FEV 2-stage VCR - A Solution for Future Emission Legislation and High Performance

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Summary

Variable compression ratio (VCR) for reciprocating engines has longtime been a dream. Recently, concepts are being developed for series production maturity in passenger cars gasoline engines [1, 4]. In the paper given, the benefits of VCR in terms of engine efficiency and emissions with respect to legislative requirements are shown. The FEV 2-stage VCR is characterized by a modular approach that only requires minor change of an existing base engine. This technology leads not only to significant fuel consumption and emission benefits but also to substantial cost reduction of the entire engine family. Supported by FEV enhanced simulation methods and test benches SOP is expected around 2020.

1 Introduction

Increasingly tightened CO2 regulation demands as well as more severe pollutant emission regulations will be the key drivers for future technology changes in the automotive industry. Beside the clear trend towards electrification of the powertrain a further development of the internal combustion engine in the direction of highest efficiency and environmentally clean operation in the entire engine map will be mandatory. Especially for Gasoline engines the Variable Compression Ratio (VCR) technology can improve its efficiency significantly. By 2016 Nissan presented a new "VC-Turbo" engine using a link mechanism for a fully variable compression ratio [1, 2]. Furthermore, VCR shows high synergy with state of the art engine technologies such as downsized engines featuring Variable Valve Lift (VVL) and Miller cycle while supporting the combustion stability at low load and increasing the engine performance at the same time [3].

FEV is the "VCR company" and is working on different solutions since the foundation of the company in the early 70s (figure 1). There have been many different technologies with a fully variable compression ratio. Such solutions can realize the highest benefits of this technology, which has been already proven by FEV in a vehicle with fully variable compression ratio in the 1990´s [4]. Nevertheless, a simplified VCR system with a 2-stage variability can realize already the majority of the thermodynamic advantage from a fully variable approach. Furthermore, the FEV system has a very low effect on friction as the switching is passively driven by gas and mass forces. FEV has developed such a system using a variable connecting rod length by 2003, which is available in demonstrator vehicle since 2011. First mass production of this technology can be expected by 2020. In the following the current development status as well as ongoing development steps of the FEV 2-stage VCR system will be described.

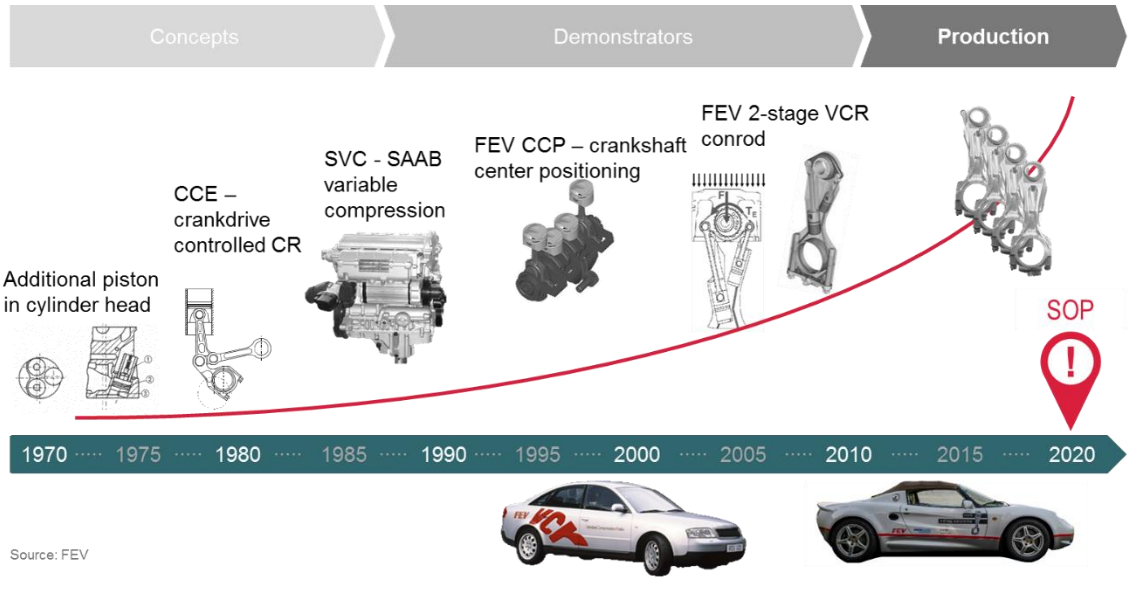


Fig. 1: From additional piston to 2-stage VCR: Development history at FEV

This VCR system was developed with focus on six major requirements (figure 2):

- The major motivation is the reduction of fuel consumption and CO2 emissions. This comes along with the requirement to cover an appropriate VCR range and to maintain a low friction level.
- Another focus is the potential to reduce exhaust gas emissions. Especially at high engine load and speed VCR can reduce the exhaust temperature of a Gasoline engine and thereby expand the area of stoichiometric operation significantly. Furthermore, the application of VCR on a Diesel or Heavy Duty engine impacts the emission and the NVH positively while reducing the peak firing pressure at the same time [5].
- The modularity of the VCR system is another decisive factor. For cost reason and synergies of the engine family, easy integration into an existing engine platform without major modification to the base engine concept is required.
- In order to provide a most cost effective solution the systems need to be as simple as possible, represented by a small number of additional parts (e. g. no additional oil pump required).
- As future powertrains will include more hybridizations, the CO2 potential in such a hybridized powertrain is crucial for the market success of this technology.

- Finally, the VCR system should be compatible for flexible fuel operation providing best adaptation of the compression ratio to the individual fuel characteristics.

