# Axial Pistons – A New Format for Implementing Variable Compression

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## ABSTRACT

The concept of variable compression promises improved piston engine performance, efficiency, and emissions, but commercial implementation has not been successful due to the complex geometries needed to implement it. With a suitable design, variable compression could improve fuel efficiencies, starting, and partial load performance, among other characteristics.

This paper briefly (1) explores the theoretical basis for improvement promised by VC in both spark ignition and compression ignition engines, (2) catalogs the principal design approaches attempted in the past, and (3) suggests some indicators of what VC might offer for improvement in piston engine performance and economic characteristics. These indicators include specific fuel consumption, power to weight ratios, and volume and cost characteristics for operation and maintenance.

Part I consists of a review of past research on how VC would affect the operating cycles of spark and diesel engines at both design power and partial power settings. Part 2 reviews the geometric approaches and solutions used to achieve VC (most of which have been limited to research projects). Part 3 takes the results of prior published research and forecasts what, if any, benefits that VC would bring to present engine design.

## WHY VARIABLE COMPRESSION?

Compression ratio is the key to efficiency of reciprocating engines. In his seminal two volume text, Taylor shows how the efficiency of a compressed air cycle is solely dependent on compression ratio (1), and how, for ideal four-stroke engine processes, efficiency is almost completely dependent upon compression and fuel/air ratio (mixture) (2). In general, efficiency rises with increasing compression ratio and drops with richer mixtures above 80% of stoichiometric.

Taylor's formula for air cycle efficiency is:

$$\eta = 1 - (1/r)^{k-1}$$

where:
$\eta$ is the efficiency of the cycle,
r is the compression ratio, and
k is the ratio of specific heat of air at constant volume to specific heat at constant pressure, or approximately1.40.

In this formulation, efficiency varies solely with compression ratio (k being essentially constant.) High efficiency, therefore, comes with high compression ratios, though at ever higher ratios there is a diminishing returns effect. Raising the ratio from 8 to 12 produces efficiency gains from 56% to 63% (a 12.5% gain), whereas going from 16 to 20 gains from 67% to 70% (a 4.5% gain). A graph of the Taylor efficiency formula is presented in Figure 1.

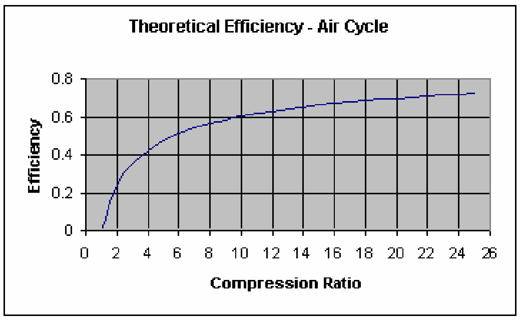


**Figure 1. Effects of Compression Ratio (1)**

The addition of fuel to the cycle requires modification to Taylor's observations about pure air cycle efficiency.

The characteristics that have the dominant effects on efficiency are compression ratio and mixture, as shown in the two graphs of Figure 2. These plots are given for atmospheric pressure and temperature at the cycle inlet.

The left plot shows how efficiency grows with compression ratio for five mixture ratios above 80% of stoichiometric; while the corresponding right plot shows how efficiency falls off with increasingly rich mixtures, for four selected compression ratios.

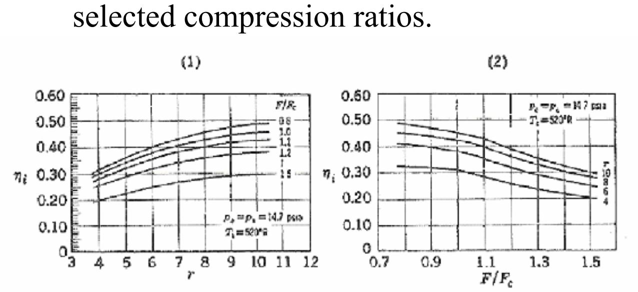


**Figure 2. The Influence of Mixture and Compression Ratio on Efficiency (2)**

In a forward-looking paper on power plants, Walzer, of FEV Motorentechnik, asserts that fuel economy and emissions reduction will be the main thrusts of future development activity (3). To satisfy future goals for spark ignition engines (SI), he suggests supercharging, a variable compression mechanism, direct spray injection of fuel, and variable valve actuation. Appropriate valve actuation could be used to eliminate throttle mechanisms and their attendant losses as well as to reduce undesirable emissions.

