Steam Direct Injection

Technology Overview: Steam Direct Injection

Motivation

- Waste heat (exhaust and coolant) contains ~50% of total fuel energy of gasoline ICE, which is more than the crankshaft power (at best efficiency operation)
- In part-load operation this is even more

Difficulties

- Waste Heat Regeneration cycles based on ORC or Clausius Rankine cycles are very expensive, relatively inefficient
- Additional costs and mass very high for vehicle application
- Instationary behaviour very bad, power control depending on heat up profile, typical delay time a few minutes

Solution

- No additional expansion unit, usage of combustion engine itself
- Dynamic behavior coupled to engine, System pressure coupled to exhaust energy

Combination of known processes in a single expansion machine is key

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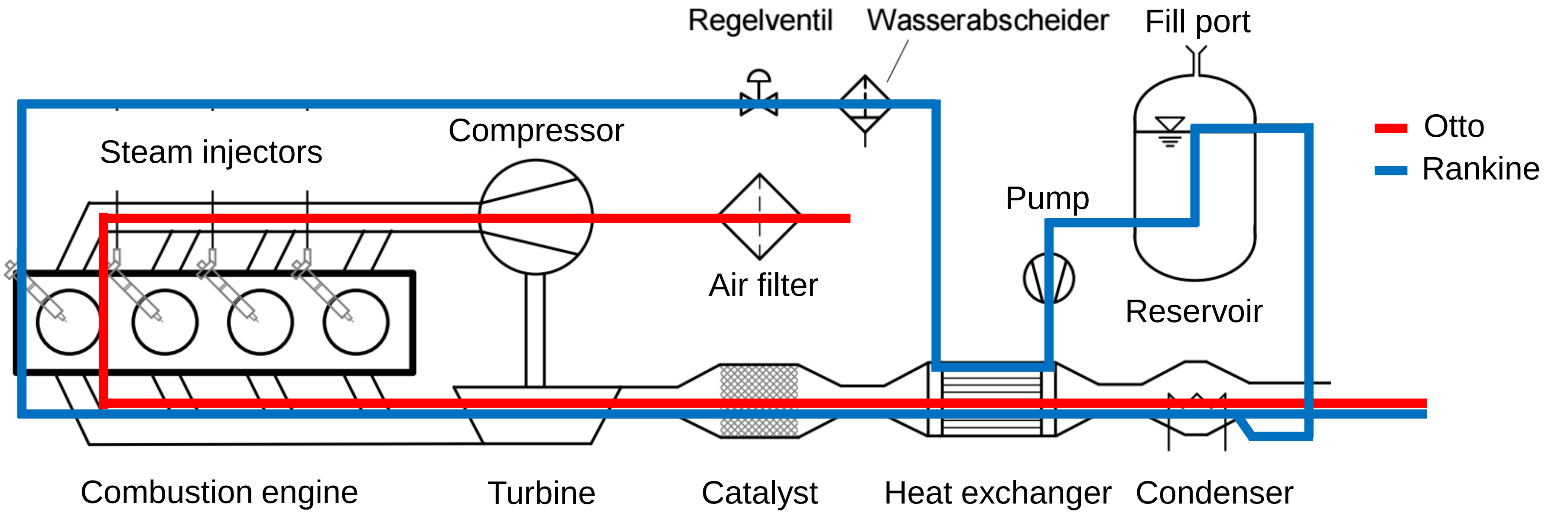
STEAM CONDITIONING AND DIRECT INJECTION

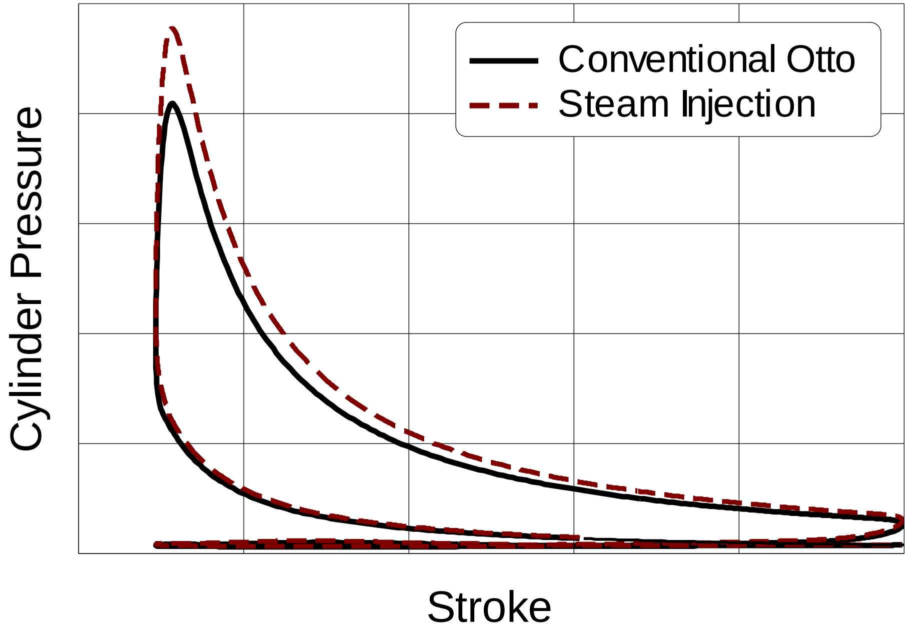
- Exhaust heat exchanger generates high pressure steam
- Steam pressure depends on waste heat energy, delayed heat up due to thermal inertia
- Steam injections depend on operating point, however it shows fast control characteristics
- Power increase and efficiency gain due to steam expansion and combustion process
- Reduction of peak temperatures and exhaust gas temperature increase component protection

