MANTECH Publications

Journal of Transportation Engineering and Its Applications
Volume 3, Issue 2, May-August, 2018

# *The Development of Variable Valve Actuation Systems and Their Effect on the Fuel Consumption and Emissions*

***Robert Spillane[1], Dr Don Law[2]***
*Associate Professor[2]*
*Coventry University, UK[1], Unitec Institute of Technology, Auckland, New Zealand[2]*
***Corresponding Author's email id**: dlaw@unitec.ac.nz[2]*

***Abstract***

*Emissions and fuel consumption are becoming a defining factor of a vehicle performance. As emission legislation becomes increasingly strict, current internal combustion chambers are limited by mechanical camshafts and their level of fuel consumption and emissions are no longer acceptable. The next logical step is to improve the control over the ICE and this can be accomplished by expanding the range of valve events with fully variable valve trains (FVVT). This report provides a brief literature of the limits and problems of mechanical camshafts, the development of partially variable valve technology, such as phase shifting the valve timing and multilobe camshafts. The focus then shifts to how electrohydraulic and electromagnetic systems can provide FVVT and the reduction in fuel consumption and emissions they provide. FVVT offer opportunities to implement other technologies such as Controlled auto ignition (CAI) and cylinder deactivation. The theory and results of these techniques are also covered.*

***Keywords:*** *FVVT, Variable Valve Actuation (VVA), Controlled auto ignition (CAI)*

## INTRODUCTION

Variable Valve Actuation (VVA) is the operation of the opening and closing of the intake and exhaust valves relative to the rotation of the crank shaft, as well as the magnitude of lift of these valves within the cylinder in an internal combustion engine (ICE). The purpose


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

of the valves is control the travel of gases and the combustion of the engine, to optimize the performance of the fuel consumption, power and emissions.

In early internal combustion chambers, only two valves were included. One for the intake and one for the exhaust. In more recent years to increase the flow area that is be available, two valves for exhaust and two or more intake have been introduced. This is a more efficient use of space within the combustion chamber and allows a greater flow area than one larger valve for each.

The movement of the air/air fuel mixture from intake to chamber and then to exhaust is due pressure differences between the areas. From intake to cylinder a scavenging process occurs. The larger pressure in the intake manifold relative to the empty cylinder draws the air or air/fuel mixture into the lower pressure cylinder. The exhaust works in the same way. After combustion has occurred a now high pressure in the cylinder pushes the exhaust gases, as the exhaust valve opens, into the exhaust as this area has a relative lower pressure. To encourage this process further the size of the intake and exhaust valves vary. The intake valve is larger although the same amount of mass is expected to flow through each type, the pressure difference across the intake is less, therefore more area is need to get similar mass flow rates. The exhaust valve does not need to be as large as the pressure inside the cylinder after combustion is sufficient to push the exhaust gases outside of the chamber. [1]

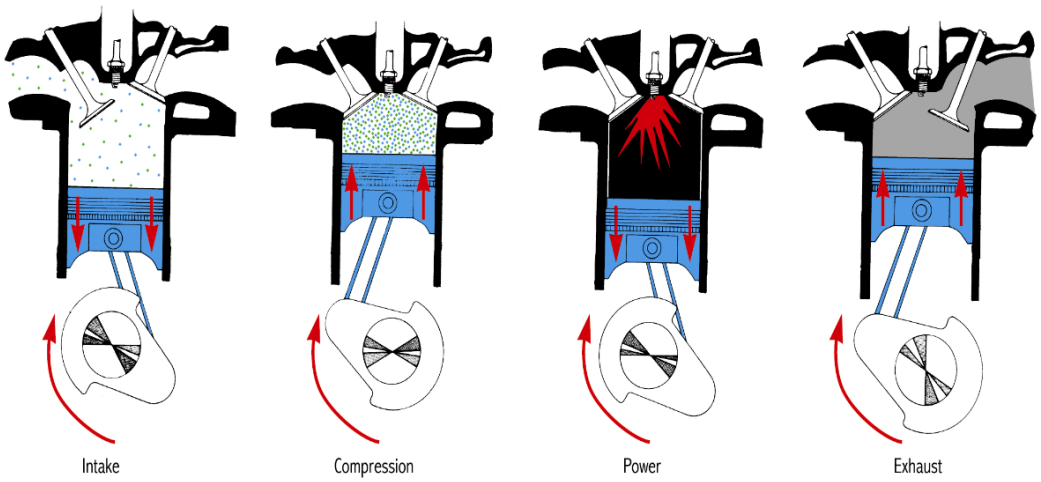



***Figure 1: Valve actuation over combustion cycle***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

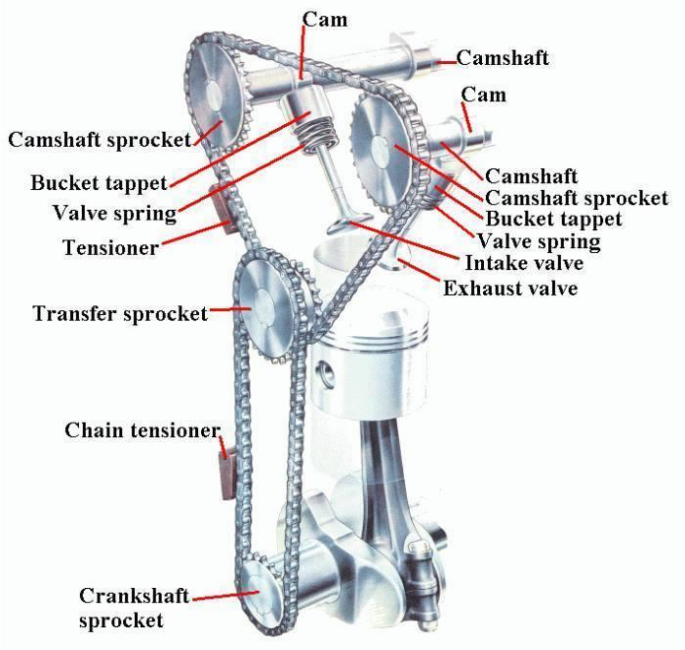



***Figure 2: Diagram of Mechanical Valve Actuation System***

There are different versions of mechanical valve actuation systems. Above is an example of a system that uses the rotation of the crank shaft to drive, via gears/belts, the camshaft. The cam shafts rotate and push the valve system open. Ideally valves would open and close instantaneously and at the appropriate times but in practice this is impossible, due to mechanical limits of the valves and their seats.

Limitations like wear, response time and noise. Mechanical systems are currently the most widely used in industry. A mechanical system comprises of a cam shaft which rotates relative to the crank shaft.

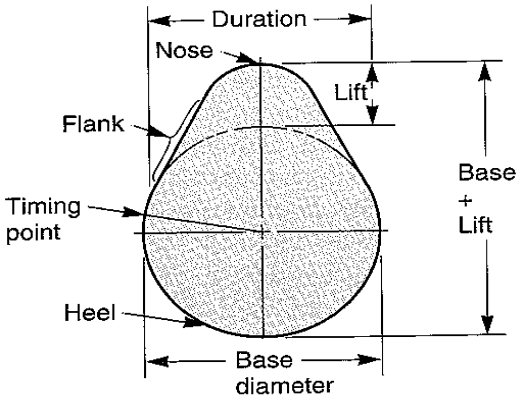



***Figure 3: Camshaft lobe profile***

The camshaft has lobes with designed profiles so that, when rotating, the valve can smoothly open and close, as quick as possible without causing damage the system. The shape of this profile determines the opening and closing time as well as the lift of the valve relative to the crank shaft angle.


