

Project Omnivore: A Variable Compression Ratio ATAC 2-Stroke Engine for Ultra-Wide-Range HCCI Operation on a Variety of Fuels

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J.W.G. Turner, D.W. Blundell, R.J. Pearson, R. Patel, D.B. Larkman and P. Burke
Lotus Engineering

S. Richardson and N.M. Green
Jaguar Cars Limited

S. Brewster
Orbital Corporation Limited

R.G. Kenny and R.J. Kee
Queen's University Belfast

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ABSTRACT

The paper describes the principal features of Omnivore, a spark-ignition-based research engine designed to investigate the possibility of true wide-range HCCI operation on a variety of fossil and renewable liquid fuels. The engine project is part-funded jointly by the United Kingdom's Department for the Environment, Food and Rural Affairs (DEFRA) and the Department of the Environment of Northern Ireland (DoENI). The engineering team includes Lotus Engineering, Jaguar Cars, Orbital Corporation and Queen's University Belfast.

The research engine so far constructed is of a typical automotive cylinder capacity and operates on an externally-scavenged version of the two-port Day 2-stroke cycle, utilising both a variable charge trapping mechanism to control both trapped charge and residual concentration and a wide-range variable compression ratio (VCR) mechanism in the cylinder head. This approach permits individual control of retained and compression heat as separate inputs to the ATAC combustion process (now commonly referred to as HCCI), an ideal situation which is not possible when attempting to operate a traditional fixed compression ratio, variable valve timing 4-stroke engine in HCCI combustion. The ease of application of the VCR system due to the

elimination of poppet valves for gas exchange is fundamental to the concept and this feature is discussed in detail, together with the very wide range of compression ratios that the chosen solution permits (from 10:1 to 40:1 in this initial configuration). In addition to describing the engine and its technologies, test results from its initial operation on 98 RON gasoline are presented, including stable operation at idle load and 450 rpm in true HCCI (i.e. without spark assistance).

OMNIVORE ENGINE COMBUSTION SYSTEM - CONCEPT RATIONALE

Figure 1 shows the relationship between compression ratio (CR) and air standard cycle thermodynamic efficiency for different ratios of specific heats (γ) of the working fluid using a simple calculation assuming a constant γ throughout the cycle. The specific heat ratio γ varies during the cycle as a function of the gas composition and temperature. The gas composition in the combustion and expansion strokes is clearly a function of the air-fuel ratio (AFR) and the progress of the combustion event, and in the compression stroke it is also a function of the degree of vaporization of the fuel.

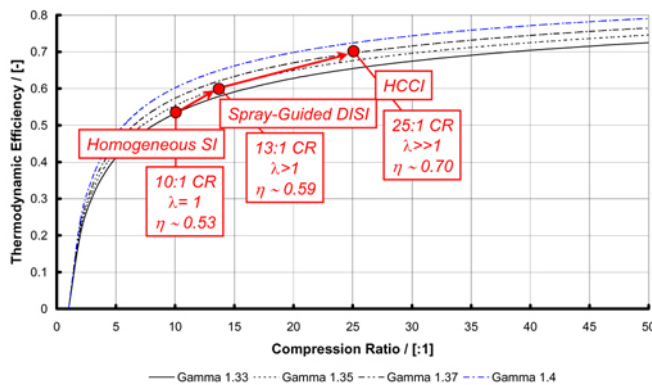


Fig. 1. Air standard cycle efficiency for different compression ratios and ratios of specific heats.

Progression from homogenous operation at a CR of 10:1 and $\gamma = 1.33$, to SI lean at 13:1 CR and $\gamma = 1.35$, to high CR HCCI at 25:1 and $\gamma = 1.37$ is shown. Limiting efficiency for $\gamma = 1.4$ also depicted. (Note: γ is assumed constant throughout the cycle - see text with regard to this simplification)

Clearly using a single value of γ throughout the cycle is a large over-simplification (in addition to neglecting heat transfer and the finite rate of combustion), but some useful general observations can be inferred. As can be seen in [Figure 1](#), there is a general trend for efficiency to improve as both CR and λ are increased¹, but closer examination reveals two further things: the rate of improvement in general tends to tail off at or around a CR of 18, with leaner air-fuel ratios showing higher values of thermodynamic efficiency at high values of CR. These observations are often used to justify both the limitation of CR to less than 20 and the pursuit of stratified-charge SI combustion systems, where fully-throttled SI engines operating at stoichiometric air-fuel ratio (i.e. $\lambda = 1$) at about a CR of 10 are replaced by ‘spray-guided’ direct-injection spark-ignition (DISI) engines operating lean (i.e. $\lambda \approx 1.35$) at a CR of approximately 13:1 [[1,2](#)].

