CHALMERS

Variable Valve Actuation in Marine Leisure Diesel Engines

Examensarbete inom högskoleingenjörsprogrammet Maskinteknik

JEFFREY DENIAN

Institutionen för Tillämpad mekanik
Avdelningen för Förbränning
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Preface

This Diploma work was carried out at Volvo Penta, Göteborg, 2012. The work is the terminative part of a 180 credits education in Mechanical engineering at Chalmers University of Technology.

I would like to thank my supervisors Erik Olofsson and Stefan Riedel. I also want to thank Bertil Karlsson, Hans Melin, Anders Leandersson, Daniel Thörsman and Rolf Westlund.

Finally, I want to thank my examiner Professor Ingemar Denbratt at Chalmers University of Technology.

Jeffrey Denian

Abstract

Volvo Penta is a supplier of marine and industrial engines. To further develop the existing D4/D6 engines (3.7L 4-cyl and 5.5L 6-cyl marine leisure diesel engines) Volvo Penta wants to evaluate the possibility of adding a variable valve actuation (VVA) system to increase performance and improve efficiency. The objective for this study is to recommend a VVA system from the market for Volvo Penta D4/D6 engines for further development.

The effects of different VVA strategies for diesel engines and the emission standards are described in the literature study.

A research was performed to find VVA systems on the market. The research is summarized in the VVA system chapter. In this chapter the VVA systems working principles and the different valve lifts they can perform are explained.

The VVA systems were evaluated in two steps. The first step was an evaluation matrix to compare different VVA systems. The evaluation matrix resulted in that three VVA systems were decided to be evaluated further. The second evaluation of the VVA systems was focused on which types of VVA strategies that can be used and which benefits they provide and the applicability in the engine architecture.

The system that finally was recommended was Mechadyne VLD system with duration control on the intake valves. VLD is highly applicable in the D4/D6 engines and enables several VVA strategies that are suitable for diesel engines. VLD can be added to the exhaust valves for further development of VVA strategies.

Abbreviations

AVT	Active Valve train (Lotus)
BDC	Bottom Dead Center
BSFC	Brake Specific Fuel Consumption
CAD	Crank Angle Degree
CR	Compression Ratio
EVC	Exhaust Valve Closing
EVO	Exhaust Valve Opening
IEGR	Internal Exhaust Gas Recirculation
IVC	Intake Valve Closing
IVO	Intake Valve Opening
TDC	Top Dead Center
VIC	Variable Inlet Closing System (Wärtsilä)
VLD	Variable Lift and Duration System (Mechadyne)
VTC	Valve Timing Control
VVA	Variable Valve Actuation
VVL	Variable Valve Lift

Contents

1. Introduction

This chapter presents the background, the purpose, the limitations and the objective for this project.

1.1 Background

Volvo Penta is a supplier of engines and complete power systems for marine and industrial use. Marine diesel engines, both leisure and commercial are produced in Vara and in the Volvo Group factory in Skövde. Marine gasoline engines are built in Lexington, Tennessee, USA.

Volvo Penta wants to evaluate the possibility of adding a VVA system to reduce emissions and improve the engine efficiency. With VVA systems the timing, lift and duration of the engine valves can vary. This gives the opportunity of implementing different VVA strategies for different engine speeds and loads.

1.2 Purpose

The purpose of this project is to evaluate different VVA systems and strategies to improve the efficiency and emissions for the Volvo Penta D4/D6 engines (3.7L 4-cyl and 5.5L 6-cyl marine leisure diesel engines).

1.4 Objective and limitations

The objective for this project is to recommend a variable VVA system available on the market for the Volvo Penta D4/D6 engine family for further development.

This project time is limited to 10 weeks, therefore the project does not involve concept generation and concept testing of VVA systems.

2. Method

In this chapter the process of the project is presented. The process of the project is a Literature study, VVA research, VVA evaluation and recommendation.

The literature study is used to enhance the understanding of the technical aspects and to improve the knowledge needed in the project. The literature study is performed by research in different forms of literature and by discussions with experts in the matter. The material is summarized and presented in the engine theory chapter.

A research is of use to gather information on different products on the market. The research is done by searching patents, articles and databases. The information on the different VVA systems functional principle and valve lift capabilities is summarized in the text.

The different VVA systems are analyzed with an evaluation matrix. The evaluation matrix is based on Pughs decision matrix which is described by Johannes et al [1]. The modifications made were on the scoring scale which was changed to 5 grades and the VVA systems were evaluated in groups with similar systems. The scoring grades are (++), (+), (0), (-) and (--), where 0 is the same as the reference. The evaluation matrix compares the different VVA system with the existing valve train as reference (see figure 1 and appendix A).

VVA EVALUATION																
	Concepts	Valve timing Control				Continuous VVA				Discrete VVA				Without cam		
nr.	Properties	**Reference**	Cam phasers	Cam folower positioners		electrohydraulic	Electromechanical	Mechanical VLD		Cam Switching	Electrohydralic	Valve duration Extender		Hydraulic drive	Pneumatic drive	Electromechanical drive
1	Performance															
2	Fuel consumption															
3	Emissions															
4	Response															

Figure 1: *Evaluation Matrix*

With help from the evaluation matrix it is decided which systems that will be further evaluated.

A more detailed evaluation will be done on the VVA systems that are most suitable for the D4/D6 engines. The aspects that will be evaluated further are what types of VVA strategies can be used with the specific VVA system and the applicability on the engine.

The evaluation of the VVA systems shall result in a recommendation of a specific system with possible VVA strategies for future concept generation and testing.

3. Engine theory

This chapter presents the result of the literature study. The 4-stroke diesel cycle, valve timings, VVA strategies and tier 3 emission standards are described in this chapter.

3.1 4-stroke diesel cycle

The 4-stroke diesel engine cycle consists of intake, compression, expansion and exhaust strokes. The 4-stroke cycle is completed in two revolutions of the crankshaft. During the intake stroke fresh air is inducted in the cylinder through the intake valve(s). The fresh air in the cylinder is compressed by the piston in the compression stroke. Fuel is injected in the cylinder near TDC and the fuel ignites due to the high temperature caused by the high pressure. During combustion the gases expands and pushes the piston down in the expansion stroke (power stroke) and work is generated. When the piston reaches BDC the exhaust stroke starts and the burned gases exit the cylinder through the exhaust valve(s). The 4-stroke cycle is illustrated in figure 2.

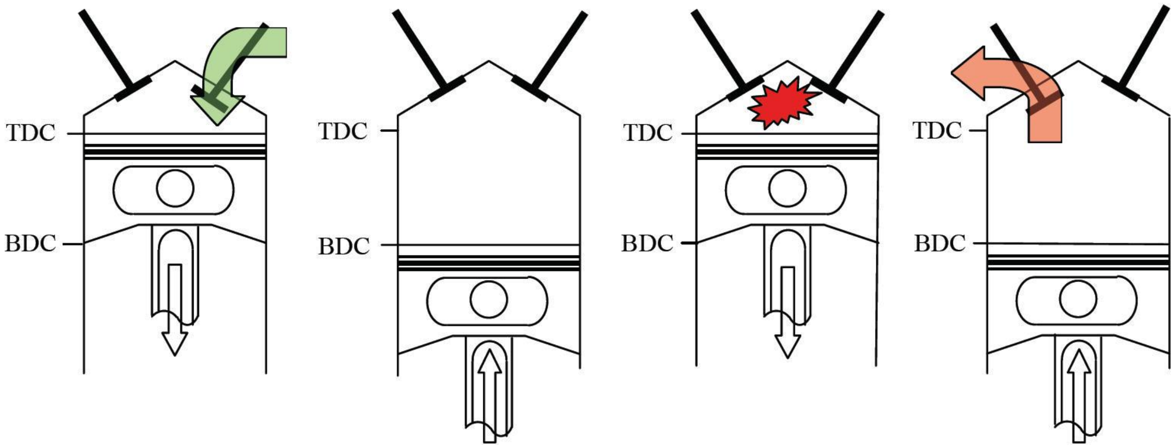

Figure 2: *The four-stroke cycle*

3.2 Valve timing

Exhaust valve opening (EVO) generally occurs 40-60 CAD before BDC during the expansion stroke. EVO is set to minimize loss of piston expansion work due to EVO before BDC and at the same time minimize piston pumping work which requires EVO before BDC. These two requirements are contradictive which means EVO timing is a tradeoff between lost expansion work and pumping work.