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

## DISCUSSION

### *Mechanical Valve Actuation Systems*

As mentioned previously it would be ideal for the valves to open and close immediately but this is not possible. The valves need some time to open to their required lift and shut. The timing and lift of the valves has a significant effect on the performance of the ICE.

### *Valve Overlap*

There are moments where both intake and exhaust valves are open, this is called valve overlap i.e. at the end of the exhaust and start of the intake stroke (TDC). At this point it is possible for some fuel to flow straight out of the exhaust causing high levels of emission. It is also possible for residual exhaust gases to be pushed back up the intake valve and reducing the volume of incoming air fuel mixture. This decreases the volumetric efficiency and is generally a larger problem when this at low revs where the real overlap time is longer and intake manifold pressure is relatively low [1]. This is not a problem with boosted systems as turbochargers and superchargers will create intake pressures above the cylinder pressure.

### *Volumetric Efficiency*

The volumetric efficiency of an engine is the ratio of the volume of air fuel mixture the engine can draw in on the intake stroke divided by the volume of air that would be able to fit into the cylinder at atmospheric pressure.

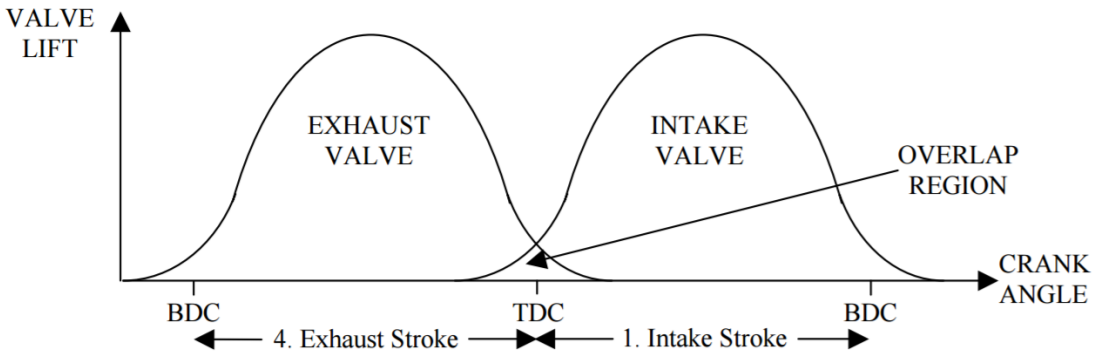



***Figure 4: Valve overlap***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

***Exhaust valve timing***

For the engine to optimize efficiency the valve timing can be used to reduce the forces acting upon the piston. During the power stroke the exhaust valve can be opened before BDC, this enables the high pressure in the chamber to push out the burnt fuel during the downward stroke, blowdown, so that when the upward exhaust strokes starts there is less net pressure from the remaining exhaust volume, acting upon the piston head resisting the upward motion [1]. If the exhaust valve is close too early, exhaust gases can be trapped. If closed too late the valve overlap is greater, meaning there is greater levels of back flow into the intake.

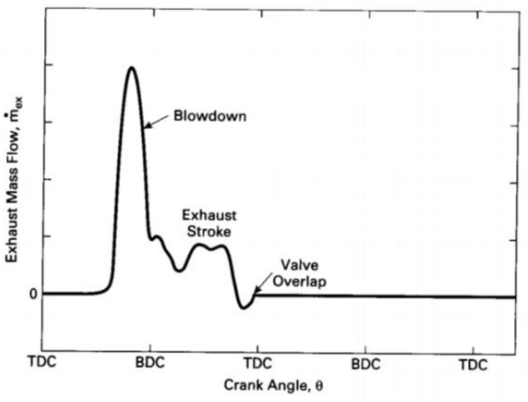



***Figure 5: Exhaust mass flow against crank angle***

***Promoting the mixture of Air and Fuel***

The lift and opening time of the valves can be used to influence how the fuel and air mix in the chamber. Increasing the time the fuel has to mix or by promoting turbulence of the mixture and improving the homogenous distribution of the fuel. This does not mean that the intake valve lift always needs to be high to allow more flow. It has been observed that high intake flow velocities can be caused by very low lifts of the intake valves [2]. With a more homogenous fuel distribution during combustion, the flame distribution is spread evenly and improves the performance of the downward power stroke. A well distributed mixture reduces the amount of unburnt fuel that can be exhaust. Incomplete combustion can still occur even with a stoichiometric mixture as there can be fuel rich and fuel lean areas within the chamber itself when the fuel has not mixed.

Apart from valve lift and timing, the valve orientation can play a part in promoting turbulence and swirl to mix the fuel and air. This is closely linked with the shape of the piston head and therefore will not be covered in any further detail in this report.

***Stoichiometric Air-fuel Ratio***

The basic purpose of valve timing is to control the air fuel mixture prior to combustion and to control the exhaust


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

gases post combustion. This is achieved by controlling the timing of the valves. To reduce emissions, it is ideal to have a stoichiometric mixture. A stoichiometric mixture is a mixture where the ratio between air and fuel where all will be consumed in combustion and not result in emissions. This stoichiometric ratio changes for different fuels, for petrol this is 14.7 parts air to 1 part fuel. Although ideal for low emissions there are situations where having a rich, less than 14.7:1, or lean mixture, more than 14.7:1, is more appropriate.

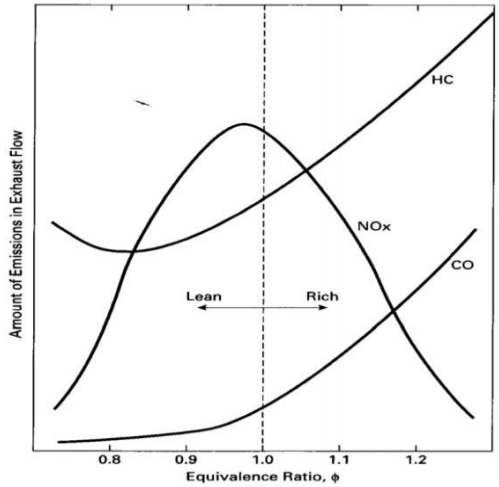



***Figure 6: Emissions against air fuel ratio***

***Rich Air-fuel Ratio***

Where the mixture is rich there is not a sufficient amount of oxygen to react with the carbon. This results in higher emissions of hydrocarbons and carbon monoxide. A rich mixture is sort after when starting up the vehicle and when high levels of acceleration are required. More fuel is purposely included to ensure the engine can produces the higher levels of torque required when accelerating and to start the engine.

***Lean Air-fuel Ratio***

When the levels there are too little fuel to react with the oxygen it is considered a lean mixture. This result in higher levels of NOx The relationship between emission and air to fuel ratios is shown in figure 6. If the mixture is too lean it can result in a misfire, which then results in unburnt fuel being exhausted.