Walzer sees the direct injection Diesel engine best way of reducing fuel consumption, and therefore $CO_2$ emissions, but he does not advocate for variable compression.

Al-Sood and others at Assiut University in Egypt presented a paper on a project using simulation techniques to study a 4-stroke direct injection diesel engine with a means of varying compression ratio. They concluded that the VC feature would allow the engine to achieve maximum brake torque with savings in fuel consumption, higher overall efficiency and reductions in soot emissions. Because of the VC feature, higher internal maximum pressures and temperatures would be experienced. Unfortunately, considerably higher $NO_x$ emissions would be delivered (4).

## DESIGN APPROACHES TO VARIABLE COMPRESSION

A crankshaft engine offers a variety of approaches for implementing VC. These are described and diagrammed in a paper by Schwaderlapp et al of FEV. In a section on the ways to realize VC, the paper describes the different basic approaches and who has implemented them (5). Moteki et al, in a paper describing a VC project at Nissan, offer a classification of approaches to VC. The classification diagram from this paper is shown in Figure 3 (5).

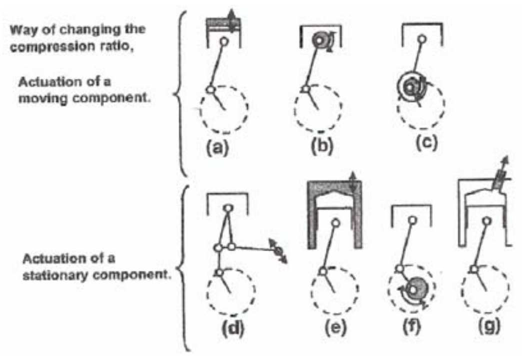


**Figure 3. Classification of VC Designs.**

Nissan, Saab, FEV and the U.S. Department of energy (DOE), among possibly others, have developed research prototype engines using one or more of these VC approaches. Each of these projects is described below.

**Nissan**

The Nissan project uses a multi-link system to achieve VC. By inserting a control linkage system between the connecting rod and the crankshaft and connecting this system to an actuator shaft (Figure 3d), compression ratio can be varied. The links are claimed to smooth out some of the sliding friction loads at the connecting rods, resulting in no increase in overall internal friction due to the introduction of the multi-link system. At the same time the link system is configured so that second order vibrations (induced by the "hop" of the piston at TDC) are cancelled out (6).

The project design was incorporated in a stock Nissan 4 cylinder engine (SR20) without major modification of the block. A shorter crank throw allowed room for the link system, which was anchored by an eccentric rotary actuator. Compression is varied from approximately 10 to approximately 15 by a $70^0$ rotation of the actuator. At TDC, the piston position is changed by 3.1 mm. This paper includes a long list of references on VC and an appendix describing the kinematics of the link system.

**Saab**

The Saab project engine is a mechanically supercharged 5 cylinder in-line design featuring a block hinged to the crankcase, but schematically similar to Figure (3e). The lower half of the block includes the crankcase and engine mounts, and it carries the crankshaft, gearbox, oil cooler, and auxiliaries. The upper half includes the cylinders, their liners, camshafts, and an integrally cast cylinder head. This part is referred to as the "monohead". By means of an actuator and linkage mechanism, the compression ratio can be varied from 8 to 14. The linkage serves to tilt the monohead relative to the crankcase to vary the TDC position of the pistons (7).

The design concept for this project was to provide a 1.6 liter VC engine that would equal the performance of a 3.0 liter naturally aspirated engine. At full throttle (and full boost) the CR is reduced to 8 to avoid knock, but at part throttle operation, typical of most driving, the CR can be raised to 14 to gain additional fuel economy without knock. For this engine the screw type supercharger provides a 2:1 boost pressure when wide open throttle conditions are called for. Rated power is 165 kW @ 5800 rpm, and torque is 305 Nm @ 4000 rpm. In a Saab 9-5 vehicle, the company anticipates fuel consumption reduction from 11.1

liters/100km. to 8.3 liters/100km. This is a reduction based upon replacing the 3.0 liter engine with the 1.6 liter VC engine. It amounts to a 25% improvement, based upon the larger engine's consumption.

Other approaches to increasing efficiency and controlling emissions are described in the Saab paper. These include air-assisted direct fuel injection and a beefed up ignition system integrated with the injection system.

