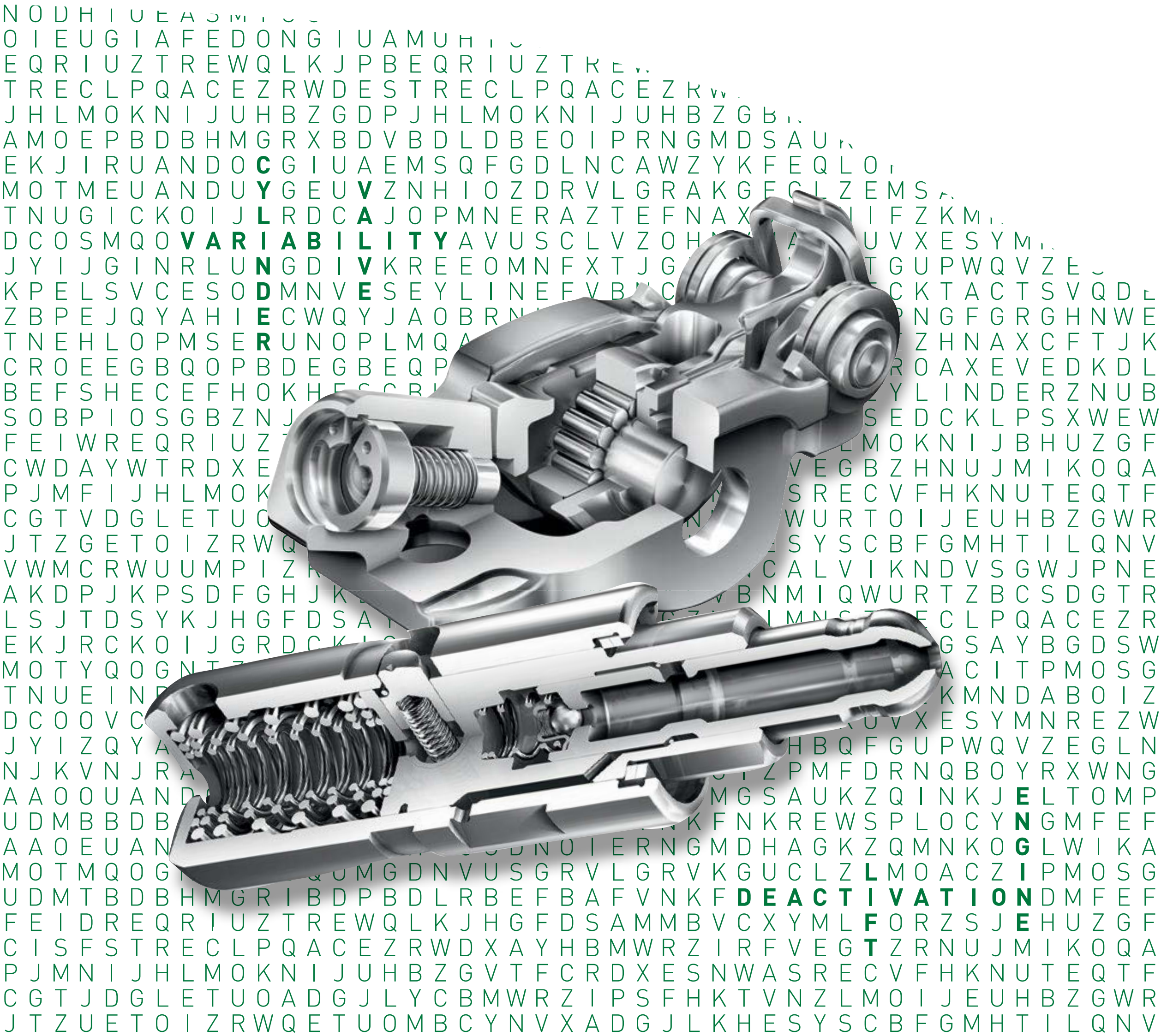
VARIABILITY
CYLINDER
VALVE
ENGINE
LIFT
DEACTIVATION

# Cylinder Deactivation

## A technology with a future or a niche application?

Arndt Ihlemann
Norbert Nitz

11

# Introduction

One of the ways manufacturers can minimize fuel consumption is to downsize the engines they offer. A cylinder's volume can only be restricted to a certain extent, however, if the thermodynamically ideal volumetric capacity of 400 to 500 $cm^3$ per cylinder is to be retained. In practice, downsizing therefore frequently leads to a reduction in the number of cylinders.

"Temporary downsizing" in the form of cylinder deactivation offers an attractive compromise, since this allows an engine to shift its operating mode to achieve the specific consumption figures it is rated for, especially when low loads and operating speeds are encountered. At the same time, the driver still has a sufficiently powerful engine at his or her disposal that ensures the same level of driving pleasure and comfort with regard to acoustics and vibration characteristics.

An additional key success factor that can help this technology to be deployed in a more mainstream fashion is that it can be integrated into existing engine concepts at acceptable costs.