Intake valve opening (IVO) normally takes place before TDC during the exhaust stroke and exhaust valve closing (EVC) normally takes place after TDC during the intake stroke. The time when both exhaust and intake valves are open is called overlap. The purpose of the overlap is to increase the scavenging of the residual gases in the cylinder so that more fresh air can be trapped. The overlap length is in many engines restricted to avoid contact between piston and valve due to geometric limitations [2].

Intake valve closing (IVC) is generally set to 20-60 CAD after BDC during the compression stroke. IVC timing is in most cases set to maximize the volumetric efficiency. At low engine speeds earlier IVC timing is advantageous and at higher engine speeds later IVC timing is beneficial to get higher volumetric efficiency. Other strategies for IVC timing are late or early Miller timing to lower the effective compression ratio this is explained in more detail in chapter 3.3. The valve event process is described in figure 3.

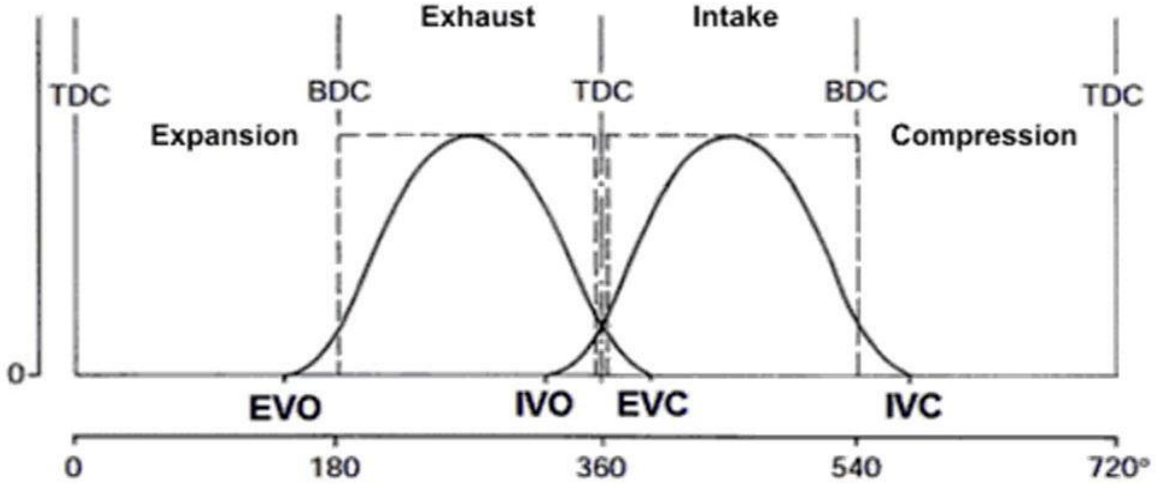

Figure 3: *Valve timing diagram. X-axis: Crank Angle, Y-axis: Valve Lift* [2]

3.3 VVA strategies for diesel engines

Variable VVA-systems can be used to avoid the compromises of fixed valve timing. With a fully flexible VVA system almost all compromises can be avoided. However the more flexible the system is the more complex and more expensive it becomes [4]. Due to geometrical limitations in the D4/D6 engines the overlap is limited and cannot be increased: Therefore changes to IVC, EVO and lift are evaluated.

3.3.1 Miller cycle

Miller cycle, i.e. changes in IVC, can be used in diesel engines to improve efficiency and reduce NO_X emissions. Miller cycle can be achieved by closing the intake valve earlier or later than normal. Late or early IVC reduces the effective compression stroke so it becomes shorter than the expansion stroke [4]. Reducing the effective compression stroke lowers the combustion temperature. Lower combustion temperature is one of the key factors to reduce NO_X emissions. Wang et al have tested three different early Miller timings on a 4 stroke diesel engine [3]. The result shows NO_X reduction of 4.4-17.5 % compared to the standard cycle. The test also showed a small improvement of brake-specific fuel consumption and a small increase in power output.

The tested Miller cycles indicated an increase of CO emissions and one of the cycles showed increase of HC emissions [3]. The Miller cycle can give cold start problems, increased smoke emissions and give some operating problems at part loads [4]. With variable IVC these problems can be avoided by switching to a more beneficial timing.

3.3.2 Low compression ratio

Many manufactures are exploring the effects of low compression ratio to improve efficiency and reduce emissions to meet future emission standards. For example Mazda has developed the Skyactive-D engine with a 14:1 CR and Mitsubishi has developed the 4N1 engine with a 14.9:1 CR [4].

Mazda has achieved Euro 6 emission standards with the Skyactive-D without additional NO_X after-treatment and soot formation. They have been able to improve low end torque with 40% and extend the engine speed from 4400-5200 rpm [5]. The fuel economy was improved 15-20% compared to their previous engine [5]. To ensure start quality and prevent misfiring during warm-up they have used Switching Cam Finger Follower to be able to slightly open the exhaust valve a second time during the intake stroke so that exhaust gases are drawn back into the cylinder [5].

Mitsubishi has another approach. They use their MIVEC cam switching system on the intake valve, which enables them to switch between two different valve lift modes [6]. Their strategy is summarized in table 1 and illustrated in figure 4.

Operational Mode	Valve Operation	Effect	Objective
Low speed mode	Both intake valves: opening timing is advanced	Increased effective compression ratio	Ensure startability
	One intake valve switches to low lift	Enhanced swirl	Combustion improvement
High speed mode	Both intake valves: high lift and large opening period	Supercharging efficiency improvement	Smoke reduction, high performance

Table 1: *Mitsubishi 4N1 Valve timing Strategy* [6]

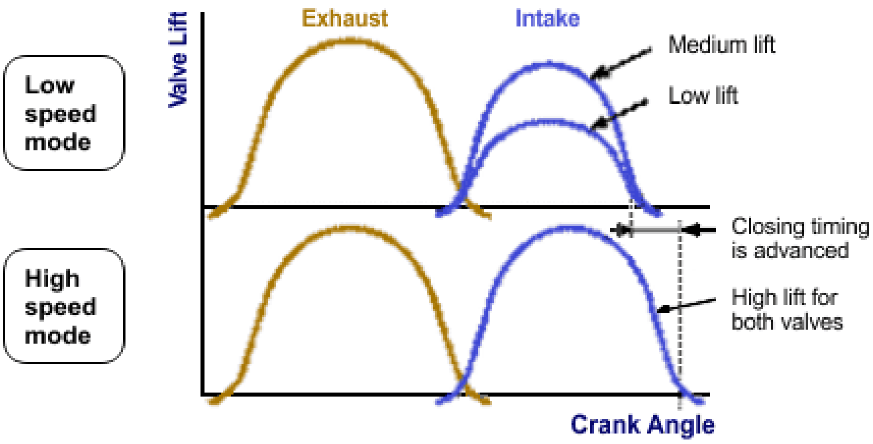

Figure 4: *Valve timing diagram for 4N1 engine* [6]

3.3.3 Variable exhaust valve timing

As discussed earlier in the text, EVO is normally set to when the sum of pumping losses and lost expansion work is lowest. For most engine speeds this occurs near 40-60 CAD before BDC but for low engine speed it can be beneficial to move it closer to BDC to increase the torque.

