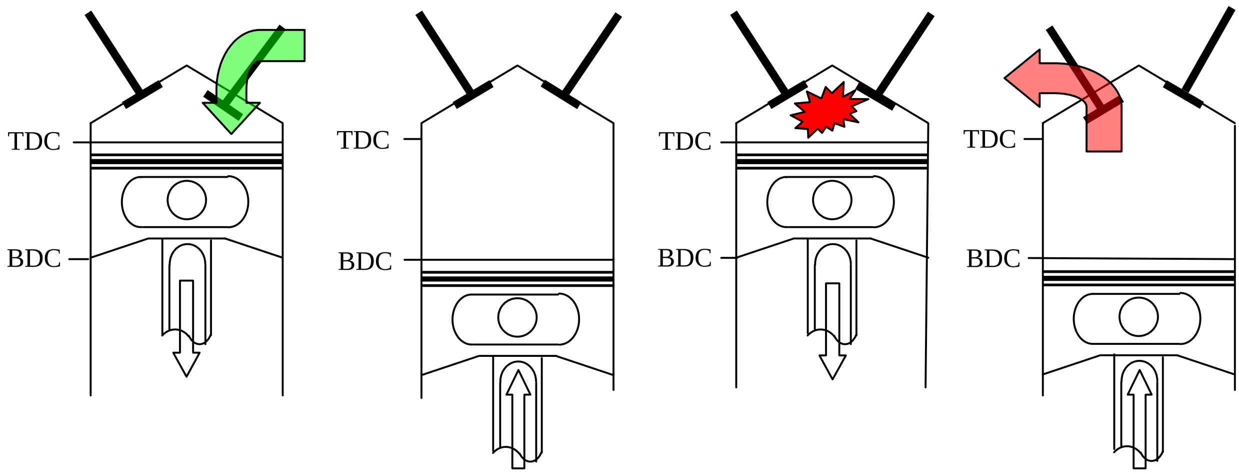
THE IMPACT OF VALVE EVENTS UPON ENGINE PERFORMANCE AND EMISSIONS

Summary

This paper seeks to provide an overview of the basic parameters used in the specification of valve timing in spark ignition engines. The effect of these parameters on engine performance and emissions will be discussed in general terms rather than with reference to any particular engine or type of engine. Some of the current industry trends will be discussed in terms of their impact on the engine valve timing parameters.

General



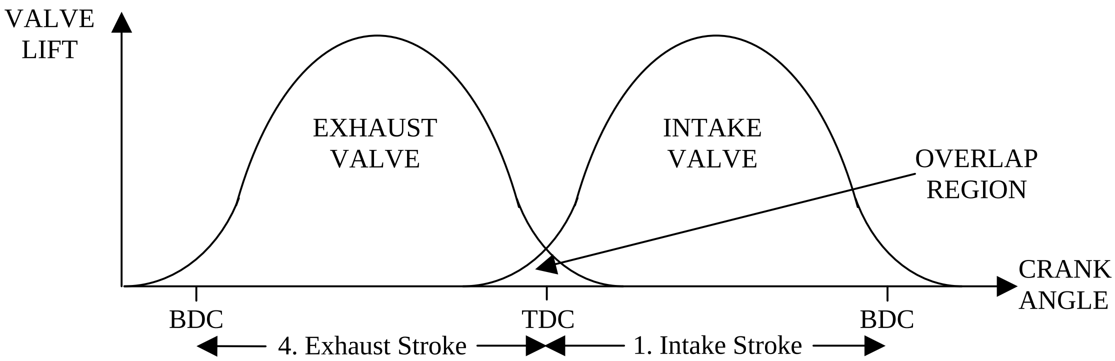
1. Induction **2. Compression** **3. Ignition** **4. Exhaust**

The diagrams above illustrate the conventional 4-stroke cycle of an internal combustion engine. It can be seen that both the intake and exhaust valves remain closed during the compression and ignition phases of the cycle. It is therefore usual for any discussion of valve timing to focus on parts 1&4 of the cycle, that is the valve motion in the periods either side of piston Top Dead Centre (TDC) on the non-firing stroke.