# Designs

The most consistent form of cylinder deactivation is to not only to cut injection and ignition for the respective cylinders, but also to stop all moving parts (including the pistons). This, in turn, utilizes the entire thermodynamic potential available and considerably reduces the friction that occurs inside the engine. It goes without saying that com-

| Manufacturer | Type of engine | Valve concept | Status |
|---|---|---|---|
| **GM** | **6.0-liter V8-6-4 engine** | **Pushrod actuation, switchable rocker arm pivot point** | **SOP/EOP 1980** |
| | **3.9-liter V6 engine** | **Switchable roller tappet** | **EOP 2008** |
| | **5.3-liter V8 engine** | **Switchable roller tappet** | **Volume production** |
| | **4.3-liter V6 engine** | **Switchable roller tappet** | **Volume production** |
| | **6.0-liter V8 engine** | **Switchable roller tappet** | **Volume production** |
| **Daimler** | **5.0-liter V8 engine** | **Switchable rocker arm; MB** | **EOP 2005** |
| | **5.8-liter V12 engine** | **Switchable rocker arm; MB** | **EOP 2002** |
| **Chrysler** | **5.7-liter V8 engine** | **Switchable roller tappet** | **Volume production** |
| | **6.4-liter V8 engine** | **Switchable roller tappet** | **Volume production** |
| **Honda** | **3.5-liter V6 engine** | **Switchable rocker arm** | **Volume production** |
| **AMG** | **5.5-liter V8 engine** | **Switchable pivot element** | **Volume production** |
| **VW Group** | **1.4-liter inline 4-cylinder engine** | **Cam shifting system, VW/Audi** | **Volume production** |
| | **4.0-liter V8 engine** | **Cam shifting system, Audi** | **Volume production** |
| | **6 3/4-liter V8 engine** | **Switchable roller tappet** | **Volume production** |
| | **6 3/4-liter V8 engine** | **Switchable roller tappet** | **Volume production** |
| | **6.5-liter V12 engine** | **Only the fuel injection supply is cut** | **Volume production** |

**Figure 1** Examples of engine concepts featuring cylinder deactivation

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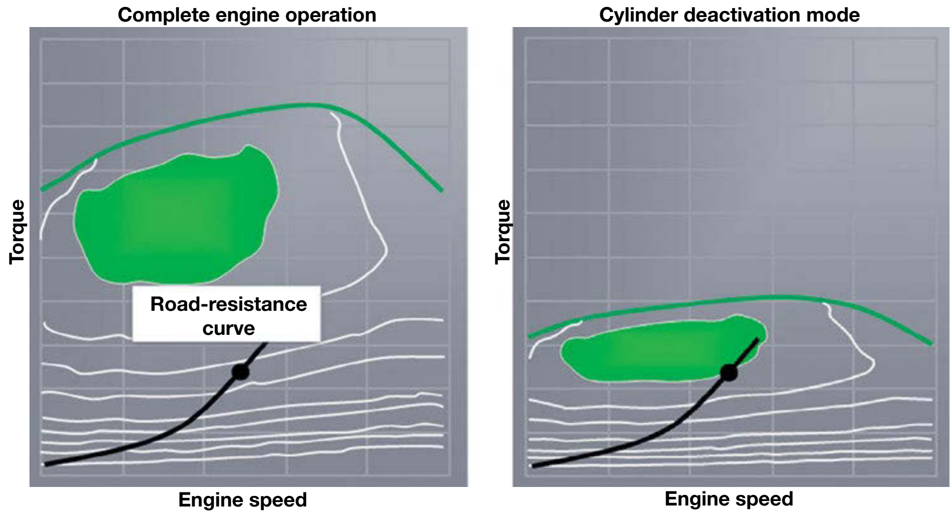


**Figure 2** Operating data map and driving resistance curve: The operating ranges associated with the lowest specific fuel consumption are approached in cylinder deactivation mode (graphic on the right) and not when all cylinders are operating

promises must be made when it comes to the ignition sequence and dynamic balancing. What is much more significant, however, is the outlay required to separate the engine into an area that continues to run while the other area is activated and deactivated as required. Even the coupling mechanisms on the crankshaft and camshaft cannot be justified by a cost-benefit analysis, which is why implementation of the system looks somewhat bleak at present.

Almost all cylinder deactivation systems currently used interrupt the injection and ignition as well as valve actuation sequences for the cylinders to be deactivated (Figure 1). Today's applications range from engines with 4 to 12 cylinders. Analyses conducted by Schaeffler, however, reveal that temporarily deactivating one of the cylinders in a three-cylinder engine can also further reduce consumption.

To ensure that the engine continues to run smoothly enough, only certain cylinders are deactivated in accordance with the ignition sequence.

## Effect and potential

When there is a specific performance requirement, the cylinders that are still being operated following cylinder deactivation must generate a higher mean pressure. This load-point shifting leads to a reduction in the throttle losses of the engine and ultimately helps to conserve fuel (Figure 2). Deactivating the valves also reduces friction loss in the cylinder head, which further minimizes consumption.

The potential for reducing consumption when an engine is operated on two as opposed to four cylinders can be illustrated in a simulation exercise carried out on a 1.4-liter four-cylinder engine. Line "a" plots the mean pressures at which the engine operating in two-cylinder mode can achieve its optimum combustion point (8 crankshaft degrees after TDC) (Figure 3).

