VARIABLE COMPRESSION RATIO FOR FUTURE EMISSIONS STANDARDS

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FUTURE ENVIRONMENTAL STANDARDS REQUIRE IMPROVED ENGINE EFFICIENCY. VCR IS THE KEY

Countries around the world have introduced strict regulations to limit the emission of pollutants and CO_2 from vehicles. The new Real Driving Emissions (RDE) tests will see a further tightening of these very strict standards. In 2025, the great majority of vehicles will be powered solely by petrol engines. Future environmental standards cannot be met without radically improving the efficiency of these.

Current automobile engines manage 35% average efficiency in the best of cases, and only over a very limited range of operating conditions. The required incremental improvement cannot be achieved without a technological leap. In the history of engine development, each significant gain in efficiency has resulted from new technology controlling an influential parameter: air-fuel ratio (fuel injection), ignition timing (electronic ignition), combustion cycle (variable valve actuation), flame dynamics (direct injection, exhaust gas recirculation). The only major influential parameter left to be controlled is the Compression Ratio (CR).

MCE-5 DEVELOPMENT's VCRi variable compression ratio technology will enable optimum use of high-efficiency thermodynamic cycles without impeding driving dynamics and will provide a profitable technology platform for future 48V hybrid electric and advanced combustion powertrains.

VCRi-MILLER ENGINE

To maximise the benefits of the Miller cycle, the effective[1] Expansion Ratio (ER) and the ratio of ER to CR must be maximized while maintaining a high effective CR. By coupling continuous Variable Compression Ratio (VCR) with Variable Valve Actuation (VVA), a major advantage is obtained over Fixed Compression Ratio (FCR): ER can be as high as the maximum volumetric ratio provided by the system, while the effective CR remains high despite the use of LIVC/EIVC[2] strategies, which produce an effective CR lower than the volumetric CR.

Trade-offs between VCRi packaging, cost, and performance have resulted in a CR range of 8:1 to 18:1, giving a Brake Thermal Efficiency (BTE) of more than 35% across 75% of operating range, with a peak BTE of 40% as shown in **Fig. 1**. This shows the "sweet spots" (BSFC[3] < 240g/kWh) of FCR benchmark engines and VCRi-Miller engines by dotted grey and red lines respectively.

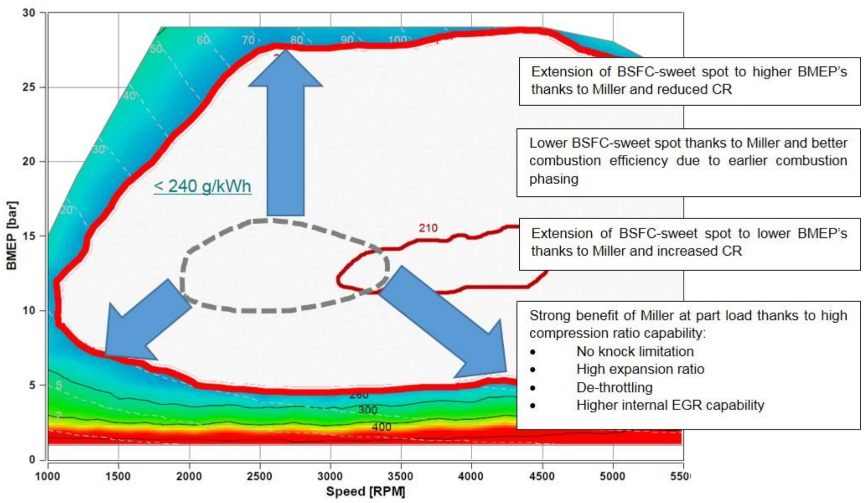

Fig. 1 - VCRi BSFC map

At part loads, the ER reaches 18:1 while the effective CR remains high (> 12:1). 18:1 is near- optimum as regards the maximum volumetric CR for VCRi Miller applications. A lower CR value decreases ER while a higher value reduces turbulence in the combustion chamber, thus reducing combustion

