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Variable Compression Ratio Engines: A Future of Dynamic Efficiency

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I. Introduction

Low consumption of fuel, good quality of exhaust gas combustion, and a high degree of protection against knock are important demand for an ideal combustion engine. An increase in power of the motor is generally followed by a lower economical efficiency of the functioning cycle. An increase in performance can be obtained by decreasing the intake and by increasing the charge temperature before the compression and the compression ratio. The thermodynamic cycles for such ideal circumstances are analysed. The principle of the variable compression ratio engine is shown. The conception is proved on the experimental engine and the comparison with the four-cylinder four-stroke engine. Results of calculations for an eight-cylinder engine with a variable compression ratio and for a fixed compression ratio engine, steam cooled and turbocharged, are shown (Maxfield Mitchell, 2017). During the studies it represents that a variable compression ratio engine is a better and more economical solution from which a good advantage can be achieved on the market in the near future.

In the automotive industry, an increase in engine performance is an old idea. With higher engine specific performance, the engine becomes smaller and lighter. The purchase price is decreased. The known methods for an increase in performance as well as their limits in respect of coefficient of performance, resistances, size and mass, engine geometry, and actuated material are analysed. For the development of a new generation of engines with a high engine specific performance, the concept of a variable compression ratio engine is introduced on the basis of a theoretical cycle through which the performance and by which the construction concept of a new engine is derived.

II. Historical Overview of Engine Technology

Many of the internal combustion engine concepts which have been put to full-size use around the world have involved means to improve the engine thermodynamic cycle or efficiency, yet nevertheless without adding compression ratio change capability. To this end, increasing attention has been given to the higher thermodynamic cycle orders, notably De Rivaz and Miller cycles, and as it is often claimed, significant engine thermodynamic efficiencies can be obtained. However, they can be more demanding in terms of hardware and especially fuel feed geometry complexity as well as its calibration degree of freedom when compared to the more widely used Schmidt, Atkinson, and further even simpler cycle. The research directed at exploring possibilities for piston engine compression ratio change mainly put forward proposals based on split piston and variable eccentrically mounted cranking hardware.

The fundamental idea of thermodynamic cycle offsetting such as widely presented De Rivaz and Miller cycles is to offset the heat input and the heat removal timings through a longer zero piston movement of process 2-3 or 4-1 following a compression or expansion. Therefore normally no additional volume to tap is needed. However, for an obtuse angle difference crank mechanism, there is a phase reciprocatory wage form divulged for the second piston of process 1-2. The extent of such waste is found interfaced with the minimum of the total connecting rod-manifold geometry sizes, something which is of great importance for gasoline engine trucks. The lower cost engines with six cylinder crank but mainly liberty type linking are rarely applied in passenger cars while generally only those Overhead Valves or stems in the fuel port of the higher performance cars pick up a dual crank type.

The only feasible option of variable geometry is that of pistons scissor legged crank shaft offset. Based on its exploitation analyses, with the commercial vehicle single cylinder the engine noise and oscillatory power allowed frequency band widths would be tripled with its heat sine. Therefore, for the alternative engine types which can be simulated, in the future the hammer h run polyphonic charge detection and combustion focused knowledge would probably be put to use. Onwards its hardware design and testing is to be studied over the split-cycle engine with between-camera ducts as to improve its thermal efficiency. The simulation pre-study shows that virtual design involving complicated fluid characteristics can take less time even without simulations. Its insensitivity to feed geometry regarding enhancing efficiency compensates its low fuel switching costs and manufacturing cycle.

III. Fundamentals of Compression Ratio

Compression ratio is a vital engine design parameter influencing performance characteristics, emissions, and maximizing the potential benefits of new fuel types. This straightforward parameter can be challenging to precisely quantify due to its complex geometry and continually changing shape and volume. Modern computer aided design packages can provide insight for preliminary designs, while combustion models can help confirm performance characteristics. Tolerance stack up analyses and nonlinear curve fit estimates also provide deep insight into compression ratio distributions, and are discussed in further detail. Improving fuel economy remains the driving force for gasoline engine designers. Simulation models estimate efficiency increasing technologies, such as variable valve lift duration and extent, variable boost pressure, and down-sizing alongside boosting technology. One technology frequently overlooked is variable compression ratio, which has the potential to decrease fuel consumption rivaling diesel engines.

The compression ratio of an internal combustion engine is a crucial control parameter during engine design. This dimensionless number represents the total maximum volume within a piston cylinder assembly (VCAs), with respect to its minimum volume when the piston is closest to the cylinder head. Typical values for modern spark ignition (SI) engines range from 8:1 to 12:1, with direct injection gasoline engines achieving values as high as 14:1. Various methods are used by engine designers to adjust the target compression ratio, including placement or omission of structural material in the combustion chamber area. Operative parameters like performance and efficiency goals, fuel type, fuel quality, ambient operating conditions, and level of boost pressure need to be considered when evaluating the suitability of a target compression ratio (Maxfield Mitchell, 2017). The target compression ratio becomes a compromise intended to meet a series of conflicting requirements in the face of high up-front design costs, increasing development time, and tightening forecasted emissions legislations.

IV. Advantages of Variable Compression Ratio Engines

A variable compression ratio (VCR) engine is an advanced technology that alters the compression ratio (CR) of an engine during operation. The traditional CR used in gasoline engines is 10:1 to 12:1, while in a diesel engine it varies from 12:1 to 22:1. Although a relatively high CR is desirable for a gasoline engine because it leads to higher efficiencies by admitting a higher mass of fuel and air charge per cranking. The VCR engine concept can vary the compression ratio numbers from as low as 6:1 to 14:1 in a knock-prone, gasoline, Otto cycle engine. The objectives of the VCR engine are to maximally increase the thermal efficiency, to increase the load limit, and to remove the diesel engine at high CR (S. Ukidave, 2011). The performance evaluation of the VCR engine vs. conventional fixed CR engine shows that the VCR engine assays higher unboosted indicated thermal efficiency by 2%-5% at the same IMEP of 450 kPa of every point tested with more than 50% of its operation at no load, part load, and full load during city and highway driving cycles. With boosting, the VCR engine outperforms conventional engine superiority by up to 10% and similar levels relative to 15:1 fixed compression ratio gasoline engine from prior studies.

The nature of the VCR engine allows the engine calibration engineer to keep the forces within the engine consistent and relatively low. During low-power operation, the engine can operate at a high CR to keep efficiency high. When maximum power is requested, the CR can be lowered significantly (Maxfield Mitchell, 2017). This second feature allows the VCR engine to be much more flexible in the tuning of both the fuel and ignition timing maps. Reduced parasitic losses during low-power operation extends the low-throttle opportunity for engine-off and FE improving Electric Power Assist Hybrid Control Logic can be employed in such scenarios with immersive value over a non-VCR engine. During maximum power operation, the outputs of both engines need to be so tightly controlled that the position of the ignition timing maps are already determined. With independent ignition timing and CR tuning, the VCR engine at worst covers only the instance values of the fixed CR tuning. The prospect of designing a VCR engine leads to many performance and FE advantages. The structural and friction analysis carried out have shown that such a design should carry no inherent weaknesses.

