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Ignition- and combustion concepts for lean operated passenger car natural gas engines

Patrik Soltic[1], Thomas Hilfiker[1]
Severin Hänggi[2], Richard Hutter[2]

[1] *Empa, Automotive Powertrain Technologies Laboratory, CH-8600 Dübendorf*
[2] *ETH, Institute for Dynamic Systems and Control, CH-8092 Zürich*

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Project partners in the work described here are Volkswagen Group Research, ETH LAV, ETH IDSC, Empa, Poznan University, Ricardo Software, Continental Corp.

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- Project: Find Diesel-Like Efficiencies in a CNG Engine
- Description of the Engines
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Introduction: Today's CNG Engines and their Limitations

- Today's modern passenger car natural gas engines are based on petrol engines, with some adaptations
- Typical adaptations are
  - Increased compression ratio (due to knock resistant methane fuel)
  - Adapted valves/valve seats (due to missing lubrication from methane)
  - Increased boost pressure (to compensate the loss of volumetric efficiency)
  - High-temperature turbine material (due to the lack of evaporative cooling effects)
- Typical limitations are
  - Peak pressure (100-120 bar)
  - Emission reduction with three-way-catalysts (λ=1 combustion)

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Project: Find Diesel-Like Efficiencies in a CNG Engine

- Omit $\lambda=1$ combustion → lean (diesel-like) combustion
- Omit petrol engine peak pressure limitation → use diesel engine as a basis
- Investigate the effect of the ignition system / ignition energy → use the fundamentally different ignition systems
  - Highly insulated spark plug
  - Prechamber in unscavenged and gas scavenged operation
  - Diesel pilot ignition
- Prechamber design: using CFD (by Volkswagen, Ricardo Software and ETH LAV), the data presented here and optical experiments will lead to an updated design later in the project

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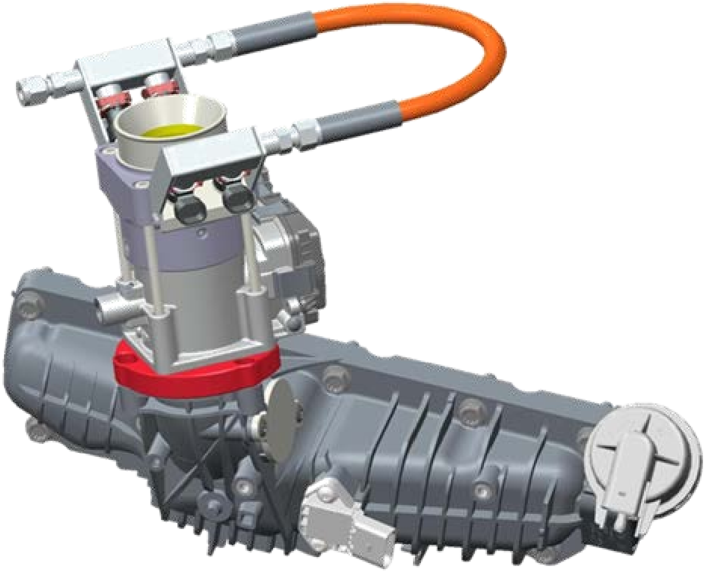
Description of the Engines

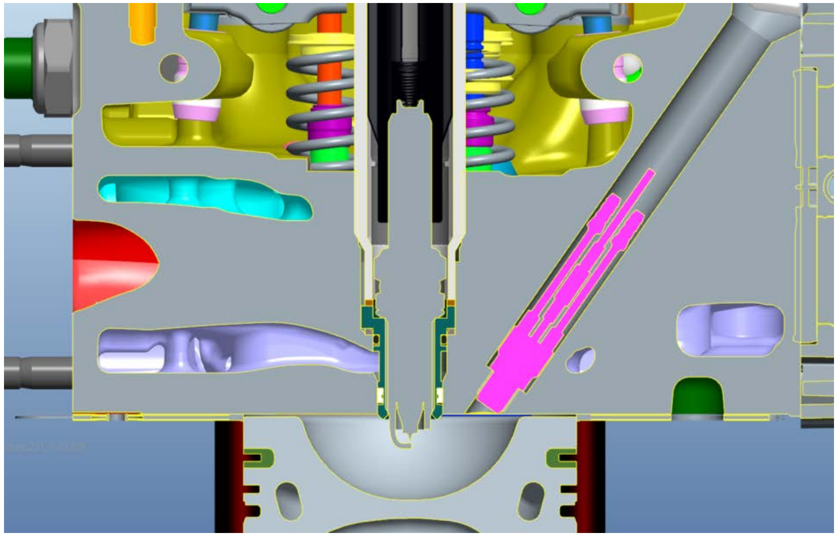
Parameter	Engine 1 Spark Plug Engine	Engine 2 Prechamber Engine	Engine 3 Diesel Pilot Engine
# of cylinders / valves per cylinder	4 / 4	4 / 4	4 / 4
Displacement [cm^3]	1968	1968	1968
Bore/stroke [mm]	81 / 95.5	81 / 95.5	81 / 95.5
Compression ratio	14.5	14.5	16.5
Ignition system	Inductive	Inductive	-
Spark plugs	NGK M12 in open chamber	NGK M10 in prechamber	-
Diesel injection system	-	-	Common Rail with Piezo Injectors
Gas port fuel injectors	Bosch NGI2 (via mixer)	Bosch NGI2 (via mixer)	Bosch NGI2 (MPI)
Prechamber injectors	-	Special design	-
EGR	-	-	-