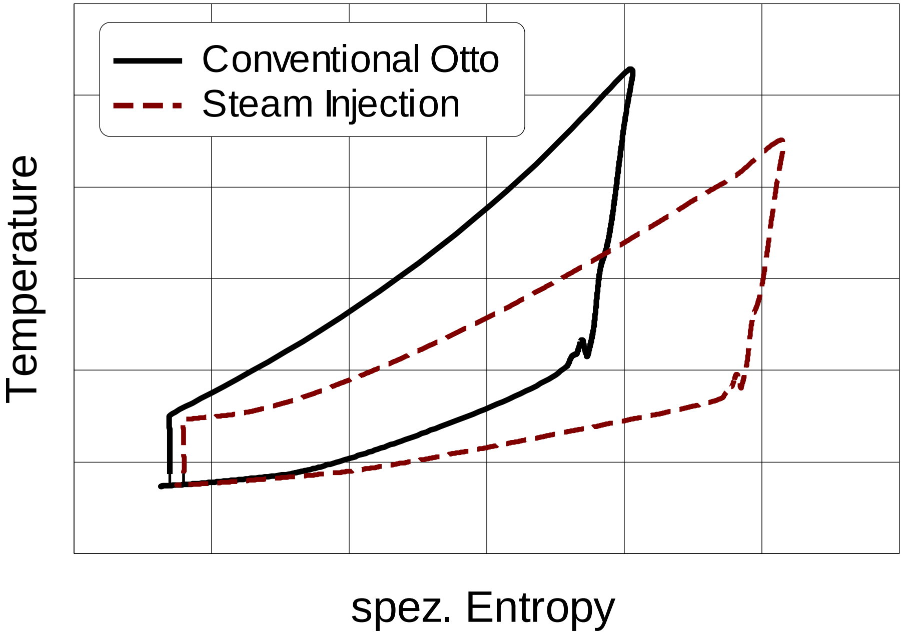


Thermodynamics
Impact of steam injection on process control

P-V AND T-S DIAGRAMS

- Increased overall cylinder pressure due to increased trapped mass
- Heat supply and heat dissipation happen at lower temperature levels
- Additional mass during injection leads to higher specific entropy
- Decreased temperatures throughout the whole combustion cycle result into higher efficiency





Component design
Rapid heat up vs. sufficient steam delivery rate

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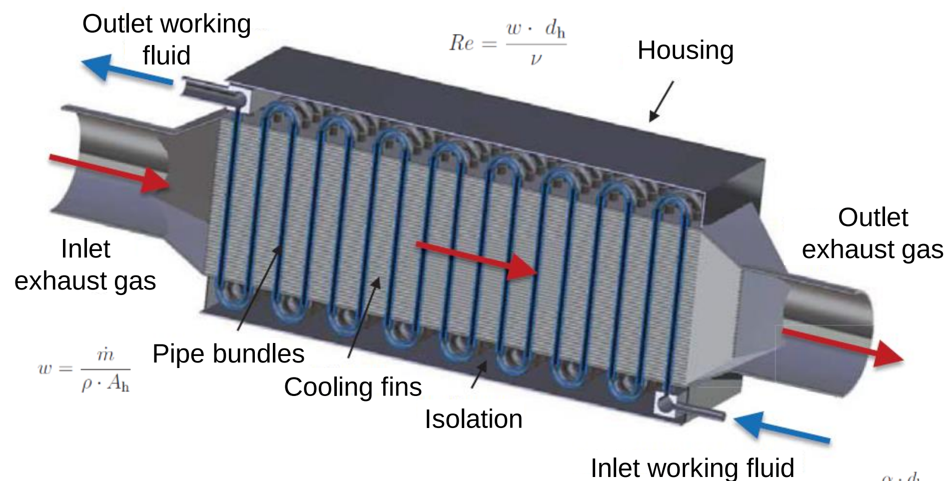
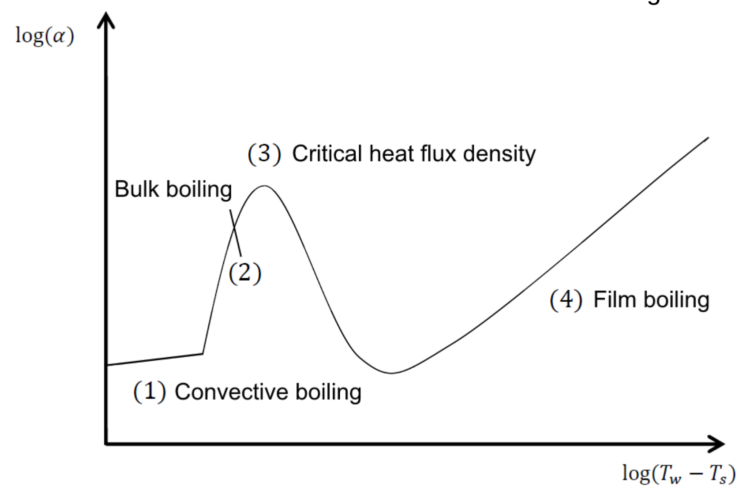
HEAT EXCHANGER