Fig. 2: Major requirements of VCR system in gasoline powertrains

2 Working principle of FEV 2-stage VCR

The 2-stage VCR system of FEV is based on the principle of a variable connecting rod length. For this purpose, the small end of the connecting rod is mounted eccentric (figure 3).

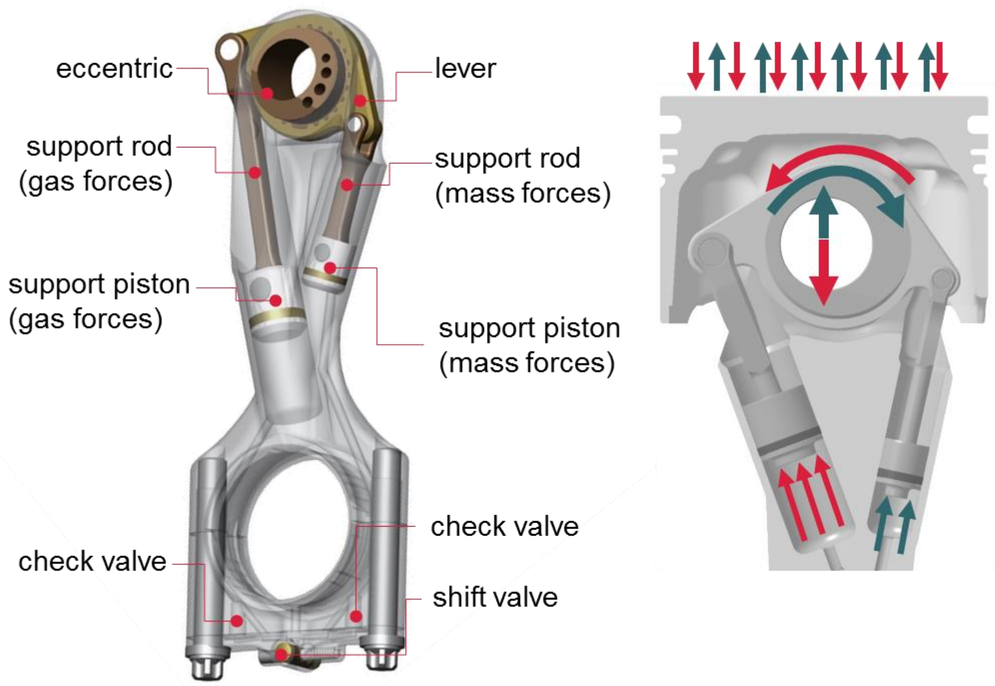


Fig. 3: Working principle of FEV 2-stage VCR

The gas and inertia/mass forces acting on the piston pin, which is eccentric, result in a rotating torque. A support mechanism (lever, two support rods and two support pistons) is connected to the eccentric mounting and transmits this torque to two supporting cylinders integrated in the connecting rod. One of the supporting-cylinders counteracts against the torque caused by the gas forces, the other cylinder correspondingly against the torque caused by the mass forces. Both support cylinders can be filled with oil from the crank bearings if necessary and each is linked with a check-valve which prevents the cylinders from draining. One of these cylinders can be opened selectively with a 3/2 directional control valve. This combination of check valves and directional control valves form a hydraulic free-wheel clutch whose direction is selectable. In case the position according to a high compression ratio ("CR_high") is selected, the mathematically positive acting torque is supported on by the oil column of the gas force supporting cylinder. In this position the mathematically negative-acting forces - accruing from the mass moments - will be supported by a direct metallic contact of the supporting piston to the connecting rod. In the 'low compression ratio' - position ("CR_low"), this situation is reversed. A positive side effect of the position “CR_low” is that the typically higher gas forces are no longer supported by the oil column which means that the oil pressure remains at a lower level in the support cylinder.

3 CO2 benefits of VCR in combination with hybridization

There are many technologies in the market which provide a fuel consumption reduction. Currently the car certification is done with the NEDC cycle. The Worldwide harmonized Light vehicles Test Procedure (WLTP) and the real driving emissions (RDE) shows a more realistic customer driving behavior and will be used in future. The fuel consumption benefits of different technologies is shown in figure 4

The focus of the simulation study is the CO2 emission calculation for a C-segment passenger car that represents a full picture of the fleet distributions for Diesel and gasoline passenger cars.

The 2-stage variable valve timing (VVT) address the pumping losses in the lower part load operation. For that reason, the fuel consumption benefit is higher for test cycles with a high share of operation in this area as the NEDC. Cylinder deactivation is not very favorable in this car concept because the DCT transmission shifts the operation points out of the cylinder deactivation area.

An optimized friction leads to a fuel consumption benefit in the complete engine map and can be done independent of the use of other technologies.

Using Miller valve timings in combination with a high CR improves the fuel consumption due to de-throttling in part load and reducing the knock tendency at higher loads but it is mandatory to increase the engine displacement or to have a boosting concept which provides high boost pressures at higher loads to achieve the same performance targets. Furthermore, the transient response can be negatively affected due to the reduced cylinder filling.

A boosting concept with E-compressor allows an engine matching with a bigger TC which reduces the pumping work in part load and especially in full load. Furthermore this technology is often used to improve the transient response.

Water injection allows to increase the compression ratio and reduces enrichment which improves the fuel economy in all driving cycles. But with an increased compression ratio a high amount of water needs to be injected, therefore on board water regeneration is required or the driver has to be forced to refill for legislation aspects.

Cooled EGR mainly helps to reduce the knock at higher loads. For that reason, the fuel consumption benefit is higher for test cycles with higher loads (RDE and WLTC).