Engine 1: Spark Plug Engine

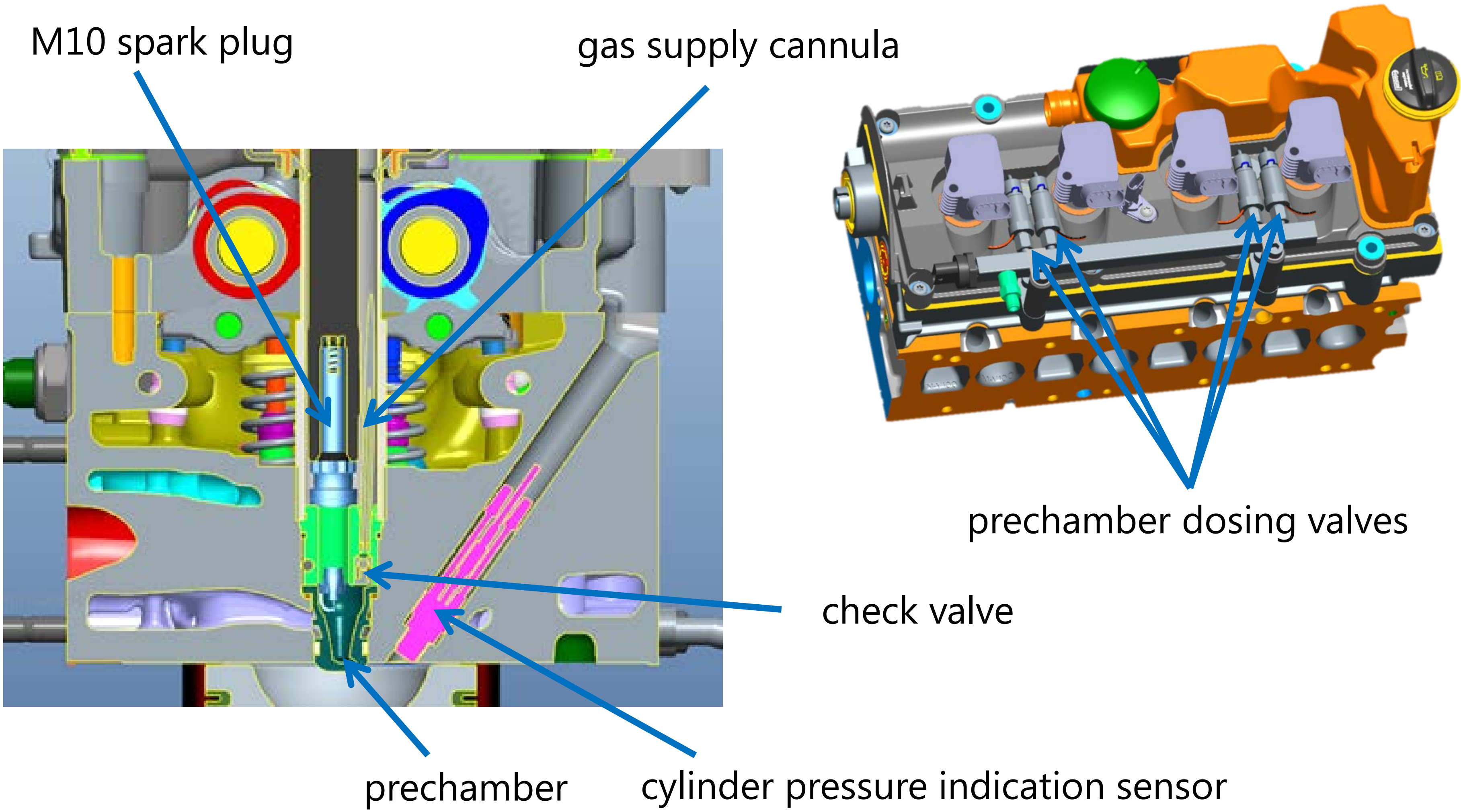
Gas mixer upstream of the throttle



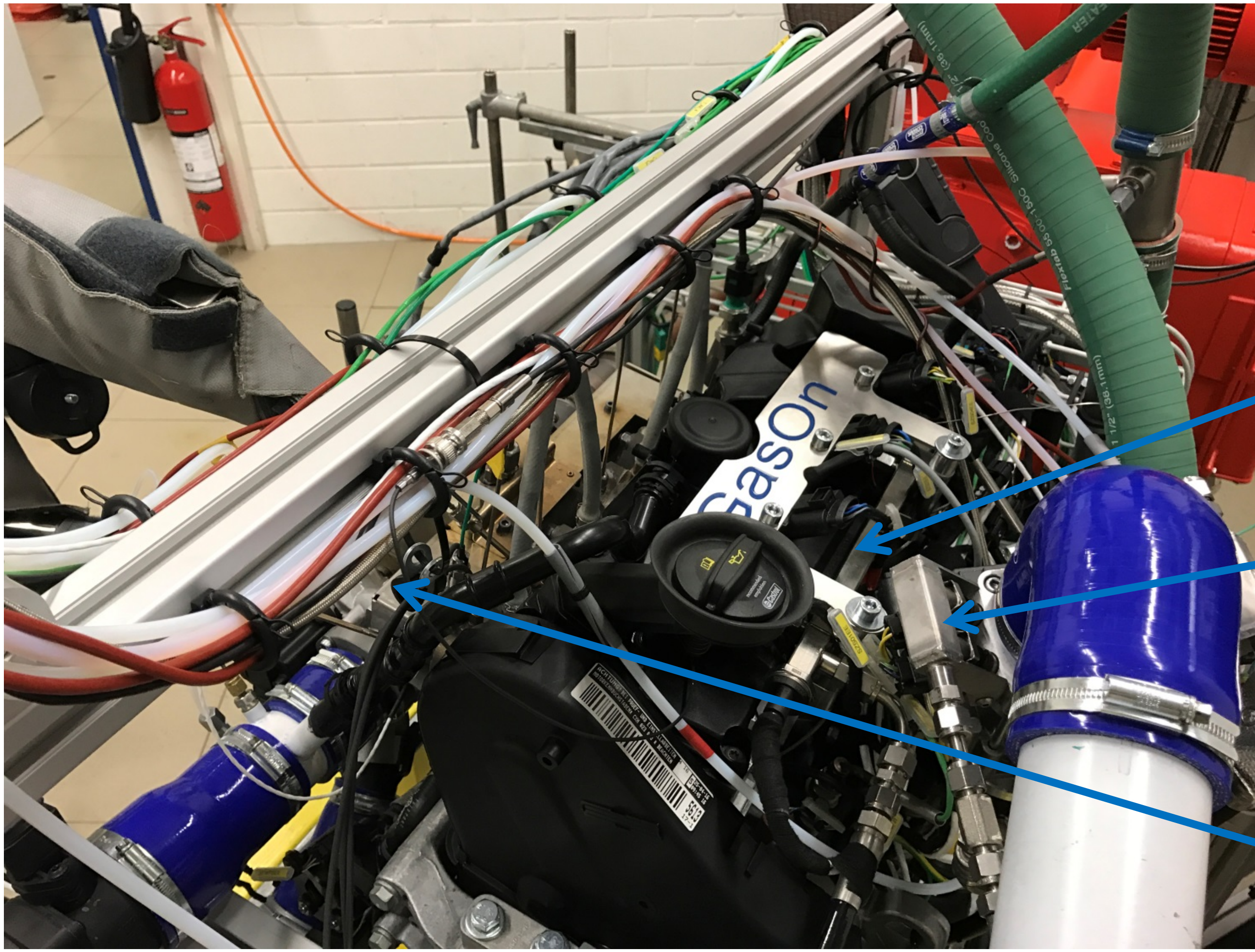
M12 spark plug insert
(instead of diesel injector)



