

# Application of Concentric Cam Shafts to a Passenger Car Diesel Engine to Significantly Improve the NO<sub>x</sub> / Soot Tradeoff

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## ABSTRACT

Trying to improve the modern diesel engine's NO<sub>x</sub> / Soot tradeoff without giving up fuel economy continues to be a core target for the engine development community. One of the options not yet fully investigated for the diesel is applying variable valve events to the engine breathing process. Already used in some heavy duty applications, late intake valve closing has long been regarded as a possible strategy for small diesel engines. Single cylinder tests applying fully variable valve events have demonstrated potential but also raised doubts about VVA benefits on automotive size diesel engines. Full engine testing using realistic valve train technology is seen as key to judging its true performance because it covers not only combustion benefits but also influences like engine pumping on emissions and CO<sub>2</sub>.

Different to past publications, this paper focuses on testing a production feasible variable valve train technology on a fully instrumented modern Common Rail diesel engine. Applying a concentric intake cam in the described way to increase valve event duration allows running an over expanding combustion cycle (Miller Cycle). The benefits on the NO<sub>x</sub> / Soot tradeoff as well as other effects are described.

## INTRODUCTION / LITERATURE REVIEW

For many years, until the early 90's, the diesel engine was trailing the spark ignition engine in technology and performance. Diesel engines were used in heavy duty applications. Simple air systems were applied to achieve the required power and meet the required emission levels. Cylinder head designs were very conservative. Due to the turbo chargers capability to provide the air needed at WOT, the VT system was not considered a good opportunity to optimize performance. Valve trains were specified to reliably deliver gas exchange between the plenum and the cylinder.

In [Figure 1](#), a technology roadmap for the passenger car diesel engine is shown. It was the introduction of VTG turbo chargers, common rail direct injection and cooled EGR that made the diesel engine into a highly accepted power train. Increasing power and torque demand as well as improved emissions capability were satisfied by air system efficiency enhancements. When single stage turbo charging was not able to deliver enough air, two stage turbo charging was introduced. When cooled EGR was not able to provide the required emission benefit, a second EGR cooler or an EGR cooler bypass was added. Common rail started with two injections, today more than six injections are applied under certain engine operating conditions. Still, the diesel engine VT was left nearly untouched. Most passenger car size

engines migrated from a single to a dual cam shaft layout and valve sizes were adjusted. But the basic VT concept was left unchanged. The cost/benefit ratio of any valve train variability was considered to be unfavorable for a boosted diesel engine.

On the gasoline engine however, where turbo chargers were not applied for many years, much more effort was put into optimizing the gas exchange process and the valve train - cam phasers on both cam shafts as well as variable lift valve train systems are state of the art. Benefits in fuel economy and performance led to a clearly positive business case.

One of the innovations in both diesel and gasoline valve trains was the introduction of assembled cam shafts. This concept led to weight reductions while simultaneously meeting increasing mechanical requirements.

Today's diesel engine is more complex and, due to complex after treatment systems like DPF & SCR, significantly more expensive than a boosted gasoline engine. But it has been able to retain its CO<sub>2</sub> benefit. Therefore, especially for engine displacements >1.5 L, the diesel engine will continue to play a key role in helping the OEMs meet fleet CO<sub>2</sub> targets.