The increase of the compression ratio is a measure in order to increase the combustion efficiency. However, this is limited by high peak cylinder pressures and temperatures, which affects a higher knocking tendency in gasoline engines especially for high boosted downsizing engines. As a consequents the spark timings needs to be retarded which leads to high exhaust temperatures at high engine speeds and loads. Enrichment of the mixture is a typically measure to reduce the exhaust temperature for component protection. The enrichment leads to high CO and particle emissions. To get the best of both trends, a 2-stage compression ratio can be used for working with a higher CR at low and part load operation; and a lower CR at higher loads. With such system, an improved full load performance, reduced emissions and friction might be realized with lower CR. while at lower loads the higher CR allows to increase the combustion efficiency. Moreover, the compression ratio can be maximized at lower loads without redesigning the different systems which are subjected to high stresses, e.g. piston or crankshaft.

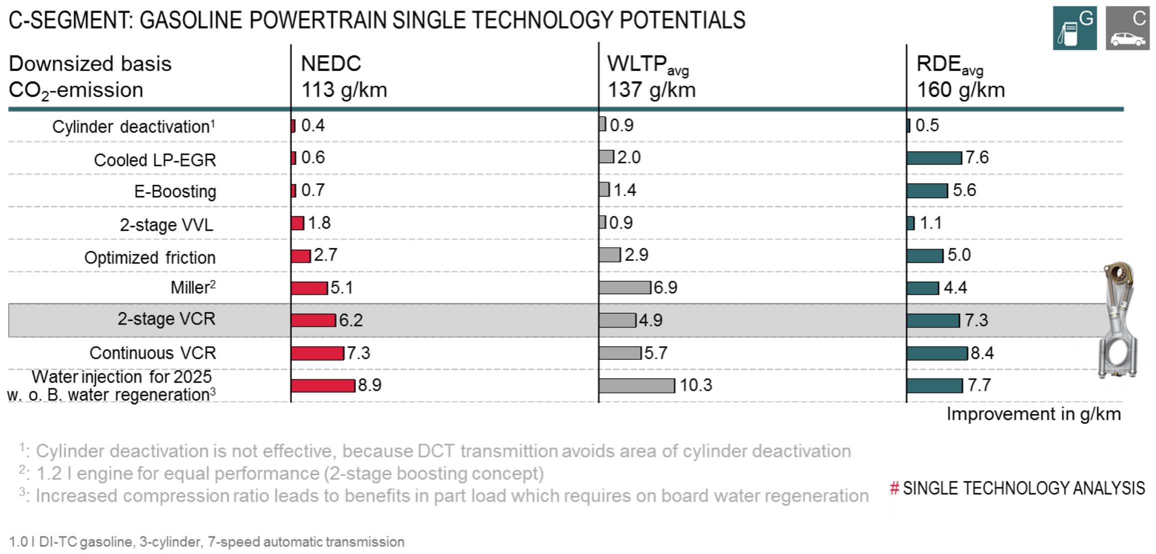
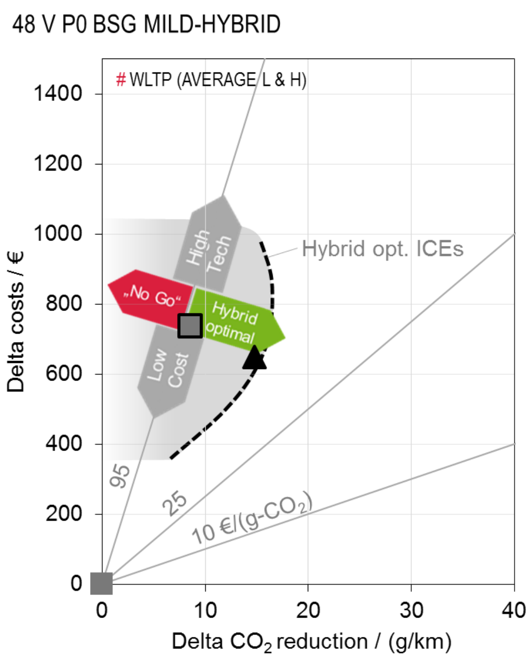


Fig. 4: Fuel consumption improvements for a 1.0 l 3-cylinder DI-TC gasoline engine, with 7-speed automatic transmission

The fully variable VCR and the 2-stage VCR system affect the entire engine map. A reduction of CR helps on solving the problems mentioned before and also getting some improved powertrain efficiency at full load operation. The 2-stage system already achieves 85% of the fuel consumption benefit of the fully variable system but with much lower costs. The FEV 2-stage VCR system shows significant fuel consumption improvements for all driving cycles.

Figure 5 shows that the FEV 2-stage VCR has one of the best cost to benefit ratios in combination with a hybrid powertrain. The origin of the diagram represents the reference powertrain. The results for costs and CO2 emissions are indicated as delta values relative to this origin. For better orientation, lines for fixed ratios of costs and CO2 emissions have been drawn into the diagram (e. g. "95 €/g-CO2") and the following classification has been defined:

- A shift on a line with a fixed ratio of costs and CO2 emissions to lower costs is considered as a measure with a focus on 'low cost'.
- A shift on a line with a fixed ratio of costs and CO2 emissions to a higher CO2- reduction is considered as a measure with a focus on 'high tech'.
- An improvement of the ratio of costs and CO2 emissions is considered superior to the previously mentioned categories and is denoted a 'hybrid-optimal technology combination'.
- A decline of the ratio of costs and CO2 emissions can make sense to achieve performance, acoustics or comfort goals, but should initially not be preferred in this evaluation of costs and CO2 emissions ('No Go').



