Gas-Only Internal Combustion Engines

Project number 652816

H2020 GV-3-2014 Future natural gas powertrains and components for cars and vans

Work Package – WP3
Advanced boosting and variable compression ratio for downsized CNG engines

Ford-Werke GmbH *(Ford)*	Continental Automotive CPT Group GmbH *(Continental)*	Delphi Technologies *(Delphi)*	Pierburg GmbH *(Pierburg)*	FEV Europe GmbH *(FEV)*	Schaeffler Technologies AG & Co. KG *(Schaeffler)*

WP3 Objectives

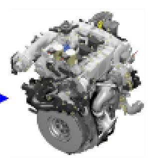
- **EU Targets**
  - 20 % CO_2 reduction
    (vs. Best-In-Class CNG Vehicle 2014)
  - 600 km range
  - EU6+ emissions
- **Additional WP3 Targets**
  - Fun-to-drive (110 kW, 240 Nm)
  - 7-seater van

Comparison of 2 Competing Technology Walks

Technology Walk #1

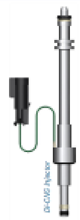
VCR engine

Basis:
1.6l 4 Cylinder
Ecoboost Engine

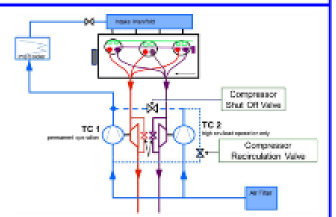


Downsizing:
1.0l 3 Cylinder
Ecoboost Engine

Downsizing enablers: re-gain power and torque



Methane Direct Injection (Methane DI)

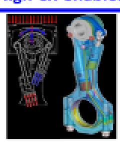


Parallel Sequential Twin Turbo Boost System

Part load de-throttling

Variable Valve Lift System Exhaust (CVVL)

High CR enabler



Variable Compression Ratio (VCR)

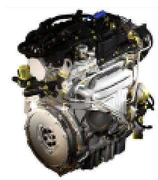
Weight Reduction

CNG Type 4 Tanks

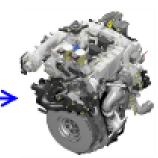
Investigated and compared in engine dynamometer tests

Technology Walk #2

Non-VCR engine & high combustion pressure capable engine architecture



Basis:
1.6l 4 Cylinder
Ecoboost Engine



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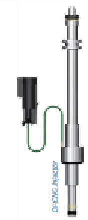

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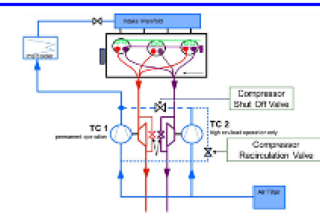


Parallel Sequential Twin Turbo Boost System

Part load de-throttling

Variable Valve Lift System Exhaust (CVVL)

Exploit high methane knock resistance

High combustion pressure capable engine components

Weight Reduction

CNG Type 4 Tanks

Selected for vehicle installation in GA 22. June 2018

Main tasks

Base Engine Design, New Technology Integration, Combustion System Development (CAE and dyno tests)
(FORD)

CNG DI injection system development and prototyping
(DELPHI, FORD)

Advanced parallel sequential boosting system development, packaging and prototyping
(CONTINENTAL, FORD)

Continuously variable valve lift (CVVA – Upvalve®) system development, packaging and prototyping
(PIERBURG, FORD)

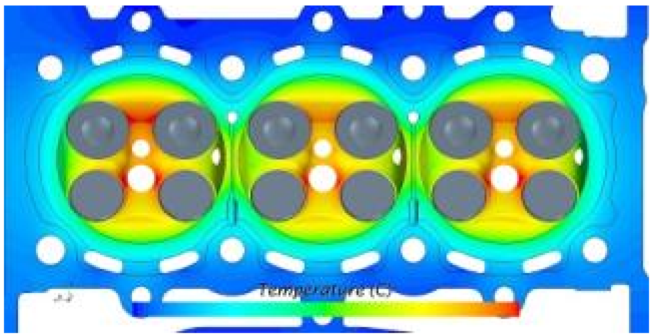
Variable Compression Ration (VCR) system development, packaging, prototyping and testing
(FEV, SCHAEFFLER, FORD)

Controls System Development, Steady State Calibration, Vehicle Calibration
(CONTINENTAL, FORD)

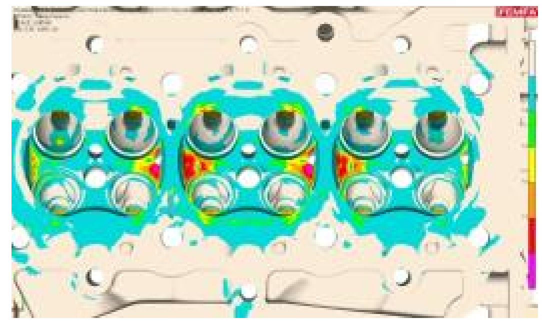
Design storage system, engine & subsystems installation on demo vehicle, refinement & full assessment
(FORD, CONTINENTAL)

Base Engine Design - CAE optimization (Ford)

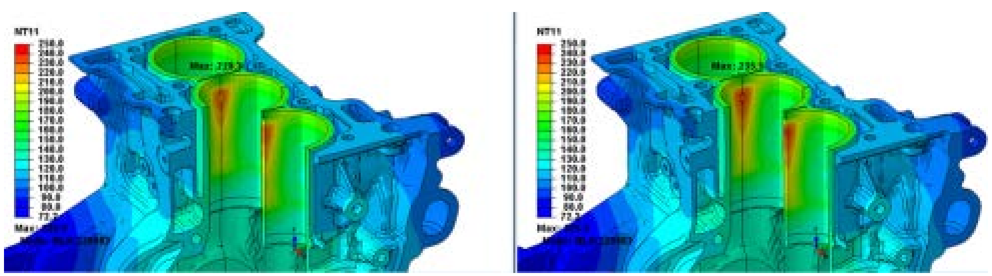
CAE optimization of all new engine components. Particular focus on high maximum pressure capability in order to exploit high knock resistance of CNG.



Cylinder head thermal analysis



Cylinder head high cycle fatigue calculation



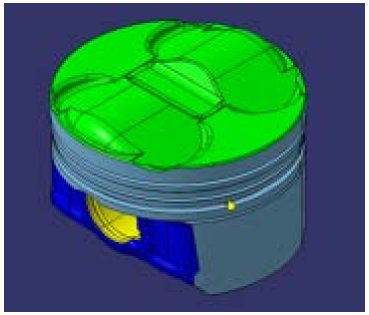
Cylinder block temperature analysis by CAE at different power levels

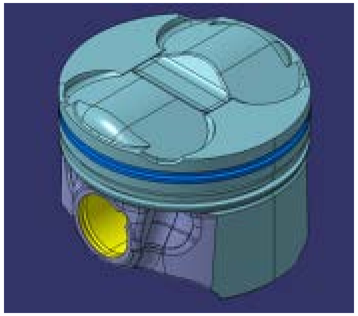
Further CAE high pressure optimization of:

- Pistons
- Crankshaft
- Con rod
- Crankshaft and Con rod Bearings

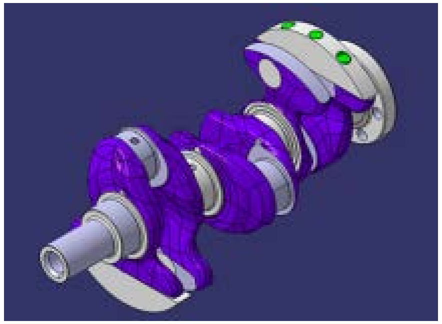
Base Engine Design (Ford / FEV)