When higher mean pressures are introduced in two-cylinder mode, the ignition se-

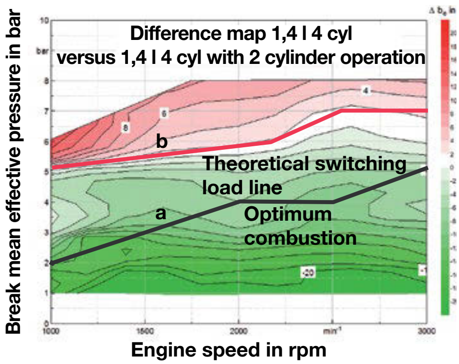


**Figure 3** Reduction in fuel consumption as a result of cylinder deactivation (simulation result)

quence must be retarded to avoid knocking. The resulting effect is that combustion no longer achieves its peak efficiency, and additional fuel is consumed. Opening the throttle valve further counteracts this and has a positive impact on consumption in cylinders running higher mean pressures. Line “b” represents the theoretical switchover or transition line, as operating the engine above these plotted points in two-cylinder mode leads to additional fuel consumption. This line can also drop considerably below line “b”, depending on the application and customer requirements.

# Technical implementation

## Deactivation mode

When an engine switches to cylinder deactivation mode, there are two basic strategies that can be implemented for introducing a charge in the cylinders (refer to Figure 4):
– Confine the exhaust gas in the combustion chamber after the combustion process has been completed
– Introduce fresh air
Both variants allow the gas confined to act as a pressure or thrust spring.

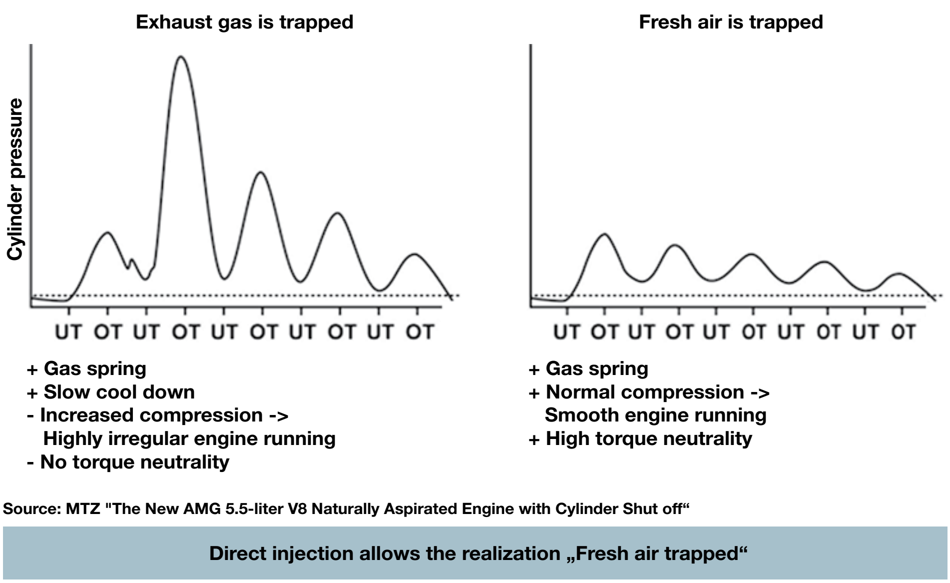


**Figure 4** Possible options for introducing a cylinder charge and their effects in cylinder deactivation mode

The heat generated by the confined exhaust gas not only makes the cylinder cool down more slowly; the larger quantity of gas also produces very different pressures inside the cylinder and thus to greater irregularities on the crankshaft. The gas pressures that form during initial compression when the exhaust valves are closed can even be higher than those experienced during combustion. The support forces not only place substantial loads on the piston and cylinder, but also lead to considerable frictional losses. The deactivation phase must then be maintained for a longer period of time to ensure that a positive overall effect is achieved.

As Figure 4 shows, peak pressures drop when the residual gas cools down as well as when gas diffuses from the combustion chamber into the crank assembly (blow by). Simulation calculations reveal that after an engine has gone through approximately ten revolutions, the pressure in the cylinder reaches the level that was present when fresh air was confined.

The latter is only possible with a direct-injection engine. The differences in compression between the cylinders are less pronounced in this application, and the switchover phase can be better coordinated as a result. This variant also requires compromises to be made, however, since the air in the combustion chamber loses all tumble or swirling motion produced at the intake point after just a few cycles. Depending on the geometry of the combustion chamber, it may still be possible to refire the engine in this operating state. The ignition timing will have to be adjusted, though, whereby the efficiency of the combustion process suffers by a corresponding amount. Care must also be taken to ensure that no suction or vacuum effect is produced in the combustion chamber, since this would lead to engine oil being drawn in.

## Alternating cylinder deactivation

Current technology dictates that specific cylinders in an engine be targeted for deactivation. Schaeffler is currently researching a concept for four-cycle engines that will allow all cylinders to be deactivated after every ignition cycle and reactivated during the next. Cylinder deactivation thus alternates within a single deactivation phase and not each time a new deactivation mode is introduced (Figure 5). The benefit is a more well-balanced temperature level inside the combustion chambers and consistent firing intervals for three-cylinder engines operating in deactivation mode.

Especially when such a design setup is used, the losses encountered when transitioning from operating mode to deactivation mode must be kept as low as possible. This is why residual gas is not confined, as the above illustration depicts. Filling the cylinders with fresh air also brings with it drawbacks due to the lower level of charge movement.