Early EVO can be used in turbocharged engines to improve boost pressure and improve the transient response. Expansion work is lost with early EVO , but this is compensated by higher boost pressure [2].

A second EVO during the intake stroke can be used to achieve internal exhaust gas recirculation (IEGR) which decreases the NO_X emissions but also normally increases the PM emissions substantially [7]

3.3.4 Swirl control

It is possible to produce high swirl at low valve lift with a seat swirl chamfer with no impact on high lift flow rate [8]. With a seat swirl chamfer the swirl strength can be adjusted to different engine speeds by variable valve lifts. The valve seat is designed so the flow of the air rotates around a vertical axis at low valve lifts. Figure 5 illustrates how a seat swirl chamfer is designed.

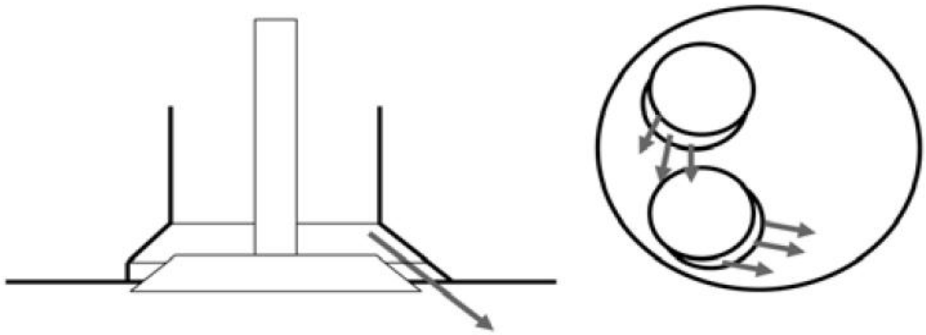

Figure 5: *Schematic illustration of swirl chamfer* [8]

With a low lift the air flow rate is reduced but at low engine speeds a higher swirl has a positive effect on the combustion and emissions [8].

3.4 Tier 3 emission standards

The emission standard US Tier 3 is implemented on recreational marine engines in 2013. The table 2 shows the Tier 3 emission standards in g/kWh for the different engines.

	CO	HC + NO_X	PM
D4/D6	5.0	5.8	0.14

Table 2: *The emission standards for D4/D6 engine* [20]

4 VVA systems

In this chapter different VVA systems and their functions are described.

4.1 Valve timing control

Cam phasers are valve timing control (VTC) systems that retard or advance the opening and closing of the valve equal distances. On engines with dual overhead camshafts cam phasers can be applied on both intake and exhaust valves. This enables intake and exhaust valve timing to be phased separately. Figure 6 shows phasing of the intake valve where the blue curve is the intake valve and the red curve is the exhaust valve.

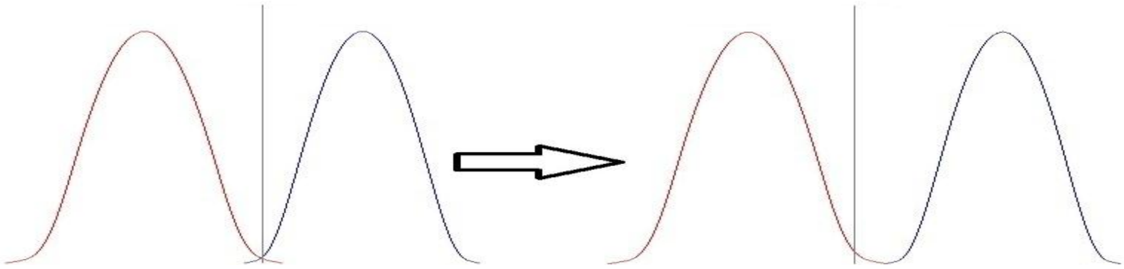

Figure 6: *Intake valve phasing*

There are many suppliers of cam phasing systems and these systems are found in many gasoline engines. The different types of cam phasers can be divided into two groups; discrete and continuous [4]. Discrete cam phasers change between two fixed cam phasing positions and continuous cam phasers can vary between two limits. Cam phaser systems are placed at the end of the camshaft and are easy to apply in different engine architectures [4]. There are electrically or hydraulically actuated Cam phaser systems.

Figure 7 is an illustration of the Delphi Variable Cam Phaser, which is a hydraulic system. To get an advanced position the advancing chamber is filled with oil and the inner wheel is pressed to the other side. For retarded position the retardation chamber is filled and for intermediate positions the inner wheel is adjusted with both chambers to get different angles [4].

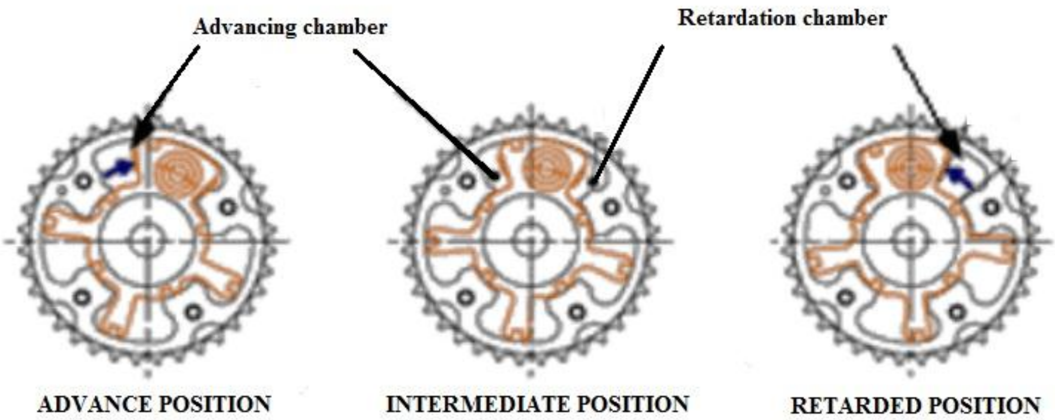

Figure 7: *Schematic illustration of Delphi variable cam Phaser* [4]

In electrically actuated systems, the phasing is performed by an electric motor for instance the Delphi E-phaser.

Mechadyne has developed a concentric camshaft that can be used to change intake and exhaust valve timing separately on single cam engines. It can also be used on dual overhead cam engines to change valves relative to each other [9]. For example, one of the valves opens earlier and the other one later.The concentric camshaft consists of a solid inner camshaft and a hollow outer tube. The moving cams are pinned to the inner solid camshaft and the fixed cams are connected to the outer tube. The assembly of the system is shown in figure 8. Mahle markets this technology as Cam-in-Cam system and it has been used in the Dodge viper [9].

