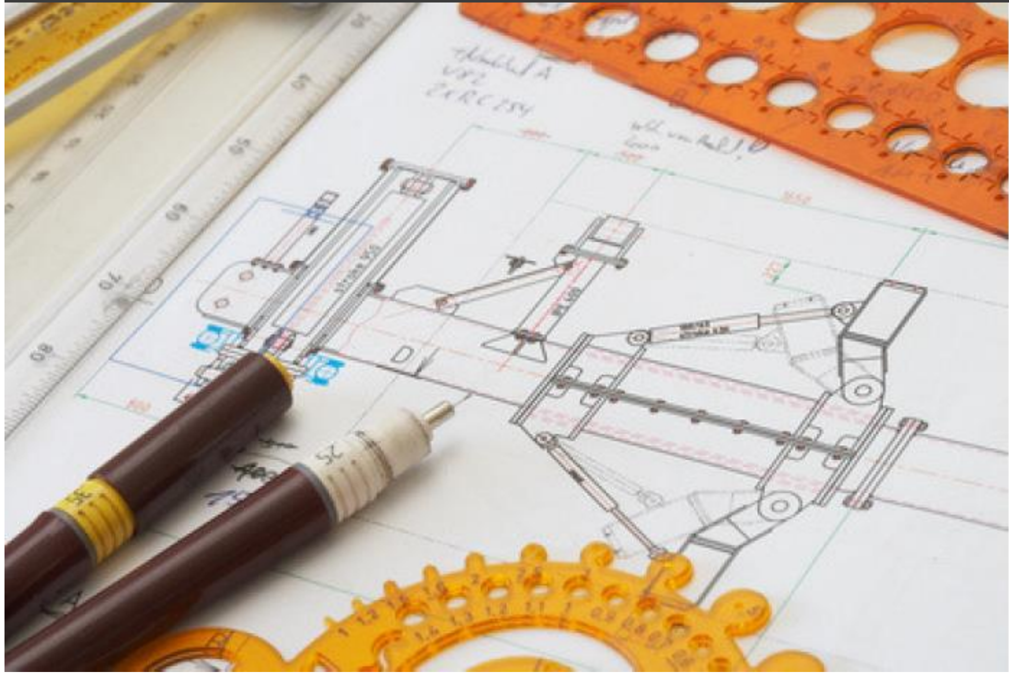
Future CO_2 Emission Technologies

Technology Overview Presentation

FUTURE CO_2 EMISSION TECHNOLOGIES



Aachen, 18.05.2017
Dr. Ing. Andreas Gotter

Agenda

gofficient

Main Topics of presentation

- Background/Reason for Technology development
- Gofficient technology spectrum
- Examples
    - Thermodynamic Efficiency Improvement: Twin AV
    - Waste Heat Recovery: Steam Direct Injection
    - Reduction of Scavenging losses: Variable Compressor/Expander Unit

