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Benefits and Challenges of Variable Compression Ratio (VCR)

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ABSTRACT

Potential benefits of Variable Compression Ratio (VCR) spark ignition engines are presented, based on an examination of the relationship between Compression Ratio, BMEP and spark advance at light load and full load. Alternative methods of implementing VCR are illustrated and critically examined. System control strategies are presented. Potential manufacturing constraints are identified and their influence on system configuration is examined. Fuel economy benefits attainable from other technologies such as cylinder deactivation, camless valve operation and GDI are shown to be inferior to the use of downsized boosted engines. VCR is identified as the key enabling technology of such downsized engines.

INTRODUCTION

Worldwide pressure to reduce automotive fuel consumption and CO2 emissions is leading to the introduction of various new technologies for the gasoline engine as it fights for market share with the diesel. So far, variable compression ratio (VCR) engines have not reached the market, despite patents and experiments dating back over decades. VCR technology could provide the key to enable exceptional efficiency at light loads without loss of full load performance.

This paper will review the many embodiments of VCR, the implications for volume manufacture and the strategy for VCR implementation in order to produce the maximum benefit.

REASONS FOR THE APPLICATION OF VCR

The search for a feasible VCR engine has been driven by the compromise between WOT (Wide Open Throttle) and part-throttle which exists on any fixed CR engine.
Detonation thresholds at WOT limit the maximum useable CR to a value lower than could be sustained at part throttle. Comparison of BMEP figures (fig 1) shows that increasing CR becomes counterproductive at values typically above 11~12:1 since the reduction in spark advance negates the benefit from higher CR (ref 1,2).

Potential benefits in fuel consumption and CO2 emissions are, however, to be expected from running at higher CR during part throttle operation. The detonation limits identified at WOT do not apply to part throttle operation as the in-cylinder temperatures and pressures are so much lower. As the majority of engine running time occurs in this mode, real world improvements should be enabled, not just theoretical or experimental gains.

A SUMMARY OF VARIOUS VCR CONCEPTS

Historically, every mechanical element in the power conversion system has been considered as a means to achieve variable compression. No attempt is made here to present an exhaustive listing but examples of the main concepts appear below.

Patents have been filed and designs presented which modify the compression ratio by :

- moving the cylinder head
- variation of combustion chamber volume
- variation of piston deck height
- modification of connecting rod geometry (usually by means of some intermediate member)
- moving the crankpin within the crankshaft (effectively varying the stroke)
- moving the crankshaft axis

In many cases, the deviation from conventional production engine structure or layout represents a significant commercial barrier to widespread adoption of the technology.

MOVING HEAD

SAAB's moving head concept has been widely publicised. By combining head and liners into a semi-monobloc construction which pivots with respect to the remainder of the engine, SAAB have enabled a tilting motion to adjust the effective height of the piston crown at TDC.

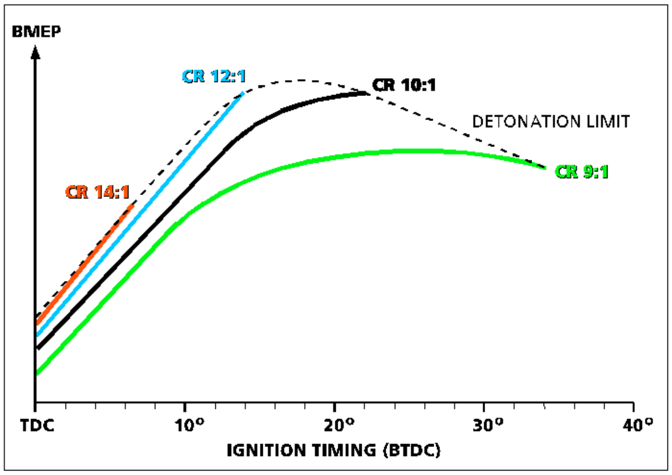
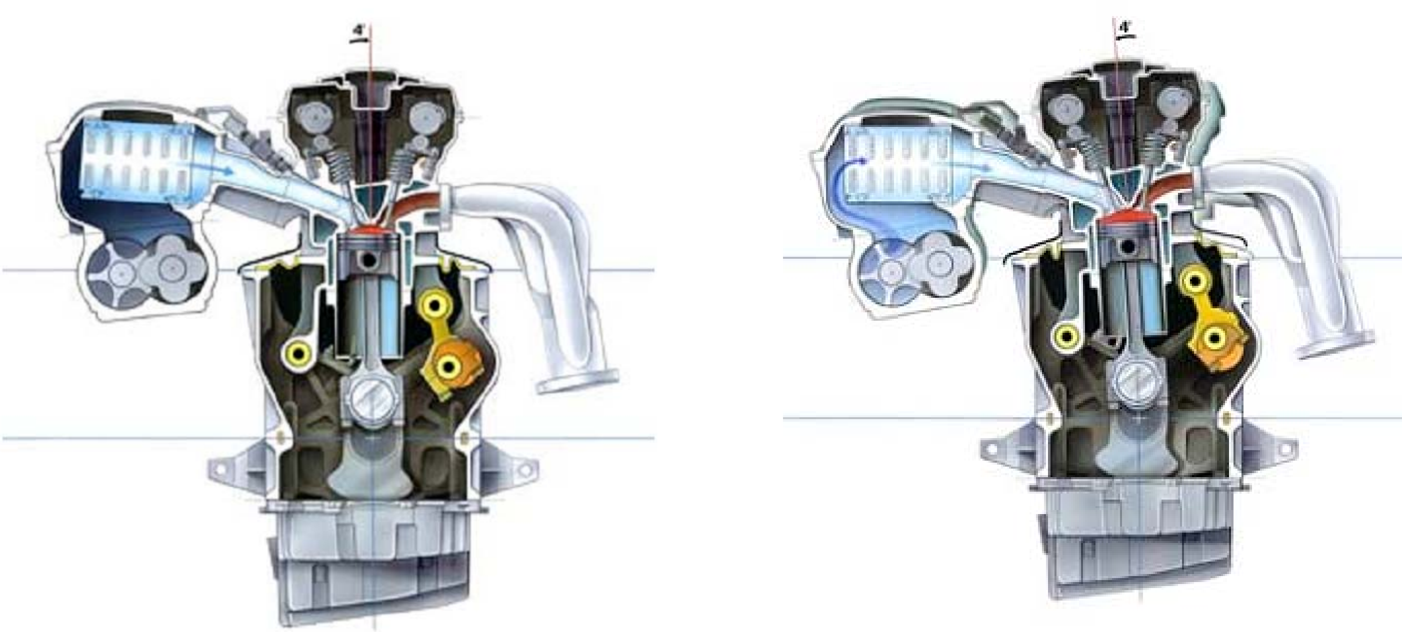