Engine 2: Prechamber Engine



Engine 2: Prechamber Engine

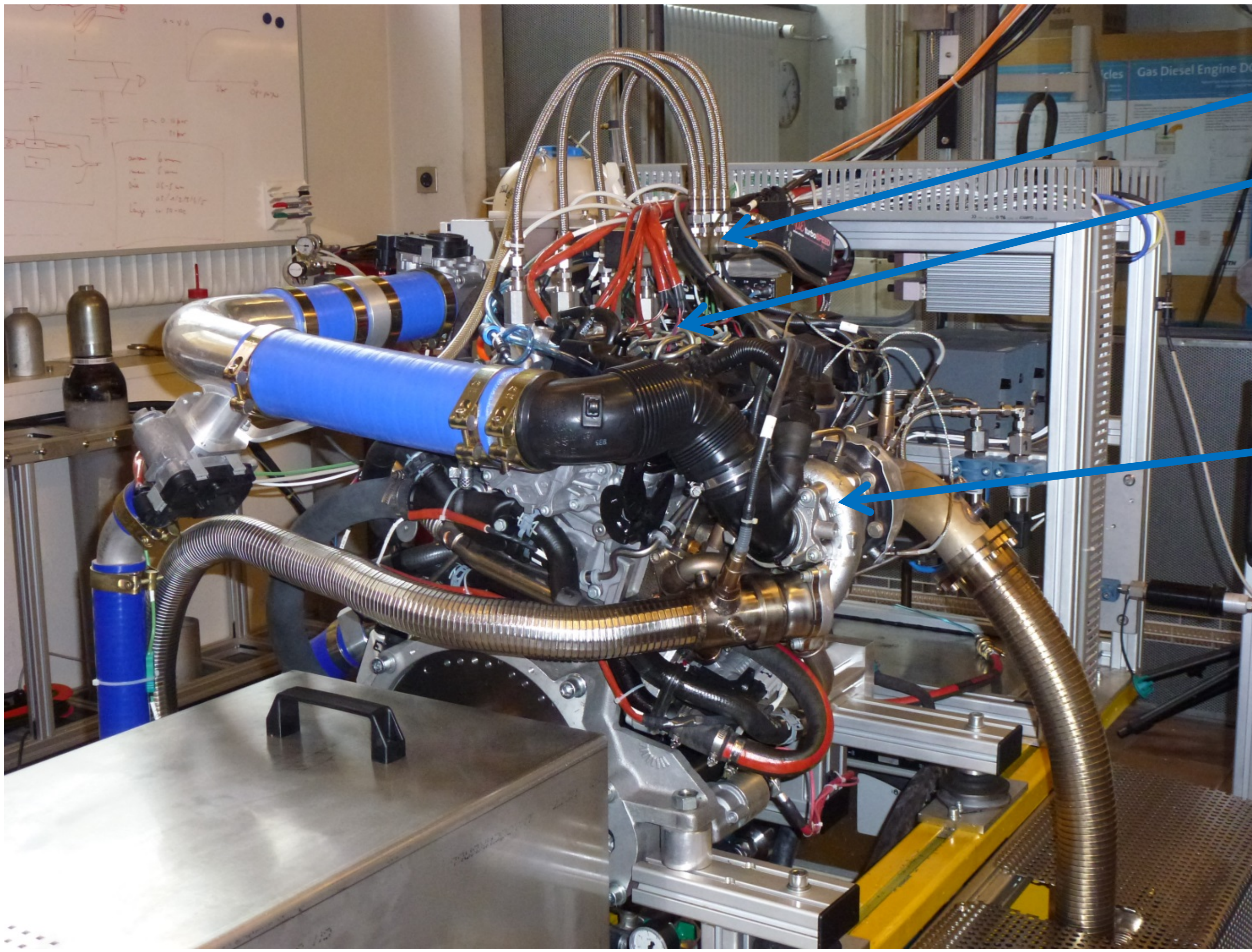


prechamber gas rail

mixer gas rail

wastegate turbo

Engine 3: Diesel Pilot Engine



gas rail (added)

diesel rail
(original config.)