***Leaking past the exhaust valve***

During points of high pressure in the compression and combustion strokes it is possible for some of the air fuel mixture to be forced into the crevice of the exhaust valve and valve seat. When these valves are then open unburnt fuel passes straight through into the exhaust manifold.

***Mechanical Variable Valve Train Systems (VVT)***

Traditionally the valve timings were fixed. The optimal valve timing will vary for different situations and therefore having one setting can be efficient for


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

one rpm but have inferior performance for every other situation. Variable valve timing is a mechanical system that allows from some variation of valve timing depending on rpm whilst on the move. There are many types of VVT in use but the most common type uses a hydraulic oil ring to either delaying the valve timing or by advancing the timing.

By varying oil pressure either side of an inner cog you can change the angle of the cam shaft relative to the crank shaft. This system doesn't affect the lift or duration of the opening of the valve but when the opening should occur relative to the crank angle. The phase change is predetermined and programmed into the engine management unit (EMU) so that it can vary with the engine rpm.

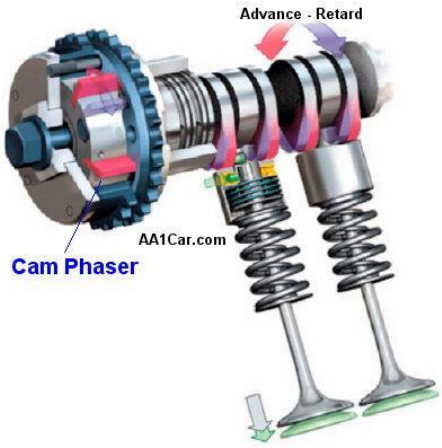



***Figure 7: Variable valve timing system***

Variable valve lift and duration systems

To improve the range of variability of mechanical system further system have started to implement multiple lobes per valve to offer not just a change in phase of valve timing but another option for lift and duration. Each company has their own form of this technology, with various mechanical systems but they all work on the same premise. At a point specified by the EMU a mechanism will switch the lobe on the camshaft another lobe with a different profile, therefore changing the lift and duration of the valve opening. This extra variation comes at an increase of cost and complexity. Below is an example of Honda's VTEC mechanism [4].

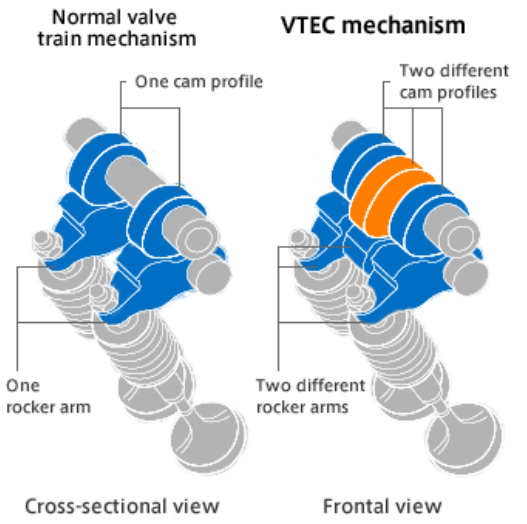



***Figure 8: Comparison of a normal camshaft and Honda's VTEC mechanism***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

***Internal Exhaust gas recirculation (IEGR)***

Variable valve actuation systems also introduce the opportunity to deliberately trap exhaust to reduce the available volume for incoming air fuel mixture, the burnt exhaust gas takes no further part in the combustion, apart from reducing the volume, effectively making a small engine size, whilst the exhaust gas is being recirculated. This can be used for when the power demand required by the engine is low and therefore save fuel and reduce emissions.

With a smaller proportion of combustion taking place, as less oxygen is available, the peak temperatures within the cylinder decrease and this corresponds to a reduction in the formation of NOx.

The recirculation also provides a second opportunity for any unburnt fuel to combust again, which would otherwise have passed through the combustion chamber and result in higher emissions.

One of the downsides of EGR is that, as a result of a lower proportion of oxygen, the proportion of partially combusted fuel and particulates is increased.

***Camless systems***

The camshaft profile can have lower lift (and therefore a lower opening area) and a shorter duration with less or even no overlap. This type of profile would provide a vehicle with low emissions and good low-end torque, but suffer at higher rpm with low power. On the other hand, for high power, a cam profile that has more lift and a longer duration, therefore more overlap, will provide better breathing. The down side of this lobe design is high fuel consumption and higher emissions at low rpm. These good performance ranges can be improved with the techniques outlined earlier in the report, they are still limited for every other rpm. In reality the timing and lift of the valves for optimum performance should vary across the whole range of engine rpms.

In recent years, there has been a development from mechanical camshaft systems to Camless systems. Most of these camless systems use electro-hydraulic and Electro-magnetic actuation to control individual valves, with the EMU monitoring engine rpm and selected the appropriate valve strategy, therefore providing a fully variable valve train (FVVT).


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

***Electro-hydraulic VVA systems***

Although their design will change from manufacturing, each trying to make the system both cost effective and practically implementable, figures 9 and 11, show a simplistic view of the concepts.

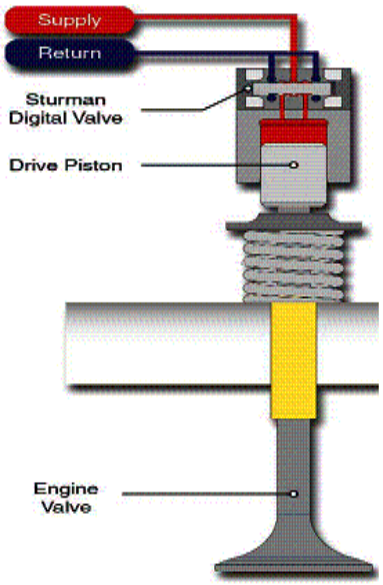



***Figure 9: Electro-hydraulic actuator, schematic layout [4]***

The electro-hydraulic systems use pressure from a hydraulic fluid to push the valve down onto a spring away from its seat. When the valve is required to close, the hydraulic pressure is removed by emptying the fluid chamber, the spring then pushes the valve back into its closed position.

Figure 10 provides an example from Ricardo [5] of the control system of an electro- hydraulic actuator.

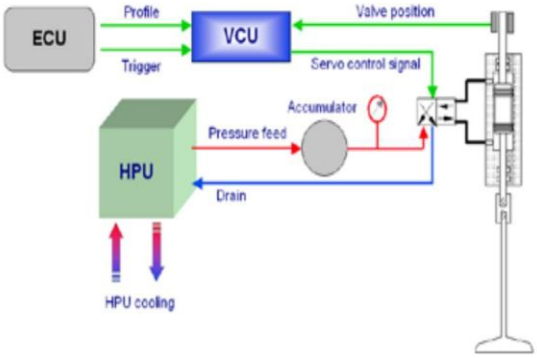



***Figure 10: Ricardo electro-hydraulic valve train schematic***

***Electro-magnetic VVA systems***

Electro-magnetic actuators use electromagnetic forces to control the valve. The forces are generated by wrapping coils around the valve stem. When a current is passed through the coils, they generate electromagnetic fields, which then influence the position of the valve stem.