The valve motion is controlled by a camshaft(s) that rotates at half the speed of the crankshaft. During the four stroke cycle the crankshaft rotates twice, causing two piston cycles, whilst the camshaft rotates once, causing one cycle of each valve. The different speeds of the crankshaft and camshaft can be the cause of some confusion when describing the timing of valve opening and closing with angles, as 360° of crankshaft rotation is equivalent to 180° of camshaft rotation.

It is normal to discuss the parameters of valve timing with reference position of the piston using crankshaft angle measured from piston TDC or BDC (Bottom Dead Centre). This paper will hold to this convention but it should be noted that the duration of valve lift in crankshaft degrees is twice the duration of the profile actually ground onto the camshaft. Duration is defined as the angle of crankshaft rotation between the opening and the closing of the intake or the exhaust valve.

The term "valve event" refers to the opening or closing of either the intake or the exhaust valve(s) with reference to piston TDC or BDC. The graph below shows the intake and exhaust valve events as they would typically appear around the end of the exhaust stroke (TDC).



The main parameters to be discussed are: -

1. Exhaust Valve Opening Timing – EVO
2. Exhaust Valve Closing Timing – EVC
3. Intake Valve Opening Timing – IVO
4. Intake Valve Closing Timing – IVC
5. Peak Valve Lift

The overlap region (if present) is the difference between IVO and EVC (if positive) and is thus affected by changes in either IVO or EVC.

It can be seen from the above graph that the valve events do not coincide with TDC and BDC as depicted in the "theoretical" four-stroke cycle. The reasons for this and the compromises inherent in the selection of valve event timings will form the basis for discussion in this paper.

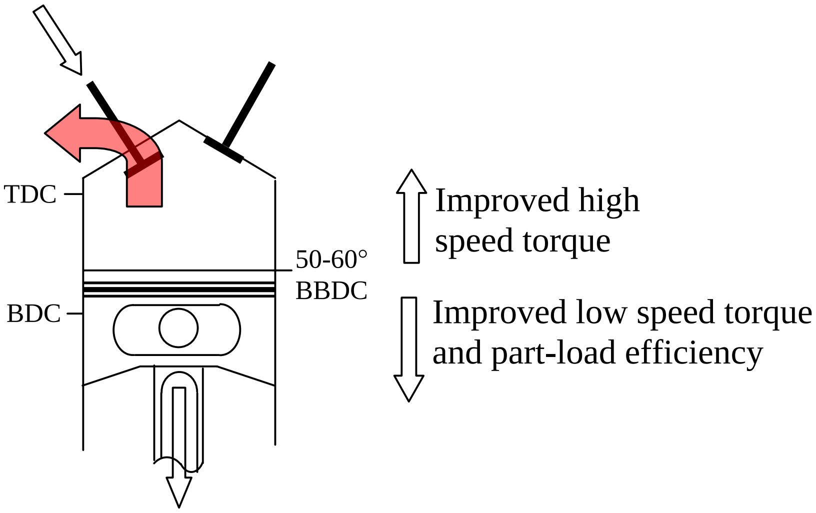
<u>Effects of Changes to Exhaust Valve Opening Timing - EVO</u>

As the exhaust valve opens the pressure inside the cylinder resulting from combustion is allowed to escape into the exhaust system. In order to extract the maximum amount of work (hence efficiency) from the expansion of the gas in the cylinder, it would be desirable not to open the exhaust valve before the piston reaches Bottom Dead Centre (BDC). Unfortunately, it is also desirable for the pressure in the cylinder to drop to the lowest possible value, i.e. exhaust back pressure, before the piston starts to rise. This minimises the work done by the piston in expelling the products of combustion (often referred to as blow down pumping work) prior to the intake of a fresh charge. These are two conflicting requirements, the first requiring EVO to be after BDC, the second requiring EVO to be before BDC.

The choice of EVO timing is therefore a trade-off between the work lost by allowing the combusted gas to escape before it is fully expanded, and the work required to raise the piston whilst the cylinder pressure is still above the exhaust back-pressure. With a conventional valve train, the valve lifts from its seat relatively slowly and provides a significant flow restriction for some time after it begins to lift and so valve lift tends to start some time before BDC. A typical EVO timing is in the region of 50-60° before BDC for a production engine.

The ideal timing of EVO to optimise these effects changes with engine speed and load as does the pressure of the gasses inside the cylinder. At part load conditions, it is generally beneficial if EVO moves closer to BDC as the cylinder pressure is much closer to the exhaust back pressure and takes less time to escape through the valve. Conversely, full load operation tends to result in an earlier EVO requirement because of the time taken for the cylinder pressure to drop to the exhaust back-pressure.