Perusal of [Figure 1](#) shows that the maximum thermodynamic efficiency for a general stoichiometric spark-ignition operating condition can be significantly extended (by about 10%) by adopting a stratified lean strategy². However, when operating on the 4-stroke cycle, the lean operation also brings significant benefits in terms of dethrottling the engine, such that the effective improvement in fuel consumption would in reality approach twice this value, despite the necessity to provide periods of stoichiometric operation to permit operation of a lean-NO_x aftertreatment system [[1,2](#)]. The subject of throttling losses and choice of engine cycle will be returned to later.

Homogenous lean-burn combustion systems have also been shown to offer benefits in fuel consumption, and Adams and co-workers [[3](#)] demonstrated a lean-operation VCR SI engine which gave an improvement in fuel consumption of the order of 12% in a vehicle. Increasing the CR has been shown to extend the lean limit of the charge by trading heat released during the combustion process for compression heat provided by piston motion. There is, however, ultimately a limit set by the flame propagation interval increasing as mixtures are enleaned, which in turn requires an increase in spark advance until eventually insufficient compression heat is available in the cycle from the time of ignition to assist in the ignition of a lean mixture [[4,5](#)]. However, with SI combustion at full load the limits of efficiency are reached very rapidly as soon as the end gas starts to knock and the ignition timing has to be retarded and/or the mixture enriched. This is a major limitation.

In 1984 Oppenheim observed that instead of viewing knock merely as a problem to be solved in spark-ignition (SI) engines it would perhaps be more beneficial to investigate the use of autoignition to improve thermal efficiency [[6](#)]. Theoretically the very rapid rise in cylinder pressure could be harnessed to permit a closer approximation to constant volume combustion than is possible with a deflagrating flame, and so permit a better approach to the air standard cycle efficiency limit. The year before Oppenheim's paper Najt and Foster [[7](#)] had published one of the first detailed experimental studies of what would become known as homogeneous charge compression ignition (HCCI) (following Thring's coining of the term in 1989 [[8](#)]). In reality all of these investigators and many more besides owe a debt to Onishi *et al.* [[9](#)] with their early publication of the phenomenon which they termed ‘Active Thermo-Atmosphere Combustion’ (ATAC).

The fact that combustible mixtures can be ignited merely by a combination of applied pressure and temperature has been known for many years; it is obviously the basis of spark-ignition engine knock phenomena and diesel engine combustion initiation [[10](#)]. To that end, and realizing the importance of knock, particularly on SI engine performance, efforts to understand autoignition chemistry have been extensive and sustained. A wide variety of experimental tools have been developed to investigate the phenomenon, including shock tubes, jet-stirred flow reactors and constant-volume combustion bombs [[11](#)], but one piece of apparatus in particular bears a significant resemblance to reciprocating engines: the rapid compression machine (RCM).

As its name suggests, through the fast movement of a piston within a combustion chamber, an RCM permits the rapid

¹The value λ is the ratio of the actual AFR to the stoichiometric AFR of the mixture. Thus as the charge is enriched beyond stoichiometric, so λ becomes less than unity and vice-versa. As a consequence, λ is the inverse of the equivalence ratio (ϕ).

²In [Figure 1](#) the value of 1.33 for λ arises solely from assuming that all combustion products are triatomic. This is not the case in reality because of the presence of unburnt gas in the air.

stressing of a charge of combustible material such that it can be ignited. The ensuing pressure trace allows the calculation of temperature rise during the cool flame period and hence conclusions and insights to be made regarding the low temperature chemistry and autoignition process of a fuel. One of the first such devices was proposed, built and tested by Tizard and Pye [12] and famously Livengood and Wu used data from an RCM to correlate with autoignition in an SI engine in their watershed publication [13]. One of the principal advantages of using an RCM is that a charge less prone to autoignition can be ignited sooner by utilizing a higher CR, and it is this fact that is employed in the engine described in this paper as a means of controlling combustion. Note that in Chapter 17 of [14], Westbrook *et al.* do in fact point out that RCMs are ‘in many ways the academic equivalent of the HCCI engine’³.