[1] *Effective CR (resp. ER) takes into consideration intake and exhaust valve events and intake boosting in addition to volumetric compression (resp. expansion)*
[2] *Late/Early Intake Valve Closing strategies keep the intake valve opening point in a fixed position, whilst moving the closing point to reduce pumping losses and thus improve fuel economy*
[3] *Brake Specific Fuel Consumption*

efficiency. In both cases, thermodynamic efficiency is reduced. The coupling of VVA with VCRi dramatically extends the sweet spot area and enables "right-speed" gear shifting strategies based on a lower number of gears, thereby decreasing fuel consumption (FC) and emissions while improving vehicle dynamics in all driving cycles, thus ensuring better compliance with future RDE regulations.
At higher loads, the boosting system limits use of the Miller cycle. Decreasing CR to 8:1 allows optimum combustion phasing while mitigating knocking, whereas FCR-Miller engines have limited high-load performances due to the high CR required to maximize BTE at part loads.

FULL STOICHIOMETRIC OPERATIONS FOR RDE

Fuel enrichment and scavenging are used for exhaust component thermal protection and low-end torque respectively. RDE regulations will disallow these strategies.

Exhaust component maximum temperature restrictions are a hindrance to higher power densities. On FCR engines, knocking is controlled by delaying combustion, causing higher exhaust temperatures and usually offset by fuel enrichment. The consequences are harmful emissions (HC, CO) that are not post-treated at RDE compliance level ($\lambda \leq 1$), and an associated increase in FC. The CR management of VCRi engines avoids both drawbacks, withstanding up to 120kW/l without fuel enrichment.

Scavenging is used to boost low-end torque by limiting turbo lag. At a given rated power, VCRi's better thermodynamic efficiency reduces boosting needs: lower inertia turbo-compressors can be used. Also, combining a high pressure ratio compressor map with high CR reduces waste gate usage, resulting in significantly higher turbo speeds than on FCR engines. When a turbine is already running, there is less turbo lag and less need for scavenging.

COST-EFFECTIVE ENGINE FAMILY

RDE compliant VCRi-Miller engines ($\lambda=1$) have an optimum power density of 80–120kW/l, while FCR engines operate at only 65–80kW/l. This, combined with the lower speed and load sensitivity of BSFC, reduces the number of engine- and cylinder unit capacity variants required to address a given power range in an engine family [Fig. 2], thus reducing development and production costs.

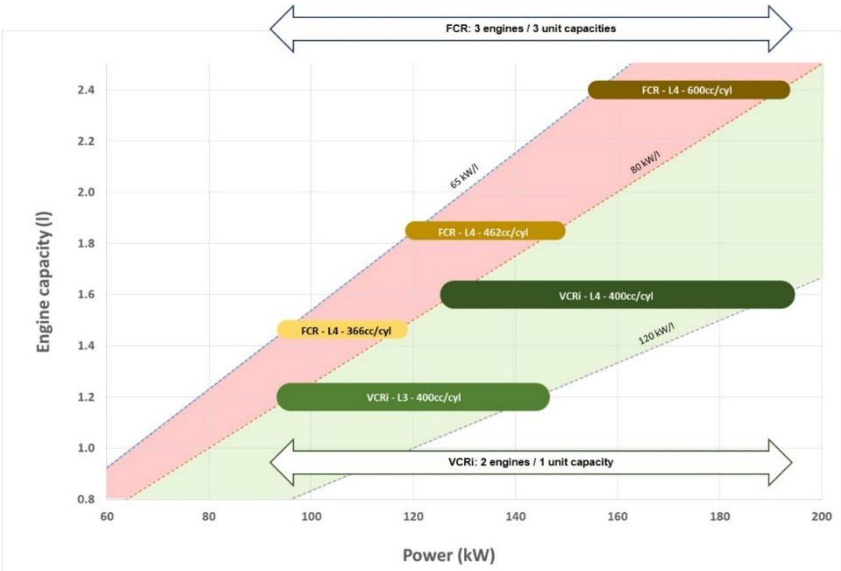

Fig. 2 - VCRi engine family

LOWER EMISSIONS, FEWER PARTICLES, HIGHER VEHICLE DYNAMICS

The low CR used on VCRi engines enables faster initial heating of 3-way catalysts than is achieved with the higher CR of FCR engines, thus reducing catalyst light-off time. Reducing the CR of a cold-running engine increases the distance between the injectors and piston crown, thus avoiding fuel impingement and dramatically reducing particle and raw emission generation. Low CR enables high intake pressures without knocking, resulting in very high low-end torque and outstanding vehicle acceleration at low engine speed, while maintaining engine speed below 3000 rpm on WLTC, thus resulting in lower FC and NVH[4]. Both the above effects are instantaneous during transients thanks to VCRi's very rapid CR change.