VTG turbo

Compression ratio, piston bowl etc. unchanged from Diesel engine

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Experimental Environment

- Dynamic engine test bench in steady-state operation
- Rapid prototyping ECU with closed-loop centre of combustion control (set to 8 °CA for non-knocking conditions)
- Two operating points discussed here
  - low load: 1400 rpm, 50 Nm brake torque = 3.2 bar bmep
  - higher load: 2000 rpm, 220 Nm brake torque = 14.0 bar bmep
- Global λ setting: from 1 … lean limit (or peak cylinder pressure limitation)
- Scavenged prechamber operation: model-based control of $\lambda=1$ in the prechamber at moment of ignition
- Diesel pilot operation: least amount of diesel possible to reach stable combustion

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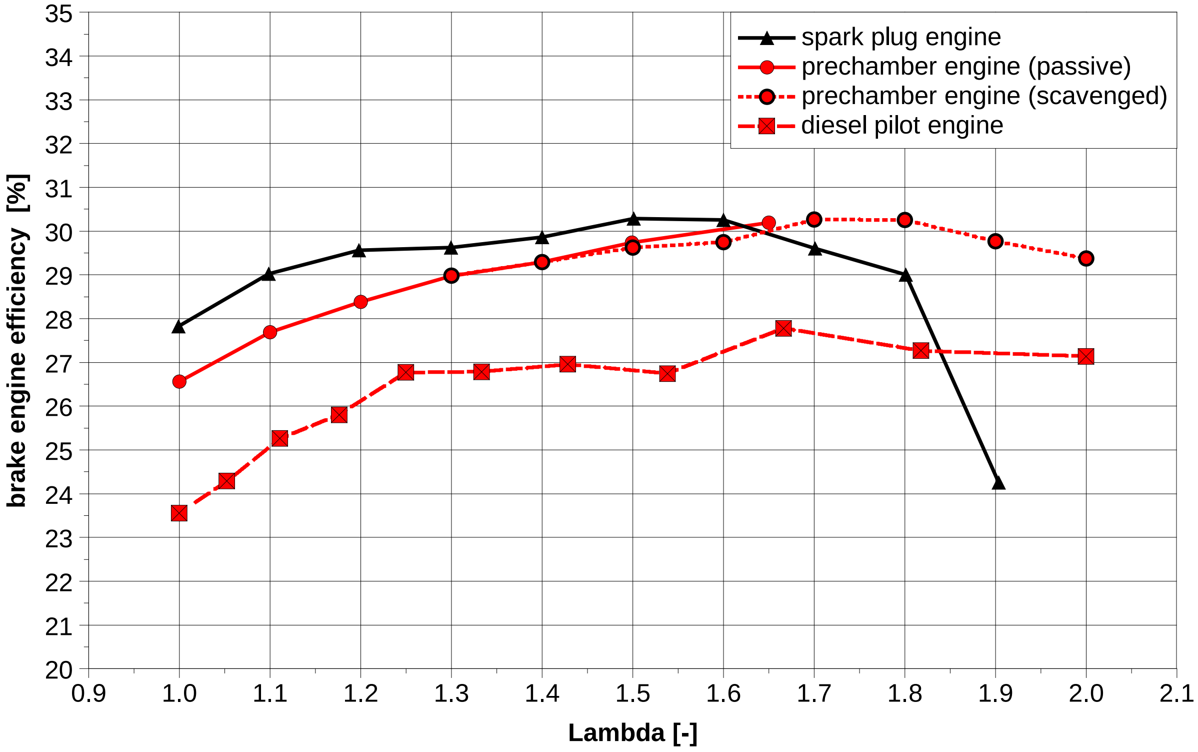
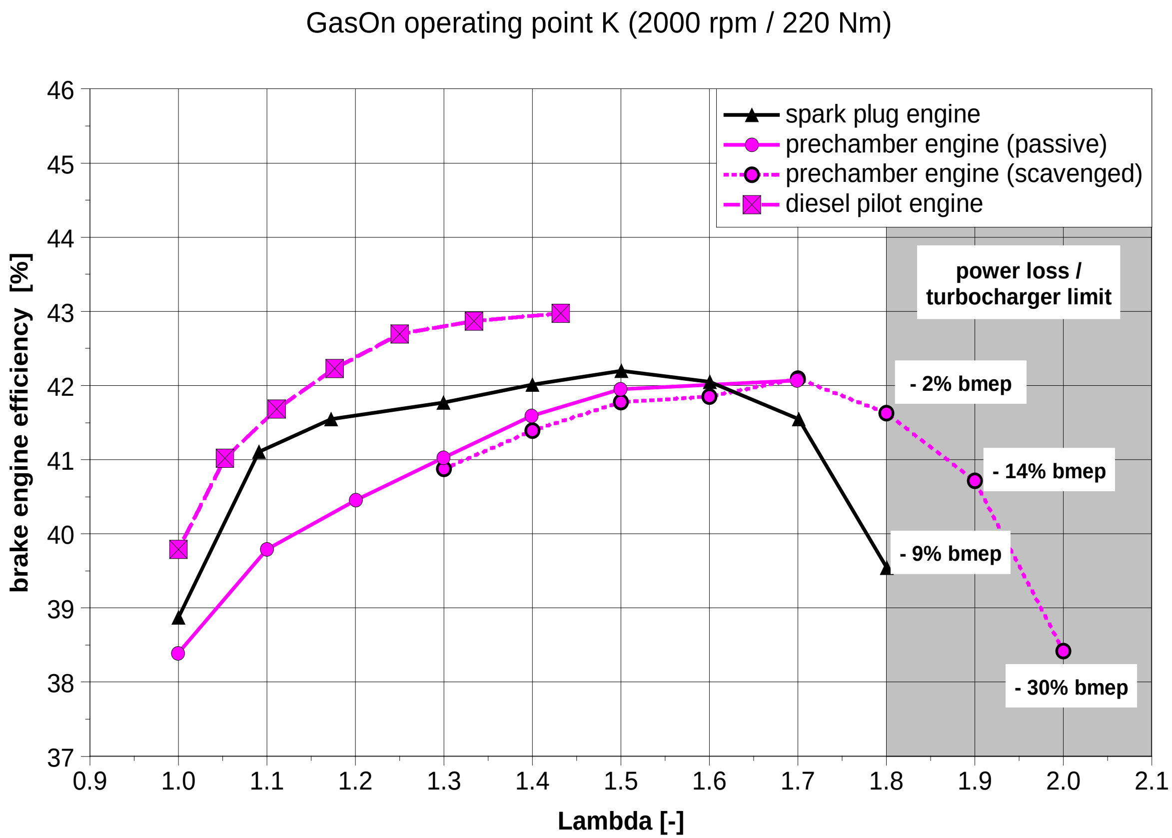
Results: Brake Efficiency (lower load)