Summary: -



Effects of Changes to Exhaust Valve Closing Timing - EVC

The timing of EVC has a very significant affect on how much of the Exhaust gas is left in the cylinder at the start of the engine’s intake stroke. EVC is also one of the parameters defining the valve overlap, which can also have a considerable affect on the contents of the cylinder at the start of the intake stroke.

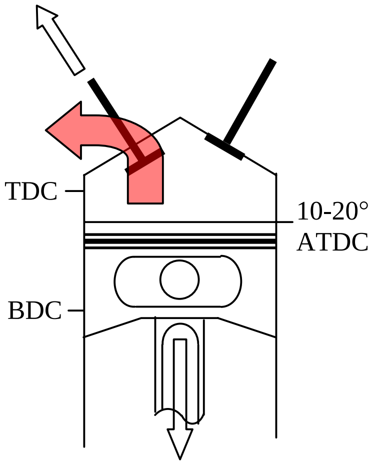
For full load operation, it is desirable for the minimum possible quantity of exhaust gas to be retained in the cylinder as this allows the maximum volume of fresh air & fuel to enter during the Intake stroke. This requires EVC to be at, or shortly after TDC. In engines where the exhaust system is fairly active (i.e. Pressure waves are generated by exhaust gas flow from the different cylinders), the timing of EVC influences whether pressure waves in the exhaust are acting to draw gas out of the cylinder or push gas back into the cylinder. The timing of any pressure waves changes with engine speed and so a fixed EVC timing tends to be optimised for one speed and can be a liability at others.

For part load operation, it may be beneficial to retain some of the exhaust gasses, as this will tend to reduce the ability for the cylinder to intake fresh air & fuel. Retained exhaust gas thus reduces the need for the throttle plate to restrict the intake and results in lower pumping losses (see Appendix A) in the intake stroke. Moving EVC Timing further after TDC increases the level of internal EGR (Exhaust Gas Recirculation) with a corresponding reduction in exhaust emissions.

There is a limit to how much EGR the cylinder can tolerate before combustion becomes unstable and this limit tends to become lower as engine load and hence charge density reduces. The rate of combustion becomes increasingly slow as the EGR level increases, up to the point where the process is no longer stable. Whilst the ratio of fuel to oxygen may remain constant, EGR reduces the proportion of the cylinder contents as a whole that is made up of these two constituents. It is this reduction in the ratio of combustible to inert cylinder contents which causes combustion instability.

Typical EVC timings are in the range of 5-15° after TDC. This timing largely eliminates internal EGR so as not to detrimentally affect full load performance.

Summary: -



↑ Improved part load efficiency and emissions due to internal EGR. Reduced full load torque.

↓ Improved part-load efficiency and emissions due to internal EGR. Reduced full load torque.

<u>Effect of changes to Intake Valve Opening Timing – IVO</u>

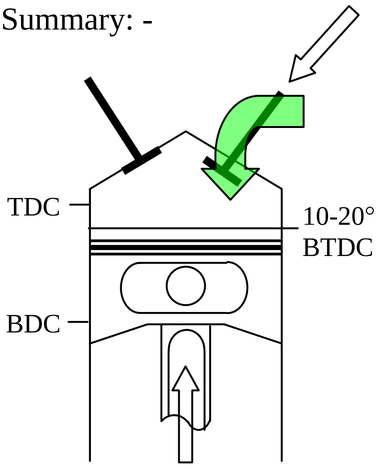
The opening of the intake valve allows air/fuel mixture to enter the cylinder from the intake manifold. (In the case of direct injection engines, only air enters the cylinder through the intake valve). The timing of IVO is the second parameter that defines the valve overlap and this is normally the dominant factor when considering which timing is appropriate for a given engine. Overlap will be discussed in more detail later in this paper.

Opening the intake valve before TDC can result in exhaust gasses flowing into the intake manifold instead of leaving the cylinder through the exhaust valve. The resulting EGR will be detrimental to full load performance as it takes up space that could otherwise be taken by fresh charge. EGR may be beneficial at part load conditions in terms of efficiency and emissions as discussed above.