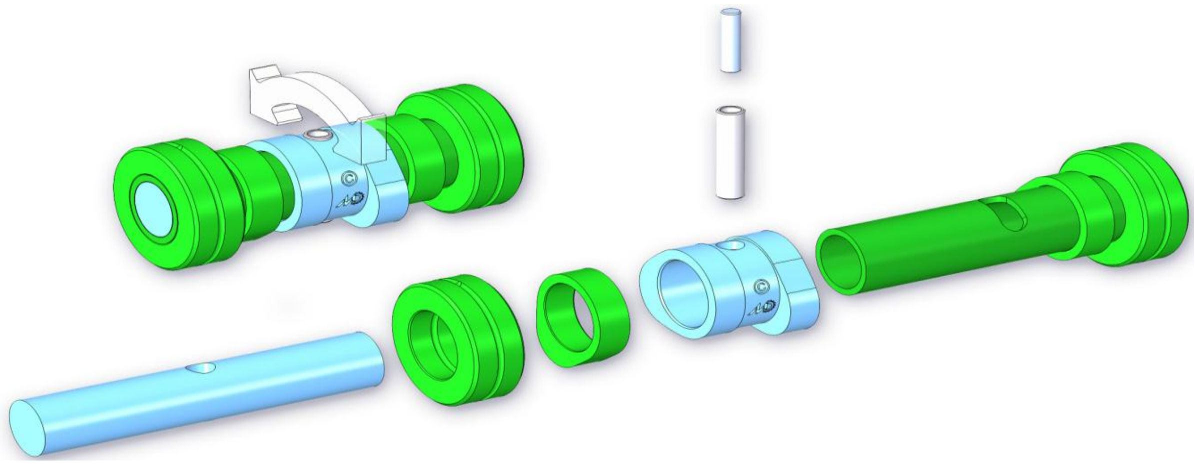

Figure 8: *Mechadyne concentric cam shaft* [9]

Other suppliers of cam phaser systems:

- BorgWarner
- Denso
- Hitachi
- Hilite
- Mahle
- Schaeffler/INA

The Cam follower positioner is a VTC system. This type of system has been used on large medium-speed four-stroke diesel engines. Caterpillar calls their system for Caterpillar-MaK Flexible Camshaft Technology [4]. Compared to a cam phaser, a cam follower positioner does not change the position of the cam instead it changes the position of the cam follower.

4.2 Cam switching systems

With a cam switching system it is possible to change between two different cam profiles. Changing the cam profile gives the possibility of changing the lift and duration. A cam switching system combined with a cam phaser also enables the timing to be changed. Cam switching systems have been used in many gasoline engines.

Honda's VTEC system is a cam switching system that has two cam profiles to switch between. It has two low lift cams and one high lift cam. During low lift modes the high lift cam rotates freely and to activate high lift mode a pin locks the cam rocker arms together. The lift is now performed by the high lift cam [4]. Honda VTEC is shown in figure 9.

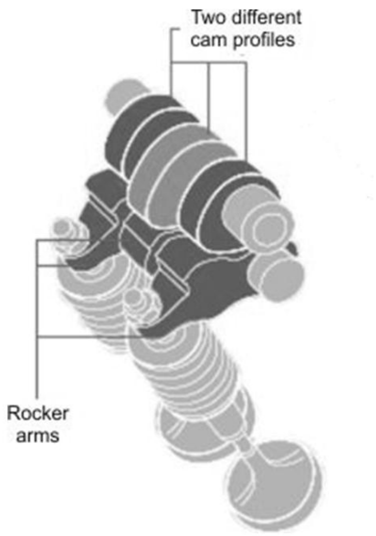

Figure 9: *Honda VTEC system* [4]

The Switching cam finger follower is also a cam switching system. A switching cam finger follower system is used in Mazda's Skyactive-D engine to open the exhaust valve a second time during the intake stroke during warm-up [5]. INA/Schaeffler and Delphi have developed switching cam finger follower technologies. A switching finger follower consists of two levers, the inner one for the primary lift and the outer one for the secondary lift [4]. Figure 10 shows Delphi switching finger follower with cams.

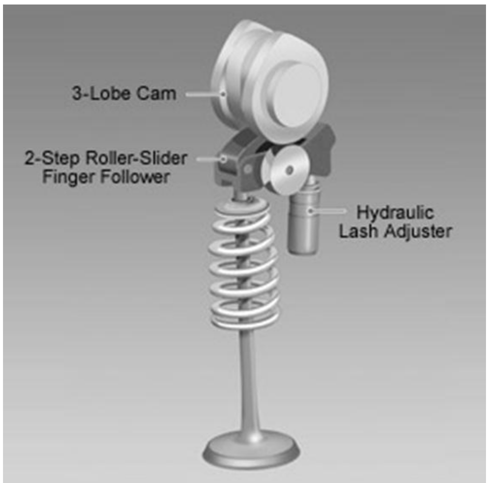

Figure 10: *Delphi switching finger follower* [19]

Other switching cam technologies are the Mitsubishi MIVEC and the Schaeffler/INA switching tappet. MIVEC is used in the Mitsubishi 4N1 diesel engine to achieve two different valve lifts [4].

4.3 Mechanical VVA systems

4.3.1 Mechadyne VLD

Mechadyne VLD (shown in figure 11) is a mechanical VVA system that provides lift and duration control with fixed opening or fixed closing [10]. It has been designed to be applicable to a conventional finger follower valve train. Two cam profiles act on a summing rocker. The summing rocker is connected with the followers to open the valves. By changing the angle of the summing rocker and by changing the lobes phasing it can achieve different valve lifts and durations. The lobe phasing is performed by a concentric cam phaser that was explained earlier in the text [11].

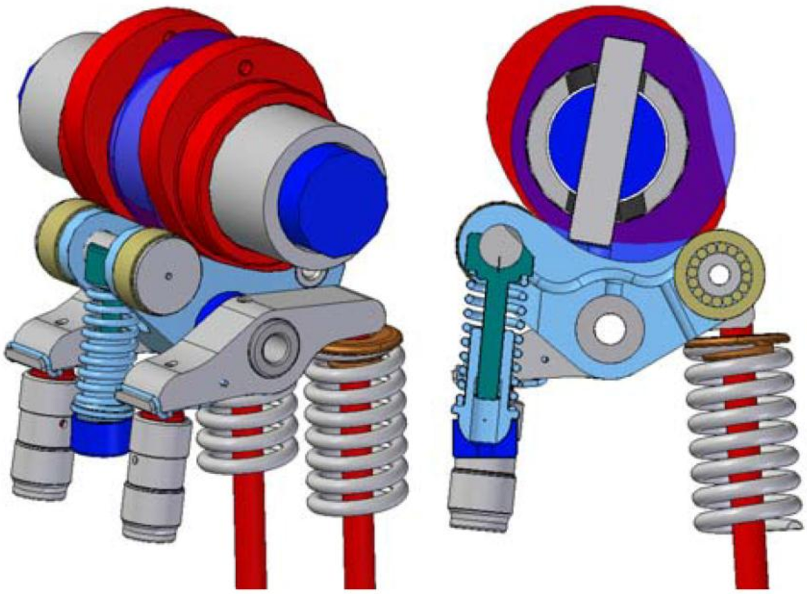

Figure 11: *Mechadyne VLD system* [10]

4.3.2 BMW Valvetronic

The Valvetronic is a mechanical valve train with an electric actuator and is electronic controlled. Valvetronic is a lost motion VVA system that can vary the valve lift fully between no lift to maximum lift. It has been used in BMW gasoline engines with throttleless application to control the load with valve lift [12]. The system has been used in production since 2001 on gasoline engines [12]. The cams movement is transferred by an intermediate arm that pushes down a finger follower on the valves. To change the lift an eccentric shaft driven by an electric motor changes the position of the intermediate arm positions. When the intermediate arm is close to the cam finger follower maximum lift is performed and when the distance is increased the lift is decreased [4]. The Valvetronic is showed in figure 12.