GasOn operating point A (1400 rpm / 50 Nm)



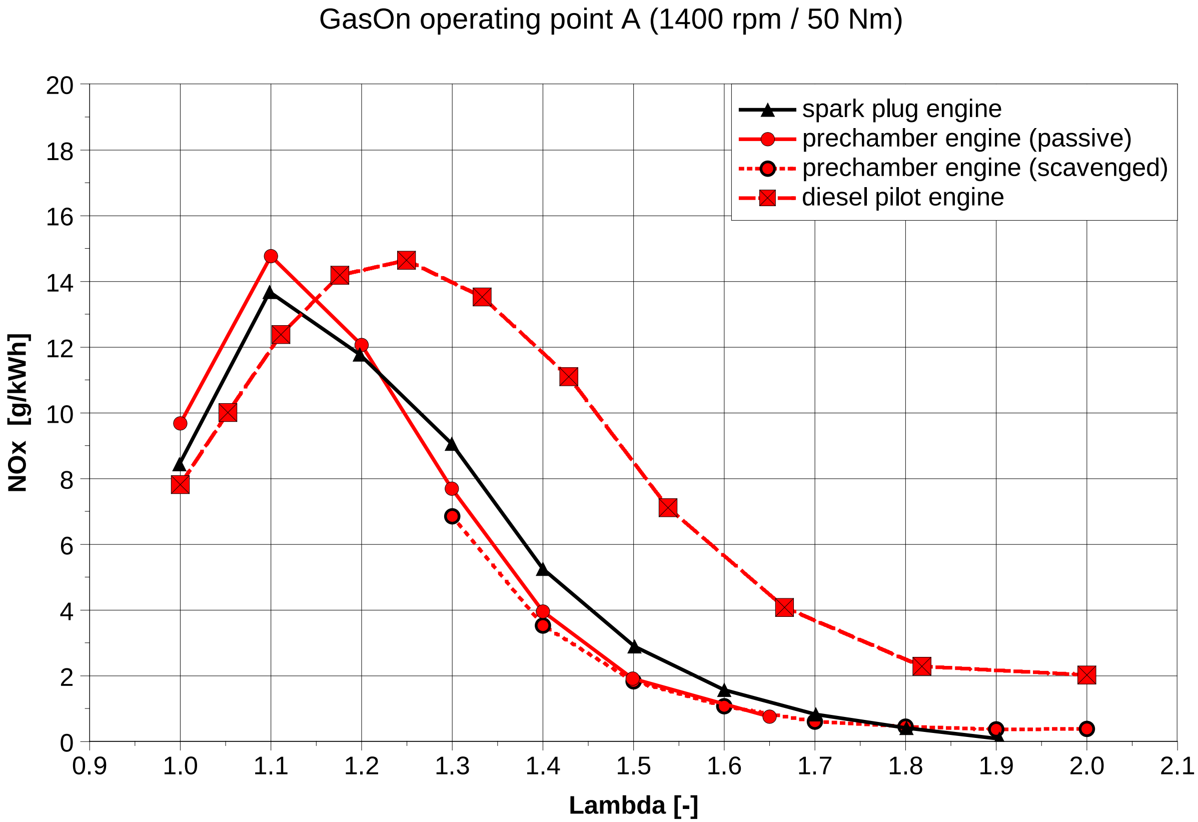
- Spark plug: best efficiency @ λ=1.5
- Passive prechamber: best efficiency @ λ=1.65
- Scavenged prechamber: best efficiency @ λ=1.7, stable combustion up to λ=2
- Diesel Pilot: best efficiency @ λ=1.65, high amount of diesel needed at throttled low load operation, inferior efficiency to the spark ignited concepts

Results: Brake Efficiency (higher load)