One variant appears to be particularly favorable in this context because it allows a small, precisely measured quantity of residual gas to be confined in the combustion chamber. The suction or induction effect that results from the expansion does not last long enough to lead to a noticeable loss in engine oil. The inherent benefit is that when the working cycle starts again, the required quantity of fresh air can be introduced without any restrictions in flow. The first and following combustion strokes then take place

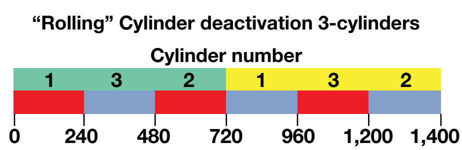


**Figure 5** Pattern of alternating cylinder deactivation (the red phase designates the active operating mode)

without a decrease in efficiency. To ensure that the quantity of residual gas and the vacuum pressure assume optimum levels, the exhaust valves must be controlled very precisely as is the case with the fully variable UniAir system developed by Schaeffler. This system realizes any required stroke in the cycle and can completely close the valves when needed. At least one two-stage switch must be fitted to deactivate the valves on the intake side. Simulations carried out on a three-cylinder engine point to lower overall fuel consumption figures being achieved when such a refined alternating cylinder deactivation concept is used in place of a conventional setup (Figure 6).

Alternating cylinder deactivation could also prove interesting when it comes to counteracting engine-induced vibration, especially in the case of three-cylinder engines.

All deactivation systems introduced in the section following the next are considered for a basic cylinder deactivation concept.

## Switchover mode

One of the logical requirements of this mode is that the driver should not be made aware of it when the switch is made. In other words, the switchover must take place in a torque-balanced manner. The transition between both modes must also occur very quickly so that the engine can provide good response at all times.

When the switch is made from operation on all cylinders to operation on half of the cylinders, the position of the throttle valve (cylinder charge), ignition timing, and fuel supply are adapted accordingly to prevent a drop in torque (refer to Figure 7). To this end, the charge is first increased and the ignition timing is delayed. When the target charge is reached, the valve train is switched over and the ignition timing for the cylinders activated is realigned with the optimum performance setting. As soon as the injection and timing sequence for the cylinders to be shut down is deactivated, the switchover is complete.