If the upper coil's current reduced from its holding value to zero, the upper spring pushes the valve open. The current in the lower coil then determines the lift of the valve. To close the valve the operation is reversed.


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

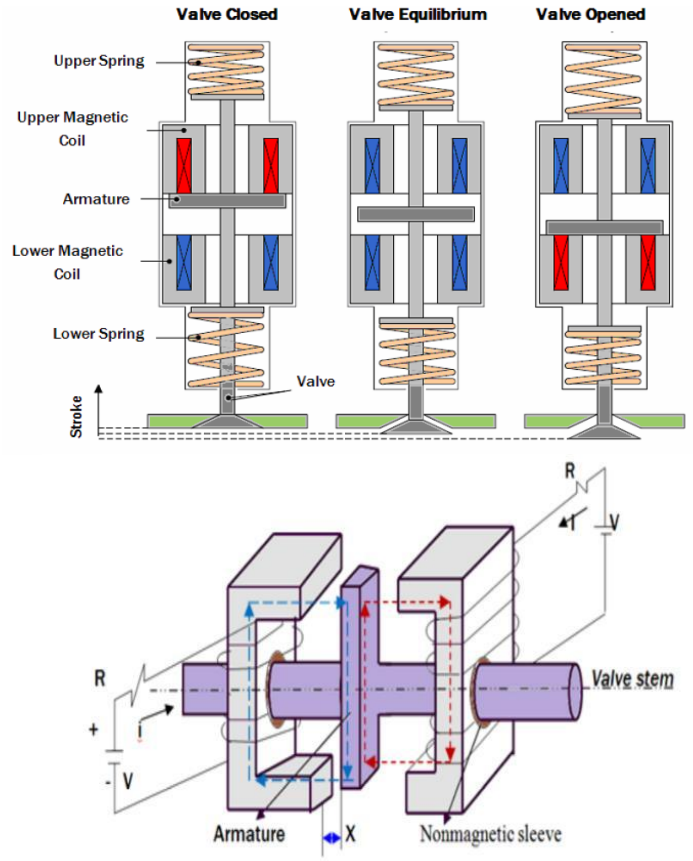



***Figure 11: Electro-magnetic actuator operation [6]***

***Benefits and Issues of Fully Variable Valve Trains***

Both systems offer a fully variable control of valve timing and valve lift. Each system is independent of any of the engines other moving parts and therefore can be control individually. They are also primarily controlled by the EMU and then by sub-controlled systems like the Valve management unit and the hydraulic management unit, as seen in figure 10. This means lift and timing can be changed digitally at any point.

As the valve timing would be no longer limited to the rotation of the camshaft, the opening and closing speeds can be increased providing a longer duration at the desired level of lift.

This will improve:

- Engine breathing Valve events can be optimized to encourage scavenging processes even multiple intake are possible with the valve speed.


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

- Reduced valve overlap and therefore remove the risk of blowback, or unburnt flow bypassing the combustion process all together.

- Obtaining a homogenous air fuel mixture by have more control over the flow of air into the chamber. This can be optimized to generate the most swirl and turbulence.

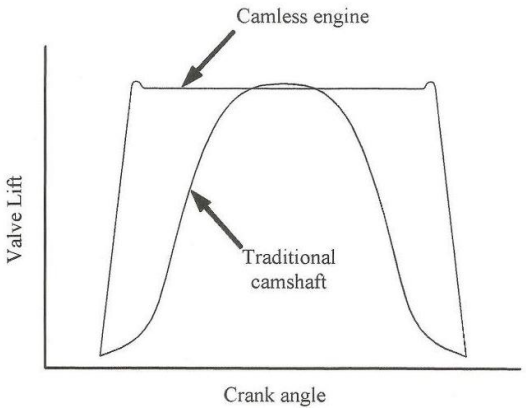



***Figure 12: Camless valve lift compared to traditional camshaft valve lift***

As camless systems have less moving parts than their mechanical counterparts, there is a reduction in the use of oil for lubrication which will also reduce the risk of burning any oil during combustion and causing greater emission. Fewer moving parts may also remove any potential losses due to friction that may be present on a traditional system, as there are no longer any physical connections between the crank shaft and the valve.

As with any new and developing technology there are some design issues to overcome before the system can become commercially viable for automotive manufacturers. Some of the issues manufacturers and research have observed are about the material robustness, power consumption, and packaging limits.

- Noise, vibration and harshness – Although the number of moving parts has decreased the valve still has the same demand of movement, if not more for multiple valve events. One of the major concerns amongst designers is the wear acting upon the valve and vale seat. Due to increase valve opening and closing speeds, the wear at this point has become an issue.

- Response times at high rpm
- Power consumption – is also one the main issues plaguing designers, particularly with electro-magnetic systems [7]


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

- Obtaining a system that has sufficient pressure at the valve for the electro-hydraulic system.

- The cost of FVVT compared with traditional system. Some designers are searching for ways to produce a FVVT system that can be retrofitted to existing assemblies.

***Cylinder Deactivation***

With full control over each individual valve the option to downsize the engine, when there no/little demand for power, on the move becomes a viable option. This can be accomplished by closing of the valves to a cylinder. Cutting the combustion chamber off from any new fuel or air, therefore effectively making a reducing the number of active cylinders. This system is generally only used when there is little or no demand for power i.e. running idle or urban environments. The benefits of this technology are fairly simple, running less cylinders means a lower fuel consumption. It will also increase the life of moving parts as they're not being used as frequently.

***Controlled Auto Ignition Using FVVT***

Improved valve control will also provide better control over existing techniques like internal exhaust gas recirculation. One technique that uses EGR is controlled auto ignition (CAI). This technique involved trapping the exhaust gases and raising the temperature of the intake charge to the point that, during the compression stroke as with Diesel engines, the fuel is ignited through pressure and temperature, not by a spark. CAI is also referred to as Homogenous charge compression ignition (HCCI). Homogenous charge (HC) referring to the method of fuel introduction and compression ignition (CI) the method of ignition. Diesel engines use stratified charge compression ignition (SCCI).

***Electromechanical Actuation systems***

Like traditional variable valve technology, electromechanical systems still use a cam to provide the valve movement. Figure 13 provides a schematic of the system. To control the valve timing and lift, the electromechanical system uses the cam and master-cylinder spring for pumping different level hydraulic fluid into the valve cylinder to realize variable valve timing and lift control according to the relief pressure setting of the proportional pressure relief valve [8]