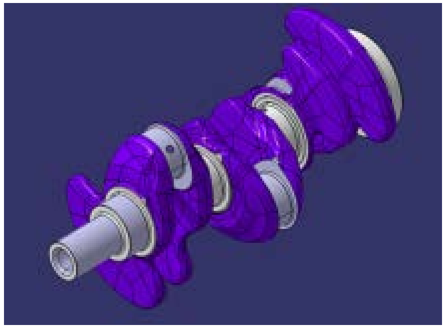
Doubled expense for dedicated VCR and Non-VCR components





Unequal piston designs for VCR and Non-VCR version





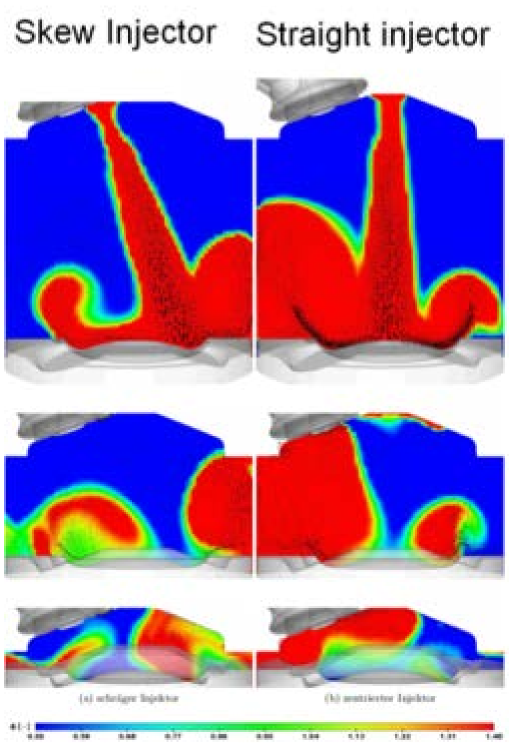
Unequal crankshaft designs for VCR and Non-VCR version

Further differences between VCR and Non-VCR version

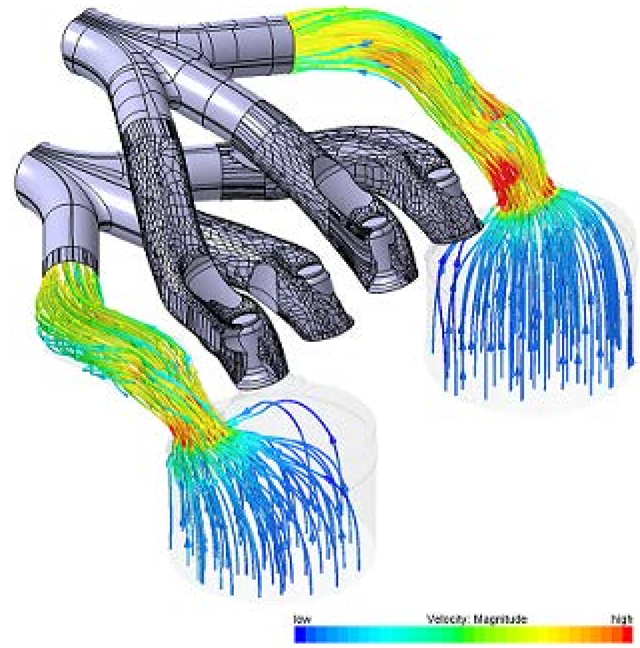
- Con rod
- Crankshaft and con rod bearings

Base Engine Combustion System Development (Ford)

CAE optimization: combustion system, port and piston design, injection process



Effect of two injector angles on the air/fuel homogeneity



CFD exhaust ports mass flow rate optimization

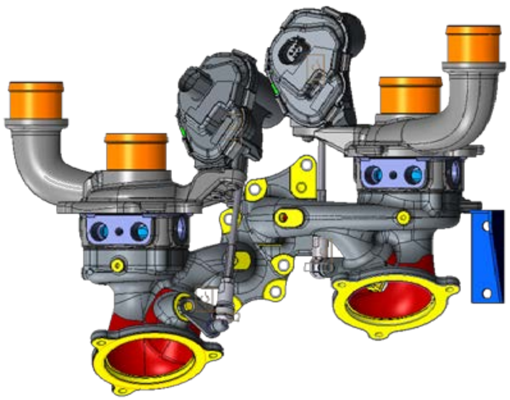
CNG Direct Injection (Delphi)

CNG direct injection developed and adapted for dedicated CNG engine (high pressure capability, high power → high flow)

- Lifetime durability demonstration on laboratory test bench
- Injector equipped with injector driver box
  → Load specific adaption of electrical current profile

Advanced parallel sequential boosting system development (Continental)

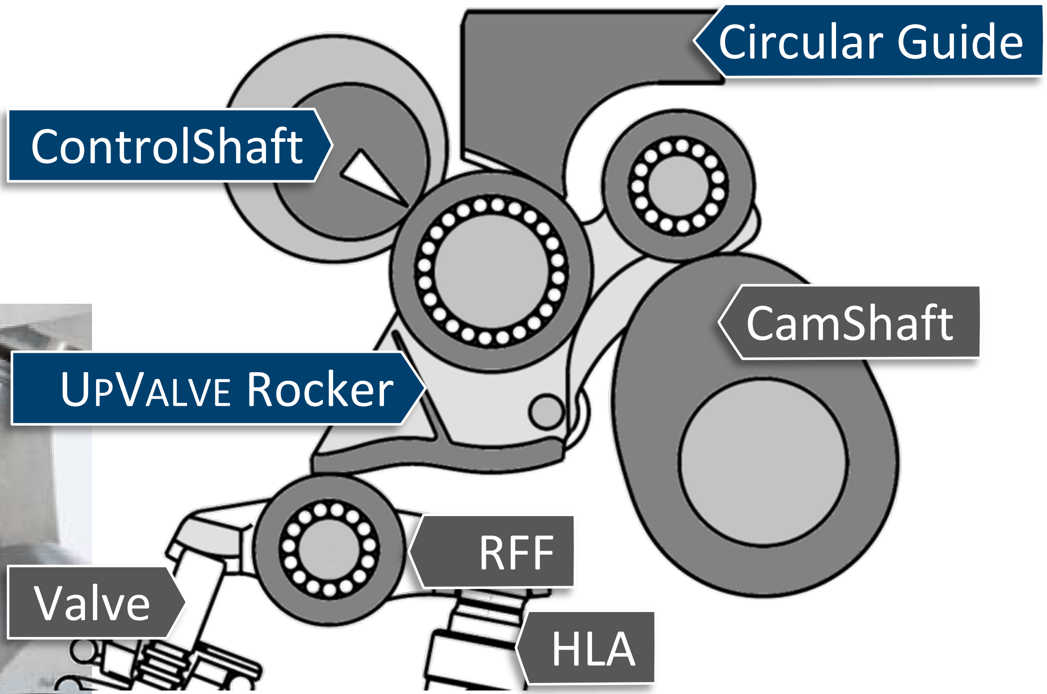
Parallel sequential boosting system matched to achieve 120 kW /240 Nm



- **Simulation of air path (Continental / Ford)**
- **Matching & aero design (Continental)**
  Challenges:
  - Design: turbine diameter D2 = 39mm
  - Number of revolutions: 285,000 rpm
    Peripheral speed: 580m/s
    Mitigation: min-min bearing & balancing
  - Compressor stability for π=3.4
- **Manufacturing (Continental)**
- **Testing (Continental / Ford)**
  - Performance testing on hot gas test bench
  - Verification of functionality and robustness in engine dynamometer tests

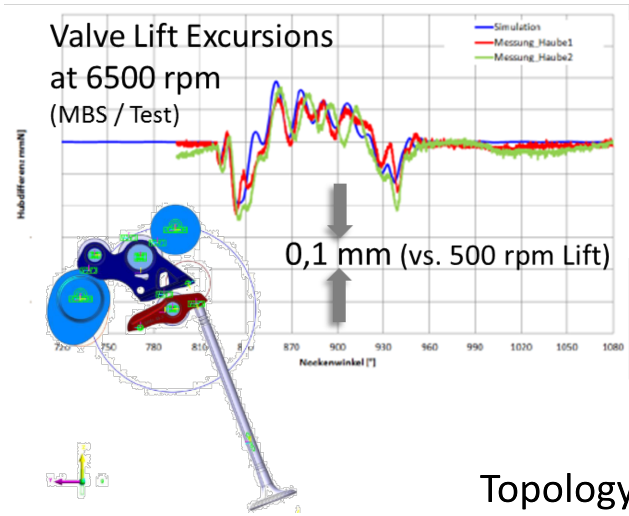
Continuously variable valve lift (CVVA – Upvalve ®) system (Pierburg)

CVVA system designed and packaged as cylinder head cover.