	Ref. engine in hybrid-powertrain								
	3-cylinder					4-cylinder			6-cylinder
Symbol Displacement /L	1.5	1.5	1.4	1.3	1.3	2.0	2.5	2.5	3.0
1 Fuel injection	DI	DI	DI	DI	DI	DI	DI	DI	PFI
2 Int. exh. manifold	X	X	X	X	X	X	X	X	X
3 Turbocharger	X	X	X	X	X	X			
4 Intake VVT	X	X	X	X	X	X	X	X	X
5 Exhaust VVT	X	X	X	X	X	X	X	X	
6 Miller/Atkinson		X				X	X *	X *	X
7 2-st.-intake-VVL		X				X			
8 1050 °C turbine	X		X						
9 2-stage TC					X				
10 VNT		X							
11 Var. int. manifold							X	X	
12 CDA								X	
13 VCR			X		X				
14 Water injection				X					
15 cEGR									X

High Tech

* “Soft”-Atkinson

Reference powertrain : 2.0 L TC DI w/ Miller, int. exh. manifold, dual-VVT, Miller, intake-2-stage-VVL, start/stop and 12 V energy management, 143 g/km CO_2 in WLTP

Fig. 5: Evaluation of FEV 2-stage VCR technology for mild-hybrid gasoline powertrain with 48 V belt starter generator (BSG mild-hybrid) relative to the reference powertrain with regards to the ratio of costs and CO2 emissions

The electrification of the reference powertrain with 48 V BSG without changes to the combustion engine costs 740 € and reduces the CO2 emissions by 8.6 g/km and therefore is located on the line for 86 €/g-CO2.

Further dowsing supported by FEV 2-stage VCR system leads to a favorable cost and CO_2 emission level (44 €/g-CO_2). To achieve the performance levels of the base configuration and to reduce cost Miller and VVL have been dropped. Similar benefits of the FEV VCR technology in combination with hybrid powertrains such as P1, for power-split full-hybrid or P2 Plug-in-Hybrid are shown in [7].

4 RDE capability

Future powertrains have to comply with current and future exhaust gas emission legislations such as EU6d and CN6b. Common opinion is that this leads to stoichiometric ($\lambda = 1$) operation throughout the entire engine map as well as in transient operation (figure 6). Furthermore, future gasoline engines are equipped with particulate filters (GPF).

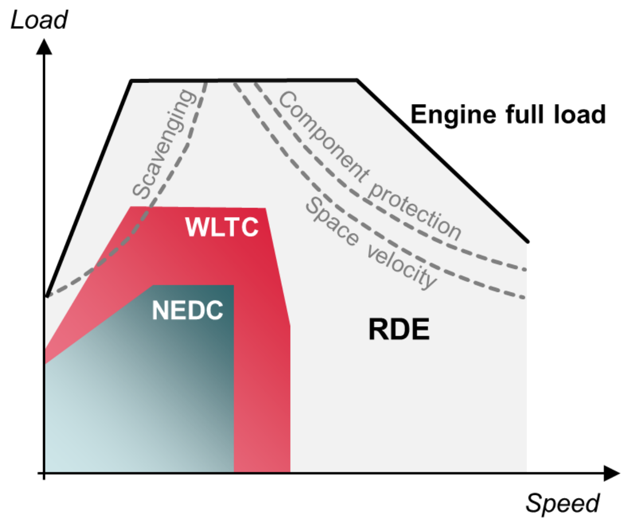


Fig. 6: Engine map operation NEDC, WLTP and RDE

Both measures ($\lambda = 1$ operation in the entire map as well as GPF) will lead to a dramatic reduction in engine performance:

- Avoiding of lean scavenging affects the low-end-torque (LET) and transient performance of a given engine
- Increased backpressure of the GPF in combination with decreased enrichment leads to a significant drop in engine power.

Based on a 2.0 l TC-DI engine it is shown that the FEV 2-stage VCR can improve the specific power output at stoichiometric operation ($\lambda = 1$) compared to the baseline configuration. Supplementary to the part load benefits, VCR permits the compression ratio to be adjusted optimal for high load. In figure 7 a comparison between fix CR = 11.7 and VCR = 10/14 reveals the advantages. At full load a low CR suppresses knocking and permits more optimum combustion phasing which at low engine speed improves full load fuel consumption whereas at high engine speed additionally the enrichment can be significantly lowered. For the example given, an advantage of >10 kW/l results at lambda = 1. Thus, VCR permits to be RDE compliant more easily.