Technical Design	
Max. static pressure @ Mass flux (exhaust) Max. Backpressure @ Mass flux (exhaust)	1330mbar @ 835 kg/h 230mbar @ 835 kg/h
Alpha on the exhaust side	10-120 [W/m²K]
Alpha on the working fluid side	2.000-10.000 [W/m²K]
Pipe Diameter (Inside/Outside)	8/12 mm
Nominal / Max. Pressure	100/120 bar
Material	X5CrNi18-10 (V2A)
Length/Width/Height	400/320/120 mm (15.4 L)
Interior pipe volume	[redacted]
Max. Steam delivery rate	[redacted]





Quelle : BMW - Betrieb eines Rankine-Prozesses zur Abgaswärmenutzung im PKW

Component design of Injector for acceptable Part-load performance trade-off

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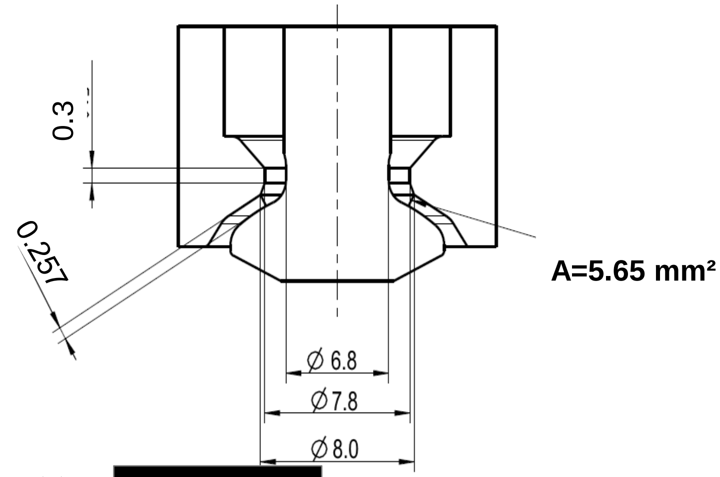
INJECTOR

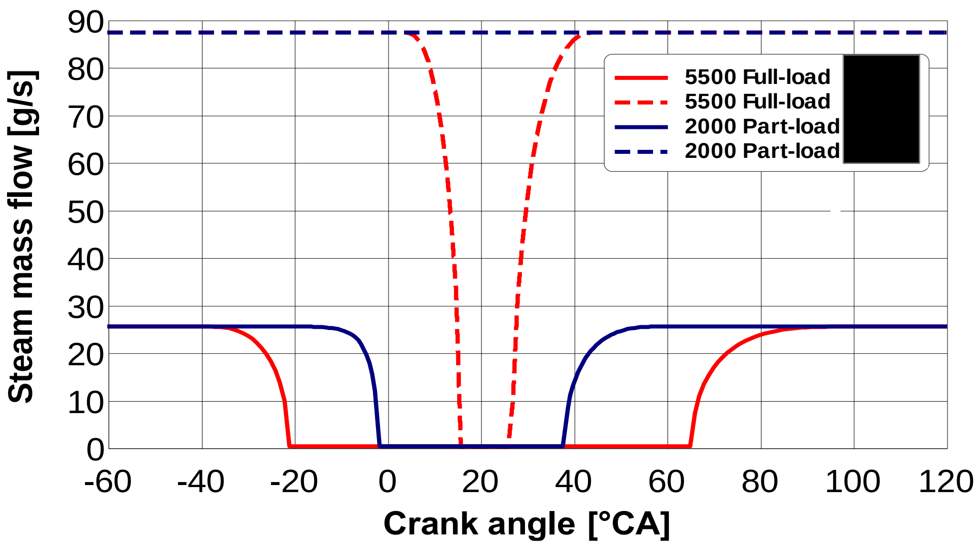
$$\dot{m}_{Inj} = A \cdot \mu \cdot \Psi(x,\kappa) \cdot \rho_{Steam} \cdot \sqrt{2 \cdot R \cdot T} \quad with\ x = \frac{p_{Cyl}}{p_{Inj}}$$