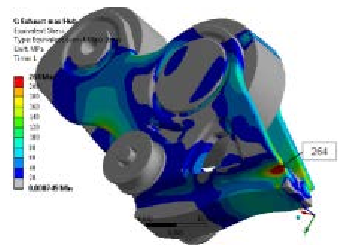


Continuously variable valve lift (CVVA – Upvalve®) system (Pierburg)

Application to high combustion pressure capable engine design by significant CAE support and extensive component testing during CVVA development.

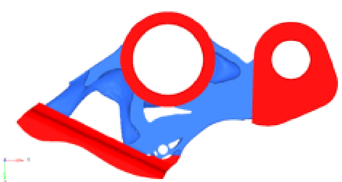


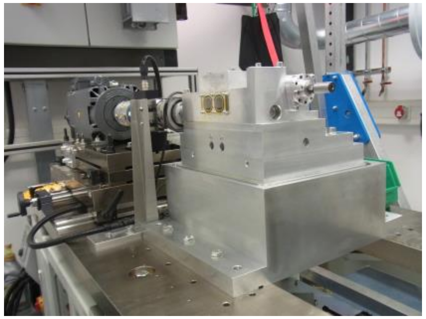
Multibody Simulation
- Dynamic Valve Train Performance
- Valve Spring Layout



FEM
- Mechanical Stress Analysis

Topology Optimisation
- Reduction of Mass and Inertia





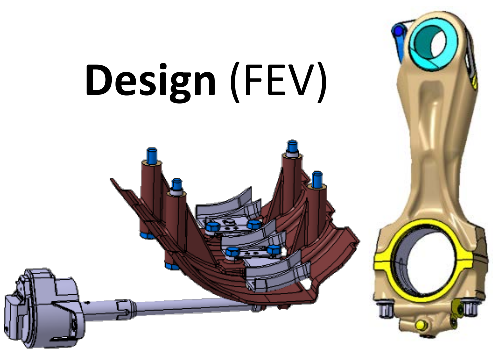
Single Cylinder Mock-Ups & Multi Cylinder Head Test Rig
- Motored Cam and Control Shaft
- Oil Conditioning (Pressure/ Temp.)
- Online Valve Lift Measurement via Laser Vibrometer

Variable Compression Ratio VCR system development (FEV & Schaeffler)

VCR, a highly effective measure for CO_2-reduction in gasoline engines, in GasOn mainly expected as an enabler for lowering peak pressure requirements.

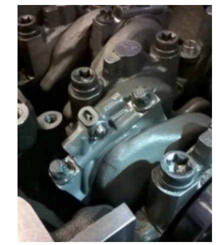
Work Share FEV / Schaeffler

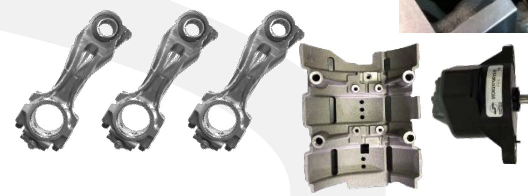
Design (FEV)



Industrialization (Schaeffler)

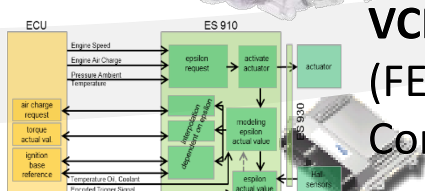
HW & Engine Build (FEV & Schaeffler)



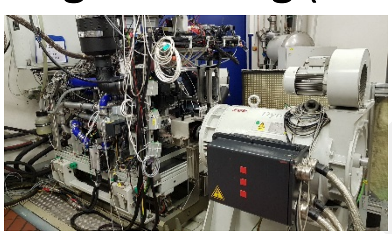


Component testing (FEV & Schaeffler)

VCR Controls (FEV & Continental)



Engine testing (FEV)

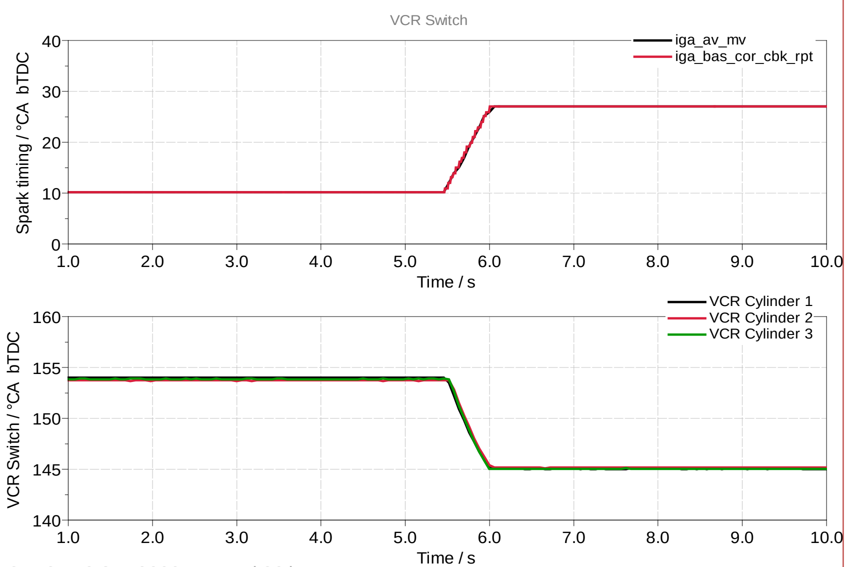


Variable Compression Ratio VCR system development (FEV)

VCR switching time satisfying (in relevant range up to 3000 rpm)

Exemplary VCR Shift CR_{high} → CR_{low}

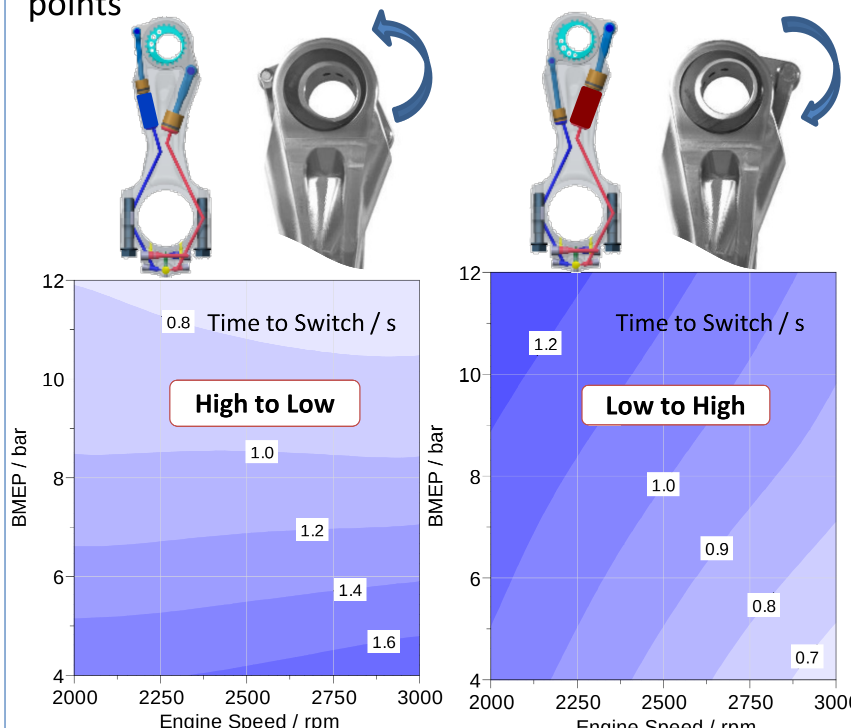
Ignition angle adaptation during shifting from CR13 to CR 9.8 using ECU Bypass → torque-neutral