**FEV Motorentechnik**

FEV has chosen to alter the position of the crankshaft in a 4 cylinder test bed engine designed to test variable compression. In this engine the crankshaft bearings are carried in an eccentrically mounted carrier that can rotate to raise or lower the TDC position of the pistons in the cylinders, as shown schematically in Figure 3f. Because the engine requires a fixed position output shaft, a coupling is required between the moveable crankshaft end and the fixed output shaft. The CR is adjustable from approximately 8 to approximately 14 by varying the rotation of the eccentric carriers $55^0$ (5).

No efficiency data was presented, but after 400 hours of testing the engine proved reliable and the adjustment mechanism proved effective and rapid. Further test were planned, following installation in a vehicle.

**DOE project**

The DOE engine, its experimental results and related simulation studies are described in a paper by Mendler and Gravel (8). The engine is a two cylinder, proof of concept prototype of 928 cc. displacement and a CR range from 8 to18. Variation of CR is obtained by means of an eccentric crankshaft cradle similar to the FEV project, above, that rotates +/- $5^0$ to raise or lower the shaft and, thereby, the TDC position of the pistons. Because the crankshaft shifts position and because imbalances are present, a fixed position balance shaft is geared to the crankshaft. The balance shaft provides the point of power takeoff and drives the cam pulley for the engine.

Preliminary test of the engine have confirmed structural integrity and the ability to vary CR while running. Runs have been made at 1800 rpm and 2200 rpm. On the first of these, CR started at 17 with torque at 12.2 Nm. Torque was increased to 78.6 Nm while reducing CR from to 10.5. At 2200 rpm, similar torque and CR profiles were run without problems. About 20 hours of test runs were accumulated.

In addition to the engine design and testing, the DOE project ran simulation studies of the fuel consumption of the VC concept. Their conclusions affirmed the value of VC in a vehicle operated on the typical power schedule used by an operator. Most of the time the engine would be working at idle or low or part power, where the advantages of being able to raise effective compression ratios are substantial. The group concluded that 80 miles per gallon in a mid-sized vehicle would be possible with a VC engine.

**BP Oil Project**

Earlier, in 1991, BP oil and Ricardo teamed up on an experimental project to investigate the use of VC in Diesel engines [9]. For hardware, they chose to cannibalize a 4-cylinder Cummins 4BTA diesel by retaining only the central two pistons. The pistons work from separate cranks that can be adjusted in phase angle with respect to each other, and the two cylinders are connected at the cylinder heads so that there is effectively only one combustion chamber. As schematic is shown in figure 4.

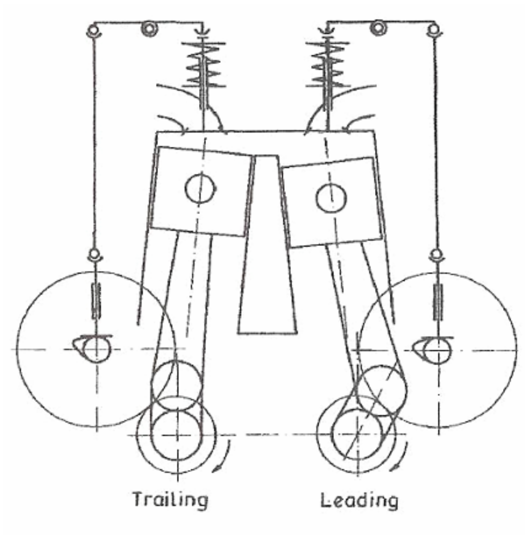


**Figure 4. BP/Ricardo Phased Pistons**

VC is implemented by adjusting the phase angle between the pistons, using a control shaft. When both pistons are at TDC simultaneously, maximum compression is achieved, and when the pistons are out of phase at TDC, lower values appear. The Cummins engine was designed with a 16.5 CR, but after modification, the CR was variable from 8.65 to 19. Phase angle adjustment between the two cranks, to achieve this CR variation, was from $0^0$-$50^0$.

Test results on this research engine revealed that power capability of the unit was the equivalent of the four cylinder stock Cummins unit that it was derived from, despite there only being two cylinders in operation. Internal friction losses were more favorable for this configuration than for equivalent power plants. Fuel efficiency at low and medium loads matched competitive direct injection diesels. High load fuel efficiency was not as good, however, because of the unusual combustion chamber shared between the two pistons. $NO_x$ and HC emissions were low, but particulates were at a high level at light and medium loads.