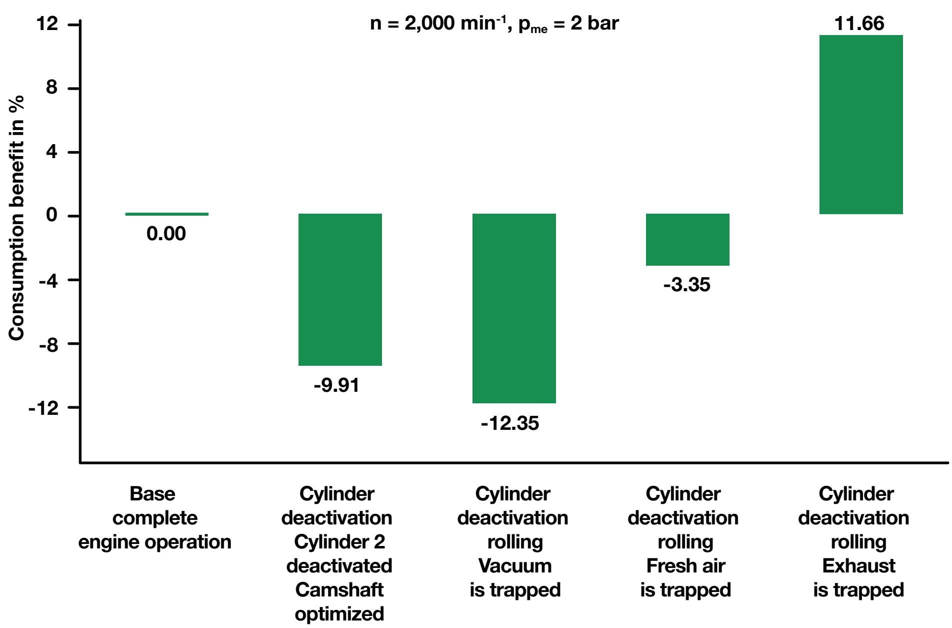


**Figure 6** Different configurations for alternating cylinder deactivation in a fuel consumption comparison

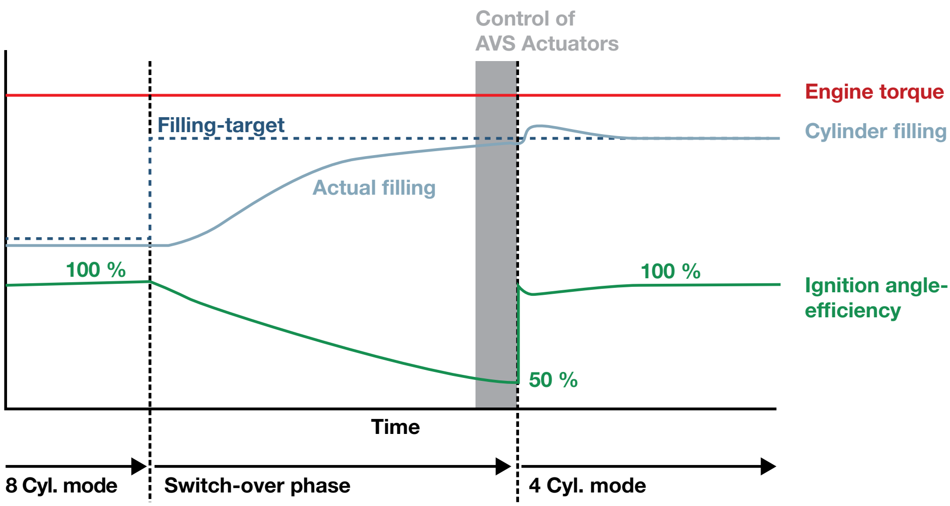


**Figure 7** Active regulation at the switchover point

Since retarding the ignition timing momentarily consumes more fuel, the deactivation mode must remain engaged long enough for an overall fuel economy benefit to be achieved. It goes without saying that the longer the engine stays in this mode, the more fuel is saved. Such is the case when traveling at constant speeds on the highway.

The following requirements are placed on the switchover mechanisms:

- The switchover process for all cylinders must take place in exactly the cycle that the control unit stipulates.
- The aforementioned design measures for compensating torque must be optimally coordinated and harmonized.
- The switchover point must occur during the ignition sequence.
- Both operating states must be stable and reliable so that no inadvertent switchovers are made.
- Since faulty switchovers and missed switchovers are relevant from an exhaust-gas perspective, a monitoring function must be implemented.

## Requirements in a system environment context

Even if the switch from one operating state to another is made successfully, in a torque-balanced fashion, the vibration characteristics of the engine and acoustic output still change. This may, in turn, necessitate modifications to the following components (refer to Figure 8):

- Phasing unit
- Timing drive
- Auxiliary drive assembly
- Clutch and dual-mass flywheel
- Exhaust system (sound engineering)
- Engine mounts

Depending on the application scenario and the requirements it entails, it is typically a good idea to integrate an active noise compensation facility for the passenger compartment. Nonetheless, it is generally necessary to operate the engine on all cylinders until the engine speed

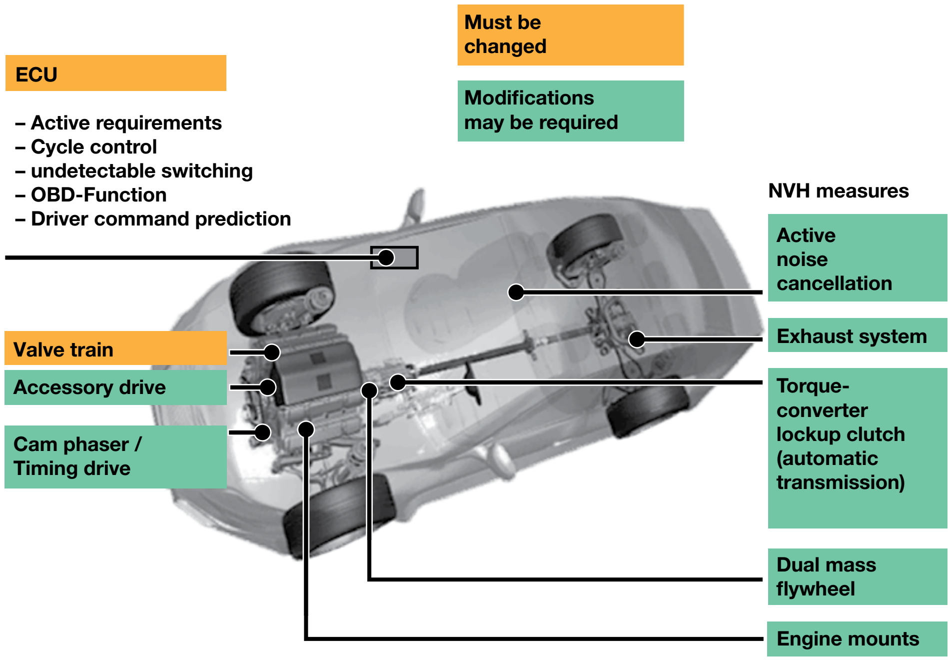


**Figure 8** Overview of the measures accompanying cylinder deactivation

reaches approximately 1,500 rpm, depending on the engine concept, as this will ensure the desired level of comfort for passengers. In addition, cylinder deactivation cannot be engaged if the engine oil has not reached operating temperature, or engaging the mode would cause the catalytic converter to drop below its light-off temperature.

## Valve stroke deactivation

As already mentioned, it is not practical to also disengage the moving parts of the crank drive during cylinder deactivation. Deactivating the valve stroke sequence, on the other hand, can be realized with comparably moderate outlay. The following options are available for this purpose:

- Switchable bucket tappets
- Switchable finger followers
- Switchable pivot elements
- Cam shifting systems
- Fully variable mechanical valve train systems based on detent cam gears
- Fully variable electrohydraulic valve train systems such as the UniAir system from Schaeffler

Most of the switchable elements are actuated using oil pressure, which is controlled and regulated by an upstream switching valve. The concept requires an additional switching or shifting oil circuit to be implemented, whereby special attention must be paid to ensuring the correct positional arrangement and geometry of the oil channels in order to create a hydraulically robust system and avoid air pockets as well as throttling or restriction points. Figure 9 shows a basic sketch of a system that has one switching valve per cylinder.