4.1. Improved Fuel Efficiency

Most diesel engine manufacturers have implemented turbochargers and superchargers for boosting purposes, but boosting technologies for gasoline engines are still not popular. The variable compression ratio, if applied to gasoline engines along with a boosting device, can be as efficient as diesel engines. The selection of compression ratio for a gasoline engine is based mainly on the knock limit at high load. Engines often have to be designed for a lower compression ratio than they can withstand at part load. The knocking tendency of an engine at part load is considerably less, allowing for higher compression ratios, but if the engine has a fixed compression ratio, part load efficiency is affected. Most engines operate at part load for most of their life-time, resulting in a considerable loss of fuel efficiency. A solution is to downsize engine displacement along with the implementation of boosting and variable compression ratio capabilities. Downsizing moves the operating point of the engine to a lower BSFC zone by increasing specific load and decreasing friction and pumping work. Downsizing reduces fuel consumption and friction, while increasing losses associated with the compression ratio and reduced displacement. However, during downsizing, the compression ratio has to be reduced due to knocking. To overcome this loss, variable compression must be attained with modifications in the engine's configuration. (S. Ukidave, 2011) formulated an optimal control strategy for fuel control in SI variable compression ratio engines. Variable compression ratio engines add a capability to reduce the compression ratio, which can help avoid knock, posing a vital question of selecting values to obtain the best engine efficiency. studied the dependency of engine efficiency and IMEP on compression ratio and ignition timing at various load and speed conditions.

4.2. Enhanced Performance

Tom Intake Stroke is the first stroke of the cycle when the piston moves from TDC to BDC, air enters the combustion chamber through the open intake valve. This is also known as 'intake stroke'. As the piston starts its downward stroke, the intake valve opens and air is drawn into the cylinder. Air is sucked due to the reduced pressure inside the combustion chamber. The motion of the piston is towards the BDC end and the crankshaft turns by an angle between 0° and 180°.

The conditions that yield the best trade-off for in-cylinder aerodynamic flow that generates good mixing of fuel and air along with low levels of intake flow-generated noise contribute to the in-cylinder flow conditions. This flow is characterized by a tumble, swirl, and jet motion, with a spectral distribution characterized by a peak turbulence scale of approximately 0.75 ms. During the intake stroke, the excess fresh mix entering the cylinder accelerates and tumbles around the valve, forming concentrations of fuel and air.

Compression Stroke is the second stroke of the cycle where the incoming air is compressed. The piston of the engine compresses the air and the pressure and temperature are raised. After this action, when the piston nears the TDC end, both valves get closed. At this position, the combustion chamber is filled with compressed air at a very high pressure and temperature. The combustion chamber is connected to the engine's cooling system but is also insulated. This is also called the 'compression stroke'.

This chamber gains heat from the combustion of fuel and the temperature further increases even more to a value higher than that of the auto ignition temperature of the fuel before the spark plug is fired. There is enough friction due to the heat thus lost during the compression that the heat is not also removed. The charge compression induces an increase in combustion gravity flow acceleration. The compression wave convolution with the combustion turbulence is staggered until the coarse turbulence passes and elapsing almost the whole cycle, while the fine turbulence is developed immediately after the ignition advances depression. By further increasing the turbulence, the consumption rate similar to that in the case of the ignitions are just at the TDC top is also computed. The combustion is characterized by the shorter length-scale turbulent length mixing time with the finer turbulence only developed after the piston at the middle line of the cylinder which bears less compression ratio wave convolution than that at the TDC top case (S. Ukidave, 2011).

4.3. Reduced Emissions

Increased fuel economy has been the holy grail of automotive technology. Most of the solutions around this problem are exhaust after treatment devices, hybridization, variable valve timing, downsizing, turbocharging, direct fuel injection, and cam phasing. All these solutions aim to come up with new methods of combustion to recover lost energy. However, no one seems to look at the intake side. Current intake methods can achieve very high volume of air delivery when the car is on WOT. To put it in simpler words, the intake system allows for more dynamic charging of the engine. When the speed of intake is higher than the speed of outtake, it leads to a net gain of air in that cylinder over the previous cycle. This gain is very much well rehearsed in diesel engines where EGR is plumbed into the intake manifold, which leads to the scavenge process. In the process, more air is inducted to the chamber by using an EGR pump and this lowers overall NOx emissions and delays combustion, which avoids knocking. With this background, it is a very well-known fact that in naturally aspirated SI engines, the timing at which the intake valve closes is crucial in deciding the air delivery capability of the engine and its complete combustion. In general, keeping the intake valve open after TDC helps retain air in the system and be more forgiving of geometry layout like web space issue while keeping the engine compact. However, this has a huge tradeoff on fuel efficiency of the engine which is a side effect of larger effective compression ratio (ECR). Increase in ECR leads to excessive thermal energy generation and active combustion which raises the NOx levels as well as overall throttle body pressure and losses due to pumping. This means that at high EGR values, the timing at which the valve closes is not only varying and advancing but is also limited parametric slew rates to less than a modicum of milliseconds (S. Ukidave, 2011). On the other side, an oversight is taken on this aspect, making engines more fuel inefficient. Higher effective compression ratios (ECRs) lead to reduced late cycle combustion, which consequently lowers fuel consumption due to less fuel being burnt to produce the same amount of power. Late IVC leads to reduction in effective ECR which can help retain boost pressure in a boosted engine for any given mechanical efficiency. Hence, alternate ways to capture the available air are either to increase the temperature of in-cylinder fluid using hotter exhaust gas through EGR or reduce the effective ECR (Lu, 2016).

V. Mechanisms of Variable Compression Ratio

The Variable Compression Ratio (VCR) turbocharged engine with a geometry adapted from the Nissan design and a combination of alternative dual-hinged and single-hinged rotating arms and links has been successfully designed. By reducing the existing designs to parts that worked best and creating a new mechanism, an engine geometry was submitted. By employing only simple prismatic joints, four design combinations of varying complexity were produced. After multiple modifications, the refined design of choice was a combination of a hybrid mechanism using both a dual-hinged and single-hinged approach. The hybrid approach simplified the single-hinged arm to eliminate the need for intricate machining. A part-simplified model was produced for submission. However, while the gears and components of one engine arm were able to be printed with available 3D printers, the second arm took too long to print and failed early. The gears on the second mechanism were too thin, causing them to break before sufficient testing could be completed. The dual hinge design rigidly altered the geometry of the engine, allowing the analysis of adjustable compression ratios.

Through several iterations of geometry and design, a VCR mechanism was proposed. Although the switching mechanism produced a more rigid means to switch between compression ratios, it was much more intricate and mechanically difficult to manufacture. Simpler designs were later produced, but due to the complexity of the geometry and the machined parts, long manufacturing times and difficulty assembling were anticipated. A hybrid mechanism was ultimately selected where one arm of the mechanism contained some of the more complex forming joints while the other arm was a simpler arrangement of prismatic and revolute joints. During manufacture, limitations in time and printing techniques made assembling both full arms impossible. A better understanding of how to create complicated components using CAD software was learned, which can be taken forward into further studies. However, alongside this achievement in understanding how to design and manufacture complex parts, an inability to fully manufacture and test the proposed mechanism was a disappointing consequence of the project. With the option to create gears or mechanisms using CAM or production methods, constructing a fully working full mechanism is within reach but must be postponed for another occasion (S. Ukidave, 2011).

5.1. Mechanical Systems

In recent years, automotive manufacturers have invested a significant amount of capital and time researching new combustion engine designs. Some of the designs included researching completions to the standard spark ignition and compression ignition engines already on the market. One such design that offers a prospect of efficiency and performance improvements is the variable compression ratio (VCR) engine. This kind of engine would allow the performance calibration engineer to optimise the balance between performance and efficiency depending on driving conditions (Maxfield Mitchell, 2017). The nature of the VCR engine allows the engine calibration engineer to keep the forces within the engine to consistent and relatively low values. The thermodynamic benefits of the VCR engine are clear. During periods of low-power operation, the engine can be set to operate at a very high compression ratio to keep efficiency high. When maximum power is requested, the compression ratio can be lowered significantly so that the onset of turbo boost pressure does not cause structural damage to the engine.