In Figure 1, in addition to the arrow representing progression from homogenous operation to SI lean, an arrow is shown indicating what would generally happen were one then to move to extremely lean operation at very high CR. This is what would be the case for high compression HCCI. It can readily be seen that if such mixtures can be combusted at these high compression ratios, a further increase in thermodynamic efficiency over DISI stratified charge engines equivalent to or greater than that of such engines over homogeneous throttled engines can be achieved; in fact, spray-guided DISI to HCCI at a CR of 25:1 itself offers the potential of a further relative improvement in thermodynamic efficiency of 15-20%.

Hence, although there is a question mark over the benefit of employing ever-higher values of CR in homogeneous SI combustion systems, perusal of Figure 1 shows that in a combustion system which demands very high CR to ignite the charge, the adoption of a higher CR will *never* reduce the thermodynamic efficiency of the air standard cycle. This gives rise to the observation that the use of a high CR merely to ignite the charge is entirely permissible from a thermodynamic standpoint, and if the CR itself be variable then it can become a major control parameter for the operation of the engine. In fact, when operating their 4-stroke VCR engine in HCCI, Haraldsson *et al.* noted that “any negative influence of too high CR, up to 17:1, ...on brake thermal efficiency cannot be seen” [15]. Subsequent work on this engine continued this investigation up to 21:1 CR and drew similar conclusions [16].

Given this observation, it is perhaps surprising that attempts to develop engines operating with HCCI combustion processes utilizing wide-range VCR have not been stronger. However, researchers at Lund have utilized a Saab Variable

Compression engine to extensively investigate the trade-off between CR, inlet air heating, fuel octane number (ON) and trapped residual concentration on HCCI combustion. This 4-stroke engine was fitted with modified pistons to increase the available range of CR from 8-14:1 to 9-17:1. Their results clearly indicate that increased CR can be used to reduce the amount of inlet air heating required to support HCCI operation, to reduce the requirement for residual trapping, or to increase the permissible ON of the fuel. Nevertheless, when they operated the engine on commercial 98 RON gasoline, only a single speed and load point of 1000 rpm, 2 bar brake mean effective pressure (BMEP) could be supported, and this was at the highest CR of 17:1, an inlet air temperature of 150°C and maximum residual concentration [15]. Later work by these researchers did succeed in enlarging its area of operation on 92 RON commercial gasoline, but again this required significant inlet air heating together with an increase in available CR to 21:1 [16].

Thus from this and later literature the present authors inferred that, since CR is in itself a major lever on the autoignition process, creating an engine with a sufficiently wide and controllable range of variation of this parameter should yield an interesting new avenue for HCCI research. The caveat was that the available range would have to be very large, considerably above that which the present authors had ever seen in connection with VCR engines; the work by Haraldsson and co-workers showed that even a CR of 21:1 was too low an upper limit during transient tests of their modified SVC engine [17]. This ultra-wide-range VCR approach should also yield the possibility to increase the area of the potential speed-load map in which the HCCI process can be utilized very significantly, together with the ability to combust a wide variety of fuels of differing autoignition propensities. If such a concept were realized, and since inlet air heating would not be used as a combustion control parameter, such an engine would follow one definition of HCCI and not controlled autoignition (CAI) [14].

There is no reason why the true compression-ignition concept of an RCM should not be made to function cyclically; indeed, it could be argued that this was the original intention of investigating HCCI in reciprocating engines. Rapid compression-expansion machines (RCEMs) have been used for some investigations [18] and spark-ignition has been used in RCMs, too [19]. Thus there is a blurring between the functionality of engine and pure RCM. However, the use of a truly wide-range VCR mechanism to control the phasing of combustion and rate of stressing of the charge, and thus to control an engine in ‘pure HCCI’ over a practical speed and load range with commercially-available fuels and without the use of inlet air heating appears not to have been attempted.

³One could make the observation that the RCM probably owes more to the internal combustion engine than vice-versa, since the RCM originated as a result of a desire to simplify the study of fuel autoignition in engines [12]. It also permits study of small amounts of difficult-to-manufacture or unusual fuels which would be prohibitively expensive to test in continuously-operated engines.

The ability to combust a wide range of fuels would realize an 'omnivorous' engine. Consequently this is what the Omnivore engine project set out to do, in the process creating what is functionally a cyclic-operation rapid compression machine.