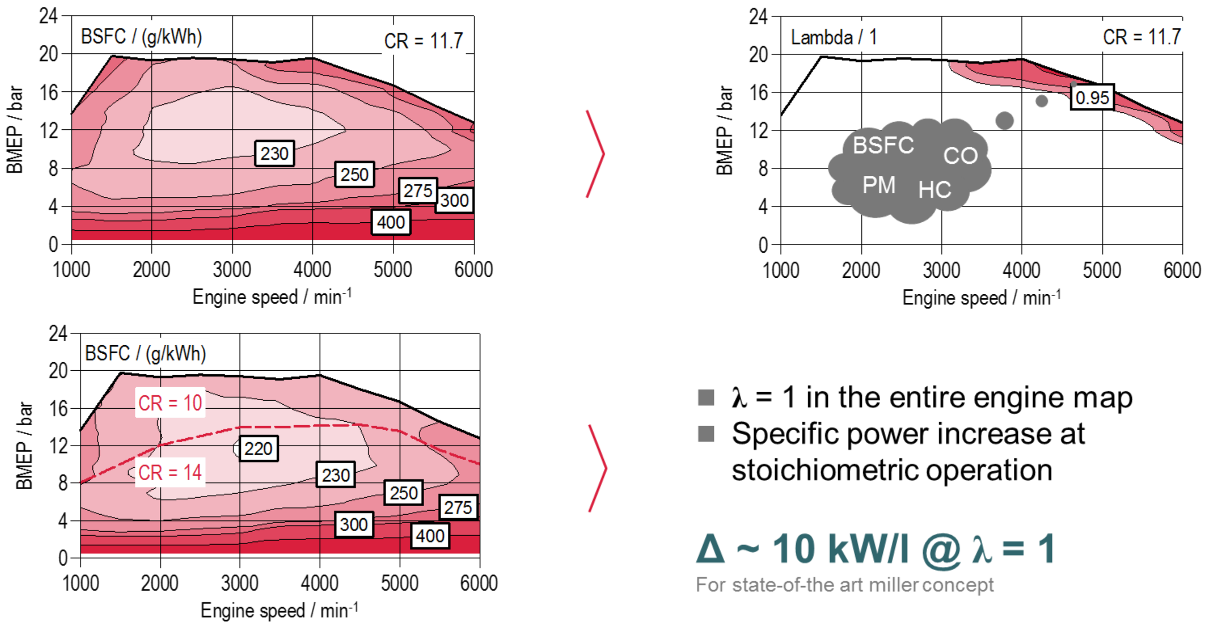


Fig. 7: Impact of FEV 2-stage VCR on specific engine power at fully stoichiometric operation for a 2.0 l TC GDI Miller concept

In particular, high performance engines profit from VCR due to their wide load range. For example, FEV mixed-sequential boosting combines high low-end torque with high power through serial arrangement of the compressors and parallel arrangement of the turbines of two turbochargers (Figure 8). The TC-control is managed via split exhaust ports with one on each turbine, and variable valve lift [6]. Based on a 1.0 l engine, a specific power of 110 kW/l can be achieved without enrichment.

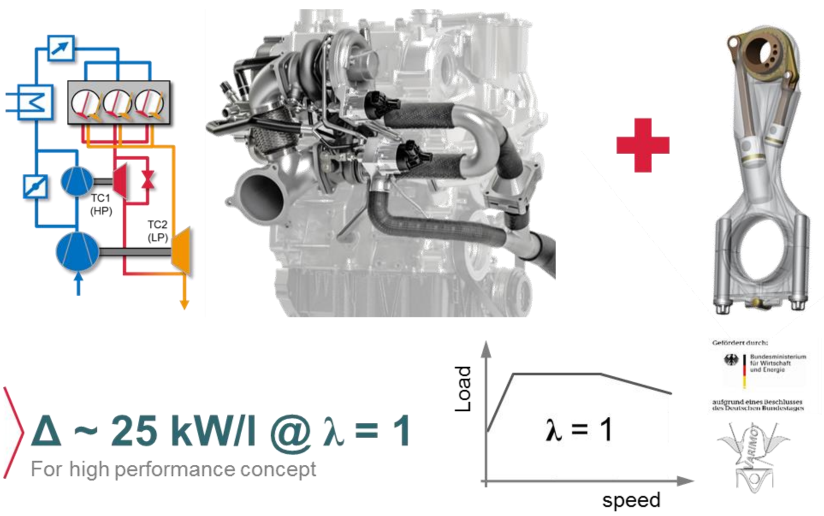


Fig. 8: FEV engine "Varimot" with FEV 2-stage VCR and mixed-sequential boosting system for high performance at fully stoichiometric operation

Besides the positive effect of lowering the knock sensitivity with low compression ratio, the latter can also be used to lower the peak pressure of a combustion system for a given engine with limited design peak pressure. Figure 9 gives an exemplary application for a CNG engine with Diesel-like peak firing pressure demands. In this case, VCR would permit the engines peak pressure to be lowered and to maintain the engines initial mechanical layout.