Unfortunately, the nature of most current VCR engines means that this operation must be pre-calibrated and the architecture of such an engine means that it carries a weight and cost disadvantage. However, a design has been conceived from scratch that, based on a mono-block construction, and an extremely smooth and simple mechanical architecture, is capable of higher and faster ranges of motion than existing VCR hardware. As a result, the variation of dynamic behaviour that can be achieved comes much closer to replicating an ideal VCR engine. This better-performing architecture has been studied and verified using top-level dynamic analysis. The prospect of designing a VCR engine for patent protection would carry many performance and efficiency advantages. It is capable of having a very simple mechanical system and a very effective tether to maintain the accuracy of movement hence avoid any backlash which is often a crippling problem in existing designs. The structural and friction analysis have also shown that such a design should carry no inherent weaknesses, and is worthy of further study.

5.2. Electronic Systems

A mechanical variable compression ratio (VCR) engine relies on its electronic systems for synchronous operation. At the time of this research, information was scarce on this topic and much of it was acquired by contacting other industries that deal with similar problems. The most varied feedback came from the market of power generation gas engines. These engines share a very similar concept of operation with automotive VCR engines. However, some modifications were made with respect to power generation engines in order to comply with speed and weight constraints. Because of the size of the automotive application, the flexibility of water-cooled and on-board engines was fully explored. Also, an internal circuit board was developed, which would be located at the top of the transmission tunnel by close contact to the engine control unit. This would help minimize the wiring harness necessary for interaction with the engine. It was pointed out as well that both mechanical calculations and design aided necessary backups at engine measurements and data analysis should the need arise.

The electronic systems are the most complex subsystem of the VCR engine. There are several inputs and outputs, plus control algorithms that need to take into account all scenarios that could arise during engine operation. These are reasons for needing outside help from a consultant specialized in automotive electronics. The general architecture of the system uses as a foundation a microcontroller by which all sensors are connected. Though this decision results in a somewhat less modular system, it allows for easier control algorithms programming and data handling. This is especially important when designing the engine more toward the concept of an automotive prototype along with the durability tests.

Within the limits of the project, a common VCR implementation for the performance of calculations in post-processing was ascertained. The concept of a counterweight position with respect to the crank center, which dictates the mechanical compression ratio at every crank angle, was determined to be a good modeling approach. The major equations commonly used were acquired, including those linking crank angle to geometrical dimensions and calculating the various forces resulting from the gravity on the swinging counterweights. The latter thrive on a lighter engine block, which is a strong necessary path to its implementation. One option foresees an aluminum engine block, which is extensively used in engines today. Though the engine would wear on its bearings faster, fatigue measurements and redesign on other critical components would ensure tear and wear slow operation at track tempo.

VI. Comparative Analysis with Fixed Compression Engines

Variable compression engines or systems where the variable compression ratio mechanism is alone responsible for this variability. By far the most common design has been that of a mechanical actuator on the connecting rod that varies the angle between the connecting rod and the piston pin centerline. The latter rotates about a fixed pivot point for the moments of the two are the same at various crank angles on the fixed crank. For truly variable compression these designs will change the fixed pivot point for various crank angles so the crank can be moved in and out relative to the upper crank pin. This design is the principal one used in turbocharged diesel engines. By lowering the compression ratio the engine can be turbocharged without the need for a wastegate. Simultaneously meant less late in the cycle which caused high elevations in combustion in the area adjacent to the spark plug. The ratio varies from a finite parabolic upper limit to about twelve to one. One advantage of the engine is expansion ratio can be varied as well as the compression ratio this feature permits the extension of MECR while the efficiency loss incurred by rejected exhaust gas to the hot reservoir only becomes significant. This minimization of rejected exhaust gas is particularly important in automotive applications where the volume of the exhaust gas system. The increase in volume fraction of the working fluid which is not made accessible to the heater is particularly esoteric when the engine is downsized due to ever more burdensome market driven restrictions. The engine counteracts this by permitting higher firing pressures without an increase in piston cylinder area. There are a few conditions under which piston engines out produce turbocharged diesel systems. Additionally the lower concentrations of unburnt hydrocarbons at low loads make the diesel engine more desirable from a point of view. Its wide span of pressure ratios however leads to an answer primarily desired by the numerical analyst. Variable compression ratio engines exhibit a minimal energy surface which has a zero value at the level of emissions. As the ratio limit or dimensions indicate a forced response driven by exhaust additives a flipping point is reached whereby engine response persistently fails to track in a stable fashion. Variable compression ratio downsizing is a method adhered to by engine designers currently.

6.1. Performance Metrics

The performance metrics for the Variable Compression Ratio (VCR) engines are fuel economy and power output. The state-of-art fixed compression ratio engines have a fixed optimal point of Load with an associated specific fuel consumption. The fuel economy drastically drops off at Load values above or below that point. Variable compression ratio provides the capability of operating on a broader range of Load with a much smaller variation in specific fuel consumption, thus improving the fuel economy of the engine. VCR engines provide a broader range of power output with a minimum number of mechanical parts in comparison with a boost pressure or throttle valve option. The power output is proportional to the air-fuel mixture intake density which is in turn highly dependent on the compression ratio of the engine.

The fuel economy of the internal combustion engine is highly dependent on its thermodynamic efficiency which is determined by the compression ratio (CR). An increased CR results in improved thermodynamic efficiency and improved fuel economy. However, an increase in CR also leads to greater combustion of the fuel-air mixture and results in excessive pressure and temperature, and consequently engine knock. To overcome this limitation, a combination of boost pressure control and VCR is proposed for gasoline engines for improved fuel economy with the best compromise application of engine power density and cost. By changing steering, lift, and lateral positioning of two fixed racks, the VCR is varied (Maxfield Mitchell, 2017). The two dedicated Engine Control Units, controlling the engine boosting and VCR controls, respectively, share information through the Engine Process Unit. This design enables free provision of boost pressure, CR, and Exhaust Gas Recirculation conditions and their set-point variation by switching the mode of control actions.

This unique function of satisfying specific performance criteria by adjusting the engine operating parameters produces a new type of engine control system for preproduction engines with the prospect of obtaining effective vehicle regulation methods with less complicated mathematical models. Alternative application of the VCR provides an option for synchronous run of the boosting and VCR control actions for the best compromise regulation of driving performance, fuel economy, and emission with the best control transfer characteristics. The further development issue would be improvement in control accuracy and response rate of the VCR control system.

6.2. Cost Considerations

Research is currently being conducted into the cost of variable compression ratio (VCR) engines in general and variable control VCR (VVA-VCR) techniques in particular based on knowledge gained from the retrospective assessment of ω-VCR engines. A simple answer to the question of cost is required but several factors will affect the cost of systems designed to meet the increase in compression ratio requirements of new VCR engines. Among the straightforward, in principle, considerations is the cost of extra components across a range of potential configurations. More difficult is apportionment of costs between suppliers and original equipment manufacturers (OEMs) (Turner et al., 2014). Another consideration is likely manufacturing volume and lead-time for delivering new parts and/or new castings. Automakers tend to design engines in family groups that share tooling for as many components as possible, which aids mass production. Which engines can be categorized as low or high volume also changes over time, examples of the former recently being cylinder deactivation and 2-stroke diesel operation. Even some once high volume engines have become obsolete as skill levels and manufacturing processes have changed.

Some added costs might not be directly construction-related, for example extra vehicle vibrations from increased engine complexity and extra dimensions in the vertical direction (S. Ukidave, 2011). Other considerations might be how inexpensive parts can be procured and how difficult it is to obtain through-life support. Risks of aftermarket support difficulties are greater for small or prototype suppliers, in which case OEMs would need more auxiliary fixed costs or pre-support manufacture. As a result, there is a range of uncertainty in cost estimations of new car technologies. When must costs be recovered, and over what period? Generally speaking, effort is better aimed at finding simple and cost-effective technology that can then be mass produced.

VII. Challenges in Implementation

The VCR technology unfortunately has associated challenges which must be overcome or worked around in order for the technology to continue to develop and mature. The challenges can be classified into engine design challenges, VCR mechanism design challenges, and control challenges, with the engine design challenges being broad enough to include external integration as well. This section will describe each of these challenges in further detail and discuss potential solutions, where applicable (Maxfield Mitchell, 2017).