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

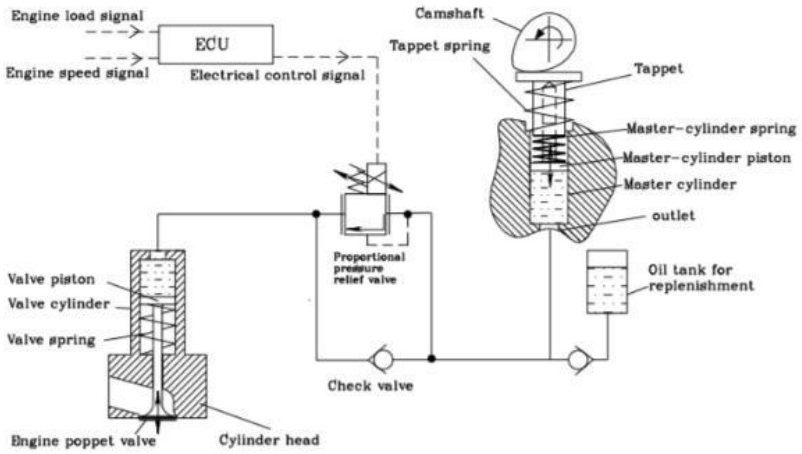



***Figure 13: Schematic of the electromechanical variable valve system***

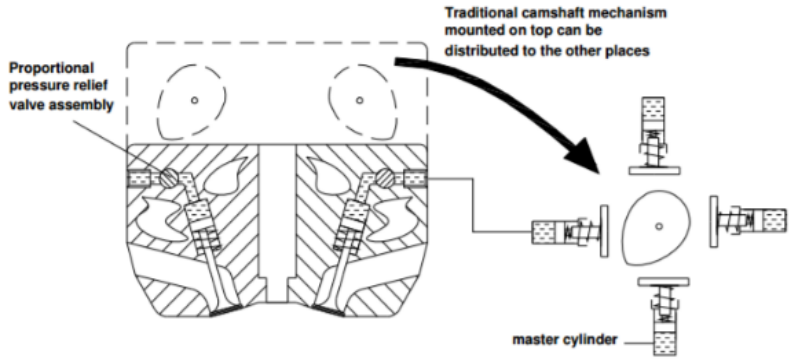



***Figure 14: Single master cam lobe controlling four valves***

One of the added benefits of this system over traditional cam system is that as system is mainly connected by hydraulics the various components can be located in other empty spaces. The system can also function with a single cam controlling at least four valves, figure 14. Removing the need for a long, multilobe camshaft. Further reducing engine size and mass

The electromechanical system does not off the flexibility of valve timing and lift is not than camless systems because it is dependent on camshaft, but the system does offer an alternative at a lower cost solution, that may suit existing manufacturing suppliers and engines. [8]

***Further Developments***

Now that FVVT are being more widely tested, designers are thinking of new


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

ways to alter the VVT system,that were perhaps not possible before. An example of this is, DigitalAir™ Camless FVVA System [9,10]. This system removes poppet valves and replaces them with a horizontal valve, where the actuation pushes the valve shut by displacing it horizontally, see figure 15.

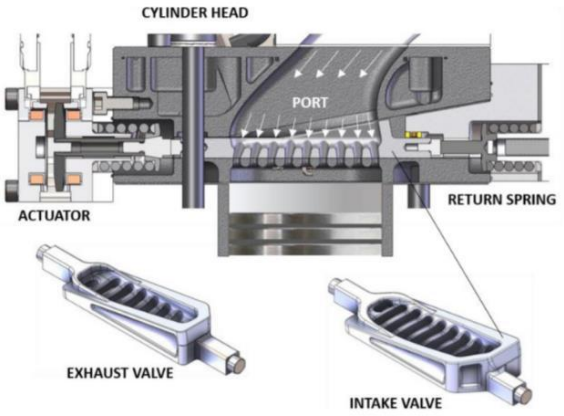



***Figure 15: Horizontal intake and exhaust valves by electro-hydraulic actuation***

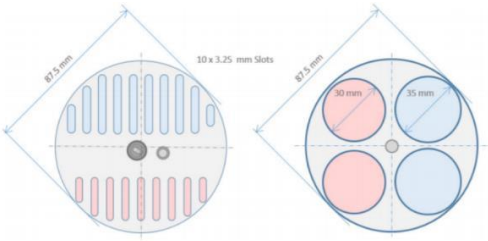


***Figure 16: Plan view of DigitalAir Valves (left) and traditional popper valves (right)***

Some of the benefits claimed in the report were:

- Short stroke from fully closed to fully open
- Direct solenoid actuation
- Fast opening - 2 ms
- No possibility of valve-to-piston contact
- Low opening forces
- Low power consumption
- Control of seating velocity

Design problems encounter which are covered in further detail in their report were:

- Volume of slots added to the combustion chamber
- Sealing between cylinder and ports
- Surface area, heat transfer and cooling of the valve bridges
- Potential for quenching and hydrocarbons in the slots
- Wear on the mating faces due to debris
- This system would require a major redesign of the cylinder head.

## RESULTS

### *Controlled Auto Ignition*

Previously with limited valve variability, within a 4-stroke engine CAI would be hindered by the lack of flexibility using


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

EGR because of strict valve events. FVVT now provide full control of the magnitude of EGR and companies like Lotus [11,12] have developed CAI into a viable option for 4 stroke FVVT engines.

The below figure provides a visible representation of the pressure differences caused by the trapped residual exhaust gases. Ignition appears to happen at a very similar crank angle degree to the SI engine.