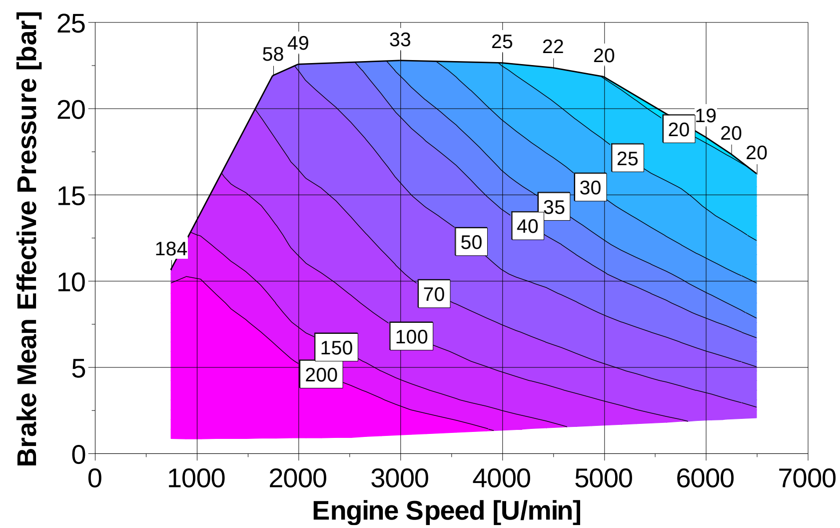
46 times more dense than air at 20°C

$$\Psi = \begin{cases} \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \cdot \sqrt{\frac{\kappa}{\kappa+1}} & x \le \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \\ \sqrt{\frac{\kappa}{\kappa-1} \cdot \left[x^{\frac{2}{\kappa}} - x^{\frac{\kappa+1}{\kappa}}\right]} & \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} < x < 1 \end{cases}$$



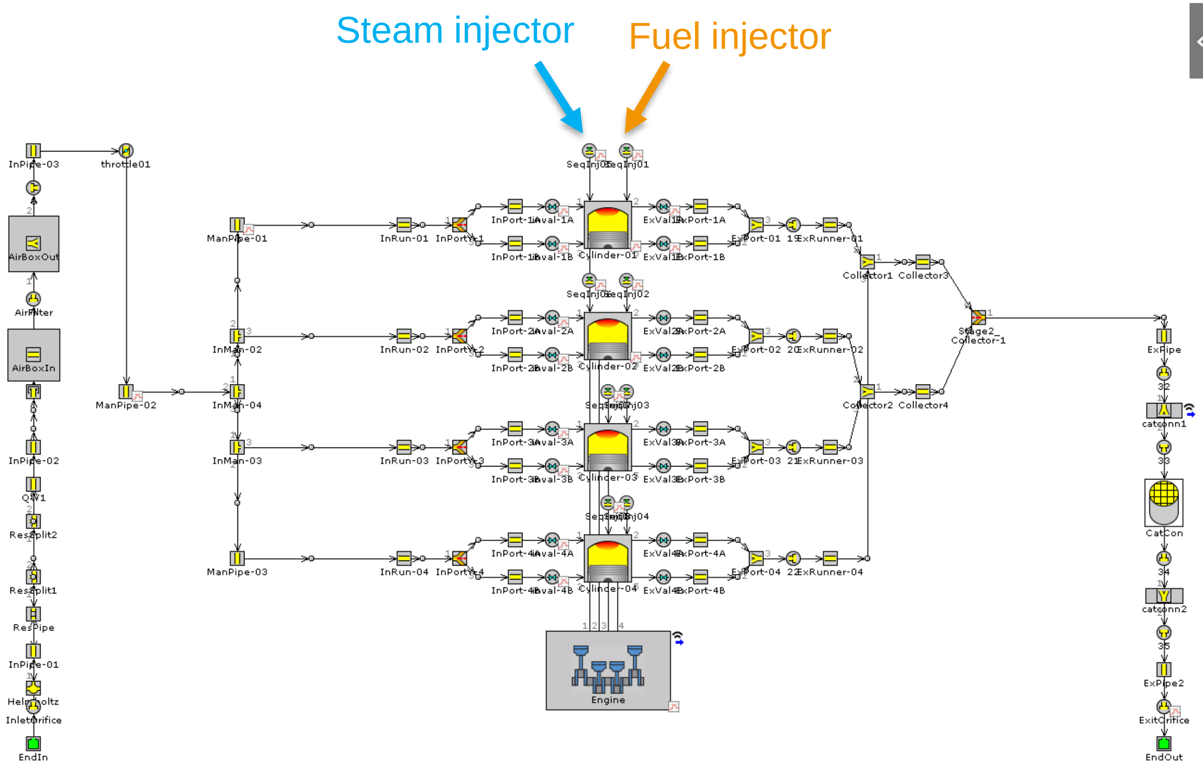
Max. rel. steam mass at $\Delta\alpha_{max}$ [redacted]
at operation with [redacted]