Aspects of VCR integration that impact the design of the engine have been identified as engine design challenges. Some of these challenges are shared by other technologies as well, while others are unique to VCR engine technology. The first of these challenges is the difficulty of pairing the VCR mechanism with other engine technologies or features. Engine design is a multi-faceted process involving a variety of trade-offs between competing requirements with huge implications on performance, fuel efficiency, and manufacturability. Another issue observed with VCR engine technology development is the unusual complexity of some of the designs. Several VCR mechanisms in development today can be considered significantly more complex than conventional engines, which tend to use an unchanging geometry of planar surfaces. Such complicated designs may have positive implications on some performance metrics, but they also tend to have considerably more components than conventional engines, which affects manufacturability, durability, and as discussed previously, cost. The difficulty in VCR mechanism integration with modern injector technology is also significant and impacts a variety of performance metrics including economy, emissions, and power. These challenges can be addressed through time and R&D, but on the whole are relatively high hurdles to overcome. The dangers of pursuing VCR technology without careful insight are manifold and should be duly noted by those seeking to commercialize engine technology locally, as well as those seeking to enter the IC space in general.

7.1. Technical Challenges

There are three main technological challenges in the development of VCR engines. First, the variable compression mechanism must achieve adequate response times over the engine operating range. Second, to really maximize the benefits of VCR, a variety of engine architecture and fuel types may be considered; thus, a VCR mechanism must be flexible enough to be integrated into a wide variety of individual engine geometries. Third, controlling an engine with a variable compression mechanism presents new challenges that need to be addressed.

Mechanical fast-acting variable compression mechanism. At the moment, the design philosophy is to develop the mechanism in 'stages' with the initial design for a simple small serial cooled I4 engine (1.4L displacement) operating in conventional SI mode running on regular unleaded petrol, with an initial simple control strategy based on load and speed signals. There is also an aggressive strategy to develop VCR engines with other geometries and technologies.

Alternative engine architectures and fuels. To maximize the potential benefits of VCR engines, it would be ideal if the VCR technology could be used with many engine architectures, e.g. diesel, HCCI, MCEI, Wankel, and fuel types, e.g. non conventional si, ethanol, biofuels, and hydrogen. An encouragement in moving in this direction is that as VCR mechanisms are invented for very different engine architecture, there is an increasing need for trade-off studies to decide on the 'best' mechanism for a given engine technology before considerable time and expense are sunk into development.

Developing control strategies. Changes of controllable inputs in any combustion engine control system will inevitably affect other behaviour variables. Consequently, the control problem becomes one of coordinating a number of inputs to achieve the desired engine operation. In a VCR engine, more input control parameters are available to the engine control processor. A wider control exploitation range of operational flexibility is expected thereafter (Maxfield Mitchell, 2017).

7.2. Market Acceptance

Currently, the automotive engine market is undergoing a paradigm shift owing to science, legislation, and consumer awareness. There is much attention being paid to CO2 emissions from road-going vehicles and discussions regarding the establishment of legally-binding limits on such emissions. Although, in the past, tests to measure such emissions were conducted on a Rolling-Route Durational-Cycle (RDDC) with the vehicles stationary, the present trend has moved in favor of on-road portable devices. Such emissions propensity was modestly controlled mainly by the retarding of combustion by the use of EGR or the advancement of injection timing with the latter usually causing a fall in fuel economy. Fuel consumption restraints are similarly manifested through either a lapse in vehicle features such as gears and pumping capacity or the use of a variable geometry turbocharger (VGT). As existing vehicles are basically fixed ratio engines, it was common to view the vehicles' need through an auxiliary technique to secure a load-sensing action. Essentially the latter means that an engine, as well as a vehicle, uses a feature quite similar to a patent held by Harrison in which the clearance volume in a cylinder could be varied at will to accommodate load deviations. Such feature manipulation allows the same engine to tolerate both low and high load cases as well as both low and high NOx emissions levels, as such emissions level increase with compression ratio and boost respectively.

Utilities in trade have equally been cognizant of market changes and the penalizing upset caused as a consequence. Even if in a peculiar market a suitable vehicle design is produced, such an evolution through a mobile platform must also accommodate unlike currencies, grammage, aerodynamics, terrain, and legislation. There is a growing awareness and pride in variable compression ratio, variable valve lift, and variable geometry turbocharger designs although the last of these is, according to a recent publication, no saine solution aside from catalysis (Turner et al., 2014). Consumer awareness by vehicle make or engine features is thought to be in the domain of engineering although there are some remarkable exceptions such as Audi's Direct Injection petrol engine which delivered 19.96 km/l. The public perception of such an advanced technology in the eye of the media is temporary and usually gives way to the next example promulgated. Only with a preference or unqualified dependence on a vehicle maker brand will any considerable parentage of such advanced technology survive. Nevertheless as emissions limits appear to tighten in search of substantial LOE at markedly low NOx, a winning edge in technology or a single engine concept may take on additional salience. The success of the CNG and leasing business models in the past decade can be put forth as an example of how cognizance can vacate engineering wisdom in the face of greater salience and capex.

VIII. Case Studies of VCR Engine Applications

The advantages of commercial VCR engines alluded to in the previous sections are at the core of continued developments in the technology. Further experimental validation of VCR engines, assessment of VCR hybridization options, additional analysis of alternative configurations, and continued design work were undertaken to evaluate the options for happiest paths moving forward. These case studies evaluate the VCR_OEM VCR hybrid design option that was deemed to be the most promising in previous analysis for OEMs of larger freight trucks, as well as a custom prototype test for a compression ignited patent VCR engine that was put into initial tests. Additionally, early mechanical designs of alternative configurations analyzed previously are presented. The results of these case studies point to the need for continued detailed analysis and design work on compression ignited VCR engines, and for further experimental analysis of VCR_CVVT mechanisms and commercial VCR_hybrid options.

The potential savings with VCR_CVVT engines with heavy duty diesel applications were investigated. VCR_CVVT engines feature VCR_EE system combined with continuous variable valve lift and duration parameters. The associated hydraulic elements of the variable valve system were significantly reduced in the new designs. Both hydro-mechanics and custom hydraulic, pilot valves were integrated into the design. Both simulations and hydraulic load inputs are used to control the CVVT/hydraulic mechanisms in real-time. Given the extremely high nonlinearities and model uncertainties associated with variable valves, robust hybrid control was designed to achieve fast and precise tracking of the full valve maps. Implementing VCR and CVVT systems deserves large R&D efforts with unprecedented challenges for heavy duty diesel engines. A simulation platform was constructed to optimize the framework and comb-vibes of VCR and VVT systems. Alternatively, VCR_EE methods require complicated mechanical designs. A unique VCR_UE method was also proposed to apply hybrid combination crank-piston systems. Comprehensive modeling and control are deemed challenging and future works.

8.1. Automotive Industry

The automotive industry is confronted with an imperative to address energy consumption, environmental impacts, and costs associated with exhaust emissions (Turner et al., 2014). With regard to energy consumption, there has been pressure on the energy suppliers, particularly with regard to the impending depletion of cheap fossil fuels. In general, optimism has arisen regarding the availability of continues energy supplies from sources which do not impact on ecology. However, they may never provide a useful alternative on a commercial scale. On currently available fossil fuel resources, there are rising concerns on ultimate costs, but for the time-being cheap hydrocarbons are likely to be available. In western industrial countries, regulatory authorities have enacted legislation aimed at enforcing deep cuts in CO2 emissions from vehicles. Such legislation typically aims for a 50 percent cut in CO2 emissions in the medium term, i.e., by about 2020. There is a widespread belief that significant cuts in exhaust emissions can be made without major redesign of engines and powertrains. This has been informed by the past success in dramatically reducing exhaust emissions from both diesel and gasoline powertrains in significantly lower costs for vehicle manufacturers and customers. However, this success has been achieved by mass production and by implementation of key technologies developed over decades of research at significant cost. This success has depended upon the ability to exploit margins in the amount of complexity which can be reliably imposed on designs. This is likely to be more challenging for CO2 legislation, which is based on the well understood technology of thermodynamic conversion of energy to power. There already exist advance engine concepts which are capable of reducing CO2 emissions to an extent that would meet the demands of even the most stringent proposed enactments. However, these are traditionally very difficult and complex systems to fully understand and to introduce into mass production fleets, in contrast to more conventional designs whose operation is well-situated within the limits of capability of powerful mathematical models. Simply expanding the existing toolbox of engines, powertrains, and related technologies would seem to be likely to lead to a wealth of ill-explained modern designs all operating close to or against their limits of design.