Later intake valve opening can restrict the entry of air/fuel from the manifold and cause in-cylinder pressure to drop as the piston starts to descend after TDC. This can result in EGR if the exhaust valve is still open as gasses may be drawn back into the cylinder with the same implications discussed above. If the exhaust valve is closed, the delay of IVO tends not to be particularly significant, as it does not directly influence the amount of fresh charge trapped in the cylinder.

Typical IVO timing is around 0-10° before TDC which results in the valve overlap being fairly symmetrical around TDC. This timing is generally set by full load optimisation and, as such, is intended to avoid internal EGR.

Summary: -



↑ Can increase EGR depending upon EVC timing.

↓ Improved part load efficiency and emissions due to internal EGR. Reduced full load torque.

Effect of changes to Intake Valve Closing Timing – IVC

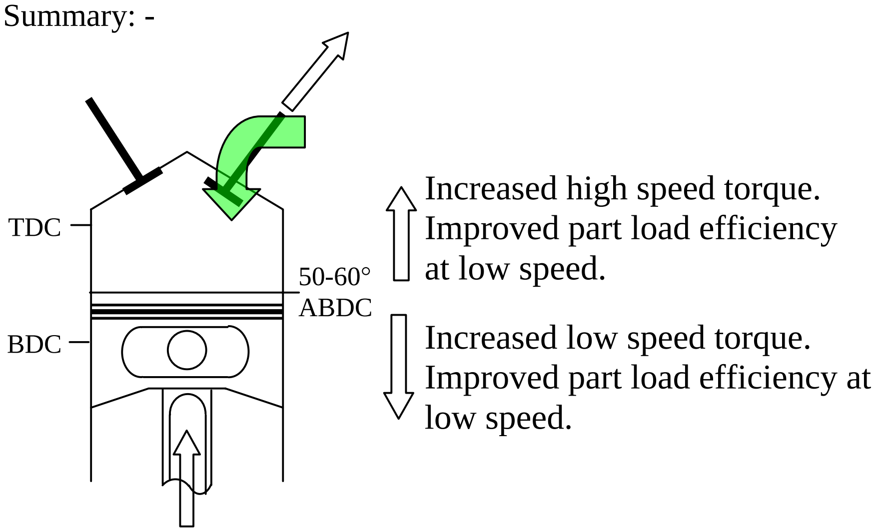
The volumetric efficiency of any engine is heavily dependent on the timing of IVC at any given speed. The amount of fresh charge trapped in the cylinder is largely dictated by IVC and this will significantly affect engine performance and economy.

For maximum torque, the intake valve should close at the point where the greatest mass of fresh air/fuel mixture can be trapped in the cylinder. Pressure waves in the intake system normally result in airflow into the cylinder after BDC and consequently, the optimum IVC timing changes considerably with engine speed. As engine speed increases, the optimum IVC timing moves further after BDC to gain maximum benefit from the intake pressure waves.

Closing the intake valve either before or after the optimum timing for maximum torque results in a lower mass of air being trapped in the cylinder. Early intake closing reduces the mass of air able to flow into the cylinder whereas late intake closing allows air inside the cylinder to flow back into the intake manifold. In both cases, the part load efficiency can be improved due to a reduction in intake pumping losses (see Appendix A).

A typical timing for IVC is in the range of 50-60° after BDC and results from a compromise between high and low speed requirements. At low engine speeds, there will tend to be some flow back into the intake manifold just prior to IVC whereas at higher speeds, there may still be a positive airflow into the cylinder as the intake valve closes

Summary: -



Effects of Valve Overlap

As discussed previously, valve overlap is the time when both intake and exhaust valves are open. In simple terms, this provides an opportunity for the exhaust gas flow and intake flow to influence each other. Overlap can only be meaningfully assessed in conjunction with the pressure waves present in the intake and exhaust systems at any particular engine speed and load.

In an ideal situation, the valve overlap should allow the departing exhaust gas to draw the fresh intake charge into the cylinder without any of the intake gas passing straight into the exhaust system. This allows the exhaust gas in the combustion chamber at TDC to be replaced and therefore the amount of intake charge to exceed that which could be drawn into the cylinder by the swept volume of the piston alone.