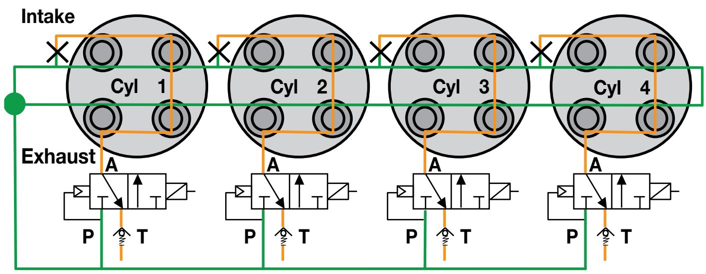


**Figure 9** Basic illustration of a valve stroke deactivation system featuring one switching valve per cylinder

## Design configuration of the shifting oil circuit

Several solutions are conceivable for controlling hydraulically actuated, two-stage valve train components and arranging the switching valves in the cylinder head. The positional arrangement of the switching valves and the design configuration of the oil channels produce different switch time intervals and system-related constraints. The following depicts two different options for deactivating cylinders 2 and 3 in a four-cylinder engine with an ignition timing sequence of 1-3-4-2 and describes the inherent benefits and drawbacks in detail.

Figure 10 shows the variant with one switching valve per cylinder, which means that one switching valve at each cylinder controls the respective intake and exhaust valves.

The benefit of this design lies in the short oil channels and small oil volume. Any oil foaming that could occur would therefore be minimal, which is why the system is highly insusceptible to fluctuations in the shifting or switching times. This concept enables a switching time interval of approximately 250 camshaft degrees, which equates to a theoretical switching time of 28 ms at 3,000 rpm. On engines with camshaft phasing units, the influence of the adjustment range must also be factored into determining the interval. By design, this variant can be enhanced or extended in such a way that all cylinders can be actively switch-controlled, which in turn means that in a four-cylinder engine application, the engine management system can deactivate one, two, or three of the four cylinders. One drawback, however, is the comparably expensive design configuration associated with the oil channel between the intake and exhaust sides.

An alternative arrangement is also possible by controlling the oil circuit using one switching valve on the intake and exhaust sides (Figure 11). The intake and exhaust valves are then actuated by two sep-

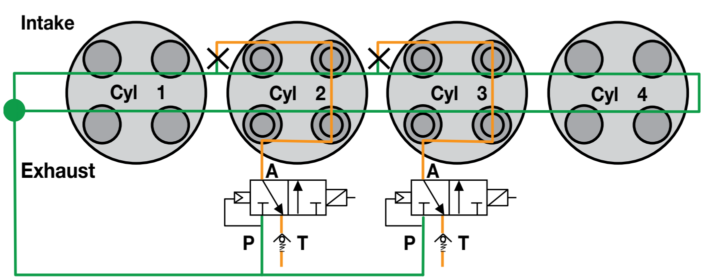


**Figure 10** Oil circuit with one switching valve per cylinder

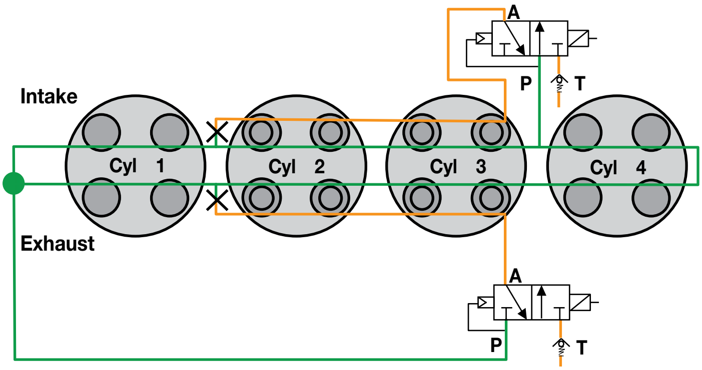


**Figure 11** Oil circuit with one switching valve per side

arate switching valves. The benefit of this arrangement is that the switching time interval can be governed independently of the adjustment range of the camshaft phasing unit. In addition, the oil channels can be designed in a more simplistic manner, and the switching valves can be integrated more easily. This design facilitates a switching time interval of approximately 180 camshaft degrees, which corresponds to a theoretical switching time of 20 ms at 3,000 rpm. The longer oil channels do pose a limitation, however, as they require a higher oil volume, which in turn makes the system more susceptible to fluctuations in the shifting or switching times as a result of the greater potential for oil foaming to occur.

The shifting oil circuit and switching valve linkage can also be implemented in ways other than the ones described here. Critical design aspects that apply in this context are the ignition timing sequence and configuration of the cylinder head and oil channels of the target engine, whereby the main focus of the design work should be on maximizing the switching time interval as far as possible using justifiable levels of outlay.

**Figure 12** Switchable finger follower

## Deactivation via switchable elements

### Finger followers

Since the design configurations for the switchable finger follower can also be applied to the switchable bucket tappet, we will not explore this topic any further.

The solutions that are based on finger followers or hinged-lever designs that can be coupled with one another and have a locking mechanism at the pivot point are numerous. All systems that rely on oil pressure require spring-actuated elements to return the deactivated components to their starting position after cam elevation (Figure 12). The shift mechanism must be designed in such a way that the entire valve stroke is traveled when no oil pressure is present (zero-pressure lock), since this safeguards operation in limp-home mode and is required for cold-starting the engine.