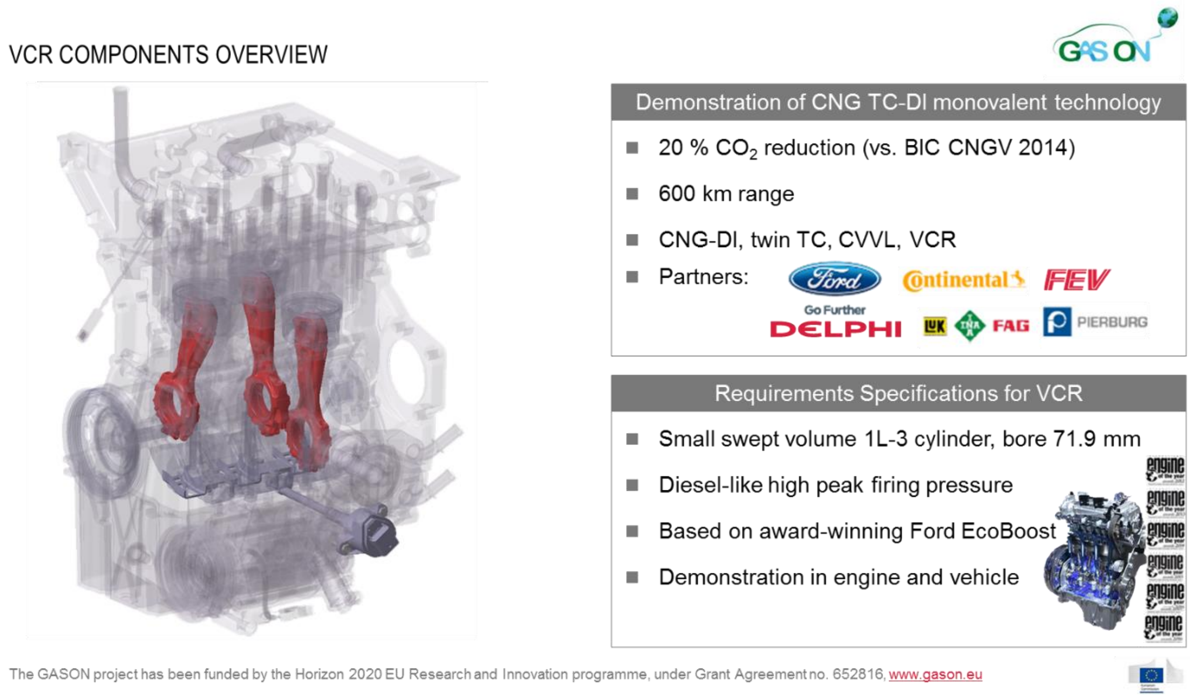


Fig. 9: FEV demonstrator CNG-engine "GasOn" with FEV 2-stage VCR

5 Modular engine concept

Technologies, which enables modular powertrain concepts, are the key for cost reduction over the entire engine family and/or vehicle fleet. As depicted in figure 10 the scaling of the engine power output in the past typically was realized by an engine family with different swept volume and hence cylinder numbers. Similar cylinder modules with identical combustions systems were a first step towards increased modularity. Nowadays the focus is reducing the number of base engines for a given engine family. Scaling of the power output by add on technologies like direct injection, (multi-stage) turbocharging, water injection and VCR leads to similar power spread with a fix cylinder number compared to an engine family of 3, 4 and 6 cylinder in the past.

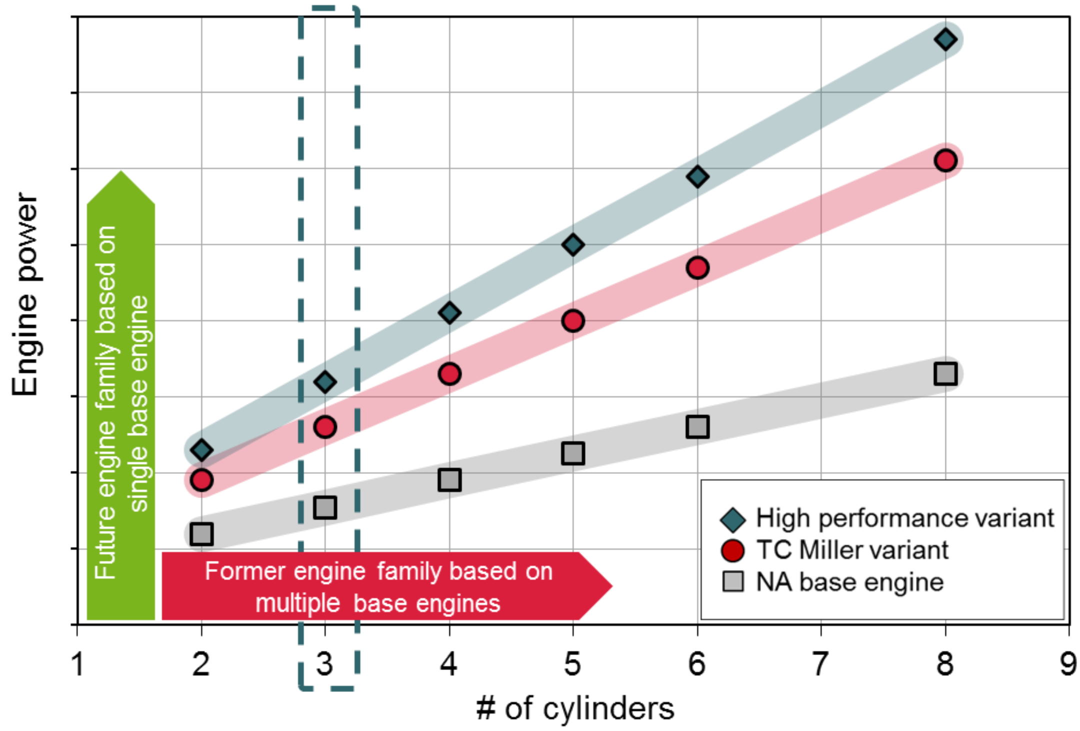
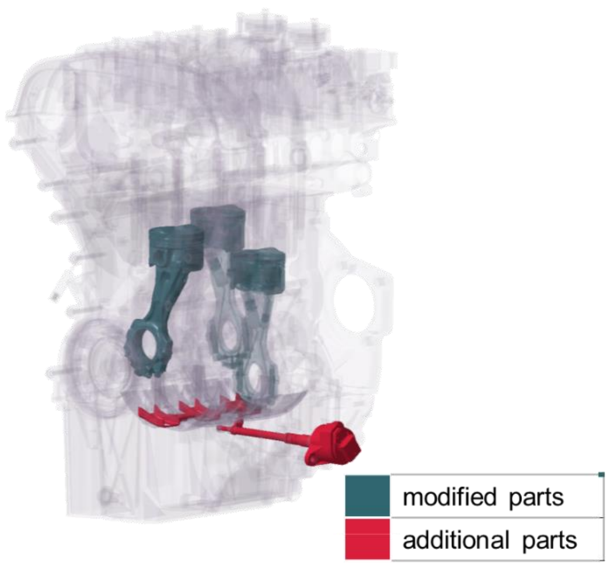


Fig. 10: Example of a future engine family based on a single base 3-cylinder engine concepts applying FEV 2-stage VCR and mixed sequential boosting

FEV demonstrated such concepts as early as in 2009 with its 2-stage gasoline demonstrator vehicle [8] providing 125 kW/l. Currently FEV is working on specific engines power beyond 200 kW/l.