A given amount of overlap unfortunately tends to be ideal for only a portion of engine speed and load conditions. Generally, the torque at higher engine speeds and loads can benefit from increased overlap due to pressure waves in the exhaust manifold aiding the intake of fresh charge. Large amounts of overlap tend to result in poor emissions at lower speeds as fuel from the intake charge can flow directly into the exhaust. High overlap can also result in EGR which, although beneficial to part load economy, reduces full load torque and can cause poor combustion stability especially under low load conditions such as idle. Poor idle quality can therefore result from too much overlap.

The valve overlap tends to be fairly symmetrical about TDC on most engines. The further away from TDC that valve overlap is present, the more effect the piston motion will have on the airflow. Early overlap may result in exhaust gasses being expelled into the intake manifold and late overlap may result in exhaust gasses being drawn back into the cylinder. Both of these situations result in internal EGR that can be beneficial to part load emissions and efficiency. As discussed earlier, internal EGR tends to be avoided due to the detrimental effect it has on full load torque.

Valve Peak Lift

Valve peak lift directly affects the ability for air to flow into the cylinder and exhaust to leave the cylinder and as a result it significantly influences engine performance. There are some practical limitations of peak lift in most engines that are dependent on the design of the particular engine: -

1. Normally the piston crown is profiled to maximise the clearance adjacent to the valves but there are limitations as to how much valve lift can be accommodated without unduly compromising the piston design.
2. The duration of the valve lift imposes a restriction on valve lift due to the acceleration required to achieve a high lift with a short duration. The higher the running speed of the engine, the more the peak lift is restricted for a given valve lift duration.

Low values of valve peak lift will clearly restrict the ability of gas to flow into and out of the cylinder, effectively throttling the engine. Maximum engine power output will generally benefit from as much valve lift as possible up to the point where air flow becomes restricted by other features such as the manifold system or cylinder head porting.

It does not follow that engines should have the maximum possible valve lift as this can adversely affect low speed performance. Lower intake valve lifts result in higher gas velocity past the valve and this improves fuel mixing and combustion. For maximum torque at a given speed, lift should be kept as low as possible up to the point where the intake of fresh charge becomes restricted.

Part load economy will benefit from the intake being restricted by valve lift, as it reduces the need for throttling by the engine throttle and this will reduce intake pumping losses. Lift is not normally dictated by part load considerations, as this would severely limit the potential output of the engine.

The chosen value of peak valve lift is therefore a compromise between low speed and high speed full load requirements. A typical value for a production engine is in the range of 8-10mm.

Industry Trends

There is a constant need for internal combustion engines to become more powerful and efficient with reduced levels of emissions driven both by legislation and increasing customer expectations. For an engine with fixed valve timing, there are inherently compromises made between emissions, high/low speed torque and full/part load efficiency. Ways of avoiding compromise between different engine requirements are constantly being incorporated into new engines and investigated for application to future engines.

The following technologies are becoming increasingly common and are discussed in the context of the engine valve timing strategies outlined in this paper: -

Exhaust Gas Recirculation (EGR) Systems

The presence of exhaust gas in the combustion chamber can be beneficial for emissions, yielding reductions in NOx, HC and CO. The timing of EVC and IVO can cause exhaust gas to be retained in or re-introduced into the cylinder as discussed earlier in this paper. This is known as "internal" EGR and is generally avoided due to its impact upon full load torque.

"External" EGR systems are now becoming more common where gas from the exhaust system is pumped back into the intake manifold at part load conditions. This provides benefits in part load emissions and improved efficiency due to a reduction in intake pumping losses (see Appendix A). As the quantity of EGR can be changed to suit engine speed and load conditions, there need not be any detriment to full load torque.

Internal EGR however, does have two significant benefits over external EGR: -

1. External systems are expensive and are prone to durability problems due to their continual exposure to hot, dirty gasses. The intricate components within EGR control systems are susceptible to the build up of deposits causing leakage or blockage.
2. The recirculated gas in the case of internal EGR is the last portion to have left the cylinder. This portion generally contains the gasses from any crevice volumes in the cylinder and therefore contains a significant portion of the unburned hydrocarbons from the combustion process. External EGR takes a portion of all the exhaust gasses once they are mixed and so has much less ability to reduce hydrocarbon emissions.