VCRi 48V MILD HYBRIDIZATION

48V hybridization of optimized internal combustion engines is a key strategy in enabling powertrains that are cost-effective while complying with future emission regulations. Combining 48V mild hybrid technologies with VCRi technology keeps most of the benefits of both. VCRi engines, however, need much simpler hybrid configurations than FCR to achieve the same fuel economy, resulting in significant cost saving.

VCRi DEVELOPMENT TOWARD 50% BTE

MCE-5 plans to increase the maximum BTE of VCRi engines to 44% through further combustion and boosting optimization. In the longer term, close to 50% maximum BTE should be possible by incorporating homogeneous charge compression ignition (HCCI) and advanced lean burn combustion (λ=2), to which end VCRi cylinder selective capability and high energy ignition "SSP" system, developed by MCE-5, will be key enablers [**Fig. 3**]. VCRi technology's development potential will enable compliance with the stricter standards to be introduced worldwide in 2025–2030, with minimum need for hybridization.

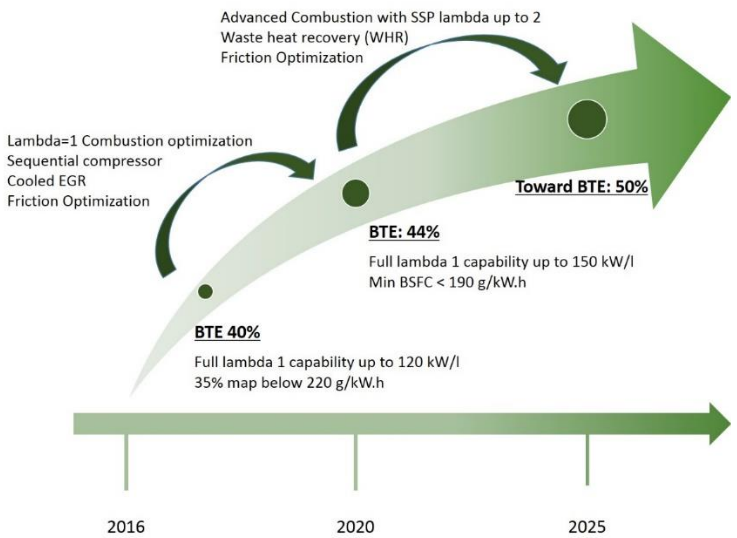

Fig. 3 - VCRi development roadmap

[4] *Noise, Vibration and Harshness*

VCRI TECHNOLOGY

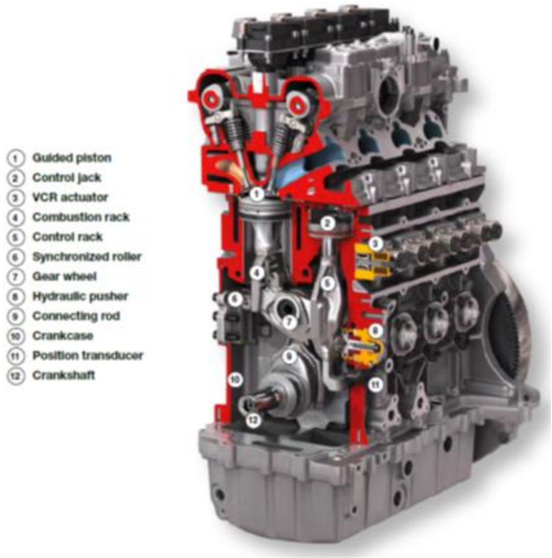

Fig. 4 - VCRi technology key features

The CR is the ratio of the combustion chamber volumes at piston bottom and top dead centre positions (1). VCRi technology adjusts the CR by adjusting the position of the control cylinder piston (2) and rack (5); this rotates the wheel (7) about a gudgeon pin fitted to the connecting rod (9), thereby changing the datum position of the combustion rack (4). The adjustment is powered by the inertia force (increasing CR) or combustion gas pressure (decreasing CR) applied to the piston. The control jack moves only when the VCR actuator (3) connects the control jack's upper oil chamber with the lower. This control is provided by the engine management system, which sets the CR to an optimum value based on the engine's running conditions and the actual CR as measured continuously by the position transducer (11). The synchronized roller (6) prevents lateral forces on the piston, while the hydraulic pusher (8) controls clearances in the system to ensure silent operation at all times. VCRi's capabilities set it apart from competing systems in that it provides continuous CR variation rapidly (2–3 CR points in a single cycle), accurately (± 0.05 CR @ 15:1), and over a wide range (10 CR points) with a very high maximum (18:1), can adjust each cylinder independently, and operates using the engine's own internal forces. These unique features enable implementation of the highly efficient thermodynamic cycles required to meet the targets set in future regulations.

TRL7 VALIDATION

VCRi technology has been developed by MCE-5 over the last 15 years. Numerous engine prototypes have been demonstrated on test benches and in on-vehicle operating environments. The technology has performed as required and limit testing and performance characteristics are now determined. The technology has been shown to be suitable for incorporating into vehicle platform development programmes. These results are characteristic of TRL7[5].