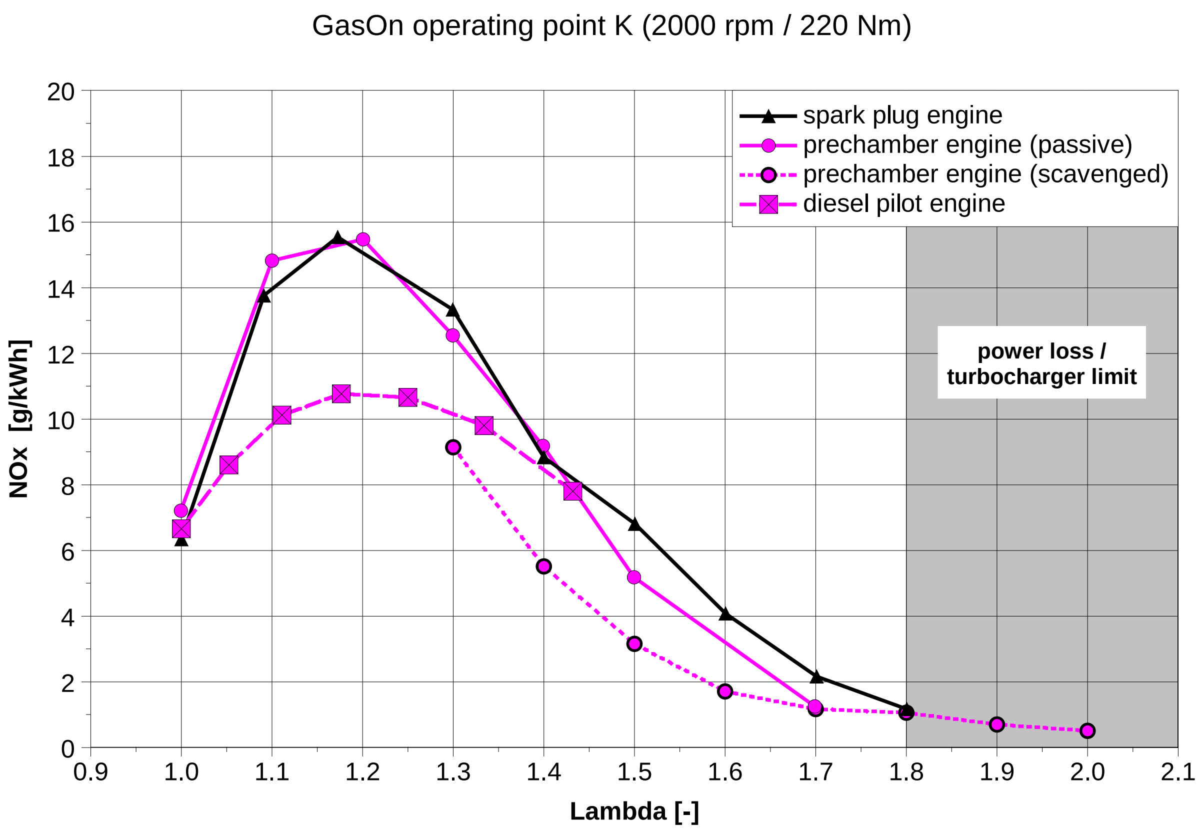
- Spark plug: best efficiency @ λ=1.5
- Passive prechamber: best efficiency @ λ=1.7
- Scavenged prechamber: best efficiency @ λ=1.7, stable combustion up to λ=2
- Diesel Pilot: best efficiency @ λ=1.45 (higher λ not possible due to peak pressure limit.)
- Power loss at very lean combustion (turbo is not able to cover everything)

Results: Raw NOx emissions (lower load)



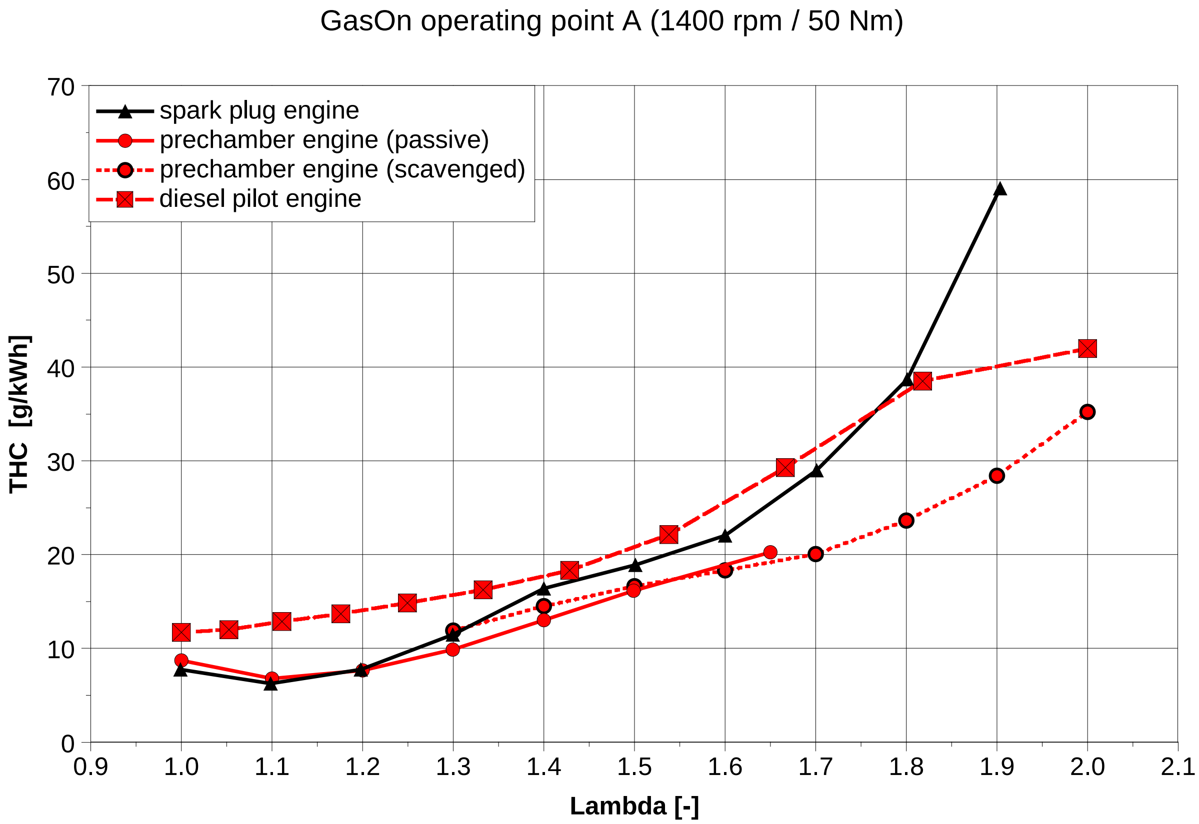
- All spark ignited concepts show similar NOx levels, scavenged prechamber shows lowest NOx (< 1 g/kWh) at best efficiency setting (λ=1.7)
- Diesel Pilot: higher NOx emissions

Results: Raw NOx Emissions (higher load)