OMNIVORE ENGINE TECHNOLOGY COMBINATION

Against the background regarding renewable energy utilization set out above, the investigation of engine concepts incorporating technologies to improve the utilization of the renewable fuel energy supplied to them is of prime importance. At the same time, such engine concepts need to be capable of satisfying the requirements to emit cleanly in order to be relevant as concepts for future production vehicles. They also need to be productionizable at reasonable cost so that economics can be used to encourage their adoption. As a consequence, regarding the compression ignition of homogeneous premixed charges there is a bundle of technologies that support each other which are quite different to the direction currently being followed to improve tailpipe CO₂. Figure 2 is a representation of the technology interactions in the Omnivore engine and this section will discuss those technologies and how they relate to each other, starting with the need for VCR.

VARIABLE COMPRESSION RATIO

In addition to the potential for VCR to be a major control parameter in HCCI combustion as discussed above, the importance of the effect of compression ratio on thermodynamic and thermal efficiency has been understood since the beginning of the development of the internal combustion engine. VCR has also been at the heart of the process of rating both spark ignition and compression ignition fuels. In the early 1920s, Sir Harry Ricardo proposed the use of a 'highest useful compression ratio' (HUCR) in a standard engine in order to rate different fuels' knock resistance [20]; this concept was considered, but not adopted, by the Cooperative Fuels Research (CFR) Committee in the US since it would require very close production tolerances to be held in order for all test engines to be considered identical (and hence for the HUCR scale to hold across different test sites). Instead, a development of the concept was used whereby the use of VCR permitted the stressing of end-gas in a controlled manner such that, once a given level of knock had been obtained, a mixture of Primary Reference Fuels (PRFs) giving the same knock limit could then be found. This desensitised (but did not eliminate) the importance of the test engine and instead led to the adoption of iso-octane and *n*-heptane as the PRFs for spark-ignition engine fuels, with the volume percentage of iso-octane in bulk *n*-heptane giving rise to the term 'octane number' of a fuel [10,21,22]. The different test procedures - 'Research' and 'Motor' - followed, in turn giving rise to two octane indices and hence to the

RON and MON abbreviations commonly in use. The CFR engine that was designed and used for this test was thus of secondary importance to the PRF fuel qualities in defining a fuel's anti-knock capability.

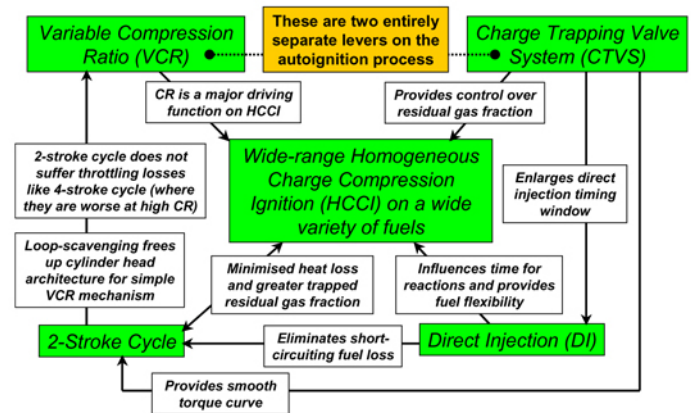


Fig. 2. Omnivore engine technology bundle interactions

Consequently the relationship between CR and the propensity of a fuel to knock has been understood for a long time and the ability to improve thermal efficiency as a consequence of its optimization similarly guides the choice of CR in production engines. The pragmatic reason for the use of fixed CR in production engines is, of course, the fact that incorporating a robust VCR mechanism against all the constraints of production engineering, NVH, durability, bill-of-material (BOM) etc. is extremely difficult in an engine employing poppet valves for its gas exchange process. However, the thermodynamic arguments in favour of VCR would, if a genuinely clean sheet of paper approach could be taken to engine design, make it *the* primary characteristic an engine designer would want to include in any SI engine. When this has been done in modern port-fuel-injection 4-stroke research engines (at the expense of significant mechanical complexity due to the presence of poppet valves), true engine downsizing is possible, and has been shown to be capable of fuel consumption improvements of 27-30% [13,24].

Therefore taking the need to incorporate a practical VCR system as a goal above all others, the fundamental question about the engine then becomes one of how to delete the requirement for poppet valves. At least one practical poppet-valve VCR engine has been shown which did not call for major architectural change [3], but its mechanism was still constrained by the presence of its two valves per cylinder and as a result its range of CR variation was relatively limited. Thus, accepting the architecturally-limiting effect of incorporating poppet valves, this leads one to want to delete them altogether and thus consider some alternative method of gas exchange such as a sleeve- or Cross-type rotary-valve or the piston-ported 2-stroke engine invented by Joseph Day [25].