CR 13 to 9.8 at 2000 rpm and 20 bar BMEP

VCR Switch Mapping

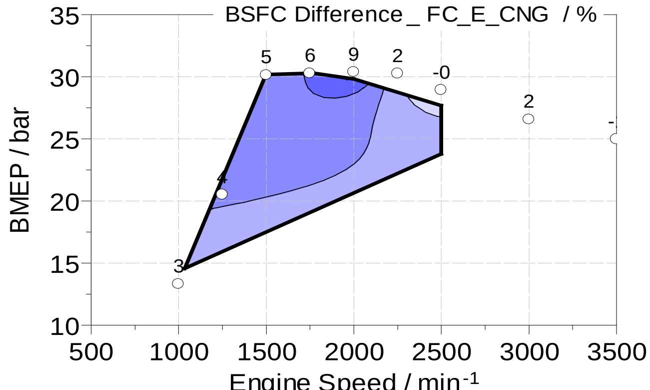
Fast switching time in relevant engine operating points



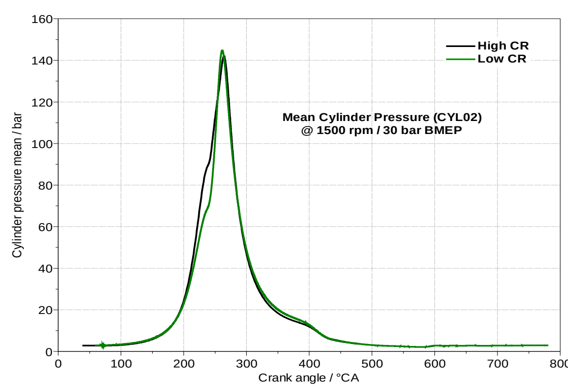
Variable Compression Ratio VCR system development (FEV)

5-9 % increased fuel consumption with VCR version (VCR at low position CR 9.8) vs. Non-VCR version (CR 13).

BSFC DIFFERENCE: VCR CR 9.8 vs Non-VCR CR 13



Cylinder Pressure Trace at full load in CR_{low} and CR_{high}



Source: FEV

- Full load torque 240 Nm, (BMEP 30 bar) at 1500 rpm achieved with VCR engine
- No knocking / no pre-ignitions with CR low
- 5-9 % higher fuel consumption with low compression ratio (which needs to be adjusted at the VCR engine for full load operation)

- Only minor Peak Pressure Difference between Low CR and High CR (at opt. efficiency settings)

=> Low compression ratio not beneficial as long as fuel is not knock limiting

Variable Compression Ration (VCR) system development (FEV)

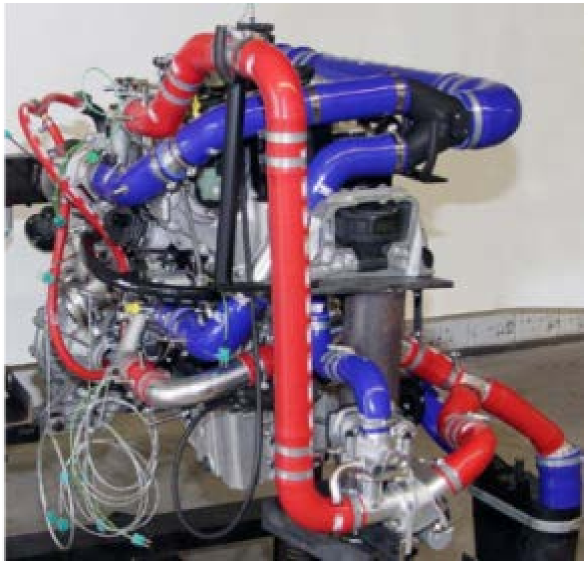
With knock resistant fuel CNG and at high engine loads: higher fuel consumption and only minor peak pressure reduction of the VCR version (@CR low) vs. the Non-VCR version

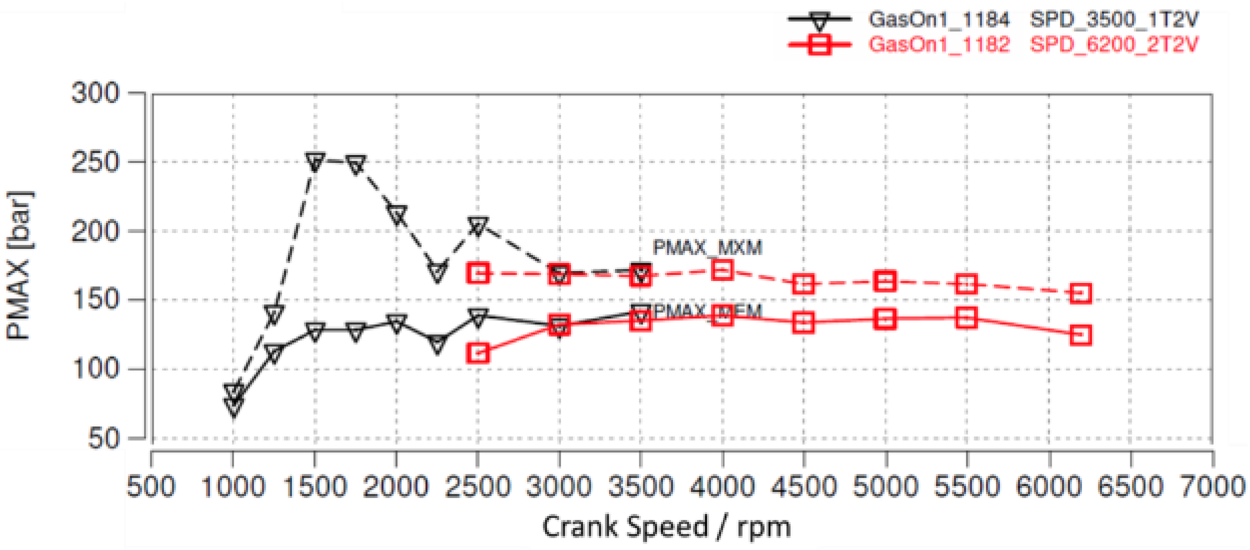
- The main reason for this unexpected results is the generally high knocking resistance of CNG fuel, combined with the achieved high combustion pressure capability of the Non-VCR engine, without increasing the engine friction significantly.
- **Due to the CO_2 penalty, it was decided to proceed the vehicle installation and calibration with the Non-VCR version (Decision GA meeting June 2018)**

Base Engine Design (Ford) - Confirmation of Base Engine Robustness

Confirmation of High Combustion Pressure Capability and Robustness by approx. 3,500 hours of dyno operation.