Figure 1, Comparison of W.O.T. BMEP versus compression ratio and ignition timing



Full throttle operation 8:1 CR

Part throttle operation 14:1 CR

Figure 2, The SAAB VCR engine

The rotary eccentric which alters the relative position of the two halves of the engine has to overcome the combined inertia of head, liners, supercharger, intercooler and manifolds.
Fig 2 shows the arrangement in both high and low compression positions.

The combination of VCR with a downsized, highly boosted engine is particularly effective and will be returned to later.

VARIATION OF COMBUSTION CHAMBER VOLUME

Typically, the volume of the combustion chamber is increased to reduce the CR by moving a small secondary piston which communicates with the chamber.

Ford type

Fig 3 shows the Ford patent for compression adjustment using a secondary piston or valve (ref 3). The device is presented primarily as a means of controlling knock as its dormant state is the high CR condition.

It is suggested that the piston could be maintained at an intermediate position, corresponding to the optimum CR for a particular condition, however this would require a finite length bore in which the piston could travel which raises further questions of sealing, packaging and durability.

Volvo/Alvar Type

Fig 4 shows the Alvar engine concept in which each secondary piston moves continuously at half crankshaft speed and could, potentially, share drive with a camshaft (ref 4). Phase variation between the secondary pistons and the crankshaft assembly enables the required variation in CR.

These systems have the potential benefit of containing all the major hardware changes within the cylinder head assembly which reduces the impact on engine manufacture – however there are obvious drawbacks :

- Introduction of additional elements within the crowded combustion chamber environment threatens to compromise ideal geometry and layout of the valves and ports
- Engine-out emissions performance is likely to be undermined by additional crevice volumes which obstruct complete burning, increasing hydrocarbon emissions
- The VCR device is subjected to full firing pressure
- In those examples where the device is driven continuously at some function of crank speed an additional parasitic loss will be incurred which will reduce the efficiency gain of VCR