Variable Valve Timing

An increasing number of engines are using variable valve timing systems to avoid some of the compromises of fixed valve timing. A fully flexible system, which could vary valve lift and intake and exhaust valve event timings independently for different engine speed and load conditions, could in principal overcome all of the compromises inherent in a conventional valve train system. In practice however, the more flexible a variable valve timing system becomes, the more complex and hence expensive it tends to become.

There are a number of different variable valve timing systems, currently available and under development, to control different valve timing parameters. Although there are many different designs for achieving such variations, these systems can be grouped in terms of their operation.

1. Phase Changing Systems

These systems change the timing of the camshaft in relation to the crankshaft in order to advance or retard the timing of the engine valve events. If applied to an engine with a single camshaft, all of the valve events are shifted by the same amount i.e. if IVC is to be retarded by 10° IVO, EVO and EVC will also be retarded by 10°. On engines with separate Intake and Exhaust camshafts, a phase change system can be used to change the timing of the intake valve events or the exhaust valve events. The use of two phasing devices can permit independent control over Intake and Exhaust timing changes. Phase change systems have no effect on peak valve lift and cannot change the duration of the valve events i.e. IVO and IVC cannot be moved independently.

Phase changing systems have been available on production engines for a number of years but have tended to be applied only to the highest specification engine in a particular range. Phasing of the intake camshaft to gain increased performance with a mechanism that can be moved between two fixed camshaft timings is the most common application with the change in timing normally occurring at a particular engine speed.

More recently, there has been a move towards more flexible control systems that allow the camshaft phasing to be maintained at any point between two fixed limits. This has facilitated camshaft phase optimisation for different engine speed and load conditions and has allowed exhaust camshaft phasing to be used for internal EGR control. Engines with both intake and exhaust camshaft phase control are now being introduced.

2. Profile Switching Systems

This type of Variable Valve Timing system is capable of independently changing valve event timing and valve peak lift. The system switches between two different camshaft profiles on either or both of the camshafts and is normally designed to change at a particular engine speed.

Due to these systems having an inherently two position operation, they are not suitable for optimising valve timing parameters under different load conditions e.g. EGR control. The ability to change valve event timing, lift and duration ensures that these systems are capable of providing very high power output from a given engine whilst still complying with emissions legislation.

3. Variable Event Timing Systems

Variable event timing systems are probably the most flexible type of variable valve timing system to be available on a production engine. Whilst they do not change peak valve lift, they are able to change both the phasing and the duration of valve events. These systems can be controlled to any setting between two extremes and are most effective when optimised for different engine speed and load conditions.

Considerable increases in full load torque can be achieved with variable event timing, generally most significant at the extremes of the engine speed range where fixed valve timing is most compromised. Reductions in part load emissions and fuel economy are also achievable through full optimisation of he system.

4. Variable Lift Systems

There are two main types of variable lift system currently under investigation, the first “scales” the valve lift such that its opening duration is unchanged whilst the second “truncates” the lift profile such that the valve opening duration reduces as lift reduces. Both of these types of system can only be used effectively when combined with a phase changing device.

One major benefit of variable lift systems is the potential of throttling the cylinder by reducing the intake valve lift thus saving the pumping losses associated with the conventional throttle (see Appendix A). This requires very close control of lift to match changes in engine speed and load conditions and has yet to be fully proven.

5. Electro-magnetic Valve Actuation Systems

In many ways, this is the system that could provide the greatest potential for optimising the engine valve events. In principal EVO, EVC, IVO, IVC and possibly valve lift could all be directly controlled by an engine management system. EVA systems are still in the early stages of development and have yet to demonstrate whether they can match the performance of a mechanical valve train in terms of durability, power consumption and refinement whilst maintaining an acceptable system price.

Gasoline Direct Injection (GDI) Engines

An increasing number of new gasoline engines inject fuel directly into the combustion chamber. Whilst this technology can be used to generate a homogeneous mixture of air and fuel at all engine speeds and loads, as with most port injected engines, most of these engines create a stratified charge (i.e. a rich mixture surrounded by a far leaner one) at part load conditions. Stratified operation can theoretically remove the need for a throttle in the intake system as small quantities of fuel can be added to an excess of air. This can create a large improvement in part load economy due to the reduction in pumping losses (see Appendix A).