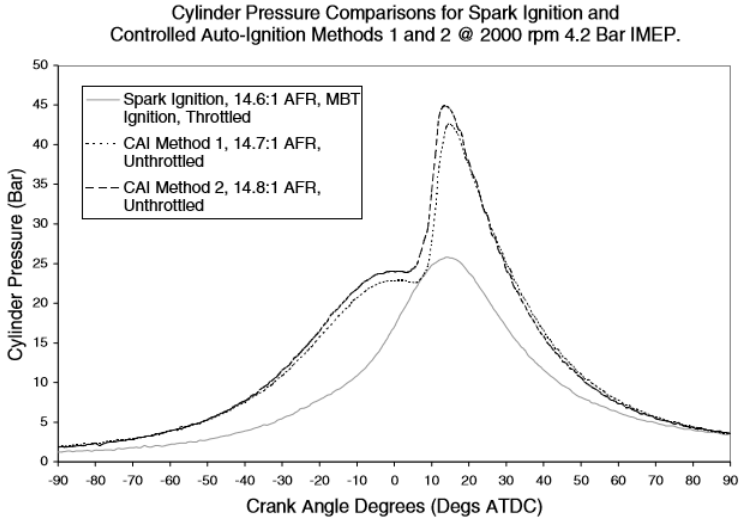



***Figure 17: Cylinder pressure comparison for CAI engine and Spark ignition engine***

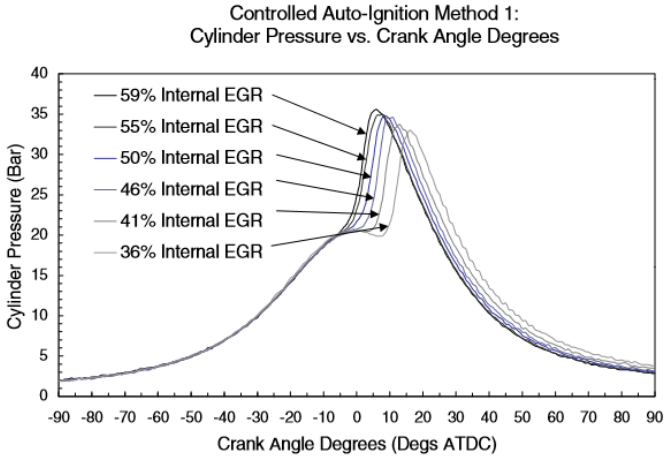



***Figure 18: How the ignition angle varies with quantity of EGR***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

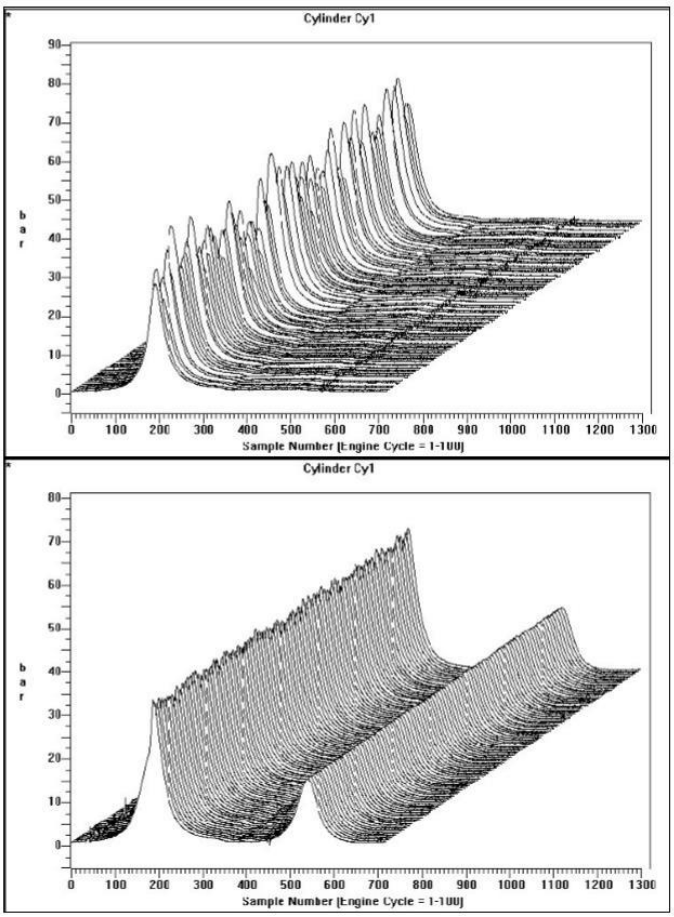



***Figure 19: Combustion stability for conventional SI (upper) and CAI (lower)***

Lotus also presented data which suggest CAI provides a more stable and consistent combustion than SI engines. Figure 19 shows visible consistent reactions throughout numerous testing, unlike the SI engine which has more peak pressure variation.

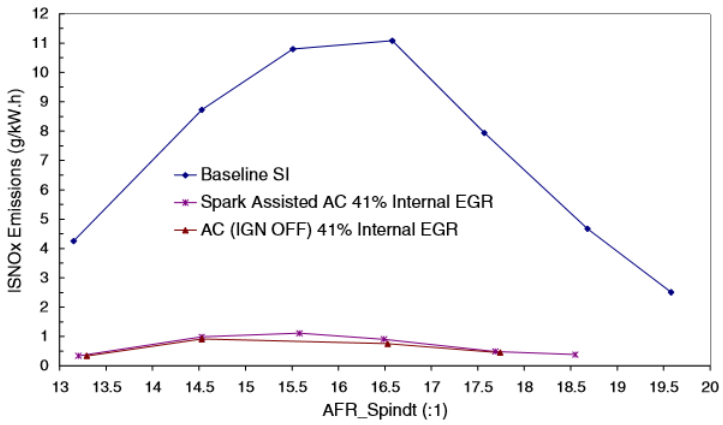



***Figure 20: NOx Emissions for SI, CAI and CA (SI assisted) against air fuel ratio***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

Possibly the most important result CAI is the reduction in NOx emissions. The figure above demonstrates the NOx emission difference from the baseline SI, which is more than 90% across the A/F ratios tested. The figure also demonstrates that the spark assisted EGR did not have any benefit over CAI. As discussed earlier in the report the NOx reduction is due to the reduction of O2 available for combustion, therefore reducing cylinder temperature and pressure.

Further testing was undertaken by Lotus, to see how the CAI would compare with an SI engine using an early exhaust valve closing strategy, where the control and combustion runs throttleless. The corresponding maps showing the differences are shown in figures 21 to 24. The following conclusions were drawn: [12]

- Improvement in fuel consumption (upto 32%), mainly at high speed and low load regions.
- Significant reductions (upto 97%) in Nitrogen oxides formation across all map speed-load points.
- 50% of speed-load map points indicate a reduction in Hydrocarbon formation.
- Reduction in Carbon Monoxide formation across all map speed-load points