Although cylinder deactivation brings with it many benefits, the concept also has several drawbacks. The additional contact points and increased number of components, for example, reduce rigidity as compared to a standard finger follower and negatively affect the vibration of the valve train. The added components also increase the mass moment of inertia of the follower, which in turn means that stronger valve springs need to be fitted, and the valve train assembly encounters higher levels of friction as a result. Potential space restrictions necessitate narrower rollers, a design that inherently increases the surface contact pressures between the roller and camshaft.

Switchable finger followers that brace themselves against a zero-stroke cam in deactivation mode create a more stable system than the variant that does not provide for this effect. The only drawback is that the camshaft then requires two different profiles per valve. If a zero-stroke cam is not provided, the acting forces must be precisely coordinated with each other; in the decoupled state, the lost-motion spring needs to be strong enough to prevent “inflation” or “pump-up” (undesired elongation) of the support element. On the other hand, the spring must not be so rigid that the motor valve inadvertently opens in the direction opposing the valve spring pressure.

**Support element**

The switchable pivot element also lends itself to being deactivated. Similar to the switchable roller tappet, the inner part of the element can be telescopically extended into the outer part (Figure 13). Here too, a spring or spring assembly is required to return the moving part to its starting position. The oil pressure, which is controlled by an upstream switching valve, is also used to actuate the coupling mechanism. The distance traveled by the oil to this mechanism is shorter, however. The same restrictions that apply to the switchable finger follower with regard to the oil pressure also hold true for this application.

The rigidity of the valve train is only reduced by the structural integrity of the coupling point in the switchable pivot element. The geometry (with the exception of the valve contact surface) and mass moment of inertia of the finger follower are unaffected. As a result, the valve spring pretension force

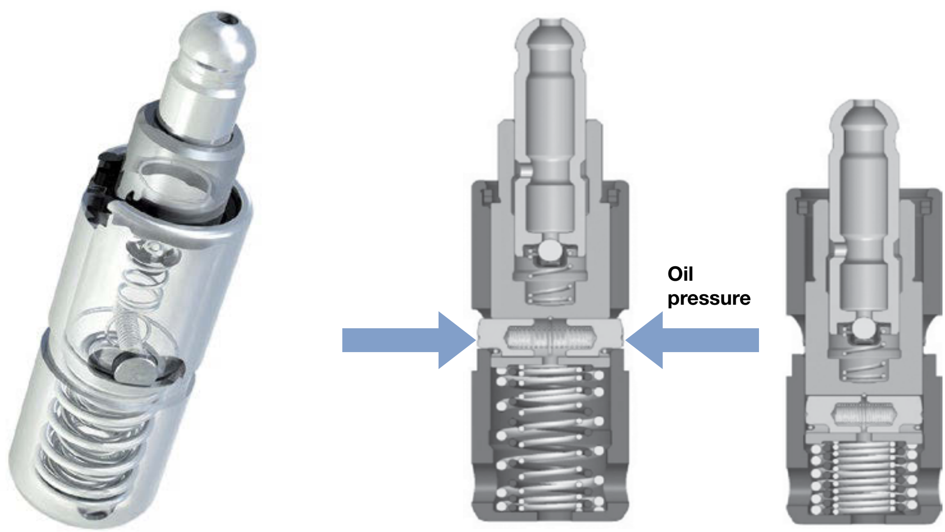


**Figure 13** Switchable pivot element

does not have to be changed in comparison to that of the conventional valve train assembly, which means that the surface contact pressures between the roller and camshaft remain at low levels.

## Deactivation via a cam sliding system

The cam shifting system allows the valve stroke to be switched in up to three stages. The switchover process occurs when a cam piece positioned in an axially movable arrangement on a splined shaft is displaced. This sliding cam piece comprises several cams sectioned into two groups, which are arranged in relation to the two valves on each side of a cylinder (Figure 14).

A control groove is integrated into the sliding cam piece. When the cam lift is to be adjusted, an electromagnetically actuated pin extends into this groove to force the entire unit to change its respective groove contour position. A second cam profile (or a third one in the case of three-stage systems) thus acts on the finger follower to transfer the new cam lift (which can also be a zero-stroke) to the valve so that each valve pair can be actuated individually. The inherent benefits of this system are that the cylinders and camshaft can be switched selectively and the sequence of the elements to be switched is variable.

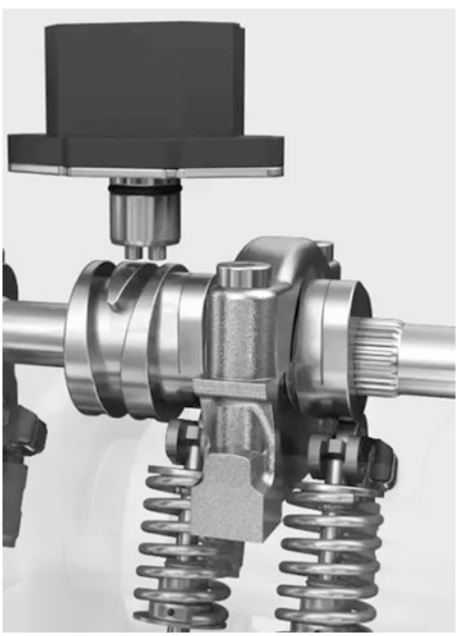

**Figure 14** Two-stage cam shifting system

**Figure 15** Three-stage cam shifting system

After the actuation sequence has taken place, a relay signal generated by the actuator pin as a result of a voltage shift in the electric coil is sent to the actuator. Although this signal provides clear indication of a shift occurring and the direction that was taken, it is not sufficient for determining positional arrangements as operation continues (OBD requirement). The cam shifting system offers a benefit here that initially appears to be the exact opposite: Both valves are forced to switch at the same time. This, in turn, makes it considerably easier to detect correct position during active operation by way of sensors (pressure or oxygen sensors) on the intake and exhaust side or by evaluating torque imbalance than when systems with individual switch logic are used.