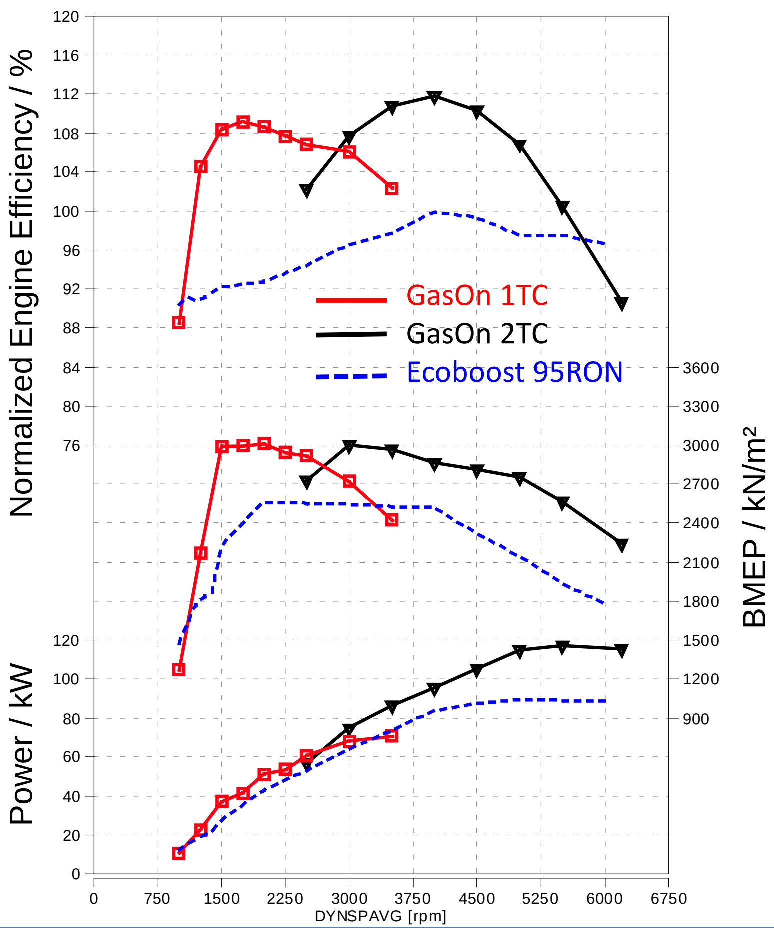
- 3 Non-VCR engines tested for ~ 1780 hrs, 700 hrs and 950 hrs (engine dyno at FORD).
- VCR engine tested for 120 hrs (engine dyno at FEV).
- Sometimes very severe conditions: peak combustion pressure up to 250 bar (due to pre-ignition → significantly higher than the development target of 185 bar).





Combustion System Development (Ford) - Power, Torque, Efficiency

Power target (110 KW) overachieved (120 kW). BMEP target (30 bar) achieved.

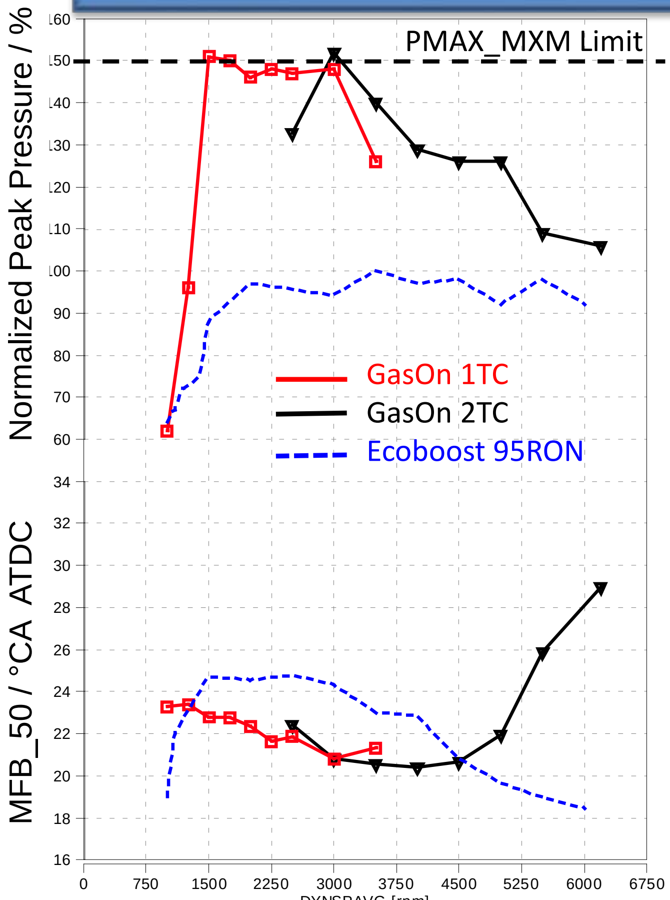


Engine dyno test data:

- GasOn WOT efficiency (normalized on basis: gasoline 95 RON; 1.0l Ecoboost ®)
  - o + 12 % peak efficiency (@ 4000 rpm)
  - o + 16 % @ 1500 rpm
- Max BMEP 30bar @ 1500…3500 rpm → **target achieved**
- Peak Power 120kW (163hp) **overachieves target** of 110 kW (150 hp) **with Lambda 1 operation !**

Combustion System Development - Peak Pressure, Combustion Phasing

Still efficient combustion phasing (22 … 21 °CA ATDC) at high BMEP level of 30 bar, limited by combustion peak pressure limit of 185 bar.

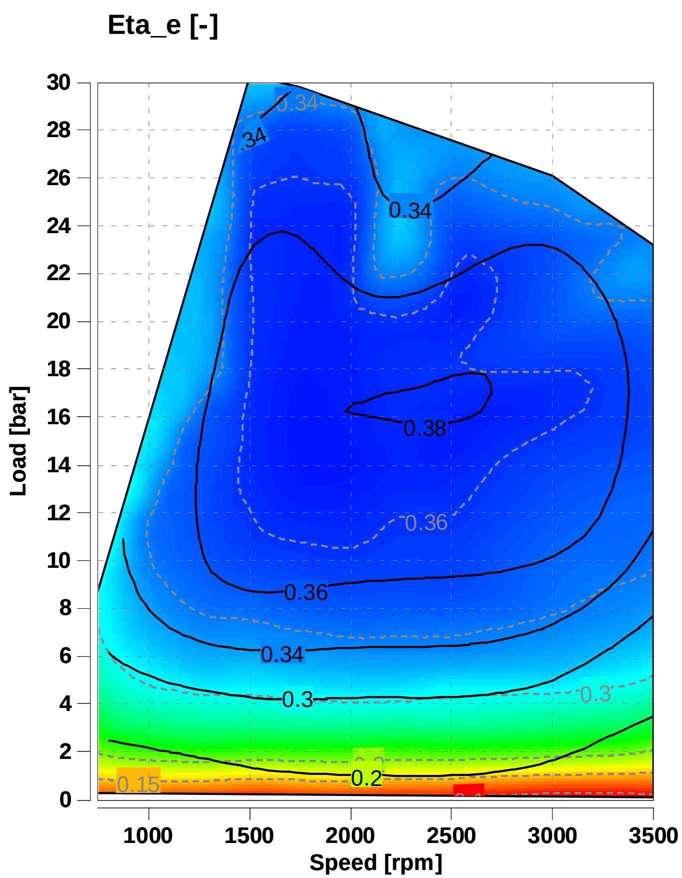


- 50% above current production engine (Peak combustion pressure 185 bar,1.0l Ecoboost, 95 RON) reaching limits of dedicated engine architecture
- Only slightly retarded combustion phasing (MFB_50 = 22 … 21 °CA ATDC) in combustion pressure limited rpm range (1500 … 3000 rpm)