2-STROKE OPERATING CYCLE

As mentioned above, removing poppet valves from a reciprocating engine in order to leave space in the cylinder head area for a practical VCR system requires the adoption of an alternative gas exchange system. A Burt-McCollum single sleeve valve engine was considered, but while such engines were shown to be superior to their poppet-valved counterparts in aeroengines before the advent of the gas turbine [26,27], a great deal of development would have had to be conducted in order to re-incorporate the concept into engines again. Alternatively, The simple piston-ported 2-stroke engine is free of moving parts in the cylinder head and so its adoption can become a key enabler in the adoption of VCR, and this configuration that chosen for Omnivore.

There are, however, significant challenges in the adoption of the 2-stroke operating cycle in an automotive engine, chiefly centred on oil consumption and emissions. The latter comprise both HC emissions from fuel short-circuiting and lubricating oil. Some of the technologies enabling emissions control in Omnivore will be discussed later. The primary concern, lubricating oil carry-over, can be addressed by adopting a wet-sump design with a long trunk piston, the oil control rings of which can be positioned at its base and which therefore do not have to traverse the ports. This is a common solution in larger 2-stroke engines and has been shown to be a workable solution providing oil consumption no worse than a 4-stroke [28]. Furthermore, rudimentary analysis of different types of engine suggests that piston-transfer-ported 2-stroke engines, as fitted to large ocean-going vessels, achieve a life 8-10 times that of an automotive engine (in terms of the total number of piston strokes they undertake during their lifetime), so bore wear should not be an insurmountable engineering problem in the automotive arena; the fact that piston-ported outboard engines require durability and reliability at least equivalent to light-duty road vehicles clearly reinforces this observation. In order to remove the need to use the crankcase as a pump, scavenge air can be supplied by external means, which is no more complicated than that required in a pressure-charged 4-stroke engine. This is the scavenging arrangement utilized in Omnivore, and a representation of the transfer port arrangement is shown in [Figure 3](#).

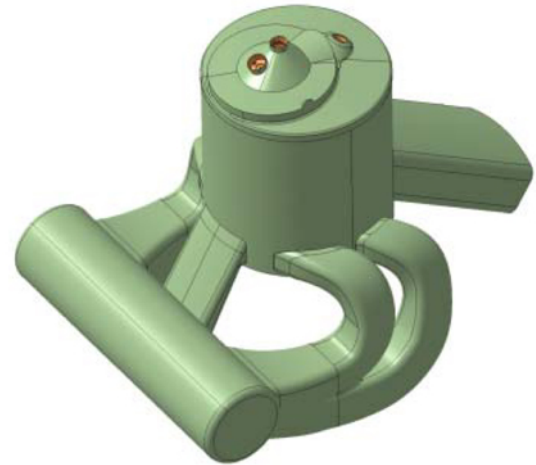


Fig. 3. Scavenge port arrangement utilized in Omnivore, showing manifold for externally-supplied scavenge air. Position of VCR 'puck' also shown at top of cylinder

Note that there is one more synergy between the 2-stroke engine and VCR: throttling losses increase in a 4-stroke engine as CR is increased, whereas the 2-stroke suffers almost no such demerit. Throttling loss at high CR and the knock limit of an SI combustion system have been shown to place limits on the efficiency of 4-stroke VCR engines [3]. Also note that, since it is fully piston-ported but utilises a variable charge trapping device affording asymmetric exhaust timing, Omnivore operates on a modification of the Day 2-stroke cycle with external scavenging [25].

DIRECT FUEL INJECTION

Accepting that the automotive engineering community should therefore be able to solve the issues of bore wear in vehicular applications, the primary emission concern is therefore short-circuiting of fuel and control of combustion. The first of these is addressed by using direct injection of the fuel. This is now a common solution in 4-stroke engines and which was pioneered by 2-stroke engines, primarily using airblast technology [29]. Airblast injection permits the rapid introduction and vaporization of the fuel in the combustion chamber and has been successfully productionized for outboard and scooter engines and demonstrated to be robust for automotive applications [30]. A form of airblast injection, developed by IFP and known as IAPAC, was utilised in the earlier ELEVATE programme [28]; IAPAC employed a poppet valve to time the introduction of air into the cylinder from a prechamber into which a low-pressure fuel injector metered its fuel.