Taylor's efficiency formula for air cycles indicates that if CR is raised from 8 to 18, the efficiency will grow from .56 to .68, an increase of .12 or 21%, based on the lower CR. Other researchers are finding or anticipating similar results with their projects. Saab anticipates a 25% improvement in fuel economy for its VC engine installed in a vehicle. BP Oil found an approximate 8% improvement in its diesel specific fuel consumption, when operating at 25% load, when it raised compression from 15 to 19. This is about double what Taylor would predict from his air cycle formula.

Offsetting improved specific fuel consumption, to some extent in all of these projects, is the fact that implementing VC requires revised designs, more parts, and a control system to change CR. To the extent that these are as simple and compact as possible, benefits seem to come from added efficiency, lower vibration levels, a more stable idle, improved starting ability, and the ability to downsize engines because they deliver more power. Variable compression, implemented simply, shows promise.

## A CONFIGURATION MORE SUITED TO VARIABLE COMPRESSION

Innovation Engineering has been developing an axial piston engine whose mechanical arrangement is more suited to adjusting and controlling compression ratios. Axial piston engines have the cylinders arranged six shooter or barrel stave fashion around the output shaft.

They are also known as Barrel Engines, and their development, particularly for aircraft use, has a history tracing back to the early 20th century. McLanahan provided a brief history of their development at SAE's 1999 World Aviation Congress (10).

To convert the reciprocating motion of the axially arranged pistons, the power shaft is fitted with a canted plate that wobbles as the shaft rotates. A spider-type of plate runs on this "wobbler" and forces the pistons into a reciprocating motion. This type of mechanism, first patented for use as a pump in 1856, has inherently low friction and smoother motion when compared to a conventional crankshaft mechanism. It also concentrates the cylinders in a compact circular cluster that lends itself more easily to actuation necessary to vary compression ratio.

The moving parts of the Variable Compression Axial Piston (VCAP) engine are shown in Figure 5. Three pistons are shown, but any number can be used with more attachment points on the wobbler mechanism. The cylinder block (not shown) would surround the pistons and support the central shaft in suitable bearings. Variable compression can be accomplished by fitting a cylinder block that would be movable along the axis of the shaft, alternately closing down or opening up the distance between the wobbler, and the cylinder heads.

An example of how variable compression ratio can be achieved using the z-crank engine is illustrated in fig(6).

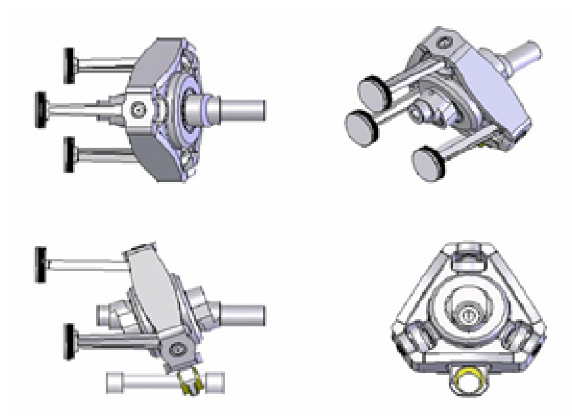

**Figure 5. VCAP Engine moving parts**

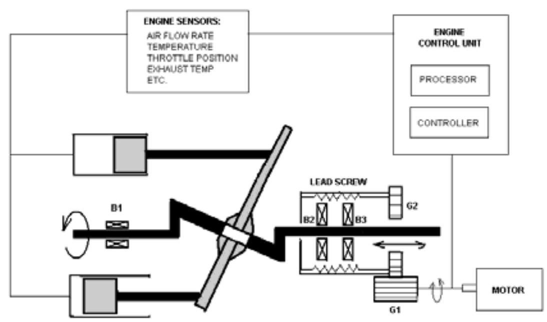


**Figure 6. VCAP Engine Concept Implementation**

The bearings B2 and B2 on which the z-crank is supported can be mounted on a threaded housing. This threaded housing can be driven axially by a lead screw which is actuated by an electric or hydraulic motor through gears G1 and G2. This way the axial motion of the z-crank assembly can be achieved. A small amount of travel can accommodate a large variation in compression ratio. The compression ratio can be dynamically controlled by a digital controller that would take input from the sensors located in the engine head.

## CONCLUSIONS

Many project teams have worked or are working on VC because it promises more efficient operation of vehicle power plants; it gives the ability to downsize engines, saving weight; and it offers the potential to revise pollutant emission characteristics.

Since the promise of significant future benefit is there, Innovation Engineering plans to undertake additional studies to find out more about VC in connection with a different sort of engine, the axial piston engine.

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