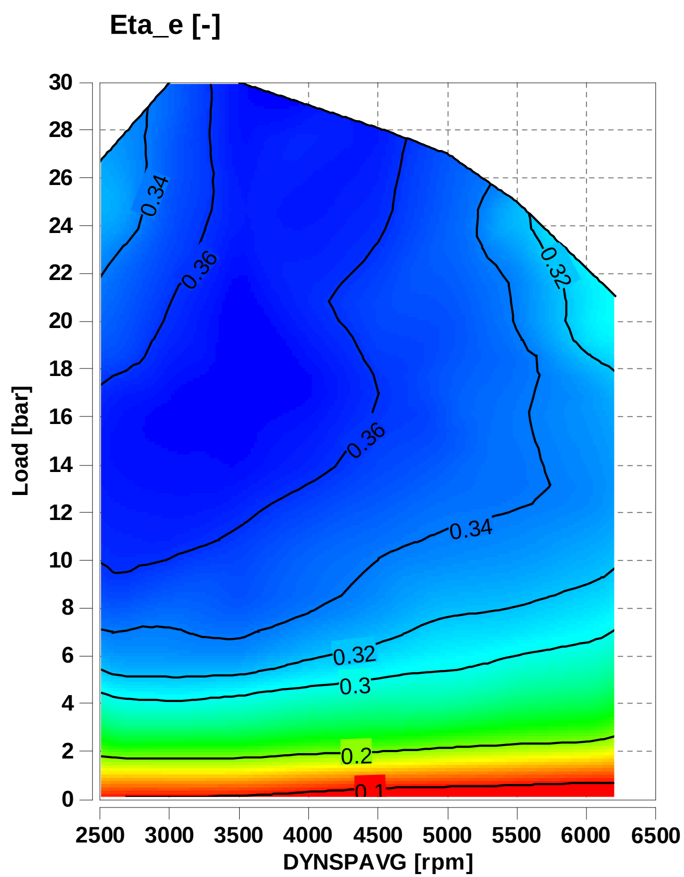
Combustion System Development (Ford) - Efficiency Non-VCR Engine

Best efficiency > 38 %. Very wide area > 30 %.

1-TC mode



2-TC mode

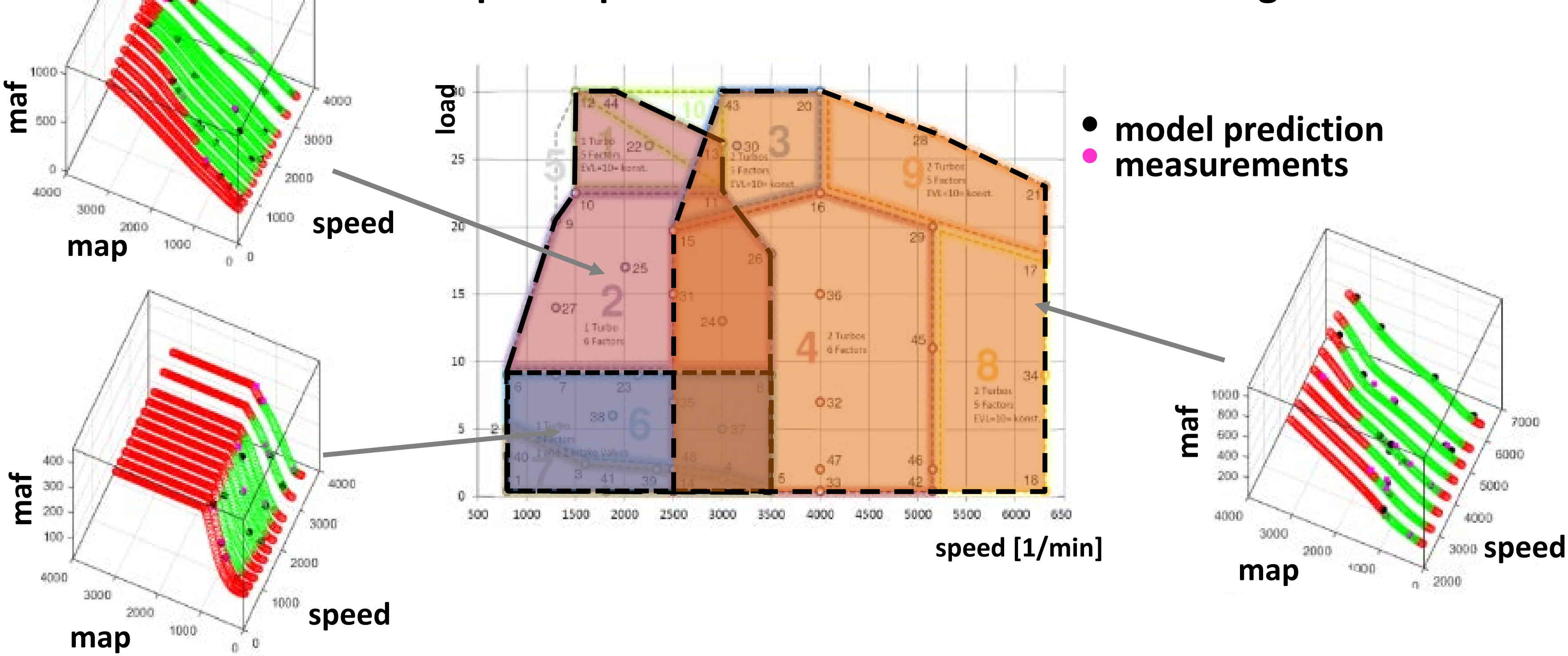


Steady State Calibration (Ford)

Large set of calibration parameters → DoE for steady state calibration → calibration time ↓.

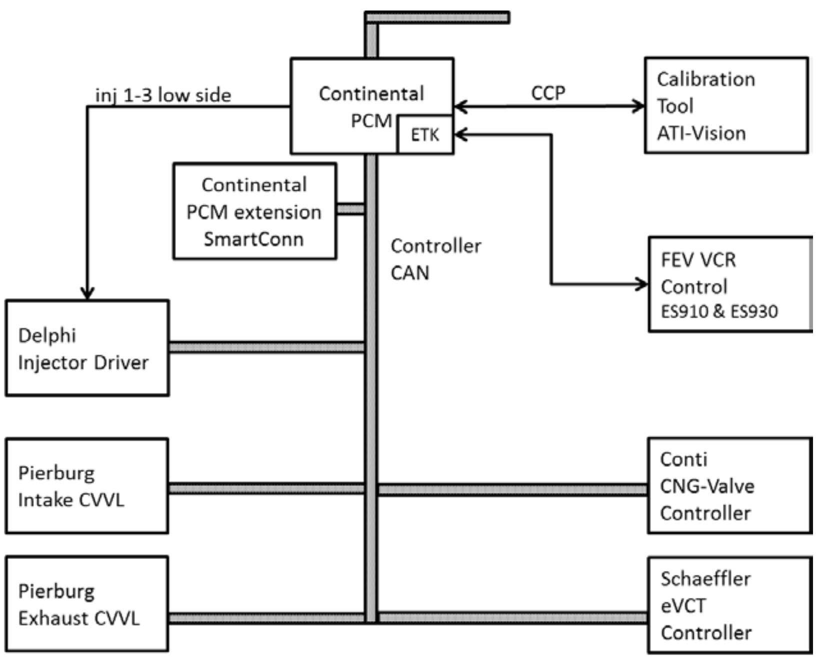
Full factorial data acquisition would have led to >1000 years of measurement time. DoE approach allowed steady state mapping in approx. 1500 dyno hrs.