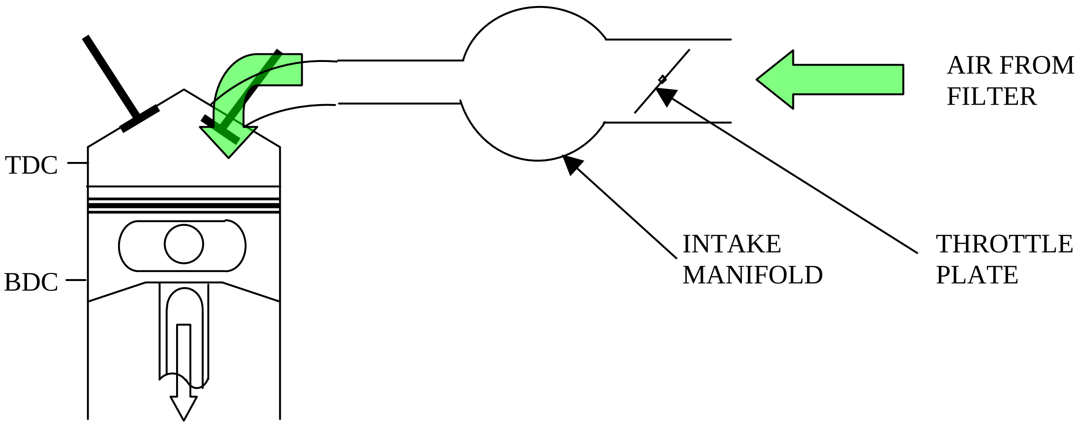
Much research is currently being undertaken to improve stratification of the fuel so that part load economy improvements can be achieved within the constraints of current and future emissions regulations. The air motion in the cylinder is taking an increasingly key role in this work and can be significantly affected by the valve events. Currently techniques such as port disablement and variable tumble ports are being investigated but it may be that variable valve timing systems can provide the required control over the combustion process.

<u>APPENDIX A</u>

Definition of Intake Pumping Loss
And Methods of Reduction

All spark ignition engines require a method of reducing engine torque output during operation. This allows engine power output to match requirements throughout the engine speed and load range.

It is not sufficient to reduce torque by restricting the flow of fuel into the engine without restricting its air intake as this would result in the air/fuel ratio increasing up to the point where stable combustion could not be sustained. An Intake throttle plate is therefore used to restrict airflow into the engine so that a suitable air/fuel ratio is maintained during part load operation.



Whilst the engine is operating at full load, the throttle plate is turned so as not to restrict air flow into the intake manifold. The piston has only to draw air into the cylinder through the slight restriction of the air filter during the intake stroke and so the incoming air is at approximately atmospheric pressure.

When operating at part load, the restriction caused by the throttle causes pressure of the air in the intake manifold (known as manifold absolute pressure or MAP) to be below atmospheric. As the piston descends, air will not flow into the cylinder until the pressure in the cylinder is below the manifold pressure. The pressure inside the cylinder will stay at approximately manifold pressure until the point of intake valve closure thus reducing the mass of fresh charge in the cylinder compared to that which would have been induced at full load i.e. MAP = Atmospheric pressure.

Intake pumping losses result from the work done by the engine moving the piston from TDC to BDC whilst the manifold depression causes a pressure differential across the piston and a resulting force in the opposite direction.

EGR produces a reduction in pumping losses because the engine torque can be restricted by a lower manifold depression when compared to the same engine without EGR. This is because it is only necessary to restrict the amount of oxygen in the cylinder to limit torque and intake air mixed with recirculated exhaust gas has a lower oxygen content than normal air. More of the exhaust gas/air mixture can be present in the cylinder at any particular load site and hence less manifold depression is required and pumping losses reduce.

Pumping losses can be reduced by using reduced valve lift to throttle the cylinder or by changing the intake valve closing timing. This creates a slightly different situation because the air in the manifold remains at approximately atmospheric pressure. As the intake valve opens, the cylinder pressure remains at about atmospheric and so no pumping work is being done. It is only towards the later part of the induction stroke that the pressure inside the cylinder falls significantly as the incoming air flow becomes restricted. This means that the force on the piston due to differential pressure is not constant during the intake stroke although it is roughly equal to that in a conventional engine as the intake valve closes.

Throttling with the valve has fairly complex effects on the thermodynamic cycle of the engine, but the PV diagram below shows the basic mechanism whereby pumping losses are reduced.