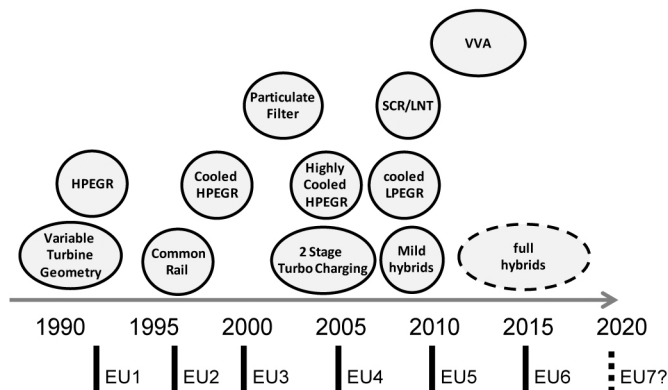


Figure 1. Passenger car diesel engine technology road map

## EMISSIONS AND CO<sub>2</sub> CHALLENGE

For the diesel, due to its combustion principle, NO<sub>x</sub> and Smoke emissions have historically been the biggest challenges. CO<sub>2</sub> emissions have typically been superior to spark ignition engines. Figure 2 shows technology steps towards minimal CO<sub>2</sub> and emissions, in this case for European passenger car applications. All emission levels, starting with EU1, always led to a step in engine technology. Up to EU3, engine internal means for reducing NO<sub>x</sub> / Smoke were sufficient. The wide spread introduction of the Diesel Particulate Filter led to the elimination of visible smoke. However, moving from EU2 to EU4, the diesel engine's fuel

consumption sometimes had to be compromised to meet emissions. The CO<sub>2</sub> gap between gasoline and diesel began to close. With the EU5 legislation that required a manageable reduction in tailpipe NO<sub>x</sub>, the emphasis could clearly be put on reducing vehicle fuel consumption. Counteracting rising fuel costs and increasing pressure to lower CO<sub>2</sub> emissions became a clear selling argument to the customer. The first applications of NO<sub>x</sub> after treatment systems entered the market in 2008. CO<sub>2</sub> reduction potential was claimed, however at high extra cost. These vehicles were also the first to achieve EU6 and even US Tier 2 Bin 5 emission targets [1].

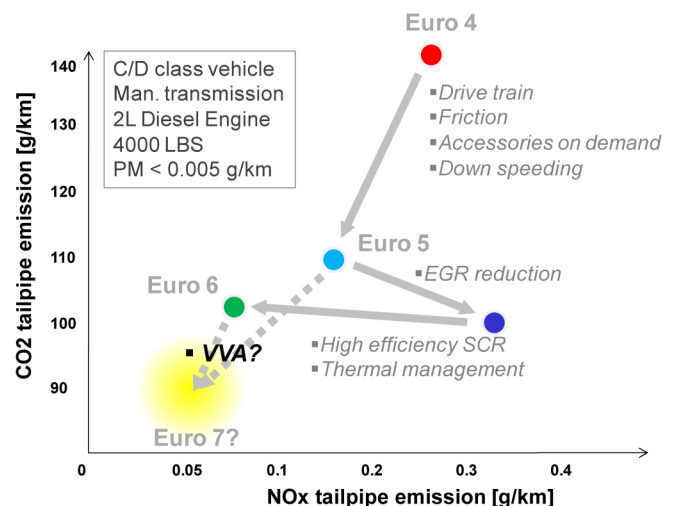


Figure 2. CO<sub>2</sub> Emission roadmap for European applications (example)

## DIESEL ENGINE EMISSION TECHNOLOGY

As the main focus in the past years has been reducing NO<sub>x</sub>, the key technology used has been high pressure exhaust gas recirculation. HP-EGR technology has matured and further optimizations seem to have a poor benefit/cost ratio. Recently introduced LP-EGR, described in [1, 2], has proven to have a NO<sub>x</sub>/ Smoke as well as a CO<sub>2</sub> benefit over HP-EGR. For this reason, it is quite likely that most small diesel engine applications will be using LP-EGR for EU6.

Apart from its prime task of providing air to the combustion, the turbo charger serves as a key enabler to the calibration of high EGR rates. It does not provide any direct NO<sub>x</sub> emission benefit - its purpose is more to provide steady state and transient performance as well as to support the delivery of sufficient EGR at the desired AFR.

Common rail injection systems were introduced not just to improve performance and NVH but mainly to help reduce

smoke emissions. Injection pressures have increased from 1350 Bar to 2000 Bar in the last years. Higher pressures led to an improved fuel/air mixing and therefore to less smoke creation during the combustion process. With multiple injection events available, close coupled post injection events were applied to support the post combustion soot oxidation (PCSO).