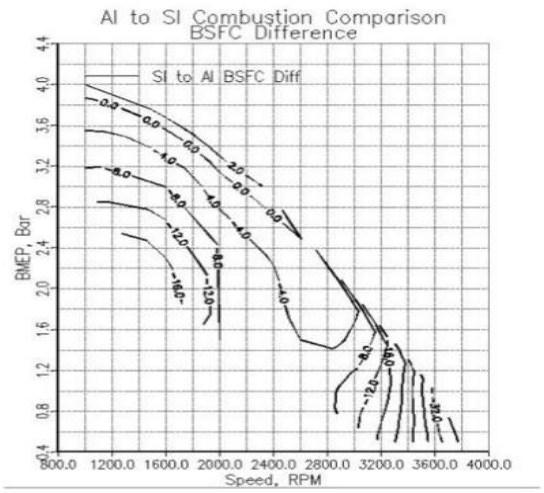



***Figure 21: BSFC comparison***

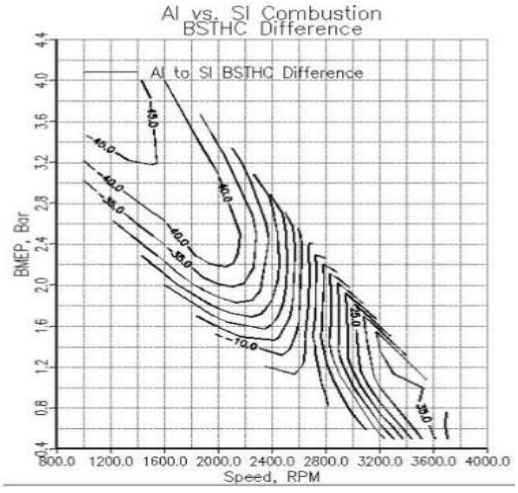



***Figure 22: BSHC Difference***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

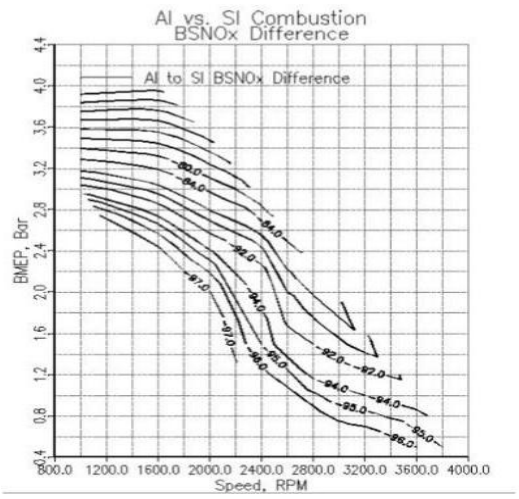



*Figure 23: BSNOx Difference*

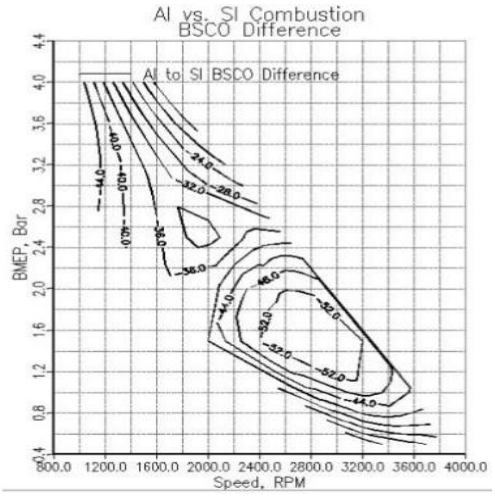



*Figure 24: BSCO difference*

***Cylinder Deactivation***

FEV have under taken cylinder deactivation tests [13] using an electromagnetic valve train (EMVT) to deactivate cylinder using figure 25 as a deactivation strategy. The vehicle was put through the New European Driving Cycle (NEDC), testing both with cylinder deactivation and without cylinder deactivation using EMVT and compared to a baseline without EMVT.

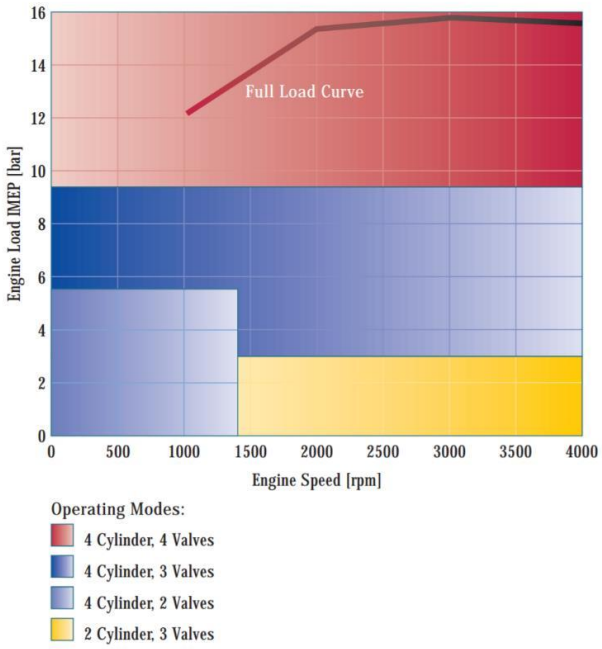



***Figure 25: Cylinder deactivation strategy***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

The NEDC consist of two phases urban and extra-ubran, shown in figure 26.

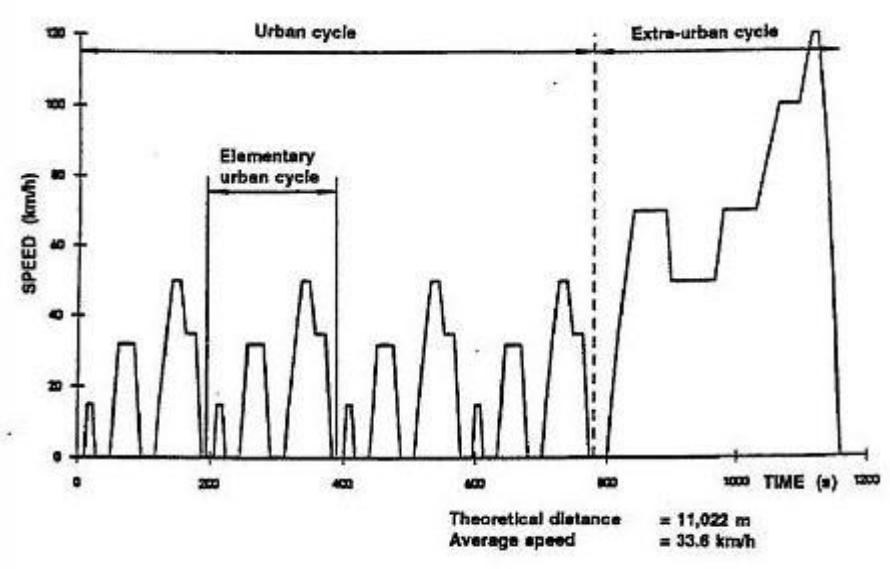



***Figure 26: New European Driving Cycle***

The results were presented in terms of the reduction in fuel consumption with the various combinations of EMVT and cylinder deactivation. Figure 27 demonstrates the benefits of the EMVT individual and when used in alongside cylinder deactivation, reducing fuel consumption by 16% over the whole NEDC.

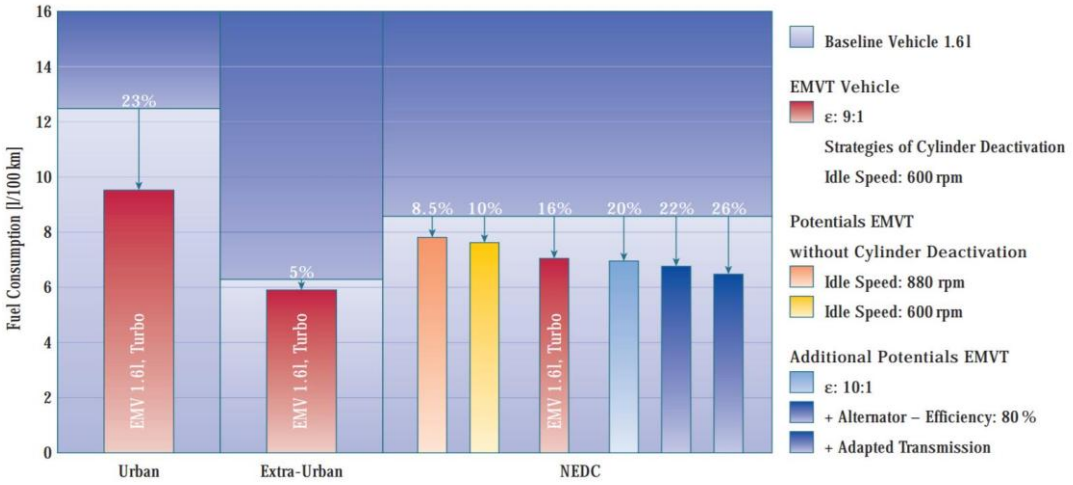



***Figure 27: Fuel consumption over the NEDC using EMVT and cylinder deactivation***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

***DigitalAir™ Camless FVVA System***

The main conclusions drawn from the report [9] focused on the mechanical viability of the system as an alternative to traditional popper valves. The data covered seems to focus on how the new valves affect the engine's breathing ability and the engine's ability to function throttleless. Comparisons of the engine using different intake valve closing strategies, Wide open throttle (WOT), partial throttle and throttle controlled were presented. The strategies are outline in figure 25. All other valve events were kept constant at the same engine speed,

1230 rpm and load BMEP = 4.8 bar.