MRL5 VALIDATION

Fig. 5- control rack forging trials at Farinia-Setforge

All VCRi-specific components have been designed, production engineered, and costed jointly with expert automotive suppliers. Detailed manufacturing and assembly processes have been defined in detail, providing the basis for assessing production and investment costs in different regions, with both the suppliers' and independent cost engineering experts involved.

[5] *Technology Readiness Level: product readiness from 1 (basic) to 9 (market ready)*

Key manufacturing processes have been characterized; it has been demonstrated that capabilities exist to produce components in a production relevant environment; prototype materials, tooling, test equipment and products have been validated with components in a production relevant environment; FMEA[6] and DFMA[7] have been initiated; detailed cost analyses have been provided and cost targets allocated and approved as viable by several carmakers; long lead-time and key supply chain elements have been identified. These results are characteristic of MRL5[8], with MRL6 already partly attained.

Fig. 6- Combustion rack tooth finishing by precision electrochemical machining at Pemtech

VCRI, A ROBUST SOLUTION IN AN UNCERTAIN WORLD

In 2025, the great majority of vehicles will be powered solely by petrol engines. Future environmental standards will not be met without radically improving the efficiency of these. VCRi technology is a key enabler when it comes to meeting these targets.

VCRi engines deliver the torque and fuel consumption of Diesel with the appeal of gasoline, thus providing both energy efficiency and driving pleasure.

In anticipation of future RDE requirements, VCRi reduces fuel consumption by 10–15% in all driving cycles compared with future 2020 FCR engines.

A CO2 reduction cost of less than 30€/g/km, added to the engine's fuel savings guarantee attractive vehicle prices and contained cost of ownership.

48V hybridization benefits will complement those of VCRi in regard to future emission targets (< 75g CO_2/km), with the prospect of extending engine production asset lifetimes by more than 10 years.

VCRi can run on all types of fuel without sacrificing performance for efficiency, thus giving access to a wider number of markets with the same hardware. This, coupled with the reduced number of variants required in VCRi engine families, is a solid basis for expecting significant reductions in development/production costs and time-to-market.

VCRi can be used by any manufacturer, opening up the possibility of its use in a large share of the cars produced from the next decade onwards. In 2015, MCE-5 signed a first strategic agreement and began development with Chinese car maker Dongfeng. Advanced discussions are ongoing with other car makers in Europe, the USA, and Asia.

[6] *Failure Mode and Effect Analysis*
[7] *Design For Manufacturing and Assembly*
[8] *Manufacturing Readiness Level: process readiness from 1 (basic) to 9 (SOP ready)*