Adding a DPF to the vehicle gave the engine calibrators a means to fully eliminate tail pipe smoke independent of the engine out soot emissions. First applications however suffered under frequent DPF regenerations, severely affecting fuel economy due to very “smoky” combustion calibrations. It was quickly recognized that low engine out soot remains a key calibration target.

When applying a highly efficient NO<sub>x</sub> after treatment system to a vehicle, the engine can be calibrated for best fuel economy, while accepting higher out NO<sub>x</sub> [3]. Increased need for reductant (Ammonia) in SCR systems or frequent LNT regenerations are the downside of this strategy. Also, high NO<sub>x</sub> aftertreatment system efficiency in the test cycle can only be achieved by warming up the exhaust system quickly [3]. This in turn costs CO<sub>2</sub>. So even when using NO<sub>x</sub> aftertreatment, engine out NO<sub>x</sub> emissions still must be lowered to a reasonable level. The biggest problems of exhaust aftertreatment systems remain to be their high cost. Despite significant cost reductions, this is a big threat to the marketability of the diesel, especially in lower displacement applications.

Modern high performance engine electronics, fast sensors and advanced controls are the basis for effectively applying emission reduction technology. [1] shows that they allow the calibrator to successfully tune all combustion parameters each for multiple combustion modes, covering:

- Normal engine operation
- DPF warm-up and regeneration
- Exhaust system warm up for LNT/SCR/DPF operation
- LNT “deNO<sub>x</sub>” and “deSO<sub>x</sub>” regeneration

Due to the vast amount of combustion tuning parameters, finding the optimal setting for each engine operating point and mode has become a challenge. Solutions like automated calibration are being applied.

## VARIABLE VALVE TRAINS FOR DIESEL ENGINES

In recent years, VVA technology for diesel engines has been discussed more and more in the automotive engineering community. Many different opportunities to apply variable valve trains to diesel engines were identified, for instance by Weber et al [4]. Some are summarized in figure 3.

| Opportunity                            | Principle                                                              |
|----------------------------------------|------------------------------------------------------------------------|
| Reduced NO <sub>x</sub> /Smoke         | reduce process temperature through reduced effective compression ratio |
|                                        | Increase swirl                                                         |
|                                        | Apply internal EGR                                                     |
| Low load / cold start / idling         | Increase effective compression ratio                                   |
| Increased low end torque               | Use engine pressure pulsations to increase filling                     |
|                                        | Recharge the cylinder with exhaust gas (“Curtill”)                     |
|                                        | shut off of internal EGR or “Miller”/“Atkinson” instantly              |
| Transient performance                  | Increase blow down energy to turbo charger turbine instantly           |
|                                        |                                                                        |
| Improved fuel economy                  | Optimize volumetric efficiency at all operating points                 |
|                                        | Provide cylinder cut out / deactivation functionality                  |
| Engine cranking                        | Reduce cranking torque (fluctuations)                                  |
| Engine shut off                        | Reduce torque (fluctuations)                                           |
| Effective after treatment Regeneration | Reduce air flow through significantly reduced volumetric efficiency    |
|                                        | Use blow down energy to increase exhaust gas enthalpy                  |
| Combustion stability                   | Control ignition delay / heat release (cylinder spec.)                 |
| Faster Catalyst light off              | Increase exhaust gas temperatures                                      |
| Engine braking                         | Use engine as compressor only                                          |

**Figure 3. Opportunities for VVA applied to diesel engines [4]**

VVA has always been considered expensive and complex while not providing enough NO<sub>x</sub> reduction. Generally, two very different approaches can be taken when investigating VVA systems:

### The research approach:

Using a SCE with a fully variable VT system, various effects on combustion (even applying new strategies like LTC or PCCI) can be investigated. This highly flexible approach clearly has advantages when trying to understand detailed effects like mixture formation or heat release. Boundary conditions can be adjusted independently which is important for isolating certain phenomena.

There are however also downsides to this approach: Due to the fact that an essential influencing factor on the full engine's BSFC, pumping work created through P<sub>3</sub>-P<sub>2</sub>, has to be simulated, BSFC results can only be calculated with some margin of error. Also, the vast amount of calibration parameters on a research engine coupled with nearly every freedom on the VT side can lead to very long test campaigns or to very “focused” approaches, with the disadvantage of potentially overlooking opportunities.