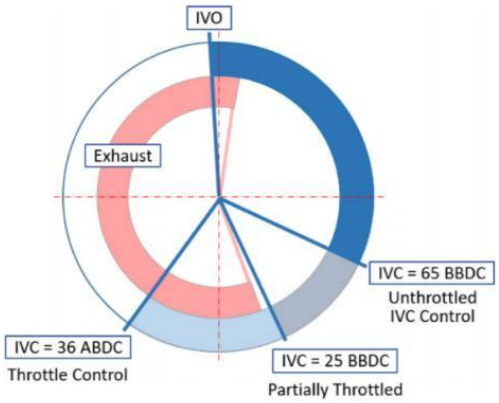



***Figure 28: Intake valve timing events***

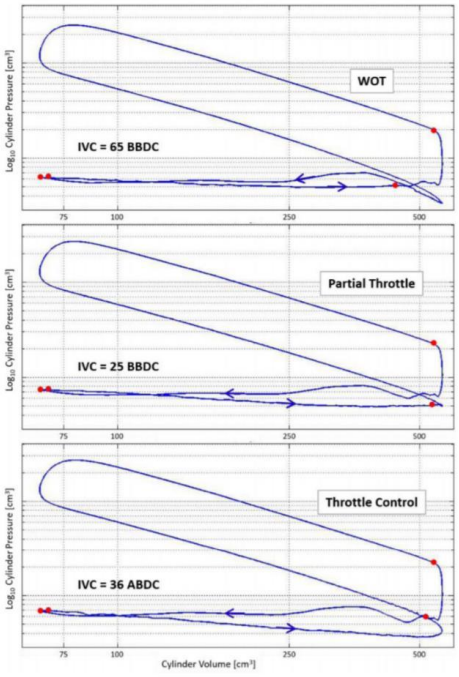



***Figure 29: Log P/ log V plots between IVC strategies***


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

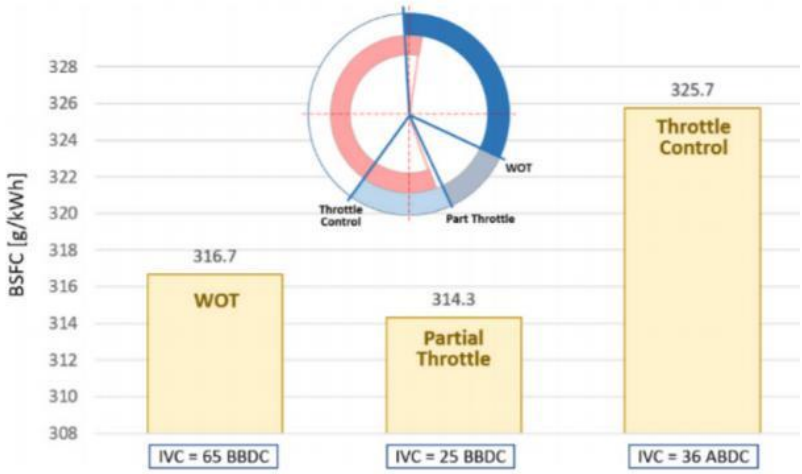



***Figure 30: BSFC between IVC strategies***

## CONCLUSIONS

In the period where camless costs are too high, electromechanical system are able to fill the gap because of their suitability with current automotive manufacturers and suppliers, making their cost relatively low to camshaft systems. Unless developed further to the point where they possess the same flexibility of camless system, emissions legislation will become stricter and they will eventually be replaced by camless systems options.

I believe there is potential with developing alternatives to the poppet valve systems, like the DigitalAirTM System. If all design issues can be solved and their durability is proven with further research, then this system or systems similar to this may provide a better alternative to poppet FVVT.

It is clear to see from the information presented in this report and the reference material that FVVT are the future of the internal combustion engine. Their almost infinite control of valve events, can improve performance in all aspects. Whilst providing the opportunities to implement valve event strategies like CAI, which drastically reduces NOx emissions further, and cylinder deactivation. Which would not be realistically possible without the flexibility of FVVT. Higher torque over all rpm ranges, improved fuel consumption, the potential of throttleless control and the reduction in emissions. Camless systems like the electrohydraulic and electromagnetic currently provide the best options for FVVT, with the small design issues being researched, the biggest hurdle to overcome is the cost. Once


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

commercially viable, there is no doubt that all future ICEs should implement these systems.

## FURTHER RESEARCH

Ideally it would have been good to compare the engine emission maps, similar to those Lotus generated [10,11], of the same size engine with FVVT implement and a baseline with a standard camshaft. The FEV report [10] provides some values on the reduction in emissions with cylinder deactivation but not in detail. Unfortunately, I was not able to obtain detail data on the subject.

## REFERENCES

**I.** W. Pulkrabek, "Engineering Fundamentals of the Internal Combustion Engine", University of Wisconsin, 1997, 262-276

**II.** p. Krueter, P. Heuser, J.Reinicke-Murmann, et al, "Variable Valve Actuation- Switchable an Continuously Variable Valve Lifts", SAEt echnitcal paper, 2003-01- 0026, 2003.

**III.** Honda, "The VTEC breakdown as of October 2004", world.honda.com/automobile-technology/VTEC/, date accessed 05.2017

**IV.** Sturmann Industries, "Hydraulic Valve Actuation", http://sturmanindustries.com/Solutions/Products/HVACamless/HydraulicValveActuation/tabid/202/Default.aspx ,date accessed 05.2017

**V.** Ricardo, "Camless Hydra", https://www.ricardo.com/PageFiles/16317/camless%20engine_V4_LR.pdf , date accessed 05. 2017

**VI.** E. Mohamed, "Modeling and Performance Evaluation of an Electromechanical Valve Actuator for a Camless Internal Combustion Engine", International Journal of Energy and Environment, Volume 3, Issue 2, 2012, 275-294

**VII.** L. Liu, S.Chang, "Power Consumption of Electromagnetic Valve Train System", WSEAS Transactions of Applied and Theoretical Mechanics", Volume 10, 2015


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved

**VIII.** P. Wong, K. Mok, "Design and Modeling of a Novel Electromechanical Fully Variable Valve Systm", SAE technical paper, 2008-01-01733, 2008

**IX.** G. Babbitt, J.Rogers, et al, "DigitalAirTM Camless FVVA Sytem – Part 1, Valve Train Design, Capability and Performance", SAE technical paper, 2017, doi 10.4271/2017-01-0635

**X.** Charlton, S., Price, C., Rogers, J., Turner, J. et al., "DigitalAir™ Camless FVVA System - Part 2, Gasoline Engine Performance Opportunities," SAE Int. J. Engines 10(3):2017, doi:10.4271/2017-01-0641.

**XI.** D.Law, D.Kemp, J.Allen, G.Kirkpatrick and T.Copland, "Controlled Combustion in an IC-Engine with a Fully Variable Valve Train", SAE Technical paper,2001-01-0251, 2001

**XII.** D.Law, J.Allen, "Variable Valve Actuated Controlled Auto Ignition: Speed Load Maps and Stretegic Regimes of Operation" SAE technical Paper, 2002-01-0422, 2002

**XIII.** FEV, "Reduction of Fuel Consumption and Emissions – Electromechanical Valve Train in Vehicle Operation", FEV-Spectrum Technology – Highlights and R&D Activities at FEV, Issue 12, 1999


Page 62-84 © MANTECH PUBLICATIONS 2018. All Rights Reserved