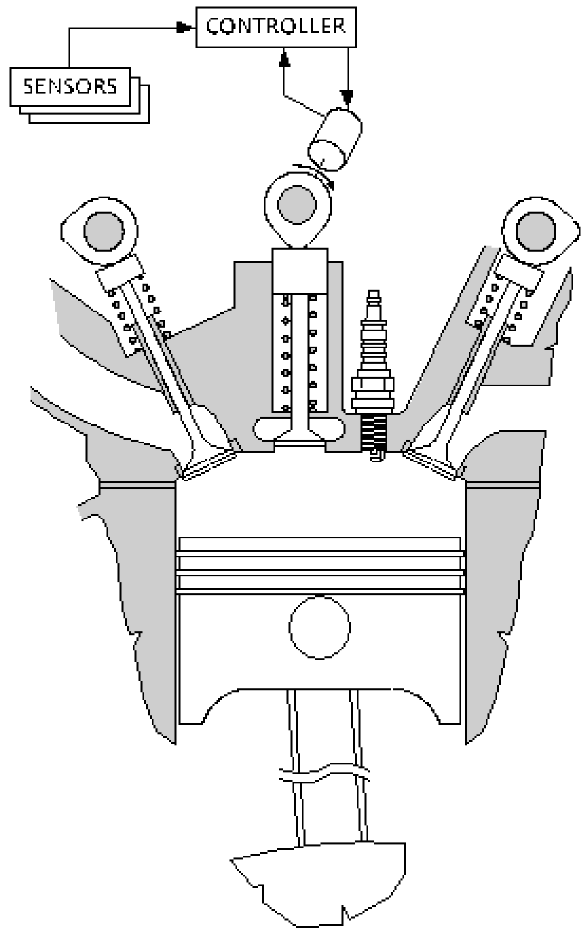


Figure 3, The Ford VCR Head

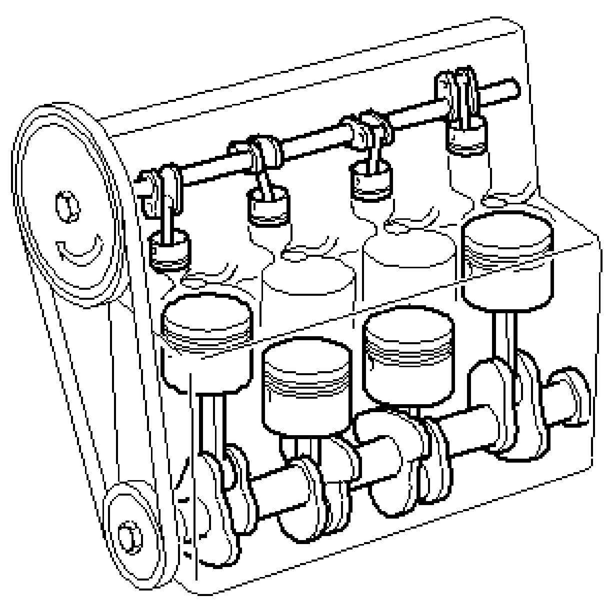


Figure 4, The Volvo/Alvar VCR Engine

VARIABLE HEIGHT PISTON

Variation in compression height of the piston offers potentially the most attractive route to a production VCR engine since it requires relatively minor changes to the base engine architecture when compared to other options (figs 5 and 6).

Unfortunately, it requires a significant increase in reciprocating mass and, more importantly, a means to activate the height variation within a high speed reciprocating assembly. This is typically proposed by means of hydraulics using the engine lubricating oil, however reliable control of the necessary oil flow represents a major challenge.

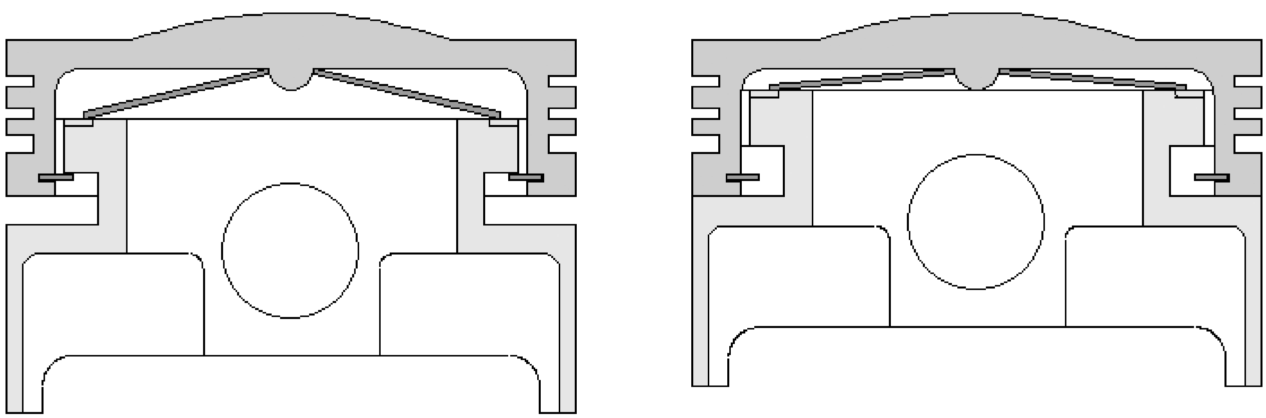
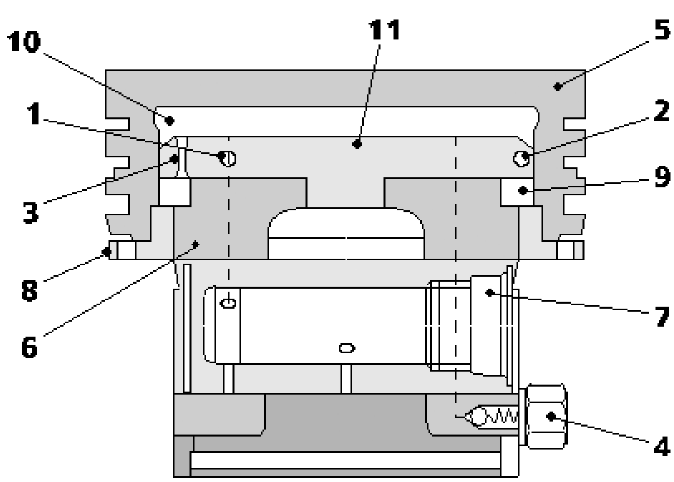


Figure 5, Ford VCR Piston (ref 5)



1	ONE-WAY VALVE
2	ONE-WAY VALVE
3	ORIFICE
4	PRESSURE RELIEF VALVE
5	OUTER PISTON
6	INNER PISTON
7	PISTON PIN
8	BUFFER RING
9	LOWER OIL CHAMBER
10	UPPER OIL CHAMBER
11	VALVE MOUNTING DEVICE

Figure 6, Daimler-Benz VCR Piston (ref 4)

An interesting alternative, within the Ford design, is to use a Belville type washer to spring the piston crown upwards against combustion forces. This is claimed to reduce the peak firing loads so the CR variation becomes self-acting rather than externally controlled. A side-effect would be the momentary variation in clearance volume during the combustion event which would, in turn, increase, then reduce the volume available to the expanding gases.