Without the limitations of a given production like hardware, optimal valve events were investigated by [5, 6, 7, 8]. NO<sub>x</sub> Emission benefits were found. However the message given especially by Guide et al [5] and Schutting et al [8] was that more effective NO<sub>x</sub> reduction could be provided by just increasing EGR rates further.

### The reality approach:

Carrying over gasoline hardware to the diesel engine seems intriguing. The technology has reached technical maturity and effects like “economy of scale” could keep the added cost low. Due to the better availability of mature hardware, full engine tests can more easily be conducted.

First investigations were conducted using cam phasers. Unfortunately, combustion chamber / piston design of modern diesel engines severely limits phasing authority. Missing piston cut outs quickly result in undesired valve-piston contact. So any valve overlap strategies, used on gasoline engines to scavenge the combustion chamber, are difficult to realize on a the diesel engine. [9] however proved, that when using special piston cut outs and applying cam phasing to affect charge motion, a benefit in the  $\text{NO}_x$  / BSFC tradeoff could be found. Variable intake valve lift was proven [10] to show BSFC benefits through more efficient swirl creation at low valve lift using a two step cam lobe switching system and a special seat chamfer design.

## “MILLER” / “ATKINSON” CYCLE APPLIED TO DIESEL ENGINES.

Adjusting the effective compression ratio, often described as “Atkinson cycle” or “Miller cycle”, has been published [4, 5, 6, 7, 8, 9] and [11] as one of the more important methods requiring a variable valve train. In the following sections, these terms will be avoided as there seems to be no industry wide consensus on their meaning. Instead, the terms “Early Intake Valve Closing” (EIVC) or “Late Intake Valve Closing” (LIVC) will be used to describe methods of influencing effective CR.

Focusing on advanced combustion strategies (“PCCI” or “LTC”), it was shown through SCE testing by Durrett et al [8], that LIVC, applied while maintaining AFR constant, can provide both an ISFC and  $\text{NO}_x$ /Soot emissions benefits between 2 and 11 BMEP. Applied in conjunction with a single injection, the smoke benefits were attributed to improved mixture formation. Ignition delay increased by up to 10 degrees and lower  $\text{NO}_x$  levels were stated to be caused by resulting decreased peak flame temperatures. In figure 4, synthesized from [8] and [11], LIVC is schematically compared to the baseline VT in a well known fashion, explaining the benefits. However [8] mentions, like [5, 7] that the pumping work increase needed to overcome the loss in volumetric efficiency results in a higher BSFC especially at higher loads. Higher efficiency boosting was mentioned to be one possible solution.

Applying intake cam phasing and, together with a variable lift system, using EIVC or LIVC to reduce the effective CR down to 12.5 was also investigated [9]. A BSFC reduction up to 10g/kWh at constant  $\text{NO}_x$  and acceptable smoke was reported.

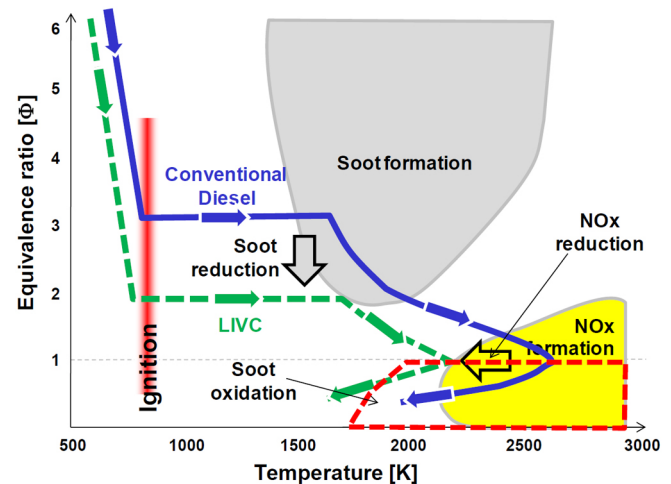


Figure 4. Reduction of smoke and  $\text{NO}_x$  by LIVC - Schematic diagram synthesized from [8], [11]