Simulation model
Crank angle resolved model illustrates the steady behavior

GT-POWER MODEL - STEADY STATE



Engine displacement : 2.2 L

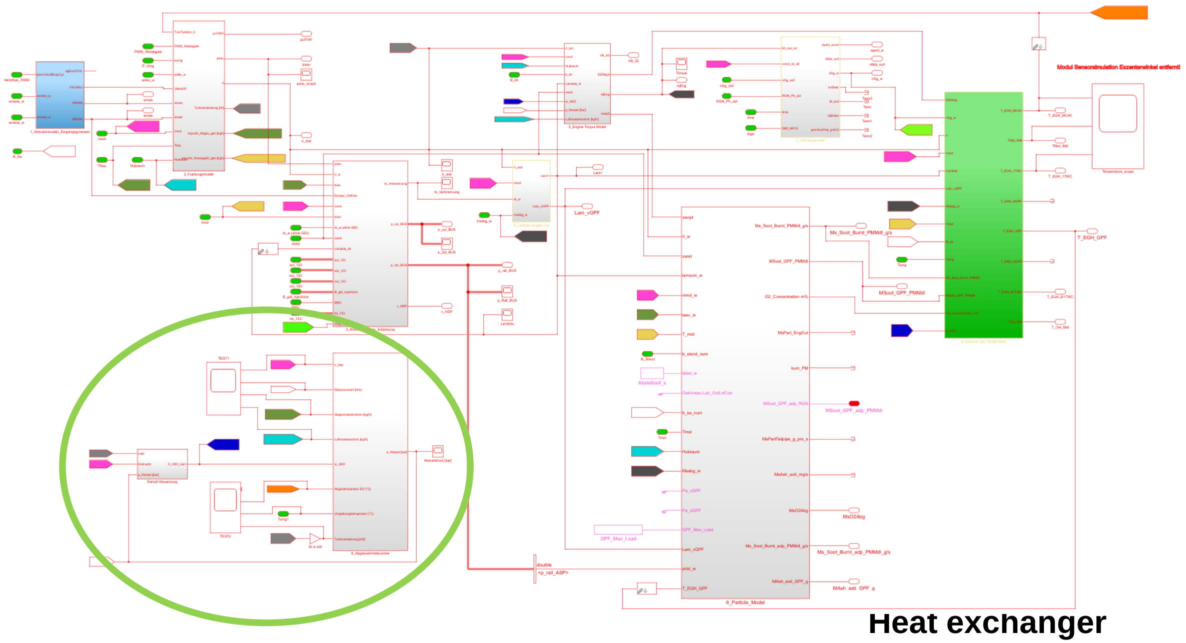
Vehicle gross weight : 2830 kg

Background

- No test engine with direct steam injectors available
- 1-D Simulation tools used to simulate the behavior
- The baseline model is tuned with readings from the engine test bench
- The steady state behavior lies in focus
- Steam injectors were implemented as described previously
- Steam injection is overlaid onto baseline burn rate to avoid side effects

Simulation model
Time resolved model illustrates dynamic behavior and cross-interference

SIMULINK MODEL – DYNAMIC



Background

- Component heat up is simulated
- The whole exhaust gas system needs to be simulated to determine the exhaust energy at the heat exchanger
- Time constants have been derived from real world measurements
- Steam pressure can be monitored
- A pressure based steam control strategy is implemented
- The model allows to simulate prebuild driving cycles such as WLTP and RDE

Simulation results
Taking full advantage of early steam injections is key to high efficiency