Due to cost reasons (equal parts strategy) the dimensioning of the bearings are typically defined by the highest power variant. The derivate with lower power, which usually have an even higher sales volume, therefore have to deal with an oversized bearing layout and hence higher friction. This effects the CO2 results of the entire fleet negatively. If the high power variant is equipped with the FEV 2-stage VCR, bearing load and hence bearing dimensions can be reduced for the entire engine family. A modular VCR system like presented by FEV (figure 11) which can be easily integrated into an existing base engines, therefore reduces the CO2 emissions in the entire fleet (even in the low power versions where it is actually not applied). The main base engine parts such as crankcase and cylinder head remain unchanged with FEV 2-stage VCR.



Modularity matrix

		carry over parts	modified parts	additional parts
1	Crankcase	x		
2	Crankshaft	x	(x)	
3	Cylinder head	x		
4	Con rod		x	
5	Piston		x	
6	Timing drive	x		
7	VCR Actuation			x

Fig. 11: Modularity of FEV 2-stage VCR system

6 Development for series production – challenges and solutions

After concept proof of the 2-stage VCR-system which could be shown in multiple demonstrator projects on engines and in vehicles, requirements need to be defined for the application of the system under series production conditions. Here, not only the engines and vehicles general terms of application are to be considered for the definition of the mechanical validation process. Also, the integration of the VCR-system into the engines crank train and lubrication system requires the adaptation of the specific system layout. These (minor) modifications need to be incorporated into the engine design and shall be validated through CAE simulation and subsequent component and engine testing.

In order to adapt the 2-stage VCR system, 1D fluid simulations of the hydraulic system are performed in parallel and coupled with elastic multi body simulations (EMBS) of the crank train and connecting rod mechanics (Figure 12). Two separate models are coupled via functional mockup interface (FMI): the Elastic Multi Body Simulation (EMBS) of crank train / connecting rod mechanics and the 1D simulation model of the hydraulics. The piston positions and accelerations in the oil columns and of the check valves are considered in the 1D model to calculate the reaction forces. The elasto-hydrodynamic EHD bearing model considers the true bearing geometry, local deformation, surface roughness and cavitation to calculate oil flow rates. Also considered are the oil supply pressure fluctuations taking into account the crankshaft angle, angular velocity and bore design.

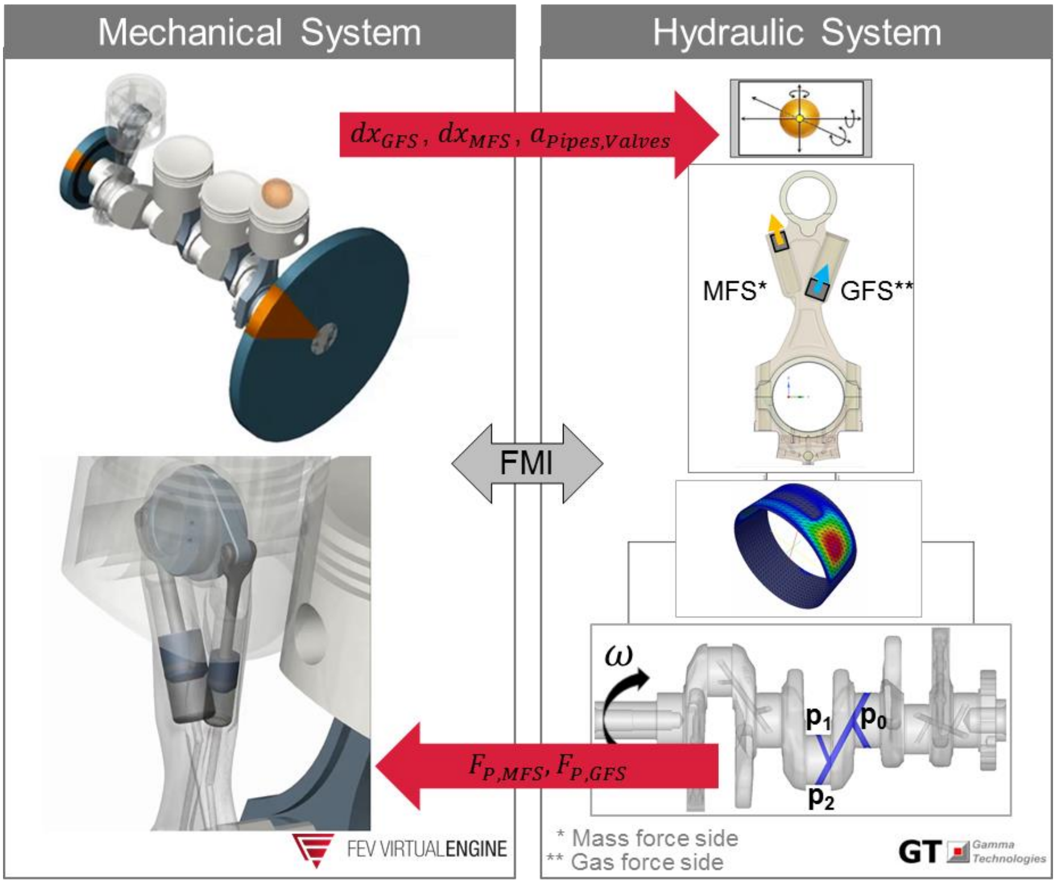


Fig. 12: Coupled 1D / MBS Simulation of VCR connecting rod - approach

As an example for the adaption of the hydraulic system with regard to the check valve layout, figure 13 shows the lever angle for switching procedures from high to low compression ratio. The valve geometry can be optimized for short switching times while assuring the absence of cavitation in the cylinder chambers. Diagram shows pressures in actuation cylinders of mass force side (MFS) and gas force side (GFS). The black curve represents the pulse force. Comparison of simulation and measurement shows excellent correlation