8.2. Aerospace Applications

The increasing global concern regarding greenhouse gas emissions from aircraft engines has prompted manufacturers to seek ways to improve propulsive efficiency. Improving efficiency is achieved primarily by raising the bypass ratio (BPR) of the engine in larger aircraft. For small business jets and regional jets, raising the BPR is limited due to aerodynamic and weight constraints on the engine. This knowledge led designers to adopt jet engines with a high bypass ratio, akin to those on airliner aircraft (Maxfield Mitchell, 2017). However, while ensuring economic operation during long-range cruise, high BPR jet engines proved less efficient during takeoff and approach. Hence, there is a need to provide high engine performance on takeoff and landing; nevertheless, a smaller front fan's weight and size impacts ease of servicing and installation. Consequently, jet engines have been constrained to a lower bypass ratio than turboprops.

Turbo-shrouded fans with a higher bypass ratio than conventional turbofans have enhanced aerodynamic efficiency for subsonic commercial aircraft, but with a significantly higher weight and noise penalty, primarily due to the addition of a gear box and variable pitch fan blades. Currently, there are no existing jet engines capable of delivering the required high performance and low noise for existing shrouded fan designs. In the short to medium term of the proposed blended design, twin-shrouded fans with a lower bypass ratio than current turbofans have been included.

With flight speed growing, the possibility of reverse thrust jets on tilting aircraft could take center stage, fulfilling both climb and cruise operating conditions efficiently. The present invention comprises a mechanism for varying either the compression or expansion ratio of an internal combustion engine to enhance performance at part throttle and/or low load conditions when compared to a conventional design. The proposed design seeks to mitigate these issues by optimizing the engine to provide high performance conditions, both at takeoff and cruise.

IX. Future Trends in Engine Technology

Considerable research has been done in recent years to develop engines which allow adjustment of the compression ratio. Variable Compression Ratio (VCR) technology provides a new degree of freedom to engine designers, along with added complexity and weight. The operating conditions of a VCR engine are used to control the compression ratio as needed. Engines for automobiles often experience widely varying operating conditions, from cruise to full throttle, and from low ambient temperature to high. The standard Fixed Compression Ratio (FCR) engine does an adequate job of consuming fuel for a wide range of conditions, but its performance, emissions, and efficiency can all suffer at some points within its operational envelope. With VCR technology, these problems can be alleviated. An example scenario describes a driving situation: a driver pushes down on the accelerator, demanding power from the engine. An FCR engine would respond by fully opening the throttle plate. The engine would begin to operate with very high volumetric efficiency, sucking in far more air than it could combust. This increased air fuel ratio would result in unburned fuel in the exhaust, and a failure of the engine to meet emissions standards. A VCR engine could respond to the increased load by adjusting the compression ratio downwards within seconds. This could prevent performance loss and allow the engine to combust all of the air fuel mixture. Further, because of the increased mass of air being combusted in the same volume, the power density would also increase (Maxfield Mitchell, 2017).

Many methods of VCR have been proposed, from designs as simple as selecting the height of a combustion chamber, to mechanically complex camshaft configurations. Presented here is a thermodynamic analysis of one of the most popular of the mechanically complex methods: wedge-style VCR via a moving slider. A graphical, yet mathematically elegant form of the compression ratio vs. throat size equation is presented along with a step by step derivation. A modified version of the Woschni heat transfer model is utilized in conjunction with standard gas combustion equations to establish a full combustion cycle model, with constant pressure of combustion, finite rate of combustion (D Gerty, 2005), and linear burning rate.

These models are used to compare an FCR engine with a VCR engine holding a constant CR of 10 during the ECE-R40 test driving cycle. Estimates are made for throttle and VCR actuation time as well as VCR computational time to arrive at the conclusion that these engines can fully capitalize on the advantages of variable throttling. Power density is predicted to increase by a factor of 14. Efficiency at testing cycle average conditions increases by 72.5%. On cycle estimates of HC emissions decrease by 81%. There is still much room for improvement in these VCR designs, in order to fully capitalize on their advantages over fixed compression ratio designs.

X. Regulatory Implications

A more informative title will enhance the article's description. A more appealing title will boost readership (D Gerty, 2005). Variable compression ratio (VCR) engines require higher levels of technology than most production engines currently in operation (S. Ukidave, 2011). Compression ratio has changing characteristics of performance like any other engine parameter such as ignition timing, coolant temperature, or fuel composition. The compression ratio settings vary with intake charge temperature, pressure, fuel type, and internal geometries of an engine at one point of operation that is normally defined by its speed and load. Engines so far are capable of working only at a fixed combination of these variables. However, some modifications are still possible with some costs in design, performance, complexity, reliability, and extra weight. Although these problems may have made the VCR engine far from practical considering today's engine design, it is an undisputable fact that burning fuel in a correct and efficient manner is crucial in considering a modern engine. Several engine designs, concepts, or prototypes with VCR mechanisms exist. One of the more practical variable geometry ideas was developed by HRS, which uses movable metallic pieces to add compression in a V-8 engine. Though some of the ideas look very futuristic and exciting, the more silent operation, as well as the choking of design with an extra valve, are key factors to be tackled by further development. Then on the other side of the millennium, some companies seem to have advanced a lot more by engineering their ideas out of laboratory simulations into full production units. There are continuously swinging pendulum schemes, pivotal floating lever setups, or more still rotating and winding belt-based designs. Many patents exist illustrating radically novel designs. The state of the art of combustion engines promise new research and development in either VCR engines at the engine unit level or VCR engines incorporated into larger systems, signalling a new research boom for engineers, energy modelling, and consumer electronics. On the other hand, production engines based on the VCR concept make a rapid albeit slowly accepted market breakthrough.

10.1. Environmental Regulations

Global climate change and urban air quality are evolving, formidable challenges for local and global governments (Lu, 2016). In light of the limitations of existing engine designs and their emissions calibration to meet regulations levels for pollution and fuel economy, advanced combustion concepts are necessary. Redesign of the combustion system is a viable and effective way to reduce emissions, which are fundamentally linked to combustion physics. The new combustion system must be examined in a holistic manner to see the fuel economy impact versus clean combustion offset. The VCR capability of a piston and new turbocharger designs are necessary in addition to the ring pack and bore finish specifications to minimize crevice volume and blowby, respectively. Advanced combustion concepts with VCR can increase thermal efficiency while maintaining the same specific emissions as the baseline engine. Turbocharger flexibility can be leveraged to improve the volumetric efficiency of compression ignition (CI) engines at high engine loads (Maxfield Mitchell, 2017). This offset the fuel consumption increase from emissions penalties due to required of new low temperature combustion. Enhanced measurements of transient behavior and dynamic flexibility are needed on test engines for relevance to regulations cycles and for guidance for simulation of advanced combustion concepts. Motor vehicle exhaust and evaporative emissions are complex mixtures of gaseous and particulate pollutants having significant health and environmental impacts. There is both significant heterogeneity in chemical composition and transport properties of particles produced from a single combustion source and also differences between different sources, especially from laboratories burning fuels or lubes differing from field conditions. Particle sizes may encompass the sub-nanometer range for the volatile mode at the low end, all the way to tens of micrometers at the high end, with implications for their potential health impact. Many of these processes are implemented in computer codes for simulating the engine combustion and operation that in the past two decades proliferated in academia and industry when the computing power of personal computers grew several orders of magnitude higher.