PART LOAD PERFORMANCE - 2000RPM 11BAR – 100BAR INJECTION

Steam injection

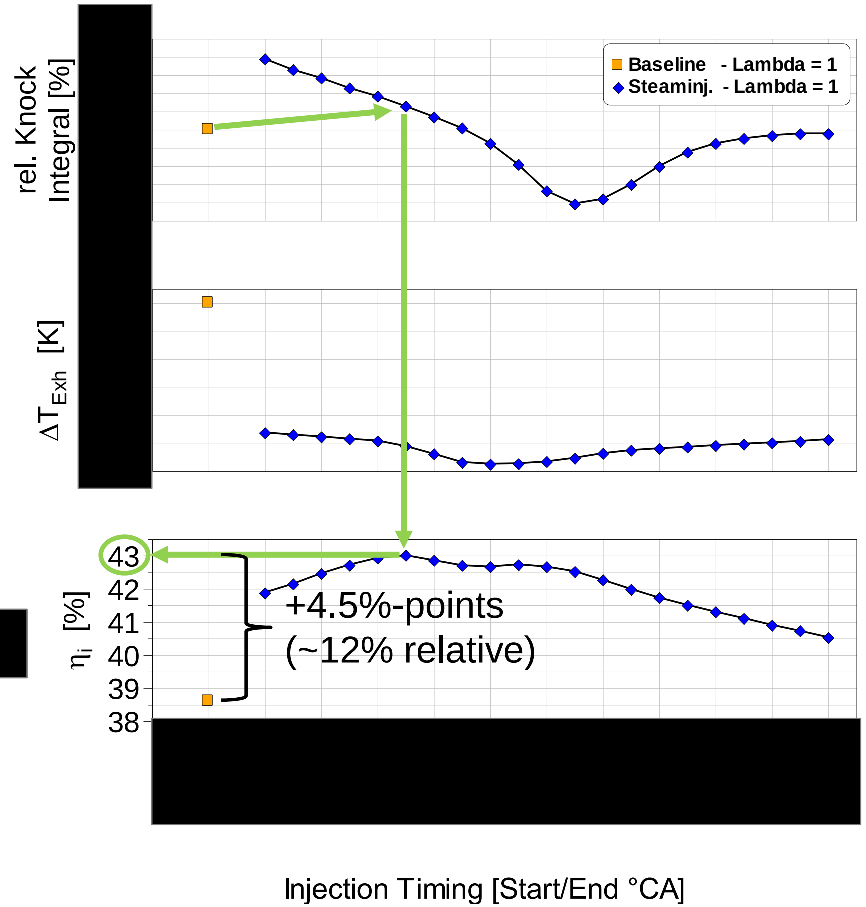
Simulation Results

Load point: 2000 rpm / 11 bar

Relative steam mass relating to intake air = 20%

Engine

Bore:	89 mm
Stroke:	88.3 mm
Cylinder.:	4
Intake Valve Lift:	8.8 mm
Exhaust Valve Lift:	9.0 mm
Vse_in:	81°
Vse_out:	90°
MBF50%:	5.7°
MBF10/90:	17°
Amb.Temp.:	20 °C
Steam mass:	[redacted]
Puls duration:	