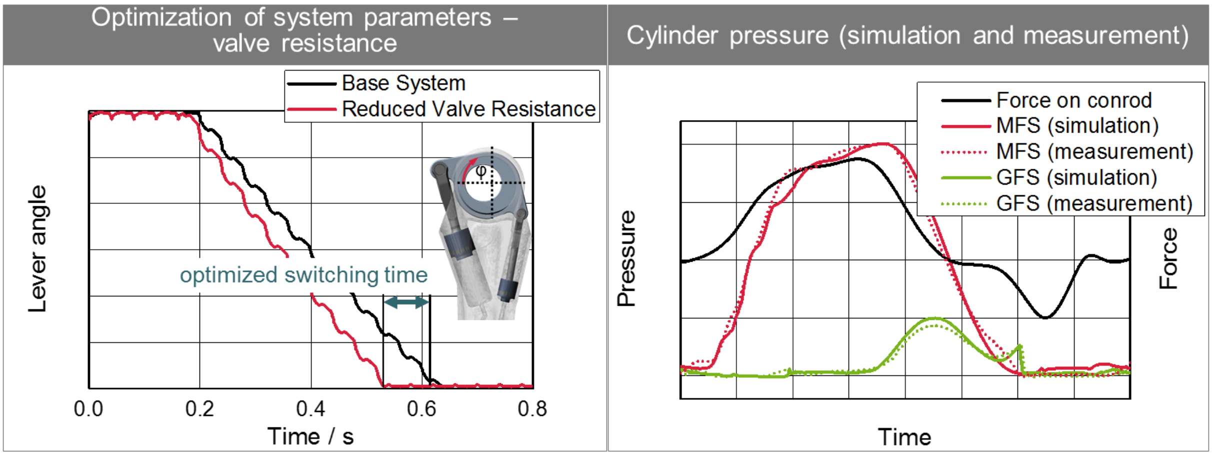


Fig. 13: Coupled 1D / MBS Simulation of VCR conrod - results comparison with measured data

7 Conclusion and outlook

The detailed analysis of the FEV 2-stage VCR system illustrates its superior benefits (figure 14).

Representing a smart, relatively simple and cost effective approach it generates the major portion of the thermodynamic potential of VCR technologies. More than 80% of the CO2 reduction potential of a fully variable system is realized. Due to its modularity it is easy to apply to existing engine family and additional technologies such as VVL, Miller cycle or exhaust gas recirculation. At the same time the costs of the FEV 2-stage VCR system are very attractive due to the low system complexity. Thus, its combination with Hybrid powertrains generates additional advantages in terms of cost to benefit ratio.

Similar applies to the flex fuel adaptation. By adapting the CR to the fuel characteristics the thermodynamic advantages of different fuel properties can be transferred into engine efficiency effectively.

For future legislative requirement such as RDE emission legislation this 2-stage VCR approach offers an attractive compensation of the losses in specific engine output coming from the request to eliminate the fuel enrichment used for component protection in a wide area of the engine map. By the 2-stage VCR solution the specific power output at stoichiometric operation conditions of a given Gasoline engine can be increased by around 15 kW/l, in combination with advanced boosting approaches, such as the mixed sequential boosting system, even further.

Therefore, FEV´s 2-stage VCR system is a very well suited approach to extend the power range of an existing engine family and thereby to reduce the number of separate base engine types for a given power demand at the same time.

Although this paper concentrated on Gasoline engine technologies it should be noted that for Diesel and HD engine major advantages in respect to performance and emissions, peak firing pressure limitation and NVH improvement have been reported as well.

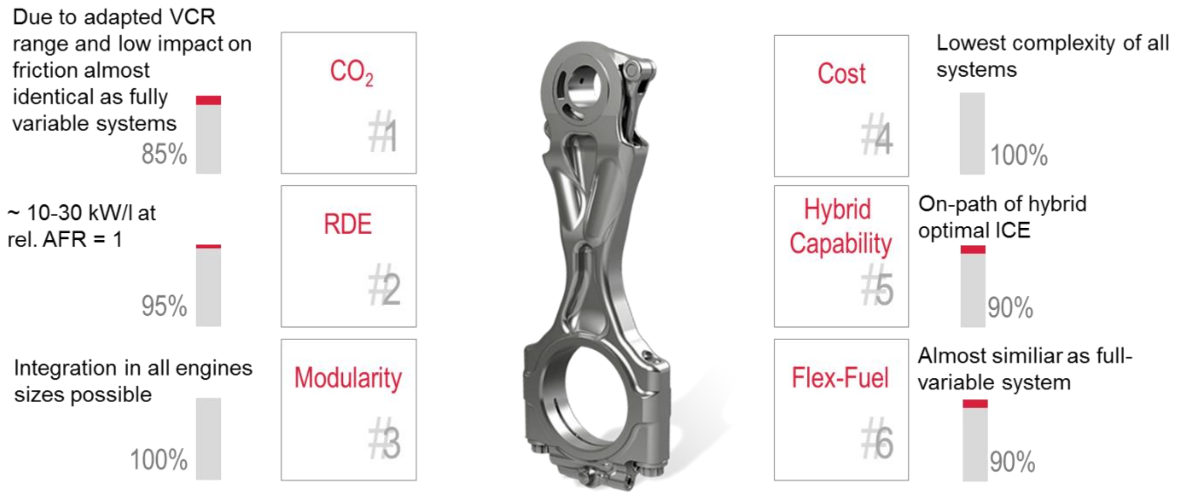


Fig. 14: FEV 2-stage VCR: The best solution for future powertrains

Acknowledgements

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