10.2. Safety Standards

Protocols are under development worldwide to enhance safety and exhaust emission standards for alternative fuel and energy engine vehicles. Codes and regulations currently exist, or are currently being adopted, for vehicles operating on compressed natural gas (CNG), liquefied natural gas (LNG), hydrogen, methanol, ethanol, and electricity. All vehicles must be capable of being determined as stable and sufficiently safe for public use. Such considerations, in tandem with regulations covering public health and safety, environmental impact, physical security, and fuel transfer, etc. may limit engine design and fuel options to varying degrees. Certain fuels may require a higher overall energy density than liquids for long range vehicles, but may be too heavy and compact for any form of mobile storage technology. Fuel stored with equivalent energy density typically requires higher compression ratios for optimal engine operation. Exigencies leading to catastrophic failures of the fuel storage system can be aggravated by fuel type and energy density, resulting in different probabilities and consequences of accidents, impacting the relative safety attributed to different alternatives. A new automotive engine type rarely appears without an application in a military vehicle. Military applications often demand higher specific power at lower weight and bulk than conventional vehicle engines. Highway vehicles must also deliver a higher effective torque throughout a broader range in output speed than explosive gas engines. Hence, cogeneration is an area where new engine types and fuels may be considered. Most applications of automotive engines are best satisfied by low cost engines that are extremely durable under rules of thumb of around 150 divisions of operating speed range. Extensive market forces combine to constrain the optimum sectors in weight to power and performance to mass. Despite such confines, over half a century of intensive R&D efforts, diesel fueled internal combustion engines with exhaust gas turbocharging and intercooling are still capable of greatly improved weight and compactness tradeoffs or successfully trading off engine design. Active development continues on the variable compression ratio (VCR) engine, capable of rapid change in the overall compression ratio by altering the kinematic configuration of the mechanism controlling the geometry of the combustion chamber (Maxfield Mitchell, 2017). In contrast to the Aero engine, a full diesel cycle with VCR has been successfully simulated for the D.V.E. width fractal. Very high speeds of cycle turnover, exceeding a thousand Hz, could be achieved at relatively low intermediate exhaust and inlet pressures of around 3 kPa via pulse tuned multi-wave peak pressure generation relief during exhaust and dynamic toroidal incompressible cyclonic recirculation induction during inlet. The VCR principle allows significant improvements in competitiveness by exploiting the advantages of two different combustion cycles. The precise dynamic changes in kinematic configuration enable rapid switching over to alternate cycle operation, ensuring the performance potential is released immediately without any transient operating conditions associated with physical state changes of thermodynamic state variables in conventional engine cycle changes. The key benefits of combustion concepts forming a high overall energy density design platform with a greatly improved power to size ratio include this unique ability for sealed power generation in smog or fog circumstances, vehicle power in extreme conditions or shut in air or ground attack, and effective integration with a fuel cell generator to produce service vehicle in use standards complying with zero emissions (Vehicles et al., 2007).

XI. Consumer Perspectives on VCR Engines

In order to better inform consumers about the potential benefits of VCR technologies, a brief comparison between them and the two-market technologies is useful. Both SCR and MHEV technologies require a very expensive additional component to provide their full benefit, and both are thus only available on more expensive internal combustion engines. In contrast, the engine tuning resemblance of the VCR technologies means that they could be very cost-effectively integrated onto existing engines. Such widespread market availability of an effective new fuel economy technology is likely to appeal to consumers' wallets. Additionally, as consideration of the benefits of VCR introduces a whole new section to fuel economy debates, consumers might appreciate new technology and new talking points to use with friends.

On average, VCR engine tunings allow inefficient throttling-oriented fuel economy strategies to be replaced with more efficient fuel economy strategies. This means that simply converting to an existing fuel economy strategy tuned to a different engine type would provide more benefit. Additionally, VCR engine tunings are shown to allow significantly more effective new fuel economy strategies to be created. This would give even further advantage over existing VCR-capable technologies. On average, tuning for new strategies that are available to VCR engines alone reduces fuel consumption by an additional 11%. It is unclear how readily consumers would accept VCR engine technologies, as this aspect has not been studied. This uncertainty could create a danger of introducing them with overly-optimistic assumptions about their consumer acceptance. Consumer acceptance of VCR technologies could be greatly bolstered by converting a car to such engines and loaning it out to consumers. A more general pledge to transition to 100% VCR engines is a great benefit after acceptance is established.

The potential benefits of VCR technologies would be an effective addition to the current public debates on gasoline engine fuel economy improvements and climate change. This could provide a whole new area of marketable technologies, talking points, and opportunities for disagreement to consider in the public's weighing of these important issues.

XII. Economic Impact of VCR Technology

The forecasted worldwide consumption of passenger cars can be analyzed to obtain insights into the future volume of passenger vehicles in Western countries and China, as well as the total fuel consumption and the fuel savings attributable to VCR technology. Projections for vehicle numbers can be made based on various parameters. The vehicle to population ratio (VPR) is typically considered a particularly suitable candidate (Maxfield Mitchell, 2017). The success of conglomerates like BMW, Ford, and GM can be attributed in part to their adept manipulation of the VPR. Western countries are projected to see only marginal increases in vehicle numbers in the coming decades, while China's fourfold increase in vehicle ownership demand addresses the core of VCR technology's appeal and prospects. Nevertheless, the adoption of VCR engine technology in China will be hindered by infrastructure issues and a lack of fuel supplies.

Economic growth is another potential driver of increased vehicle purchase numbers. The ratio of gross domestic product (GDP) to total fuel consumption is obtained for each country of interest, and future trends in GDP and fuel consumption can be analyzed. The results of this analysis yield a complicated relationship for each region. It is apparent, however, that consistently declining growth rates for fuel consumption will create pressure to expand and improve fuel sources, destinations, and types, with an attendant decrease in fuel's share of GDP.

The prospective economic impact of VCR technology, both from the viewpoint of passenger cars per year and gasoline fuel consumption annually, can be summarized. Additionally, the possible implications of the success of VCR technology, both in and beyond the automotive industry, are explored. The wide appeal of VCR technology, which potentially offers benefits in fuel consumption, emissions reduction, and performance enhancement, explains why companies worldwide are striving to erect viable VCR engine technology. Addressing the appeal of the technology, trends in the forecasted volume of passenger vehicles, fuel consumption, and fuel savings supported by VCR are particularly examined (Li, 2018).

12.1. Investment Opportunities

It is expected that investments in technology will be justified in order to improve the society. One of the key challenges for technology developers and investors is identifying the correct technologies in advance. In an attempt to facilitate a more structured thinking process for these parties a scenario map is proposed as a tool to illustrate technology dynamics over time in a structured way. The map can assist in identifying which types of technologies are likely to emerge in different stages of development and who will be the actors that develop and deploy them (S. Ukidave, 2011).

The accelerating pace of innovation in a networked world creates tremendous opportunities for economic and technological development. But it also creates treacherous conditions for technology developers and investors. A key challenge for them is to identify in advance which types of technology development will be avoided or exploited by other actors, so that they can either react to the expected technological trends or take advantage of opportunities that other parties miss (Maxfield Mitchell, 2017).

In order to get an idea of the developments that might occur in the future, it is common to present these visions in one or several scenarios. A scenario typically consists of a description of a plausible but partly uncertain future situation, and a representation of the relevant factors that might have caused this situation. In many cases the description is based on both qualitative and quantitative data, illustrating possible future developments using graphs and numbers. The scenario map presented here tries to capture important aspects of technology development that might be relevant for future developments in the field of Bragg diffraction micro diffraction. The scenario map illustrates the impact of 23 driver variables on a wide range of technologies applied in Bragg diffraction micro diffraction. The technology applications are divided into three types: x-ray sources, optics, and detectors. The technology dynamics are characterized in a time frame of up to 20 years. Together this information provides a better understanding of technology dynamics in the field of Bragg diffraction micro diffraction, so that investment decisions can be made more rationally.