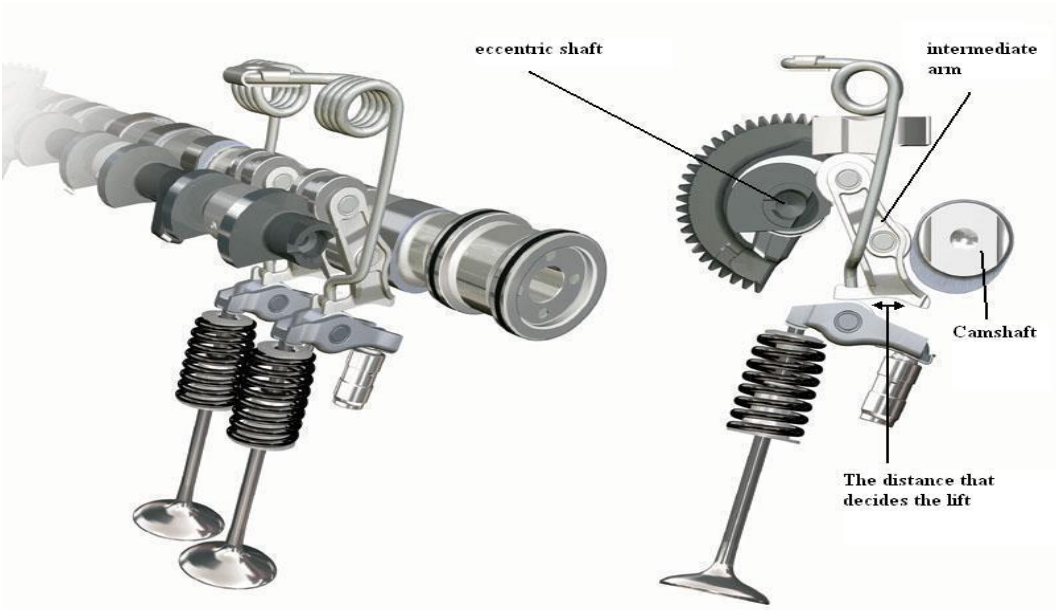

Figure 12: *BMW Valvetronic system* [4]

4.3.3 Nissan VVEL

Nissan has developed the VVEL electromechanical VVA system. The VVEL achieves lift and duration control. The cam in the VVEL systems oscillates up and down and its movements comes from the drive shaft through a number of components (see figure 13). The driveshaft rotates the eccentric camshaft which moves link A up and down. Link A is connected with the rocker arm which transfers the movement of link A to link B. Link B is connected to the cam that acts on the valve lifter. The lift is varied by changing the position of the rocker which is achieved by the control shaft. The control shaft is actuated by the electric motor [13]. Figure 13 shows the principles of the VVEL.

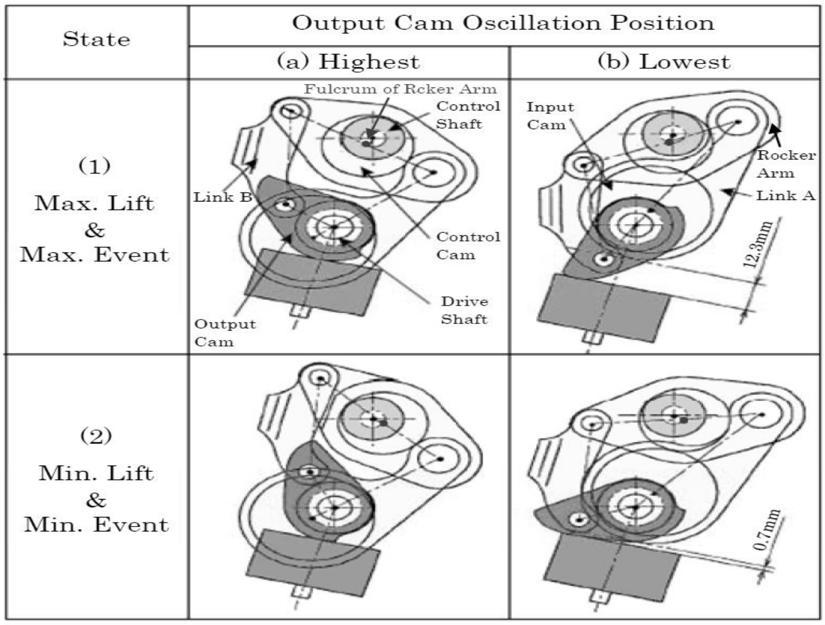

Figure 13: *Working principles of VVEL* [13]

4.4 Hydraulic VVA

There are many different hydraulic VVA systems on the market, for example valve duration extenders and lost motion systems. With valve duration extenders the valve can be held open longer. Lost motion systems reduce parts or the whole lift that the cam generates.

4.4.1 Valve Duration Extenders

Caterpillar heavy-duty ACERT engines use a valve duration extender. The intake valve is held open longer than allowed by the cam profile by pressing down the valve with oil. The extended duration provided is with partial lift. The length of the added duration can be varied [4]. Another valve duration technology is Wärtsilä's variable inlet closing (VIC). The VIC is a hydraulic system that has been used on large medium-speed diesel engines. VIC system can extend valve timing up to 30 CAD [4].

4.4.2 Jacob Vehicle Systems EVOLVE

Jacob vehicle systems have developed many hydraulic VVA system concepts. One of Jacob's vehicle lost-motion systems is called Evolve. The Evolve can achieve degrees of early IVC, late IVC with partial lift and early EVO [4]. In the Evolve system the cam transfers movement to a rocker arm which pushes down a variable collapsing element. The rocker arm has a return spring so that the valve returns to its starting position. The collapsing element is a hydraulic bridge between the cam and the valve. A solenoid valve adjusts the collapsing element so that different timings can be achieved. To reduce noise and improve durability of the valve Evolve has hydraulic valve seat dampers [4]. Figure 14 shows schematically how the system works.