Map with pre-defined and constant valve settings



ECU hardware, function and SW development (Continental)

Engine design with high degree of freedom in adjustable parameters, required complex interaction of 7 (8) control units and development of new software functionalities

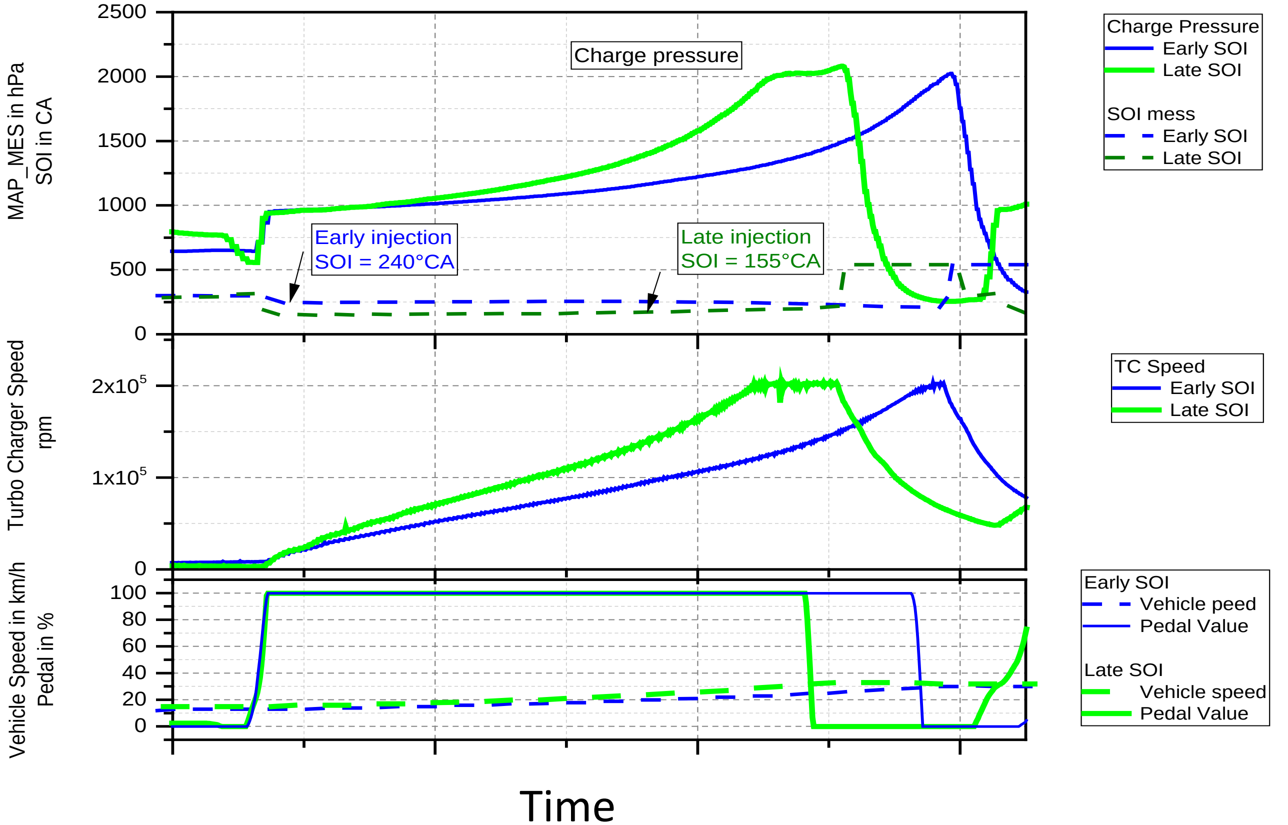


Development of project specific functionality

- Control of ECU subsystems
  - Delphi (injectors), Schaeffler (e-VCT) and Pierburg (CVVA), Continental (gas system management)
- Emission related functionality
  - Catalyst warm up strategy by lambda split
  - Catalyst keep warm strategy using CVVA system
  - Spark retard and waste gate control at engine after start
- Driveability and component protection related functionality
  - Turbo charger over speed protection TC1 / TC2
  - Time to torque improvement strategy

Vehicle Calibration (Continental / Ford) – CNG DI Injection Timing

Delphi CNG DI technology offers improved time to torque capability by application of late SOI (Start of Injection)



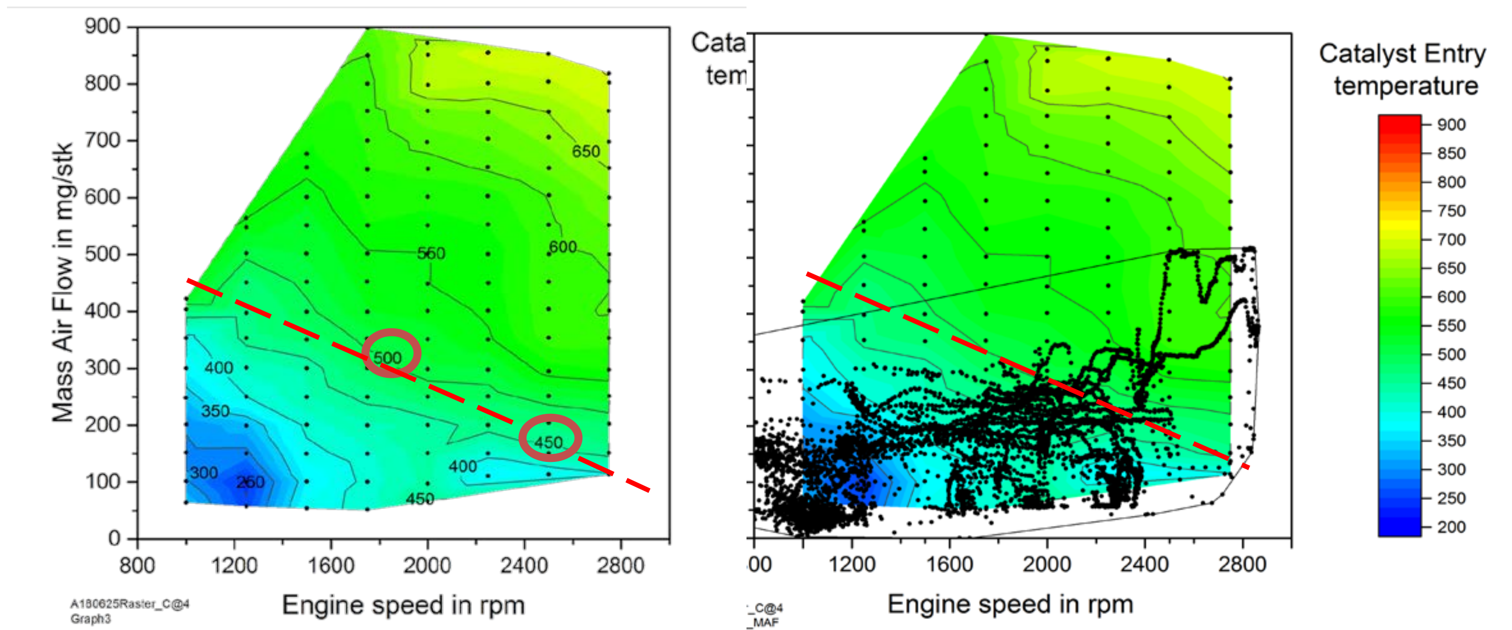
Late SOI increases air mass flow to cylinder

- increases low end engine torque
- generates additional heat for TC speed up
- improves downsizing capability