CON ROD LINKAGES

A popular approach has been to replace the conventional con rod with a 2 piece design in which an upper member connects with the piston while a lower member connects with the crankshaft.

By constraining the freedom of the point at which the two members join, the effective height of the con rod can be controlled and, hence, the compression volume.

Figures 7 and 8 illustrate the approach taken by Nissan and Peugeot Citroen, respectively.

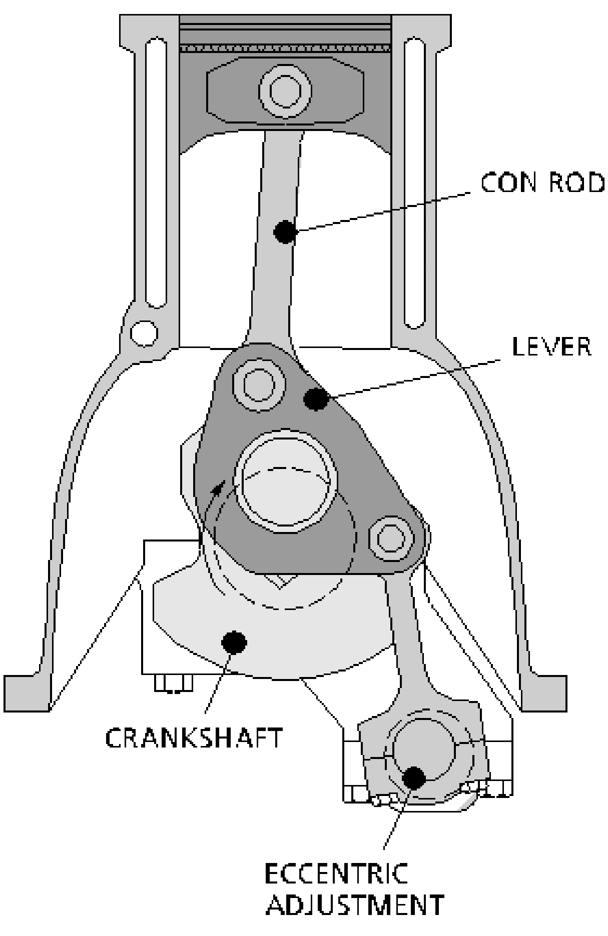


Figure 7, Nissan VCR Engine

Nissan claim to have reduced secondary vibration to a level below 10% of primary vibration by careful attention to the geometry, despite the use of a short con rod (ref 6).

PCA's approach (ref 7) produces a small change in swept volume as well as a CR change.

Similar systems have been described by Ford (patents 5791302 and 6289857) and FEV (patent 5595146).

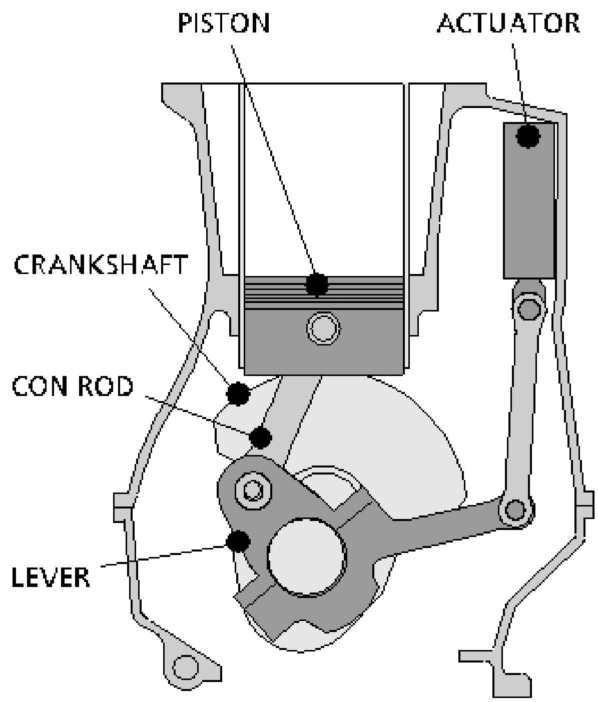


Figure 8, Peugeot VCR Engine

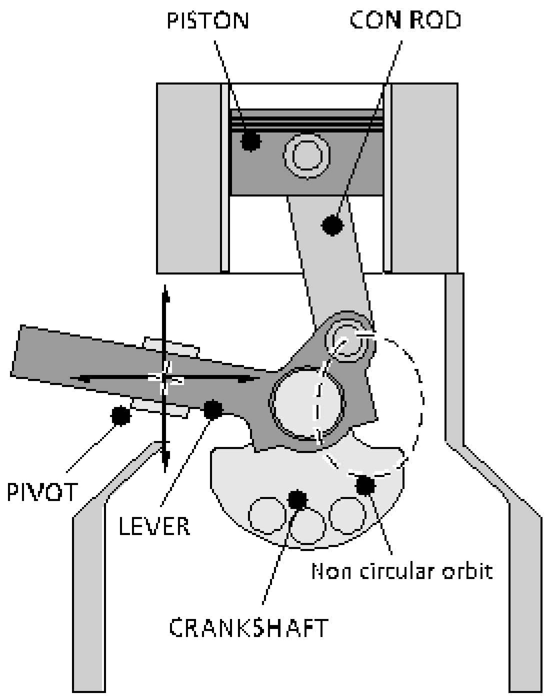


Figure 9, Mayflower e3 VCR engine, vertical movement of the pivot = compression change, horizontal movement

The Mayflower system (fig 9) separates CR change from swept volume change by moving the pivot in different planes (ref 8).
The key enabling technology for such a system becomes the positioning and anchorage of the pivot within the engine structure.