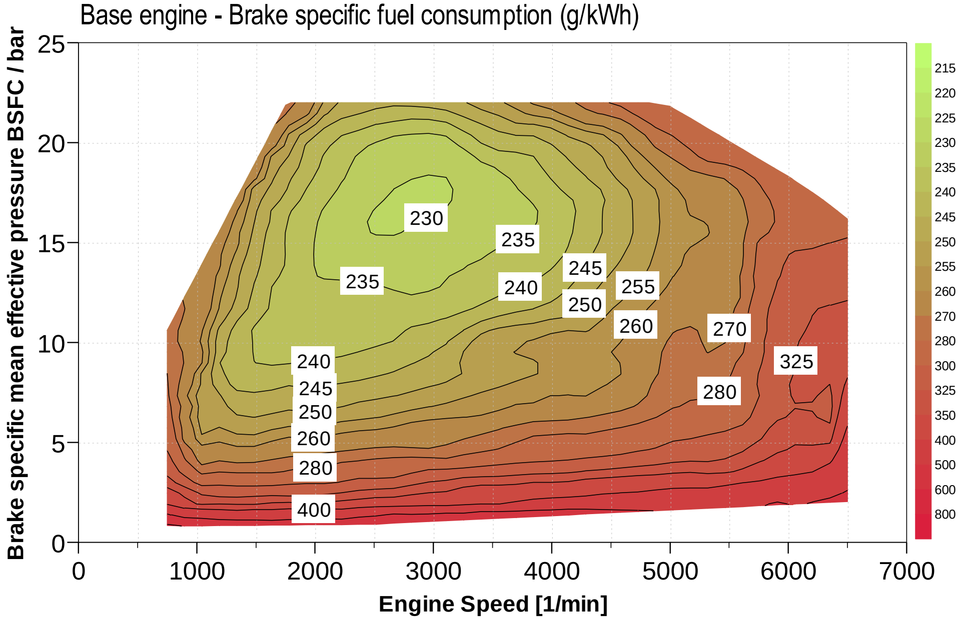
GT-Power Results

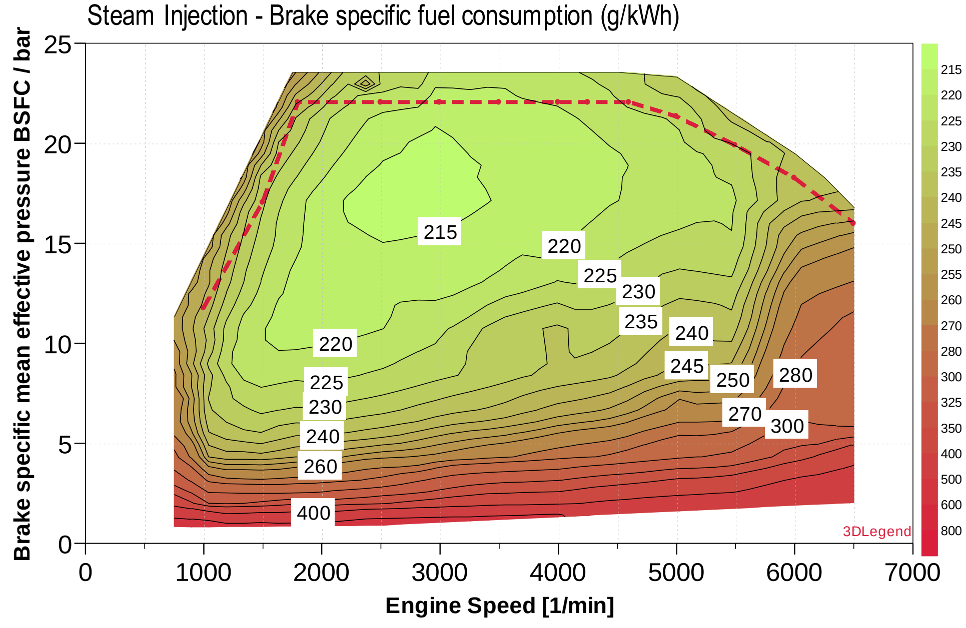
- Low rotational speed allows for short injection timing [redacted]
- Load point stability enables pre p_{max} injections leading to higher efficiency
- Combustion peak temperature can be lowered significantly by [redacted]
- Decreased exhaust temperature beneficial for component protection
- Since the baseline point is not knock limited, the efficiency gain can be pushed even further by allowing operation at a higher rel. knock level than baseline

Simulation results
Relevant engine operation points

STEAM INJECTION ENGINE MAP - OVERVIEW

- Steam injections enable λ = 1 operation on the entire engine map
- Higher efficiency leads to lower specific consumption (minimal 215 g/kWh)
- Furthermore the area of up to 230 g/kWh is expanded
- The peak torque can be achieved at lower engine speed





Simulation results
WLTP takes full advantage of fast heat up and torque boost

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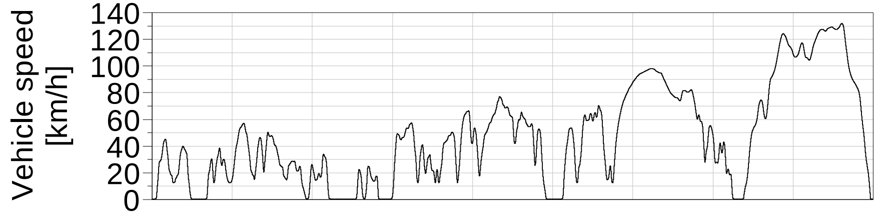
CYCLE SIMULATION WLTP