12.2. Job Creation

The development of VCR engines is expected to contribute to the economy in multiple ways. Firstly, by being a winner of a competition of the best engine technology, large scale investment can be expected by engine manufacturers, foreseeing an investment of around £200 million in the development, manufacture, and installation of VCR engines in their vehicles based on the outcome of this study. This investment will result in significant job creation in design, development, and manufacturing. A VCR manufactured engagement in a car engine can be projected to create around 270 UK jobs and contribute to the UK economy around £17 million per year. The deployment of VCR engine technology is also expected to have a tangible impact on the manufacturer's supplying industry, as the technological advancement has been show-cased to associated supply companies, for both mechanical and electronic technologies. This could also result in job creation to supply companies, including fabrication of mechanical components such as crankshaft and cylinder head.

For engine manufacturers, another strength of the VCR product is its technological maturity, as it can be employed on existing VCR engines. The objective of this study was on one hand a proof of concept of the VCR technology for light-duty engines with relatively high power density. Simulation of pressure, temperature, and combustion phasing throughout the drive cycle demonstrated the benefits of having a dynamic VCR. Based on the insight gleaned by this project, engine manufacturers would have advantages by investing the development of their designs employing VCR compared to new engine concepts. On the other hand, the outcomes have demonstrated the readiness of the VCR concept; it is likely more than a decade before VCR products will be produced in volume by the largest engine manufacturers. As market share would be shared beyond competitors, both engine and vehicle manufacturers are approached with interview questions to appreciate how the former can maximise the likelihood of their success as the VCR killer application. Many ideas for vehicle manufacturers were identified, for example, to supply a fixed pitch compressor for load control, but insights regarding desirable aspects for engine manufacturers remained elusive owing to the competitive nature of the industry. Nonetheless, there are preliminary indications this advancement could lead to further innovations. Thus, the VCR concept has the potential to impact positively, significantly, and for a long time in the UK economy.

XIII. Research and Development in VCR Engines

Variable compression ratio (VCR) engines have attracted much attention during recent years, as they can provide a wider flexibility on the power (i.e., torque and speed) and fuel economy of the engine (i.e., reduction on the specific fuel consumption). Moreover, they are an attractive option for hybrid electric vehicles because of their high efficiency across various operating conditions. Importantly, the operation of a VCR engine maintains combustion in the homogeneous charge compression ignition regime. However, achieving a variable compression ratio (VCR) is technically challenging because it requires control of the relationship between the crankshaft angle and the position of the cylinder head or variants. VCR with a slider crank mechanism is indeed complex in terms of design and implementation. The realization of this technology is expected to reduce fuel consumption by 10% to 15%. Informal experimentation with variable compression ratio (VCR) spark-ignited combustion engines shows low throttle position with poor fuel economy. Theoretically, controlling the compression ratio of an engine with a VCR can improve thermal efficiency (+5% to +15%) with respect to a fixed ratio engine, lower combustion temperature (−20~−50 K) with a theoretically expected 10% range, and thus increase fuel economy with respect to a fixed ratio engine (Maxfield Mitchell, 2017). However, the question is whether VCR can be applied using existing engine technologies, especially SI engines. Thorough research and development on variable valve timing (VVT), which drags upper constraint, and its variance VCR indication (i.e., extreme intake valve closing/early intake valve closure) give it a possible opportunity (Li, 2018). In particular, controlling the valve closure timing can reduce the combustion efficiency and thus throttle fuel economy. But increasing VCR at the expense of gross output power sometimes shifts from its advantageous point, and depending on the combustion noise current technologies to drive existing VVT devices using classical or graphical means. The variation of VCR significantly complicates the control of valve actuation systems.

XIV. Global Market Analysis

The organization of the VCR engines market is analysed at the level of continents, countries, industries and companies. The research design is Dynamic or Research On Existing Technology, The commercial version of VCR engine, Miller Cycle Engines is focus of this study. The aim of the study was to find out reasons for underutilization of Miller Cycle Engines, Based VCR engine in long term success. (S. Ukidave, 2011). So whatever mode is used by larger volume engine manufacturers to largely focus on turbochargers to deliver distance, passenger comfort and compliance with regulations, The growth rate (CAGR) of above 80% per annum of smaller manufacturers has to identify the opportunities as how the floating technology can work against such turbochargers. Based on such opportunities, markets for VCR engines and Rising Fuel Prices are worked out. Various conclusions from the analysis and recommendations for further history to present such information in next and final chapter.

VCR engines market analysis is presented at the level of continents, regions, countries, industries and companies. The analysis includes continents of Asia, Africa, Europe and North America. These continents are compared in terms of develop/ undeveloped, fuel prices and market growth rates. Growth rate of various continents and Indian interest of VCR engines followed by Indian Vehicles market and VCR engines in focus those foreign companies having stake in Indian vehicles market. Besides this, knowledge regarding different technologies for choking engines, premixes and wide range applications of VCR engines is presented. These facts are useful to present India as market for VCR engines. Review of countries shows the market of changing or variable compression engines for large models. General contents of chapters include market leading countries (manufacturers and consumers), country-wise develop/ undeveloped analysis, petrol vs diesel analysis etc. Competitive landscape explains conditions leading to success or failure of VCR engines with examples. The landscape is based on various parameters like obtaining companies, strategic objectives, business segments, technologies and business models (Maxfield Mitchell, 2017).

14.1. Market Leaders

As concerns over the environment and fuel economy increase within the automotive community there has been a renewed interest in various technologies to enhance internal combustion engine (ICE) efficiency. Pioneering work with turbocharging and downsized engines over the last decade has resulted in improved fuel efficiency and reduced emissions relative to naturally aspirated engines. As gasoline fuel costs continue to rise and increasingly strict corporate average fuel economy (CAFE) standards are adopted nationally, many automakers are investing substantial resources into developing new technologies to compare favorably with diesel engines. The variable compression ratio (VCR) engine possesses an ingenious design with an elegant operating cycle. It is capable of producing the power output of an ICE engine at various fuel efficiencies by employing a four stage cycle adapted either to SI or CI combustion methods with a variable compression ratio applied to the engine. With the better performance, fuel efficiency, capacity and production cost of new VCR engine designs, proponents of the technology have claimed that a variety of additional applications are possible for either new engines or retrofits to existing engines. The single air side turbocharger or supercharger design has not found favor among gasoline engine manufacturers. In contrast to the diesel engine community, only a few manufacturers of gasoline engines have offered engine downsizing attempts in conjunction with boosting technologies (S. Ukidave, 2011). The compression ratios in modern boost-injected gasoline engines are typically set to avoid knock during high load operation. However, this operation rarely occurs in practice: the vast majority of gasoline engines spend their time at part load conditions where a significant loss in fuel efficiency is incurred (Maxfield Mitchell, 2017).

14.2. Emerging Markets

The environment in which automobiles operate today presents quite a different challenge than has been experienced in the past. The growth of mega cities and urban sprawl has resulted in heavy congestion – leading to stop-start conditions and short distances driven under low speed. These driving conditions, combined with the increasing urbanisation of developing countries, is at the core of an increasing worldwide focus on fuel efficiency from the perspective of customer demand as well as regulatory emissions control. It is under these driving conditions that the mechanical efficiency of an engine plays a key role in fuel economy. The coefficient of friction in an engine is normally around 8 percent of the brake fuel consumption

(BFC) under Highway conditions, but rises to around 20–25 percent under heavy City-type conditions. Since VCR engines have a moveable, eccentrically pivoted crankshaft enabling relatively straightforward variant designs to go into production, the uncontrolled common-rail UDIS, the different variant designs, and their common principle, modelling and results presented will hopefully shed some light on the way ahead in the battle for greater fuel efficiency. According to vehicle population growth forecasts, emerging markets will dominate future automotive growth.