The direct fuel injection system employed in Omnivore utilises a conventional low-cost fuel injector metering fuel into a prechamber which in turn communicates with the combustion chamber via a solenoid-controlled valve. The prechamber is fed with air at a constant pressure of up to 6.5

bar, with the fuel injector necessarily having to operate at a higher pressure of 8.5 bar in order to inject its fuel into it. The components used are all production items from outboard engine applications, in which the air is supplied by a dedicated pump and fuel pressure from a conventional tank-mounted pump; here air is supplied from the test cell high pressure air supply, regulated to the required pressure. Air and fuel timing and duration are both adjustable and in the case of Omnivore their control (plus all other engine control parameters) is undertaken by a modified production 'T6e' engine management system fitted to production Lotus vehicles.

The constraints on injection timing are that air injection (and hence fuel transport into the combustion chamber) ideally be after *effective* exhaust port closure and also that increasing cylinder pressure (due to compression) does not prevent mixture flow into the cylinder. This is effectively a very short period of time in which to deliver and atomize the fuel, but the use of the air jet through the very small orifice of the air injector ensures that this is achieved. In order to further enlarge the time window, however, a mechanism of closing the exhaust port early to trap as much charge as possible would clearly be beneficial; this is partly the reason for the adoption of the only 2-stroke-specific technology on the engine, the charge trapping valve.

CHARGE TRAPPING VALVE SYSTEM (CTVS)

The CTVS is an engine-speed cyclically-oscillating valve sited in the exhaust such that when the piston uncovers the port the charge trapping valve is in a position corresponding to its uppermost travel. It then moves downwards during the period up to the piston closing the port. Generally, the exhaust timing is thus piston-controlled on exhaust port opening (EPO) and CTVS-controlled on exhaust port closing (EPC). The effective port timing is therefore asymmetric, to the benefit of reduced fuel short-circuiting should it be necessary to begin injection before the cylinder port itself is closed (as is potentially the case in high-load operation).

The CTVS concept is well-proven and has been employed on several research engines [28,31]. The side of the valve which faces the cylinder takes the form of a hyperbolic paraboloid and at high speeds and loads is shielded from the hot gas flow during the blow down period by the back of the cylinder bore. Port closure is faster than with a conventional non-cyclic variable port device (such as Yamaha's YPVS system) because the trapping valve is descending with maximum velocity as the piston is rising in the opposite direction. One of the primary potential roles of the CTVS in Omnivore is to control the mass of exhaust gas trapped in the cylinder and so to provide one of the main controlling parameters for HCCI combustion; this has been shown to be important in autoignition timing in alcohol-burning 2-stroke engines [32].

As a consequence the opening and closing timing of the CTVS is continuously-variable and this and other specific aspects of it will be discussed in more detail later. An illustration of such a continuously-variable CTVS mechanism from a single-cylinder research engine is shown in [Figure 4](#).



Fig. 4. Components of a continuously-variable charge trapping valve

HOMOGENOUS CHARGE COMPRESSION IGNITION (HCCI)

SI combustion in 2-stroke engines can suffer in relation to that of 4-stroke engines because of misfiring at part load and the fact that overall-lean tailpipe gases preclude the use of a three-way-catalyst. The former is a corollary of the high burned gas retention (and thus lower charge purity of the 2-stroke engine) and the latter makes NO_x emissions problematic at the tailpipe. Some means of addressing these problems has to be found.

HCCI has been investigated for many years as a future technology for fuel consumption improvement in 4-stroke engines. In such applications, the areas of operation achievable, even with fully-variable valve timing, are nearly always very small in relation to the whole engine operating map. This is partly the result of the difficulty of trapping sufficient hot exhaust gas in the cylinder from cycle to cycle coupled with the fact that there is significant heat loss during the extra pumping strokes of the 4-stroke cycle. These issues do not exist in the 2-stroke engine: the high burned gas retention at part load then becomes a significant virtue, and the extra pumping strokes are not present. As a consequence, the 2-stroke cycle is arguably the ideal platform for HCCI combustion, and provides the opportunity for a very complete combustion process: Ishibashi and co-workers have demonstrated near-full-operating range HCCI - from 1500 rpm up to 9000 rpm and up to 3.5 bar BMEP - in a 2-stroke engine [33]. Furthermore, the issue of balancing compression and trapped heat in a fixed compression ratio 4-stroke engine