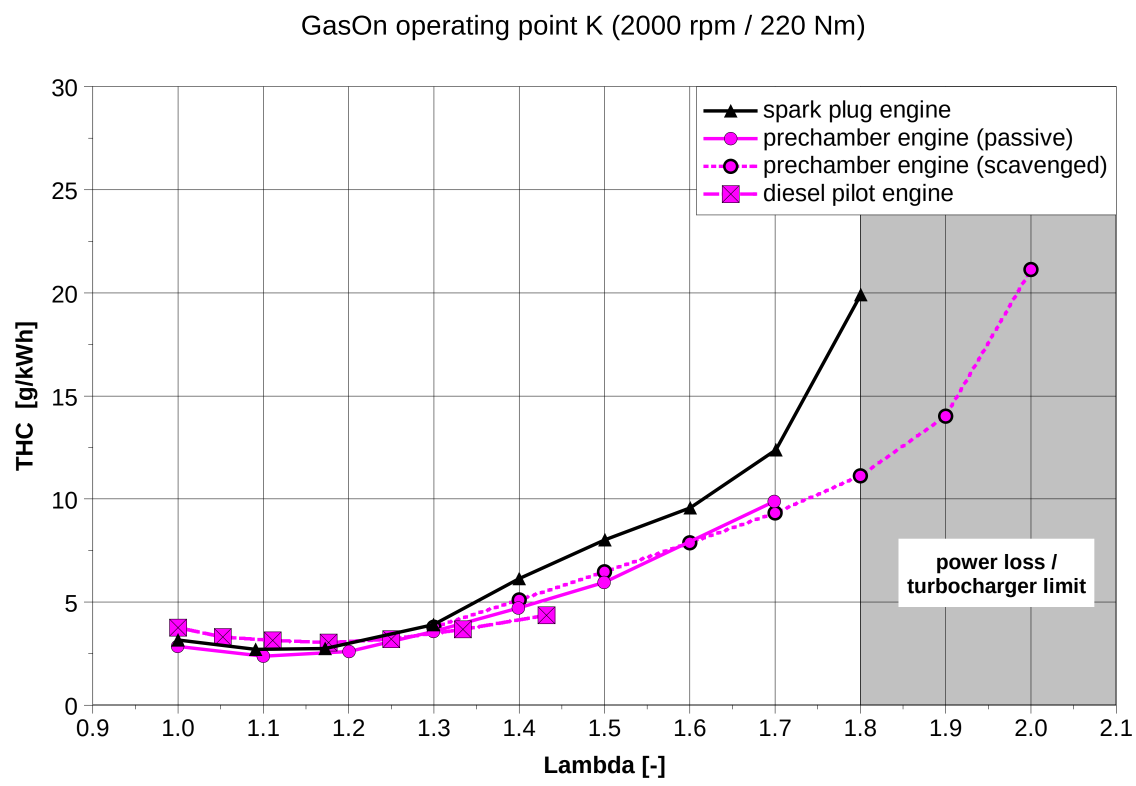
- Leaner operation leads generally to lower NOx → advantage for the concepts which are able to burn very lean
- Part of the NOx advantage of the prechamber concepts for this operating point comes from delayed ignition to prevent knock
- Lean de-NOx system is needed to for all concepts

Results: Raw THC emissions (lower load)



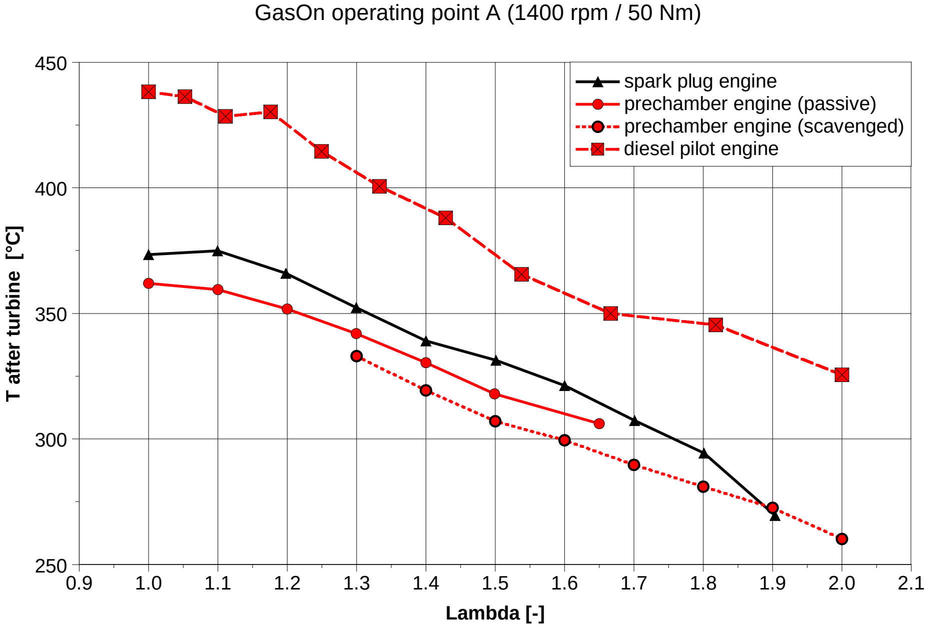
- Active & passive prechamber shows clear benefits for lean operation
- Diesel Pilot: higher THC emissions