All the compound con rod designs result in modified piston motion when compared to a conventional engine, since the piston is connected to a rod whose other end is no longer moving in a circular orbit. Mayflower, in particular, claim significant benefits from the non-standard characteristics of the expansion stroke. While not fundamental to the concept of VCR, this aspect of variable con rod designs may open up a new area of activity in optimising combustion characteristics to suit the particular piston motion.

MOVEMENT OF THE CRANKSHAFT OR CRANKPINS

Several systems have been proposed which either carry the crankshaft main bearings in an eccentric assembly or move the crankpins eccentrically to effect a stroke change at TDC.

Fig 10 shows the Gomecsys VCR engine in which moveable crankpins form an eccentric sleeve around the

conventional crankpins and are driven by a large gear. The arrangement suits a parallel twin cylinder or wide angle V4 layout (ref 9). Applications involving staggered crankpin geometry would be less elegant, requiring multiple gear drives.

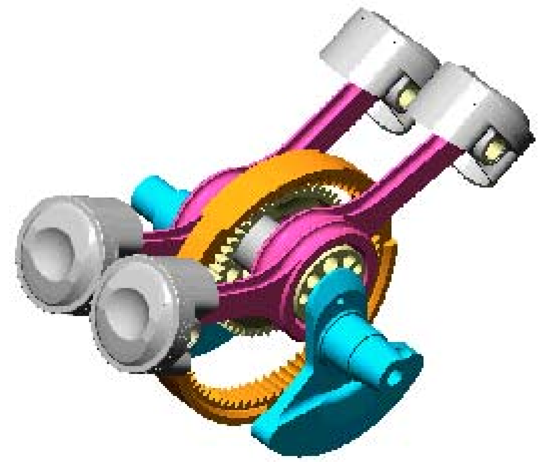


Figure 10, I-2 and V-4 arrangements for the Gomecsys VCR engine

Fig 11 shows a Romanian patent (ref 10) in which the crankshaft main bearings are carried in an eccentric housing which can be rotated by an actuator, via a mechanism, to vary the crankshaft position with respect to the cylinder head. For a multi cylinder engine, the rotating crank assembly obstructs any attempt to connect the individual housings so the challenge is to ensure simultaneous and uniform movement of the independent eccentrics.

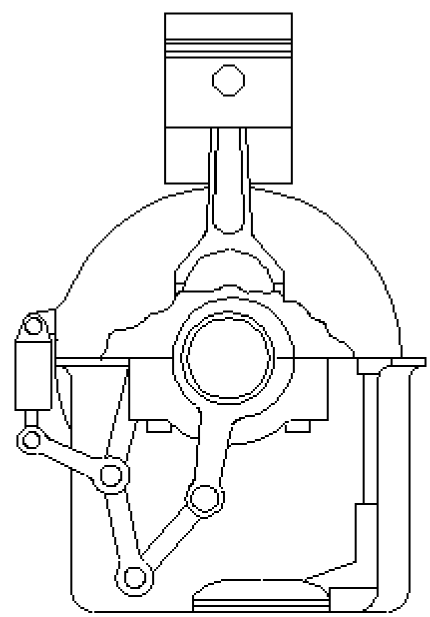


Figure 11, The Rapan VCR engine

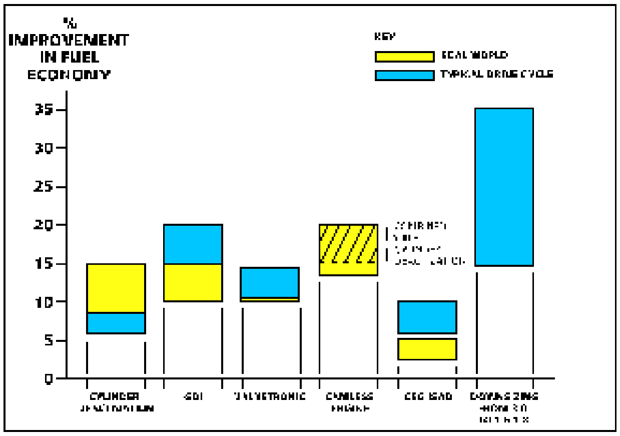


Figure 12, Typical gains in fuel economy

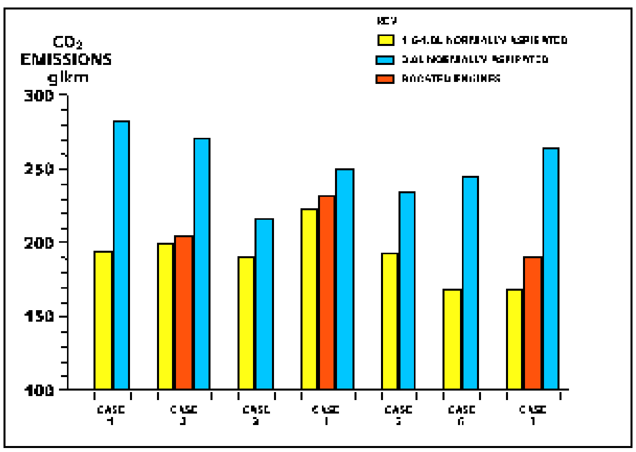


Figure 13, Comparison of CO_2 emissions

THE CASE FOR DOWNSIZING AND THE ROLE FOR VCR

Fig 12 compares the gains in fuel economy achievable with various engine technologies, as reported in various sources (refs 11,12,13,14). The downsizing benefits are based on the results in fig 13.