Vehicle Calibration – Emission Capability: Catalyst Heating Requirements

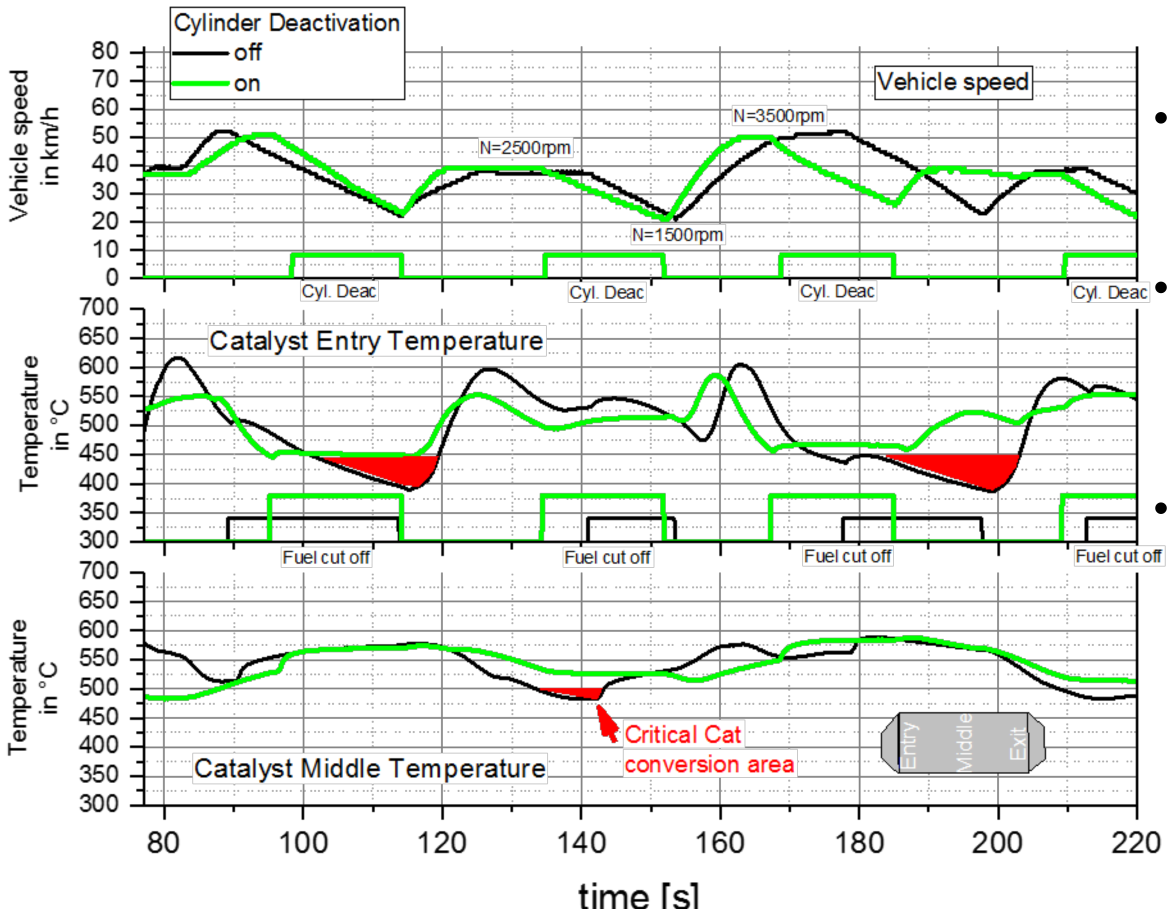
Efficiency optimized vehicle calibration leads to very low catalyst temperatures and thus conversion issues at low load → Countermeasure: Implementation of "Lambda Split"

- CH_4 conversion requires min. catalyst temperatures of 450 – 500°C
- Catalyst temperature not sufficient for CH_4 conversion in most parts of NEDC
- Countermeasure: Implementation of "Lambda Split Function" (2 cylinder rich and 1 cylinder lean) → de-balancing increases generation of CO
- CO oxidation in the catalyst generates additional heat directly in the catalyst (no heat losses).



Vehicle Calibration (Continental) – Emission Calibration

Cylinder deactivation during fuel cut off introduced to reduce HC emissions.



- Pierburg CVVA system on intake side offers cylinder deactivation
- Cylinder deactivation used in order to prevent catalyst cooling at engine motoring and fuel cut off phases
- Reduction of HC peaks after fuel cut off phases due to higher catalyst temperature

Demo Vehicle: Storage System Design & Installation (Ford)

6 tanks installed: range approx. 650 km, 600 km range target overachieved

- 4 bottles underbody replace the original gasoline tank
- 1 bottle below trunk (vehicle body modified, spare wheel well removed).
- 6^{th} mounted in the trunk behind 3rd seat row.
- 7-seater capability maintained

Demo Vehicle: Engine & Subsystems Installation (Ford)

Engine packaged in Ford C-MAX without any violation of design requirements (e.g. crash)

- GasOn engine installed in the CNG vehicle: new PCV system on top

- GasOn engine installed in the CNG vehicle: split compressor air routing

Demo Vehicle: Refinement & Full Assessment (Continental, Ford)

NEDC, WLTP and RDE Tests: HC, CO, NOx and PN below EU6 emission limits

Final emission results

- All NEDC, WLTP and RDE emissions - CO, NOx, PN, THC, NMHC below EU6 limits
- CO_2 target (> 20 % below BIC 2014 CNGV in NEDC) achieved

~1% CO2 reduction for homologation fuel G20/G25, since tests were carried out with pump fuel (approx. 95 % CH_4 and 5% C_2H_6). Replacement of 7 ECUs by 1 integrated ECU would lead to additional 0.5 – 0.7 gCO2/km reduction by reduction of electrical load

	Bag	HC	CO	CO2	Corrected CO2	NOx	NMHC	HC + NOx	Fuel econ.	Particulate	PN
		[mg/km]	[mg/km]	[g/km]	[g/km]	[mg/km]	[mg/km]	[mg/km]	[m3/100km]	[mg/km]	[1/km]
	Limits EU6	100	1000			60 84 (RDE)	68			4,5000	6,00E+11
Testbench CONTI	NEDC	62,5	188,5	100,5	99,0	34,5	8,5	97,0	5,6		7,47E+09
	WLTP	31,1	467,3	121,7	120,0	43,4	1,9	74,5	6,8	0,2	1,62E+10
	RDE - aggressiv	59,3	613,9	161,0	159,0	76,0	2,6	135,3	9,0	3,0	5,84E+10
Testbench JRC	NEDC	57,0	220,0	105,0	103,5	24,0	9,0				1,30E+10
	WLTP	35,0	510,0	128,0	126,5	43,0	5,0				2,20E+10
	RDE		540,0	148,0	146,5	73,0					1,10E+11
	RDE Urban		310,0	156,0	154,5	85,0					2,20E+11

Demo Vehicle: Refinement & Full Assessment (Continental, Ford)

NEDC, WLTP and RDE Tests: HC, CO, NOx and PN below EU6 emission limits

Final emission results

- All NEDC, WLTP and RDE emissions - CO, NOx, PN, THC, NMHC below EU6 limits
- CO_2 target (> 20 % below BIC 2014 CNGV in NEDC) achieved

For comparison:

Ford Grand C-MAX	WLTP CO2 / g/km
GasOn CNG 1.0 l (120 kW)	120 … 126
Gasoline 1.5l Ecoboost (110 kW)	169 … 172
Diesel 2.0l TDCi (110 kW)	146 … 152

Conclusion	
Engine level: Dedicated CNG engine with CNG-DI, advanced twin parallel sequential boosting system, variable valve actuation, high compression ratio and high combustion pressure capable base engine architecture vs. VCR successfully tested with regard to efficiency and emission targets. Final vehicle installation of Non-VCR version.	√
CO_2 reduction >20 % (NEDC) vs. best in class CNG vehicle 2014 achieved.	√
Upgraded CNG storage system ensures a full driving range of ~650 km while 7-seats are kept	√
EU6 emission limits met in NEDC, WLTP and RDE with a single 3-way-catalyst. PM and PN are extremely low without any filtration device.	√
Power target (110 KW) overachieved (120 KW) and BMEP target (30 bar) met.	√

Thanks for your attention