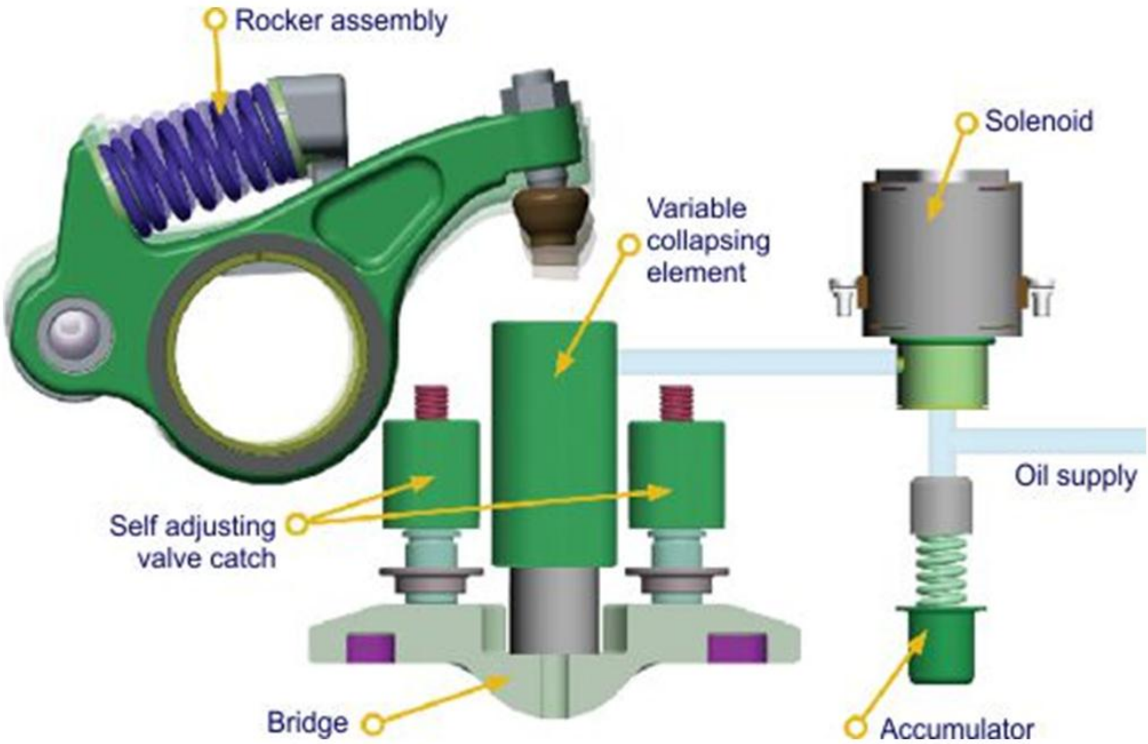

Figure 14: *Schematic illustration of EVOLE working principles*[4]

4.4.3 Fiat Multiair

Fiat's Multiair (figure 15) is an electrohydraulic lost motion VVA system that achieves fully variable intake timing, duration and lift. Fiat had The Schaeffler Group as development partner. The Schaeffler Group calls the system Uniair. Multiair has been used by Fiat in different gasoline engines. The system is flexible and can be modified to fit different engine designs and can also be applied to diesel engines [14][15]. In Multiair the intake cam pushes on a hydraulic piston via a finger follower. The hydraulic piston is connected to high pressure chamber that is controlled by a solenoid valve. When the solenoid valve is closed the movement from the cam is transferred and the intake valve opens. When the solenoid valve is open there is no transfer from the valve. Different valve timing can be achieved by controlling the opening and closing of the solenoid valve [15]][16].

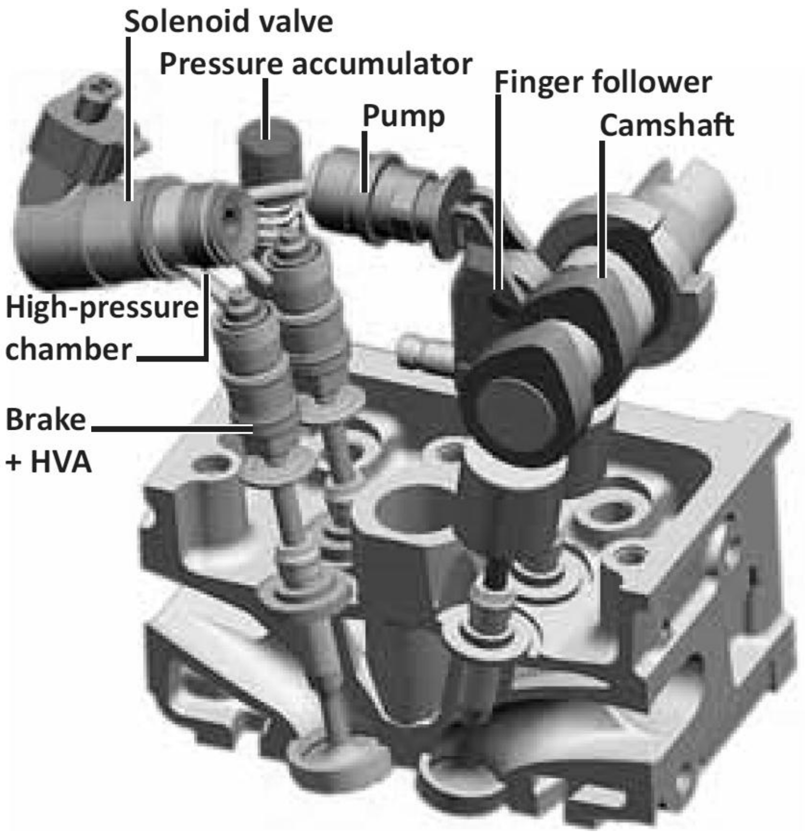

Figure 15: *Fiat Multiair system* [16]

4.5 Camless Valve trains

There are some camless valve trains available but they have not yet been used in commercial 4-stroke engines [4]. Camless valve trains are used as developing tools for valve strategies since they are so flexible [4]. These types of systems are the most variable ones, however Camless valve train has some disadvantages [4]:

- Power consuming,
- Unreliable
- Expensive
- Control issues

Camless valve trains can be divided into three types:

- Electrohydraulic
- Electromechanical
- Pneumatic

The Lotus Active Valve Train (AVT) is an electronically controlled hydraulic valve train system. It is used as a development tool in single cylinder tests. AVT can operate with 5000 rpm as the highest engine speed. The hydraulic actuator is connected directly to the valves [17].

Sturman together with International Truck and Engine developed an electrohydraulic system that was intended to be introduced in production 2003. However the system had some problems with high energy consumption and reliability [4]

FEV has developed an electromechanical system that uses one actuator per valve [4]. Valeo has developed another concept that uses electromagnets to open the valves [4].

Cargine has developed a camless valve train concept that is electro hydraulic pneumatic actuated. It uses air pressure to open the valve and hydraulic pressure to hold the valve open and control the seat landing. The system reduces weight and needs less space compared to normal dual overhead cam systems. SAAB has tested the concept from 2009 to 2011 on the intake valve of a SAAB 9-5 [18].

5. VVA evaluation

The results from the evaluation matrix is presented in this chapter, see the attachment. The result of the second evaluation of the three different concepts is presented.

5.1 Evaluation matrix

The VVA systems were sorted into groups with similar functions. The VVA systems groups were evaluated in the evaluation matrix.

Continuous electrohydraulic VVA system and continuous mechanical VVA systems were the only groups that had a positive score in the evaluation matrix. The continuous electrohydraulic VVA and mechanical VLD had the highest result.

Mechadyne VLD, BMW Valvetronic and Fiat Multiair were selected for further evaluation.

5.2 Fiat Multiair

As discussed above, the Fiat Multiair electrohydraulically actuated VVA system offers a lot of potential for different intake valve strategies. The Multiair has five main operation modes. The Multiair varies between the operation modes by opening and closing the solenoid valve on the high pressure chamber.

The first operational mode is full valve lift. During full lift mode the solenoid valve is closed during the whole event [16].The second operational mode is early intake valve closing, which can be varied fully between different early IVC timings (see figure 16). However the Multiair is limited to early IVC timings therefore late IVC is not possible. This is achieved by opening the solenoid valve early [16].