Using in-cylinder CFD simulation, Murata et al [11] describes similar benefits in  $\text{NO}_x$  and smoke reduction through enhanced premixing. In this paper, AFR is not maintained constant when changing effective CR. Improved soot oxidation described is at 0% EGR with LIVC, with obviously enough oxygen available post combustion. To achieve good post combustion soot oxidation, it is described that soot created during combustion must reach the “soot oxidation” zone also depicted in figure 4. It is stated however that with high EGR rates, soot combustion may not be as effective because the conditions are not reached after TDC. Since the air flow drop was not compensated, higher bulk gas temperatures at lower peak flame temperatures were described.

When applying reduced effective CR to a conventional combustion calibration - a pragmatic approach certainly driven by NVH and controls complexity reasons - Gulde et al [4] found certain benefits in  $\text{NO}_x$  for both LIVC and EIVC. EIVC was described as the preferred solution in terms of  $\text{NO}_x$  potential. At lower AFR, higher ISFC is described. Compensating for the “lost” air flow is clearly recommended. However, the associated negative effects on pumping work and BSFC are stated to lead to no overall benefit when applying LIVC or EIVC.

Summarizing, it seems clear that previous investigations shed neither a consistent nor a very positive light on the VVA opportunity of “reducing effective compression ratio”. Although the desired  $\text{NO}_x$  improvement potential was found, and some interesting effects were described, fuel consumption penalties would appear to remain a road block to introducing this technology for small diesel engines. So, to successfully implement LIVC, minimizing or avoiding a pumping work increase is identified to be the key challenge.

## CONCENTRIC CAM SHAFT TECHNOLOGY

The concentric cam shaft technology investigated in this paper, abbreviated by CC, has been known for years. It can be described as a relatively simple (low number of additionally moving parts), compact and cost effective solution for changing the valve event duration. [Figure 5](#) shows different options to apply CC:

**1. CC Type 1:** One intake or exhaust valve can be phased relative to the other. In 2 valve applications, intake and exhaust valves can be phased relative to each other. Each cam acts on one rocker and therefore on one intake valve only. In the initial phase of the valve event, only the first valve is opened. Then the second valve opens and the full area is available for a certain time. After the first valve has closed, only the second valve remains open till the end of the valve event. The total time-area under the open valves does not increase.

**2. CC Type 2:** Both Cams act on one rocker arm per valve. Therefore, when the inner cam rotates against the outer cam, the rocker movement is the result of the lift of both cams. At one point, one cam “hands off the task of acting on the common rocker to the other cam. Both rockers and therefore both valves follow the maximum of the two cam lifts. Depending on the valve train layout, the total flow area under the open valves increases.

**3. CC Type 3:** Based on the CC Type 2 valve lift principle, an additional cam phaser acting on the outer cam shaft / lobes now allows not only adjusting duration but also changing the opening timing of the total valve event.

For this work, the CC technology called “Type 2” was chosen, because of its ability to provide the valve lift characteristic desired for LIVC. More information on this technology can be found in [\[12\]](#).