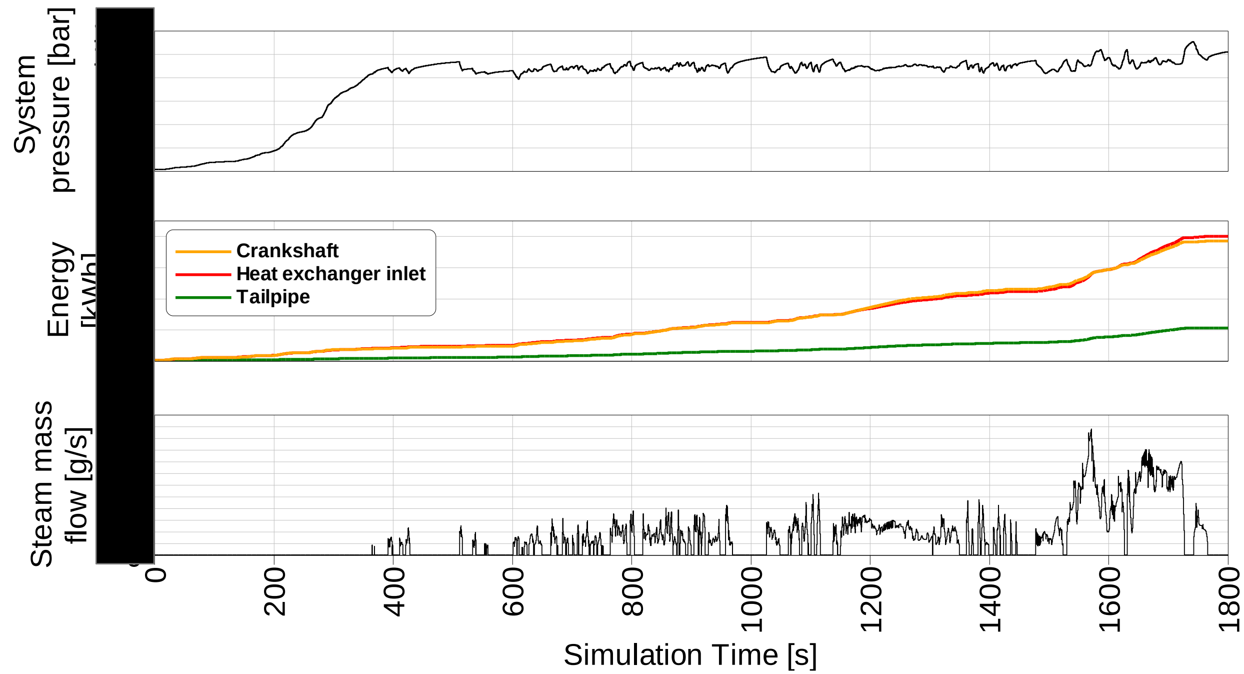
Steam injection

Simulation Results

WLTP Cycle

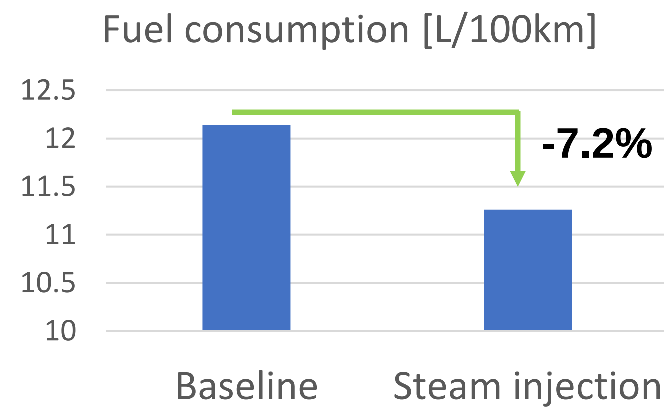
Relative steam mass relating to intake air = 0-35%





Cycle Simulation Results

- The heat exchanger is able to extract a significant amount of energy from the exhaust gas
- After short heat up period (365s) the system is fully operational
- 25.8L/100km water consump.



Simulation results
Overall benefit of in-cycle fuel consumption comes at a cost

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COST ESTIMATE

Component	Estimate
Heat Exchanger	100-200 €
Injector	4x50 €
High Pressure Pump	25 €
Reservoirs e.g.(SCR Tank)	10-30 €
Piping and Isolation Material	15-40 €
Recuperator	50-120 €
Water separator + Valves	5-15 €
Sum	**405-630€**

Opportunities	Challenges
■ Up to 21 g/km CO_2 reduction in WLTP	■ Condensation along the piping must be prevented
■ Enables λ = 1 operation at all load points	■ Water freezing must be prevented
■ Overall torque boost increases peak power output	■ High water consumption → water recuperation system necessary
■ Synergy effects with liquid water injection / use of common components	■ Validation of real combustion process necessary

Steam Direct Injection
Key facts

Key facts Steam direct injection

- Steam generation by Exhaust heat exchanger up [redacted]
- Steam Power available on demand
- No additional expansion device necessary, steam injection into main engine
- Part-efficiency of bottom cycle up to 30%
- Maximum Power gain (for limited time) ~10kW
- Additional positive influence to base engine
  - Soot reduction by agglomeration and peak combustion temperature reduction
  - Component protection included due to lower exhaust gas temperatures – all Lambda 1

Key facts Turbo Steamer

- Steam generation by Exhaust heat exchanger up to 5-50bar
- Continous steam power generation, independent from usage
  → needs to be buffered
- Expansion device is turbine or cell expander, efficiency strongly dependent on OP point
- Cycle efficiency including pinch-effect 10..15%
- Electrical power generation of max. 2kW