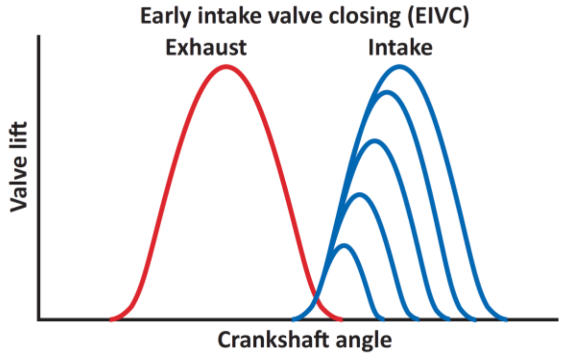

Figure 16: *Valve timing diagram of variable IVC* [16]

The third operational mode is late intake valve opening, however valve lift is lost when the valve opens late (see figure 17). Late intake valve opening is achieved by closing the solenoid valve later [16].

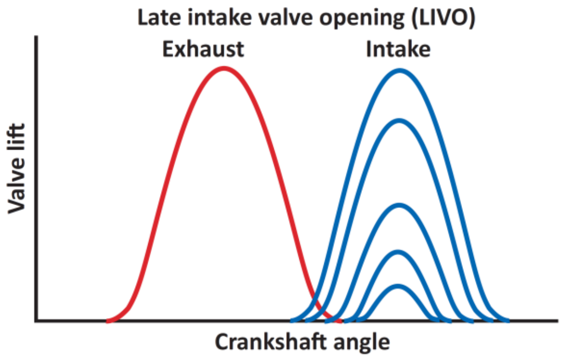

Figure 17: *Valve timing diagram of variable IVO* [16]

The fourth operational mode is multi lift, i.e. the intake valve opens and closes twice (see figure 18). This is achieved by closing the solenoid valve early and opening it again.

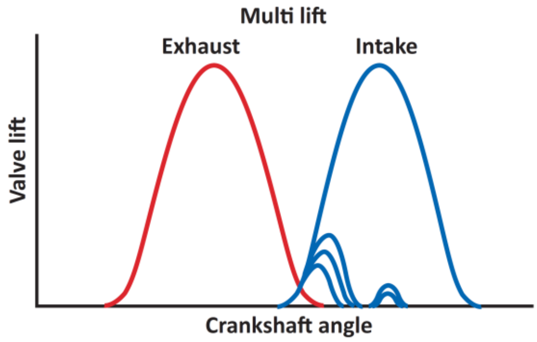

Figure 18: *Valve timing diagram of multi lift* [16]

The fifth operational mode is no intake valve lift. This is achieved by allowing the solenoid valve to be open during the whole valve event [16].

With the Multiair different degrees of early Miller timing can be used in an engine to improve emissions and efficiency. The Multiair gives the possibility to switch to full lift mode to avoid cold start problems and high smoke and high HC emissions during part load conditions. The IVC timing can be varied to optimize volumetric efficiency for different engine speeds, improve swirl by using a seat swirl chamfer and lowering the lift to improve low speed torque.

The average electric power consumption for the Multiair in a 4-cylinder engine is 20 - 30 W and during full load operation it ranges from 40-70 W [14]. The Multiair system works in temperatures down to -30˚C [14].

The high pressure chamber and hydraulic pump that transfer the cam movement to the high pressure chamber can be positioned freely in the cylinder head [15]. This makes the Multiair design flexible and easier to adapt in different engine architectures. Tests to implement the Multiair to diesel engines have been done successfully [15].

5.3 Mechadyne VLD

The Mechadyne VLD system gives the opportunity to achieve different valve timing strategies. With the VLD it is possible to vary the closing of the valve with fixed opening or vary the opening of the valve with fixed closing. There is also the possibility to achieve variable secondary valve events. The different lift ranges available are lift control and duration control (see figure 19) [10].

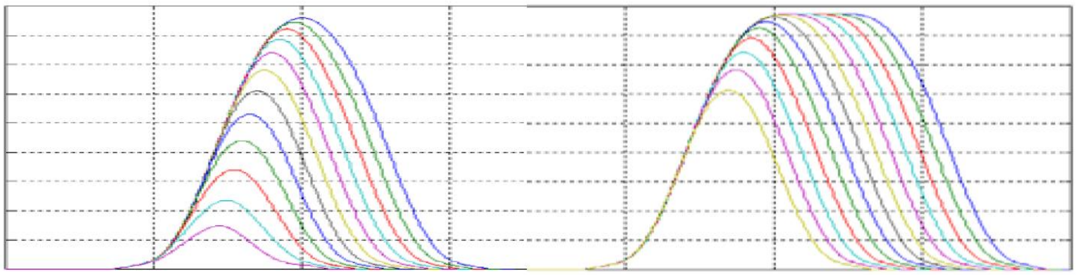

Figure 19: *The different valve ranges available for VLD* [10]

To change between different lift curves changes to the cam profile has to be done. Secondary lift or pre-opening of the valve can be used with variable or fixed main valve events [9]. VLD is designed so it can be implemented to existing valve train with minimal changes to the cylinder head geometry. The first step is implementing a concentric camshaft. The second step is implementing the VLD system (see figure 20).

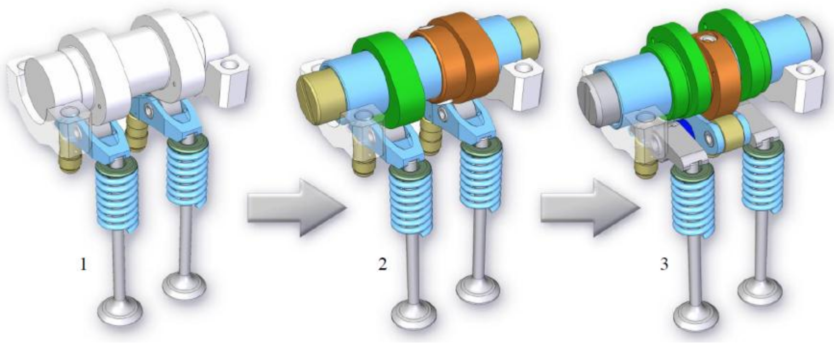

Figure 20: *The upgrade steps for implementing VLD* [9]

The VLD can be applied on both the intake and exhaust camshafts. This gives the possibility of varying IVC and EVO and performing secondary valve lift on both the intake and the exhaust valve. By using cams that allow valve duration control on IVC the possibility arises to control the effective compression ratio, i.e. to achieve late or early Miller. With lift control it is possible to achieve early Miller timings and swirl control by changing the valve lift.

By varying EVO with the VLD system the tradeoff between lost expansion work and higher pumping work can be optimized and the engine response can be maximized. A second opening of the exhaust valve during the intake stroke can be used to push back exhaust gases for IEGR.

5.4 Valvetronic

BMW’s Valvetronic is a fully variable lift control system that allows the lift to vary between full and no lift of the intake valve. When the lift is decreased the duration is shortened. The second generation of the Valvetronic shortens durations more when the lift is reduced to improve load control (see figure 21) [12].