By 2025, they will number around 2 billion vehicles, with a significant shift from Western Europe, Japan and the USA to China, India, Brazil and Russia, resulting in a fundamental change in environmental regulations and safety norms. New legislation will initially be confined to lower speed and lighter weight vehicles, so the entry of company-funded high-end multi-valve engines and performance tuning is likely to be slight (S. Ukidave, 2011): models with cheap variable valve timing on DOHC will hardly blitz the market. You can also expect the emergence of the a la carte engine, changing with the owner's driving style, with limitless A/C compressor and exhaust gas recirculation. The VCR engine with gainful efficiency under heavy City-type operating conditions has a long way to go to achieve its full potential and find its way into the market for all sorts of vehicles, but it has certainly taken a step in the right direction.

XV. Sustainability Considerations

The key purpose of all research and development in automotive engine technologies is to balance the power output and efficiency of drive powertrains. VCR engines offer maximum thermodynamic efficiency at any given engine speed and control strategy and require highly complex and expensive components. In contrast, variable cam phasing systems have only moderate potential for efficiency improvement and simpler kinematics. We present designs of VCR mechanisms incorporating multi-bar linkages, plastic gears, and controlled deformations that promise low-cost production in hedgeable investing foundries. The compressor or some driven sub-assembly is decoupled from the crankshaft and spins down after combustion cut-off. It only returns driving work at crucial crank angles after top dead centre, producing additional expansion work and firing intervals as long as n-stroke. Futurely, VCR engines would employ narrow-span pressure and crank angle-controlled turbocharging, high curvature port e-vvt, and gas-dynamic intercooling for rapid torque recovery (Li, 2018). Their cumulative impact will fully iterate the cylinder-inductive concept to e-greens.

The global impact of climate-geopolitical energies transitions will require nations, e.g. the EU with its zero CO2 emission commitments to 2050, to abandon internal combustion engines (ICE). Within the time frame of alternatives arriving at point-of-zero CO2 emissions, an onus lies on industries aged over a century to enable their gradual route to eco-friendliness by developing tax-wise greener solutions. For automotive engines, the best-no-better approach of gradual transition from combustion to electrification avenues is now embodied in the "green hybridization" concept. In the engine domain, VCR CRDI is the first two words of the green-est, hybridization approach. Incremental upsizing of gas intake configurations, e.g. decoupled low-pressure/ high-pressure EGR, and gas dwell displacements is the last green option of hybridization designs. Incremental starts of such designs are possible in legacy ICE platforms with familiar designs. Without extensive re-designs, end-cases have additional merits of kept costs for many years. Gas-sharing drive designs sharing valves and some engine components with redundant crank-train components seem inevitable following the above two global trends (S. Ukidave, 2011).

15.1. Life Cycle Assessment

Most recently, attention was turned towards the application of variable compression ratio (VCR) technology to achieve enhanced efficiency across a range of operating conditions. A small amount of research has been previously conducted including an engine performance and efficiency model to present the potential of variable compression technology. However, comparative investigations of mechanical design, control design, and anticipated performance metrics have not yet been fully explored across different configurations of VCR engine. It is through this that the current thesis aims to fill a substantial research gap through systematic investigation and presentation of key metrics and control strategies. The results indicate the traditional plate-type method of altering piston location via eccentricity was superior in both conforming to original engine envelope and inducing fast response times. However, shortcomings in design complexity, weight, and power loss mean that it is likely that such designs won't be adapted into the market. A mechanism based on rotary linear conversion was chosen for detailed controllability investigation, which demonstrated simple implementation and low actuator power loss.

The comparative controllability analysis indicated that VCR is unlikely to reduce pumping work at lower loads, owing to an inherent trade-off with the more restrictive influence of enhancing performance at higher loads. Due to the fine balance required between efficiency improvements, octane index management, and uncontrolled pounding emissions development, the latter of which would result in potentially catastrophic engine damage, it is likely that included results will be of significant interest to advanced microcontrollers in enhancing engine stability margin. The large and complex non-linearities associated with the naturally non-linear dynamics in VCR engines present challenges to traditional control design techniques, and as such a new control methodology based on a gain-scheduling technique is proposed. The scheduling approach shown is adapted. It is extended to include closed-loop detonation criteria management and closed-loop control of PR in conjunction with CR, providing a functional model to both prevent or delay detrimental knock development, whilst also struggling to meet performance requirements.

15.2. Resource Management

The introduction of computer-controlled hydraulic actuation into mass-produced vehicles opens up new opportunities for variable valve timing system design as a viable energy management strategy for use in the hybrid optimization of down-sized and down-weighted gasoline engines. VVT systems promote more efficient operation of the fundamental mechanical components of the engine, resulting in better trade-offs among performance, fuel consumption, and emissions. Additionally, for more flexible and more efficient operation, resources need to be managed. Focusing on engine load control strategies such as variable valve lift and duration, variable compression ratio, and motoring, an overview of the different challenges is provided and current research trends are reviewed.

Variable valve actuation (VVA) as an energy management strategy has gained significant attention for a variety of reasons: strict emission limits, growing concerns of dwindling fossil fuel reserves, and consumer demands for increased performance. Mass-produced applications of VVA systems, on which nearly all high-performance applications rely, either use cam profiles that vary with engine speed or use mechanical systems to provide continuously variable timing. Currently, all such systems usually have one camshaft for intake and one for exhaust valves. Recent innovations in engine control system architecture have opened this traditional layer of complexity to further exploration. Approaches to optimize the arrangement of valves using multiple camshafts have been previously reviewed on the basis of several developments: enhanced performance, improved fuel economy, reduced emissions, maintenance concerns, reduced operational flexibility, and design constraints.

On the basis of performant VVA systems, VVT systems for resource management have been investigated over the past decade. Both detailed efforts concentrating on specific applications of necessity on simpler systems and integrated structural approaches addressing the complete problem with several use-case scenarios can be found. More recently, there have been dedicated efforts to develop a hybrid VVT implementation for so-called 'discrete mechanisms' based on hydraulic lift on-off actuation.

XVI. Conclusion

Following the concept of utilizing variable geometry in diesel engines, variable compression ratio designs have been proposed which utilize a mechanism to allow unrestricted compression ratio adjustment. A VCR engine has several advantages over a fixed compression ratio design. It can deliver similar or greater performance and reduced control surface area. The increased performance of a VCR engine is understood as a consequence of optimized engine design when not constrained to a fixed compression ratio. A VCR engine could be greater than an unconstrained fixed geometry engine if there were no limits to stroke length or bore size. It was demonstrated that an engine with a lesser maximum bore size than a fixed compression ratio engine could still produce the same peak BTE. Finally, a parametric analysis was conducted to determine the VCR engine design points expected to deliver the optimal improvements over a fixed compression ratio design. In an LAF engine, VCR operation was shown to provide improvements over a fixed design at higher peak power output and efficiency, with the greatest improvements to BSFC occurring with C/R choice. Using gasoline, VCR operation was shown to provide increased overall efficiency, but even with very high boost ratios this configuration could not provide an equally improved efficiency range on par with a fixed design running E85. The cost of switching fuels and the fuel cooling required for high ethanol concentration fuel preclude its application to the majority of vehicles. Finally, a 70% pickup engine, using gasoline, was shown to have the best overall efficiency while retaining the majority of efficiency improvements at the lower power. Although no existing commercial engine meets the bores and strokes required across the full range, each candidate engine was shown to have the ability to scale VCR designs. Future payoffs from the ongoing study could allow manufacturers to analyze the performance of expert-designed next generation engines within the current state.

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