Substantial downsizing (e.g. from 3.0L to 1.6~1.8L) offers the largest improvement but carries an unacceptable performance penalty. Manufacturers have already sought to restore performance with modest boosting by supercharging or turbocharging (typically 0.5 Bar).

Fig 13 compares the UK government published CO2 emissions for 7 cases in which the same vehicle is certified with alternative engine types (ref 15).

The lightly pressure-charged engines offer almost comparable CO2 levels to the naturally aspirated equivalents despite using fixed CR. They do not, however match the WOT performance of 3.0 engines.

To achieve this, a higher level of pressure charging is required. This requires a reduction in CR which erodes the part-throttle fuel economy and CO2 emissions performance.

Adoption of VCR enables the construction of a small, highly boosted engine which can deliver the WOT performance of a larger n/a engine but also match or exceed the part-throttle fuel efficiency of the equivalent n/a base engine.

Consideration is now given to the technical and manufacturing issues to be overcome before volume manufacture is viable e.g. control strategy requirements and the impact on existing production facilities.

CONTROL STRATEGY FOR VCR

BASIC RELATIONSHIPS

Fig 14 presents a 3-D representation of the Prodrive strategy for boost and CR response to variations in load (driver demand).

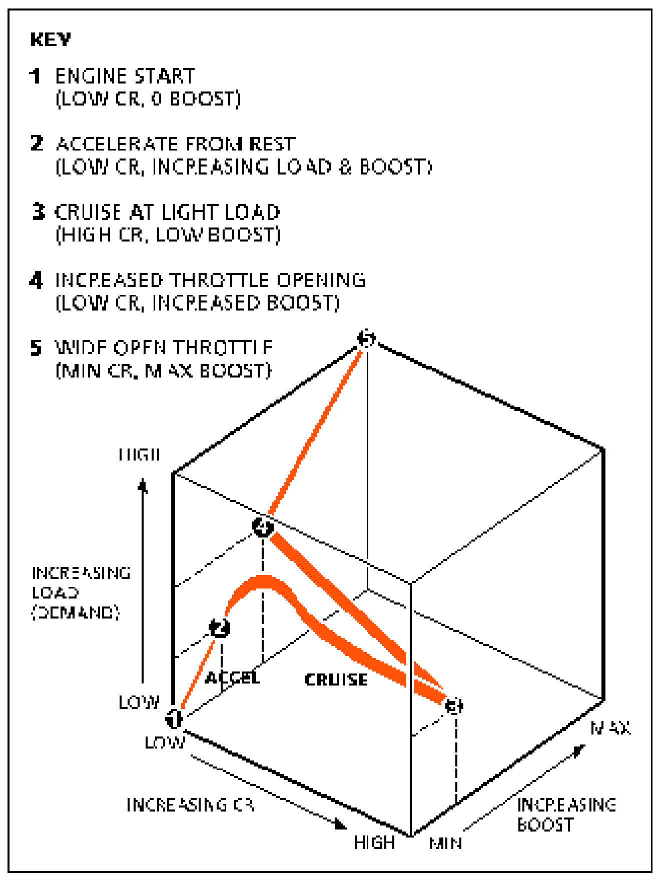


Figure 14, CR Transition vs Load for a typical boosted engine

Points 1, 2, 4, 5 lie on the plane of low compression. Point 3 lies on the plane of high compression.

The engine is started at low CR and zero boost (point 1). When the driver accelerates, load and boost increase to point 2.

When the driver throttles back into a light load cruise (point 3), load and boost reduce and CR increases. When the throttle is re-opened from this condition, CR reduces as boost and load increase, reaching point 4 and, ultimately, point 5 (WOT).

For simplicity, the figure assumes only 2 available CR values (high and low). The same logic can be applied to intermediate values of CR by considering the transition between intermediate planes of CR.

TIP-IN/TIP-OUT STRATEGY

The requirement to reduce CR during a throttle tip-in event (i.e. a transition from light throttle to WOT) is immediate and extreme. If a performance "feel" phenomenon similar to turbo lag is to be avoided, the system must migrate to the lowest CR within less than 100ms (equivalent to 8 engine rotations at 5000 rpm). If response is slower than this, the driver will perceive having to "wait" for the system. The requirement to increase CR during tip-out (i.e. transition from WOT to cruise or overrun) is not immediate and can be ramped in at whatever rate is supported by the hardware.