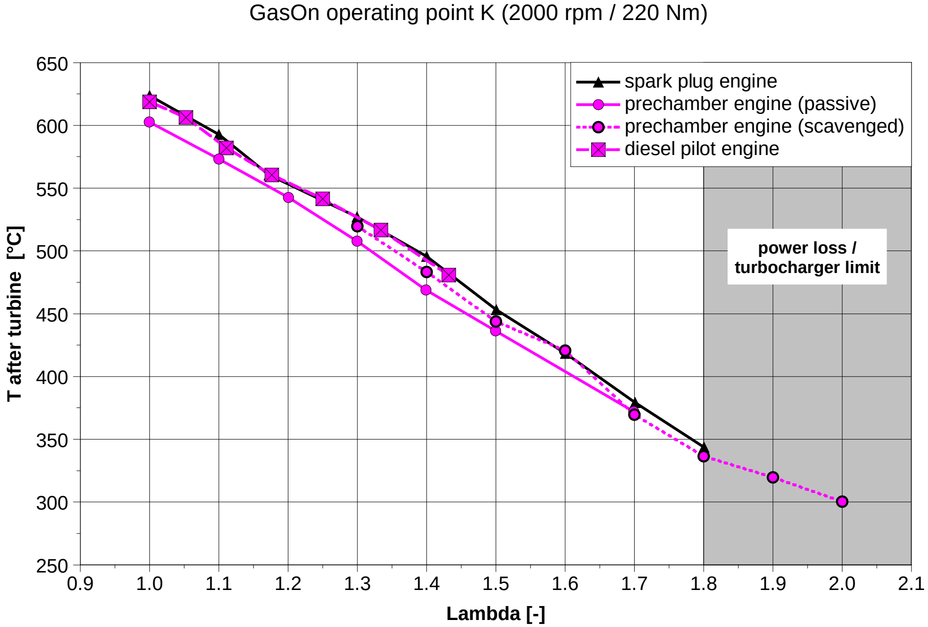
Results: Raw THC Emissions (higher load)



- Active & passive prechamber & diesel pilot show benefits compared to conventional spark plug operation
- THC (methane) emissions at lean conditions are the major (yet unsolved) challenge for all concepts

Results: Temperatur after Turbine

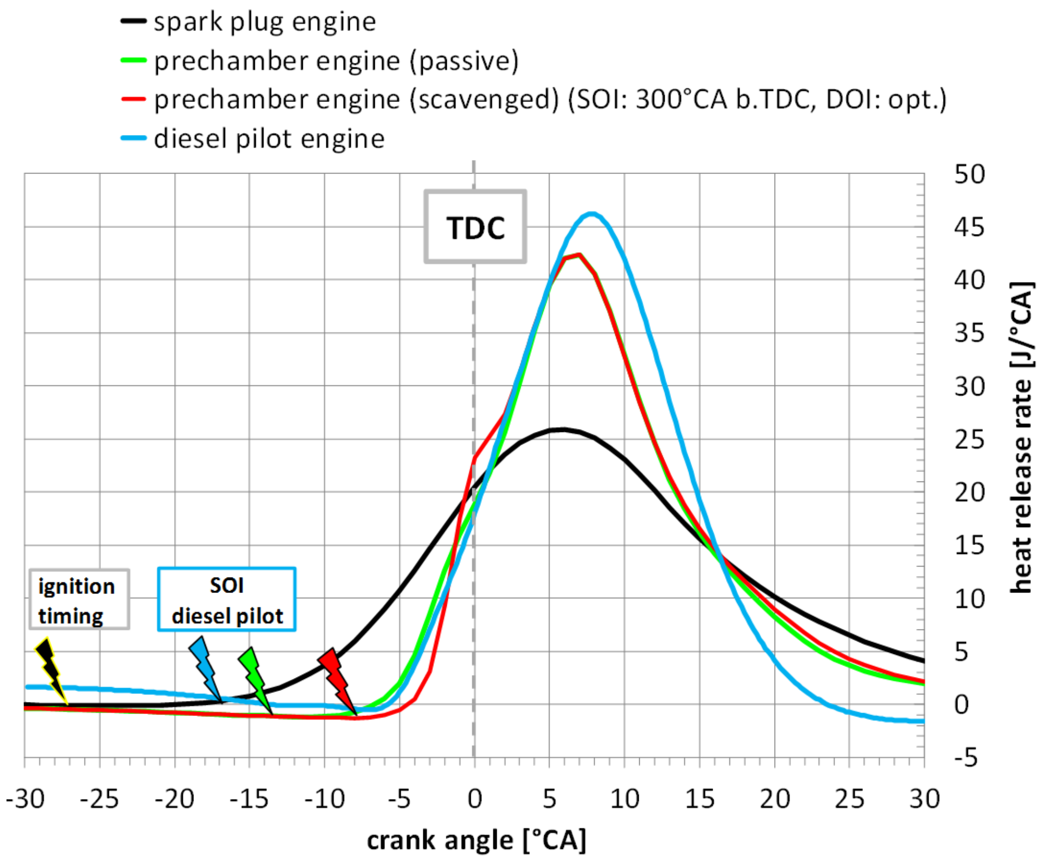




- Lean combustion leads (of course) to reduced temperatures
- Prechamber operation leads to lower temperatures (possible reason: high heat transfer to the prechamber & piston, les enthalpy to the exhaust gases)

Results: Net Heat Release

Operating point: 1500 rpm / 100 Nm
(higher load with COC at 8°C for all concepts without knock restrictions)



- Prechamber concepts & diesel pilot show considrably faster combustion than spark plug version
- Ignition delay for the scavenged prechamber is extremely short

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Conclusions

- Diesel engine was able to be operated in dual fuel operation with only small adaptations (PFI added) whereas the diesel engine had to be substancially substancially adapted for spark ignition operation
- Diesel pilot operation allows stable operation with small diesel quantities (≈ 1 energy-%) at higher loads
- Diesel quantities have to be considerably increased at lower loads / throttled operation (≈ 70 energy-% at 2 bar bmep) which leads to inferior efficiencies
- The spark ignited concepts show efficiencies very close to diesel pilot operation (even if the compression ratio of the spark concepts is considerably lower)
- Lean combustion leads to quite low NOx levels, nevertheless, NOx aftertreatment is necessary
- Lean combustion leads to quite high THC (methane) levels, this is the major challenge for such concepts, especially in combination with low exhaust gas temperature levels

Thank You!