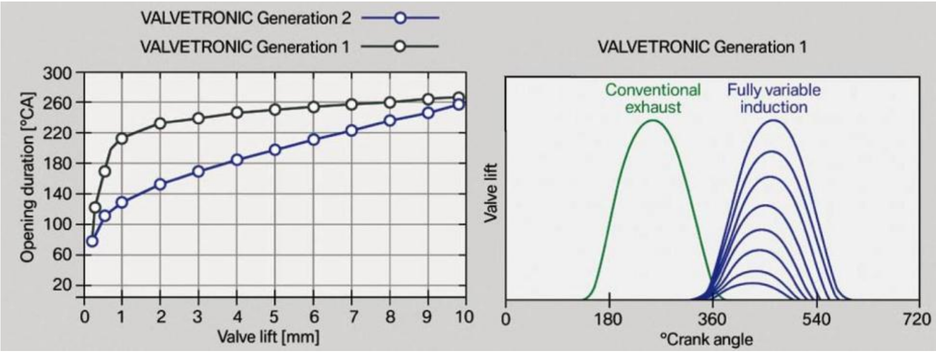

Figure 21: *shows the duration for different lifts* [12]

By reducing the lift the Valvetronic can achieve an earlier IVC than the normal lift. In this way the effective compression ratio can be lowered by reducing the lift with the Valvetronic to achieve different degrees of Miller timing. Another VVA strategy that can be used is swirl control with the VVL.

One disadvantage with the Valvetronic is its size. To implement the Valvetronic in an engine the system needs more spacing over the cylinder head than a conventional valve train. The position of the electric motor that drives the eccentric shaft is the second problem since it needs additional spacing (see figure 22).

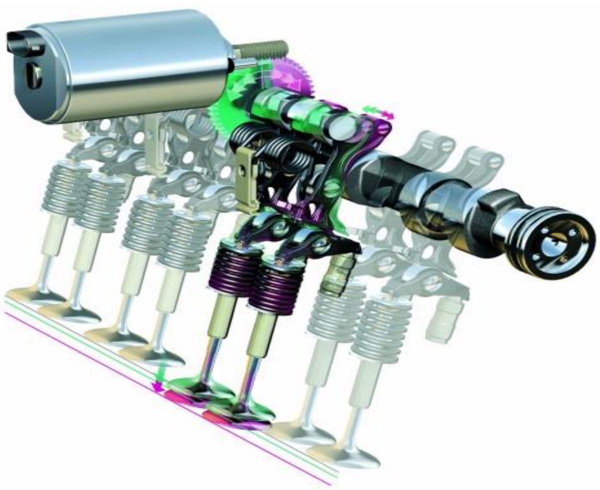

Figure 22: *Valvetronic system with the electric motor* [12]

6. Recommendation of a VVA system

The VLD with valve duration on the intake side with fixed openings offers the best potential of reducing emissions, improving efficiency and performance together with less changes of the D4/D6 engine architecture.

The VLD with valve duration cam profiles offers the potential to operate with different Miller timings for different engine speeds and loads. This gives the potential of reducing emissions in particular NO_X-emissions, improving the fuel consumption and the power output (see chapter 3.3). The IVC timing can also be set to optimize volumetric efficiency which can improve the power output for different engine speeds. The cold-start and part-load operation difficulties can be improved with the VLD by changing to normal valve timing.

The Multiair is a more flexible VVA system compared to the VLD however the Multiair cannot extend the valve duration. Multiair and Valvetronic can reduce the valve lift but the VLD with duration control cam profiles cannot control the valve lift. The Multiair and the Valvetronic can perform early Miller timings however they need more changes to the engine architecture to be implemented in the D4/D6 engine family.

One disadvantage with the VLD is that it has not been used in production yet. The Multiair has been in production since 2010 and the Valvetronic since 2001, but none of them have been used in diesel engines.

The VLD system can be applied on the exhaust valves, which offers early EVO and secondary EVO. The EVO timing can thus be set to its optimum for different engine speeds so that the sum of pumping losses and the lost work is minimized to improve the engine performance. Early EVO can be used to improve the boost pressure and the response. The Multiair cannot be applied on both intake valves and exhaust valves. The Valvetronic has no benefits for the exhaust side since it only varies the lift.

The next step could be to do a packing study of the VLD system in the D4/D6 engines and to develop a concept for testing the benefits of using the different VVA strategies that the VLD can perform on the intake valves. For further development the VLD can be implemented to the exhaust side for early EVO and secondary EVO.

7. Conclusions and comments

This chapter summarizes the work. The 4-stroke cycle, different valve timings, different VVA strategies for diesel engines and the emissions standards were explained in the engine theory chapter. The performed literature study resulted in the engine theory chapter. The literature study gave a good overview of the effects of different valve timings and VVA strategies which was helpful during the evaluation of the VVA systems.

The research was summarized in the VVA system chapter. In the VVA system chapter the VVA system’s work principles and the different valve lifts functions are described. The VVA system chapter gives a general idea of the VVA systems functions, however all available VVA systems are not described in detail due to the limited time for this work. The information on the different VVA systems was useful in the evaluation of the VVA systems.

The evaluation of the different VVA systems was done in two steps. The first step was the evaluation matrix and the second step was a more detailed evaluation of the three best systems in the evaluation matrix. The evaluation matrix fulfilled its purpose and made it easier to choose the three systems VLD, Multiair and Valvetronic for further evaluation. The aspects that were evaluated in the second analysis of these three remaining VVA systems were which types of VVA strategies that can be used and what benefits they provide and the applicability in today’s engine architecture.

The VLD system enabled most VVA strategies for a diesel engine because of applicability on both the intake and the exhaust system. The VLD system can be applied on the D4/D6 engines with small changes of the existing engine design. These aspects were the reason for the final recommendation of the VLD system.

The purpose of this study was to evaluate different VVA system and strategies for the D4/D6 engine family. This study presents an overview of different VVA systems and VVA strategies for diesel engines. The VVA systems and strategies have been evaluated to suit the D4/D6 engine family.

The objective of this study was to recommend a VVA system and strategies for the D4/D6 engines. The VLD system with duration control on the intake valves with fixed valve openings was finally recommended. For further development the system can be implemented on the exhaust valves with variable openings and second openings.

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Appendix A – Evaluation Matrix

VVA EVALUATION

nr.	Properties \ Concepts	Reference	Valve timing Control		Continuous VVA			Discrete VVA			Without cam		
			Cam phasers	Cam folower positioners	electrohydraulic	Electromechanical	Mechanical VLD	Cam Switching	Electrohydralic	Valve duration Extender	Hydraulic drive	Pneumatic drive	Electromechanical drive
1	Performance		+	+	++	++	++	+	+	+	++	++	++
2	Fuel consumption		+	+	++	++	++	+	+	+	++	++	++
3	Emissions		+	+	++	++	++	+	+	+	++	++	++
4	Response		0	0	0	0	+	0	+	0	-	0	-
5	Durability		-	-	-	-	-	-	-	-	--	--	--
6	Applicability in engine architecture		-	--	-	--	-	-	--	--	--	--	--
7	Degrees of freedom		+	+	++	++	++	+	+	+	++	++	++
8	Complexity		-	-	--	--	--	-	--	-	--	--	--
9	Maturity		0	0	0	0	-	0	0	0	--	--	--
10	Cost		-	-	-	-	-	-	-	-	--	--	--
Sum +			4	4	8	8	9	4	6	4	8	8	8
Sum -			-4	-5	-5	-6	-6	-4	-6	-5	-11	-10	-11
Total			0	-1	3	2	3	0	0	-1	-3	-2	-3
1. IVC timing (early or late Miller)			Y	Y	Y	Y	Y	Y*	Y	Y	Y	Y	Y
2. EVO timing (early EVO)			Y	Y	N	N	Y	Y*	Y	N	Y	Y	Y
3.Lift control (control swirl)			N	N	Y	Y	Y	Y*	N	N	Y	Y	Y
Further evaluation			N	N	Y	Y	Y	N	N	N	N	N	N

Y=Yes, N=No, Y*= Yes, depends on settings.