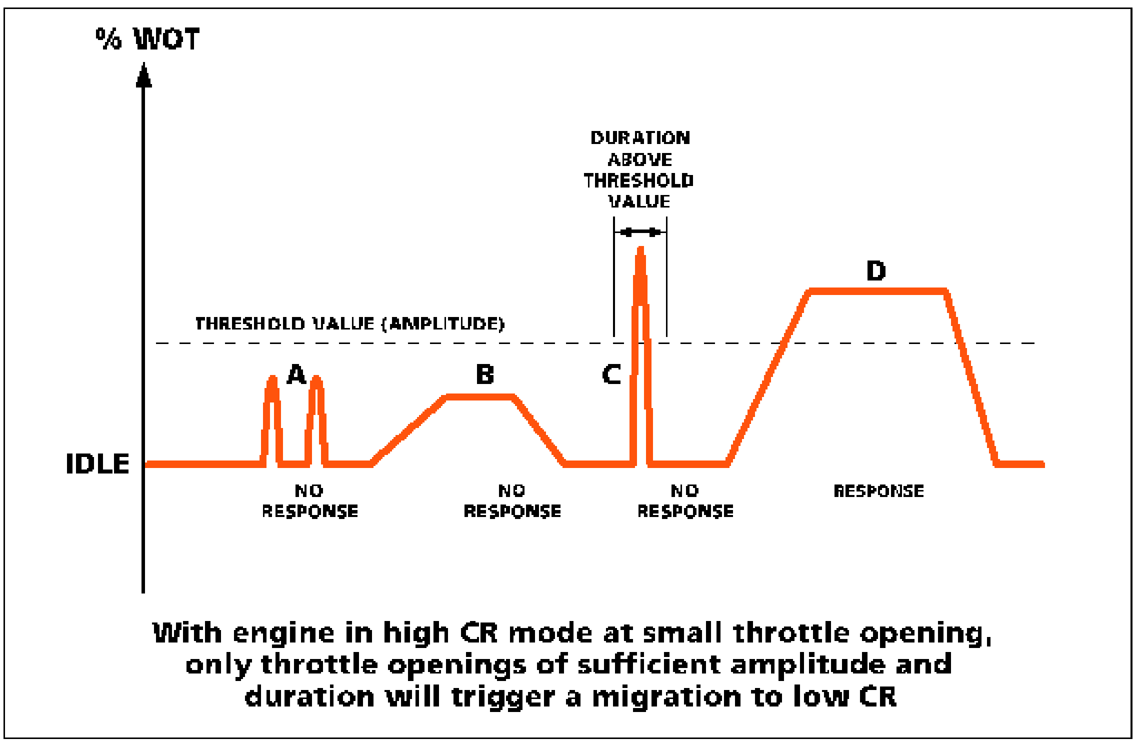


Figure 15, Suppression of unwanted throttle inputs

FILTERING

Existing strategies for filtering throttle signal can usefully be applied to VCR to suppress unwanted or spurious pedal inputs (see Fig 15).

OPEN vs CLOSED LOOP CR CONTROL

First generation systems have used maps of spark advance and CR for a range of load/speed operating conditions based on safe calibrations with a particular fuel. Transient progression between the sites has been managed by simple control functions to prevent potentially damaging combinations of ignition advance and CR from occurring.

Second generation systems based on established principles of knock control are emerging which permit active adaptation of CR to instantaneous operating conditions (such as that described in VW patent WO 01/29385 A1). Such systems appear to enable VCR to be effectively applied to engines which encounter fuels of differing knock resistance or to accommodate a range of intermediate values of CR, between the extremes. The benefits of having this capability have been questioned and the hardware implications of multiple CR values are considered later. It would be instructive to compare CO2 emissions between a vehicle with high/low CR and one with infinitely-variable CR across the same emissions drive cycle.

KEY ISSUES FOR VOLUME MANUFACTURE

HARDWARE REQUIREMENTS TO SUPPORT THE CONTROL STRATEGY

Any production viable system requires commercially economic hardware, whether hydraulic or electrical in operation. Typical response times for such hardware would be 200-250 msec for a change in CR. This is acceptable for the transition from low to high but too slow for high to low.

A primary requirement of a feasible system is to separate adjustment loads from the reaction of firing loads.

Most of the systems described earlier suffer in this respect – the firing load or a significant part of it has to be reacted by the VCR mechanism.

An elegant solution to both these issues is to configure the mechanism to “fly back” to the low compression state under the action of firing load, for example by releasing hydraulic pressure. This enables the rapid response required by the Control Strategy (above) without recourse to high power, fast-acting hardware. It is only necessary to “clamp” the mechanism once it has reached the desired steady state. As the strategy accepts a slower progression to the high compression state, this can be accomplished with hardware which is commonly available at volume automotive prices.

Clearly, if the migration between low and high compression occupies several engine cycles, the control system must also “clamp” the mechanism briefly at the point of firing to prevent regression to the low compression state. As this event only takes place under part throttle conditions, the loads involved are, in any case, much reduced.

By this means, the power consumption of the VCR device can be minimised to the level where only the friction losses in the system are overcome and no work is done against firing pressures.

LEVEL OF SOPHISTICATION REQUIRED FOR OPTIMUM USE OF VCR

Cost may be eliminated from a VCR system if only the extremes of motion are protected, i.e. maximum and minimum compression. This eliminates the need for intermediate values of CR. To engineer a system capable of intermediate values introduces the requirement for both an actuator and a controller with the necessary capability. Furthermore, the system must either deliver the necessary accuracy by close tolerance manufacture or support a feedback controller which requires position-sensing (or similar means) to detect errors in current position.