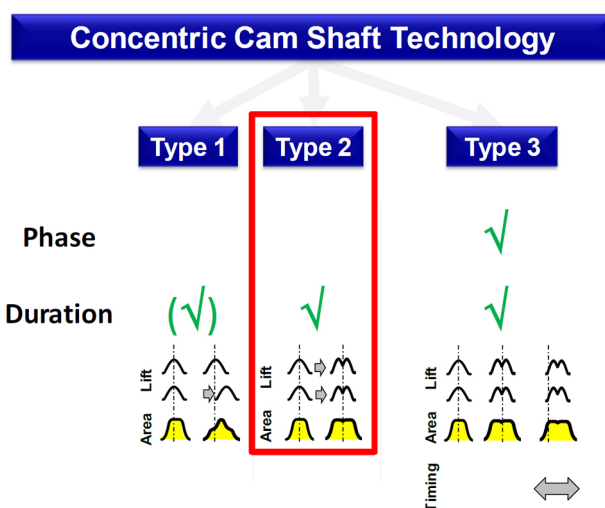


Figure 5. Options to apply concentric cam shafts

## CONCENTRIC CAM SHAFT DESIGN

The basic design principle of concentric cam technology, shown in [figure 6](#), is using an outer camshaft, supporting fixed lobes and an inner camshaft arranged concentrically inside the outer shaft providing moveable lobes. These moveable lobes, guided by the outer shaft, are connected by connecting elements like pins, screws etc. to the inner shaft. For this purpose the outer shaft includes radial slots to provide clearance for fixing the lobes. The outer and inner camshaft ends are connected separately to the rotor and stator of the phaser. Implementation of LIVC via concentric cam requires a special lobe design. The lobe is split axially into at least two lobe parallel parts, one fixed lobe and one moveable lobe, both acting on the same RFF.

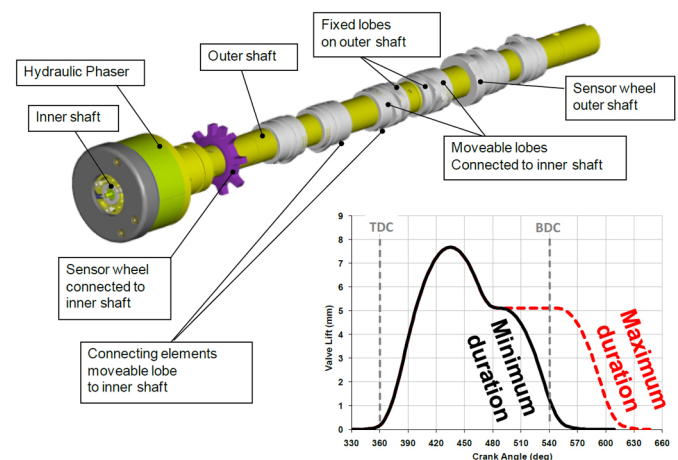


Figure 6. Basic design of concentric cam shafts

The following CC development targets were defined for the test engine:

- Concentric Cam Type 2 applied to all intake ports of the engine
- Phasing strategy / direction for Late Intake Valve Closing (LIVC)
- Phaser authority/ spread angle =  $60^\circ$  crank ( $30^\circ$  cam)
- CC intake valve lift = minimum 90% of base intake valve lift
- Bearing- and base circle diameter remain identical to baseline engine
- Sensor wheel for outer and inner shaft control

The prototype was designed with “double lobes” for functional testing, VT dynamics investigations, RFF / cam lobe lubrication and wear behavior testing. Fixed lobes were assembled by applying TK Presta's knurling technology. The moveable lobes were pinned to the inner shaft, the outer shaft joined to the cam phaser's thrust bearing flange and the inner

shaft joined to the phaser rotor by press fit and additional form fit. Cam lobe geometry and profile design were a special challenge. Effective Lobe width and pin connecting geometry were calculated by FEA to meet original RFF values. Early on, calculations showed that the required valve lift and spread angle defined by the base circle and by tolerable valve accelerations could not be achieved by just modifying standard cam profiles. These effects were detected by dynamic simulations and first prototype testing. Also asymmetric forces acting from the split lobes to the RFF caused edge loading / tilting on the (non-guided) RFF. VT dynamics were impacted and wear was identified. Therefore the development of a new cam lobe geometry and profile was started to prevent this dynamic behavior. Also a solution was found against undesired rocker arm tilting. The lobe design is shown in [figure 6](#) and also in [figure 13](#) (specific for the test setup). For testing the decision was made to continue with the double lobe system. The newly developed cam profile and a cylinder head mounted RFF guide were applied against RFF tilting. Several tests were performed on the motored test bench ([figure 7](#)) at different speeds, oil pressures and oil temperatures. A 400 hour durability test of the CC was completed successfully.

A production intent design, following the so called “triple lobe” principle, is currently being developed and validated for concentric cam type 2 systems.