When viewed from the perspective of a cost-benefit analysis, it is important to note that the cam shifting system requires more outlay than switchable elements, since in four-cylinder engine applications, both camshafts must be equipped with a deactivation function – a design aspect that also affects positional elements that are not switchable. Consequently, the cam shifting system is a commercially viable option for cylinder deactivation if an existing two-stage system for varying the valve stroke is enhanced to include a third stage dedicated to the cylinder deactivation process (refer to Figure 15).

Theory-based investigations conducted by Schaeffler indicate that a three-stage system can offer further significant potential compared to a two-stage solution in consumption testing cycles carried out under higher load conditions. When the cam shifting system is designed so that all intake and exhaust valves can be deactivated, it is possible to deactivate any desired number of cylinders. This setup also facilitates the integration of an alternating cylinder deactivation pattern [3].

## Cylinder deactivation via UniAir

UniAir not only controls and regulates valve stroke travel in a fully variable fashion, but can also completely deactivate any cylinder (Figure 16). This deactivation is achieved by actuating the system's integrated switching valves as required. In its current version, UniAir actuates both valves in a uniform manner. As a result, both intake valves are always closed in deactivation mode. The operating state of the valve train can thus be easily determined with the UniAir system as well. When UniAir is only used on the intake side, switchable support elements can be fitted in the relevant positions on the exhaust side (as is the case with the fully-variable mechanical system).

Schaeffler is currently working on additional valve stroke configurations that approach the potential afforded by cylinder deactivation while making it possible to forego valve deactivation on the exhaust side. The genuine appeal of this type of configuration is that it allows any number of cylinders to be deactivated without having to implement further design measures. Detailed information is provided in an additional article [4] in this book.

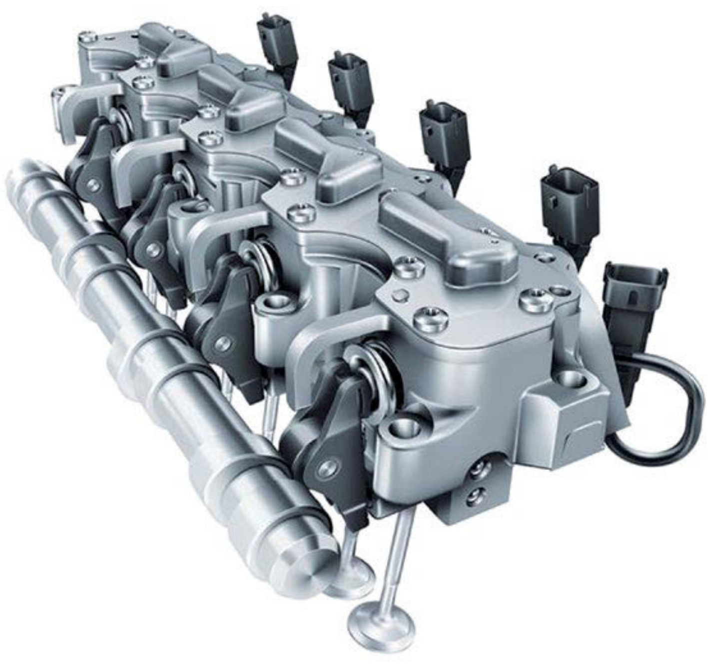

**Figure 16** Electrohydraulic, fully-variable UniAir valve train system

## Summary and outlook

Temporarily deactivating cylinders offers an attractive compromise between downsizing an engine to reduce fuel consumption and retaining high levels of comfort and driving pleasure. Even three-cylinder engines can profit from the economical benefits of cylinder deactivation. Simulations point to the potential that an alternating cylinder deactivation system has for maintaining a balanced temperature level in the engine and reducing vibrations, particularly in three-cylinder engine applications.

Several options are available for temporarily deactivating valves, especially in the context of finger follower regulation systems. When cylinder deactivation is the only variable aspect required, switchable pivot elements offer a very cost-effective solution without noticeably compromising the basic functions of the valve train assembly. In the case of multi-stage systems or entire engine families, cam shifting systems are more favorable because they can be easily adapted. Fully-variable valve train systems go hand in hand with cylinder deactivation in the presence of discretely switchable elements as a minimum expenditure item.
Depending on the size of the engine and the expectations customers have regarding comfort levels, additional design measures may be required for the engine and overall vehicle that conflict with the potential for reducing fuel consumption, which can be especially prominent in lightweight vehicles equipped with powerful engines.

In the future, it is highly probable that cylinder deactivation will play an ever increasing role in optimizing powertrains that use engines with three or more cylinders.

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