If the argument for pressure-charged VCR engines is accepted, the potential benefits of intermediate

Compression Ratios corresponding to intermediate throttle positions seem limited.

At the small throttle openings of a typical drive cycle, the engine can remain at high CR. At larger throttle openings, the optimisation of boost and spark advance within the engine’s detonation threshold will leave little potential for improvement through VCR, due to the trade off between CR and ignition advance referred to in Fig 1.

PACKAGE ISSUES

The key issue for manufacturing is not primarily the additional hardware added to the engine but the potential impact on existing base engine manufacturing facilities.

Most VCR designs require features which extend beyond the base engine silhouette. As a minimum change, these typically require an extension or addition to the cylinder block or crankcase – in more extreme cases (e.g. SAAB) a reworking of the entire engine structure is necessary.

Where the mechanism can be accommodated within a bolt-on structure requiring only an aperture or mounting face to be added to the base engine, there is the potential to machine the major engine castings on the same line as a non-VCR engine. Where this is not possible, major investment in facilities may be required, which represents an obstacle to the adoption of VCR since competing technologies are available (see below) which may require far less modification to existing manufacturing plant.

Though facility investment is not an insurmountable barrier to the adoption of any new technology, the initial market take-up is likely to be difficult to predict and the flexibility to adjust VCR and non-VCR volumes within an engine family would be highly desirable.

It is noteworthy that application of VCR with pressure charging has the potential for higher commonality than VCR with a naturally aspirated (n/a) engine. This is because the combustion chamber geometry has to be completely new for an n/a engine with VCR in order to achieve the required CR values (typically of the order of 16:1). To reach such high values with an acceptable surface:volume ratio and minimal crevice volume, dictates a very upright valve angle (typ <20 deg between inlet and exhaust). By contrast, a highly pressure charged engine can inherit the standard geometry of an n/a base engine and use VCR to reduce the compression from the base value.

COMPARISON WITH RIVAL TECHNOLOGIES

Other technologies offer improvements in fuel efficiency and CO_2 emissions. The respective gains are compared in fig. 12

GASOLINE DIRECT INJECTION

GDI enables the use of higher than usual CR even at WOT by using the cooling effect of the latent heat of vaporisation of the fuel to extend the detonation threshold.

Stratified operation at lean overall AFR offers improved part throttle fuel economy but presents similar after-treatment challenges to diesel engines. Any strategy for rich purging of the after treatment system may have a negative impact on the fuel economy benefits. This requires a trade-off between the capacity of the NOx system and the frequency of enrichment.

CAMLESS VALVE OPERATION

Benefits may be derived from reduced pumping losses - especially if the throttle is eliminated. Extreme valve timing extends the region of high volumetric efficiency over a wider range of engine speeds.

Parasitic losses are reduced (compared to conventional cam drives) assuming that a low power-consumption strategy is adopted for the movement and capture of the valves.

Packaging requirements of valve actuation systems have, up to now, limited the potential applications.

CYLINDER DE-ACTIVATION

Downsizing of 50% is typical (e.g. 4 from 8 or 6 from 12 cylinders) with reduced pumping losses by increasing throttle opening for a given road load. This is not as effective as true downsizing as much of the parasitic losses from inoperative cylinders remain.

A major advantage is the high carry-over base engine content maintained when cylinders are de-activated using tappet deactivation.

The challenges of smooth ramp-out/ramp-in behaviour and management of thermal and emissions issues have largely been met, making this a production-feasible technology for multi-cylinder engines.

VARIABLE CAPACITY

As indicated earlier, some VCR designs (e.g. Mayflower, fig 9) combine variation in stroke with variation in CR either as a by-product of the geometry change or a stated aim of the mechanism.

The potential change in swept volume is limited by crankshaft geometry at one extreme and engine silhouette at the other ; practical VCR devices are unlikely to enable capacity changes greater than 20% which falls well short of the 50% achieved by cylinder de-activation.

Unless more extreme variations in capacity can be engineered, downsized engines are still likely to require pressure charging to meet customer expectations for WOT performance. In such circumstances, there appears to be little justification for variation in capacity.

INTEGRATED FLYWHEEL/ STARTER/ ALTERNATOR (FAS/ISAD/CSG)

This technology offers the potential to eliminate idling during the urban drive-cycle through stop-restart strategies which can be worth up to 10% of the total fuel consumed (ref 14). It is also the enabling technology for simple hybrid strategies through regenerative braking and torque supplementation.

Importantly, it is an effective means of restoring “off the line” performance feel with downsized engines, while the 42v capability can support other engine technologies e.g. camless valve operation.

CONCLUSION

VCR offers the largest potential improvement in part-throttle fuel efficiency and CO2 emissions when compared to other competing technologies, if applied to highly pressure-charged downsized engines.

VCR is highly synergistic with FAS/CSG systems which can offer torque enhancement at low rpm when boost systems are least effective. FAS/CSG systems can also provide a 42v power source for VCR actuation hardware.

The main obstacles to adoption of VCR are incompatibility with major components in current production and difficulties of combining VCR and non-VCR manufacturing within existing plant. As environmental pressure on the automobile increases and investment plans for new products are put in place, the justification for VCR will become more evident.

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