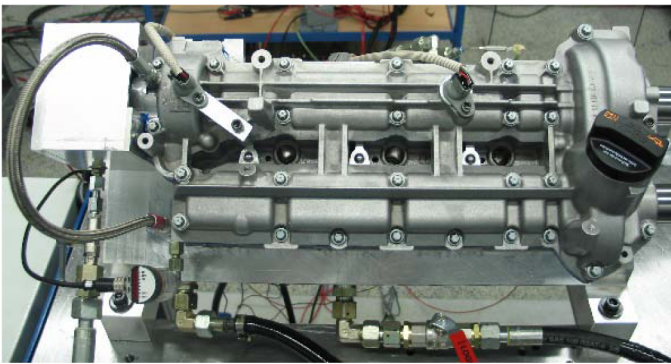


**Figure 7. Rig tests performed to ensure durable CC design**

## PHASER DESIGN & APPLICATION FOR CONCENTRIC CAMSHAFT TECHNOLOGY

Phaser technology can be selected from cam torque actuated (CTA), torsionally assisted (TA) or oil pressure actuated (OPA) derivatives based on the application & performance requirements. For this application a TA Phaser design, which uses oil and camshaft torsional energy to move the phaser, was chosen.

Camshaft torsionals are created from the opening and closing of the valves. The camshaft resists rotation as the cam lobe compresses the valve spring and accelerates the valve open. This generates a positive cam torque, or the force used to push oil from the advance chamber of the phaser through the spool (metering) valve and the retard check valve to the retard chamber. As the valve closes, and the valve spring pushes against the cam lobe it generates a negative cam torque. This creates the force that is used to push oil from the retard chamber through the spool (metering) valve and the advance check valve to the advance chamber. More details can be found in [\[14\]](#).

For concentric camshaft applications the camshaft torque is created in one direction, as the inner shaft removes the torque as shown in [figure 8](#). This requires the addition of a bias spring on the camshaft phaser to return the phaser and ensure actuation rates are similar in both directions.

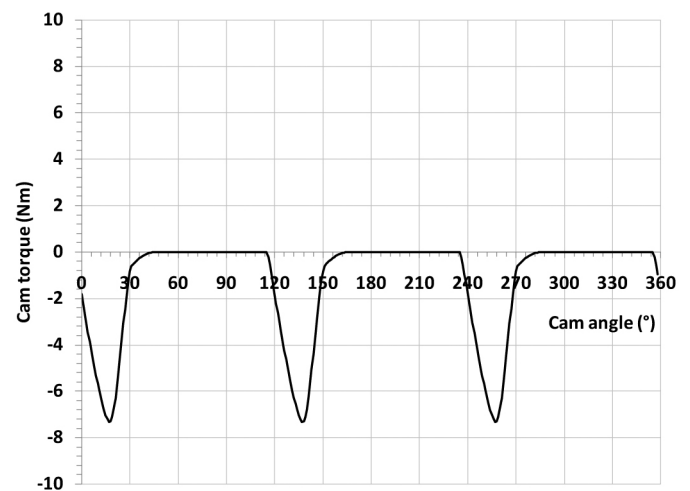


**Figure 8. Camshaft torques from the tested engine**

The T.A. phaser has the benefit of a one way check valve installed in the phaser. This ensures the oil is not directed back to the engine main oil gallery. A cross section of the phaser & camshaft assembly can be seen in [figure 9](#). The one way valve for this design was a band check mounted on the spool valve body. The rotor was mounted to the inner shaft of the concentric camshaft assembly by press fit and the inner plate was also a press fit to the outer camshaft tube.

The phaser was assembled & performance tested on a motored test stand. Phaser speed was measured to show response time in advance & retard phasing for 0 to 60 degrees crank angle. At 2000 RPM an actuation rate of 100 crank degrees per second for advancing the phaser (Duration Shortening) & over 300 crank degrees per second for retarding the phaser (Duration Extending) was achieved. A second generation design would be modified to balance the actuation rates. The cam phaser was also measured for