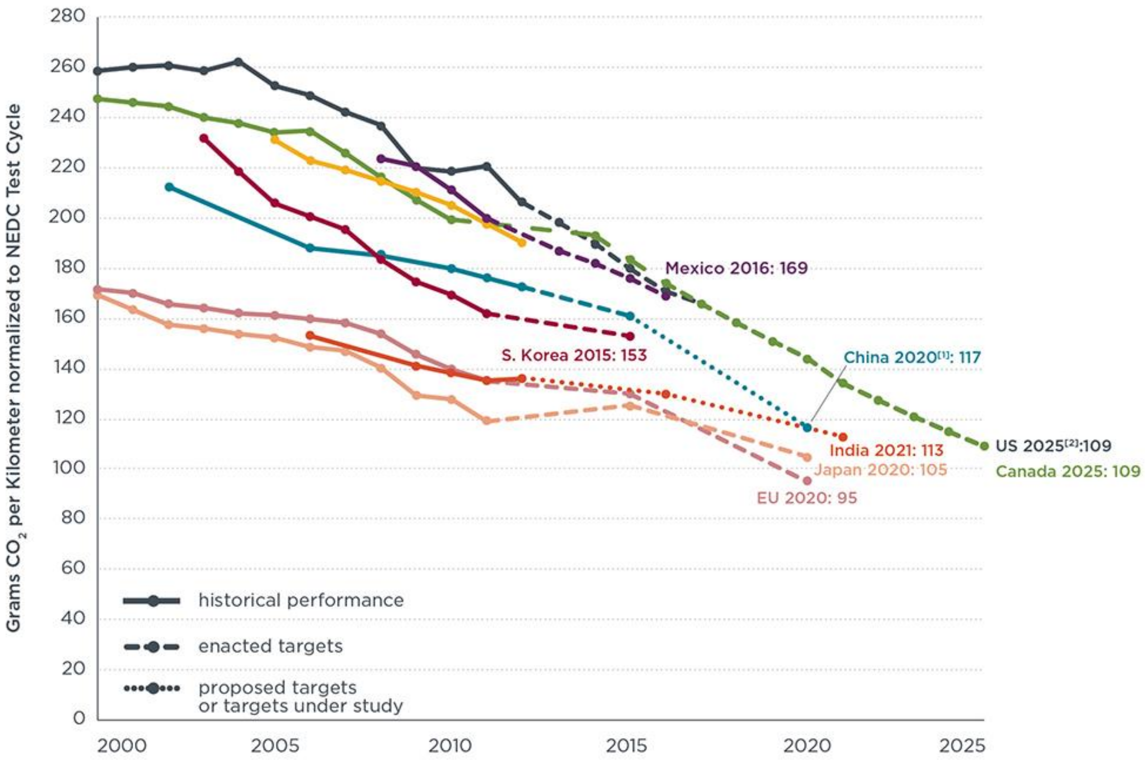
- Combination of Technologies

CO_2 emission targets

Current part-load optimization technologies were sufficient to meet past requirements, but can never fulfill future requirements

- Vehicle specific Energy Demand
  (based on vehicle inertia and driving resistances)
  roundabout 0,12 - 0,18 kWh/km
- Engine specific Technology Year 2000:
  Mainly N/A engines, vehicle 0,144 kWh/km
  NEDC-averaged bsfc = **386** g/kWh
  → CO_2 = 172 g/km
- Technology Year 2015:
  Down-sized, Down-Speeded and Part-Load optimized Engines with Start/Stop, vehicle 0,138 kWh/km
  NEDC-averaged bsfc = **295** g/kWh
  → CO_2 = 126 g/km
- Target "2020" of 95 g/km will require an average bsfc of **222** g/kWh

  ➔ This requires better efficiency than most actual engine at optimum operation point!
  ➔ Not Reachable by part-load optimizations only



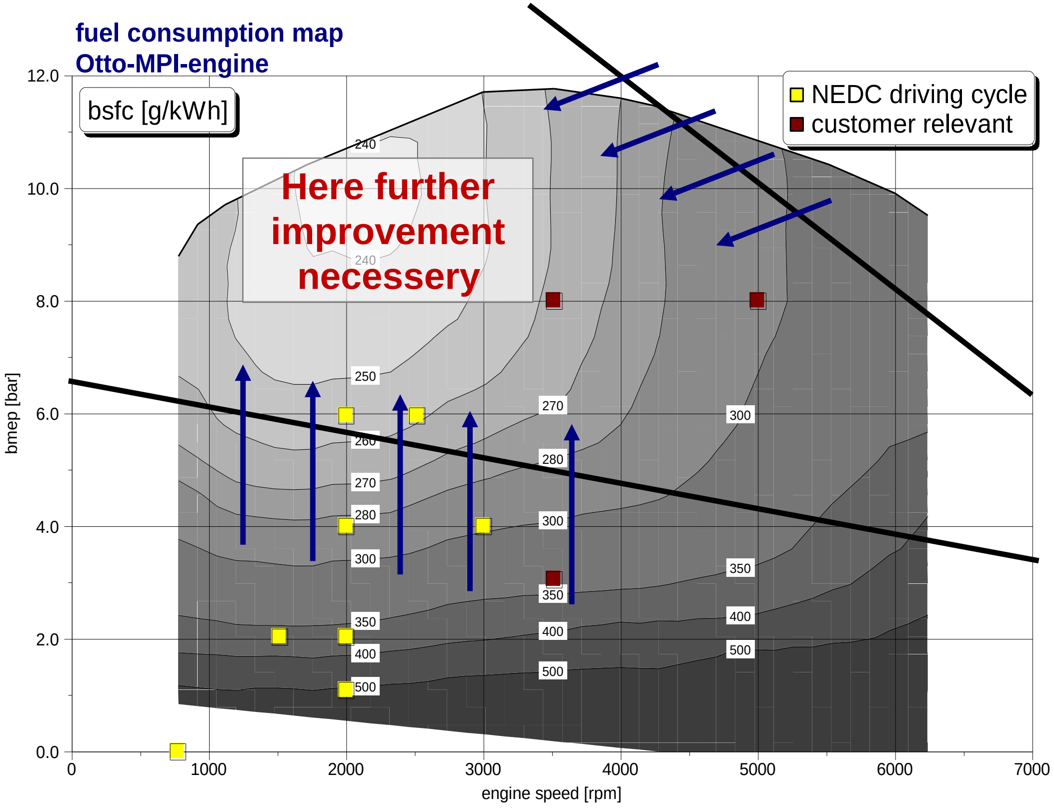
[1] China's target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[2] US, Canada, and Mexico light-duty vehicles include light-commercial vehicles.
[3] Supporting data can be found at: http://www.theicct.org/info-tools/global-passenger-vehicle-standards

Part-Load optimization

- Reduction of load-exchange losses comes to its boundaries
- All chances to optimize part-load efficiency have been explored within the last ~20 years
- New ideas need to be developed immediately to fulfil CO_2 targets

→ What is to do ?

- Optimization of be-opt area necessary
- Less part load operation fraction,
  but combustion engine
  remains main drive with dynamic
  response demands


fuel consumption map
Otto-MPI-engine

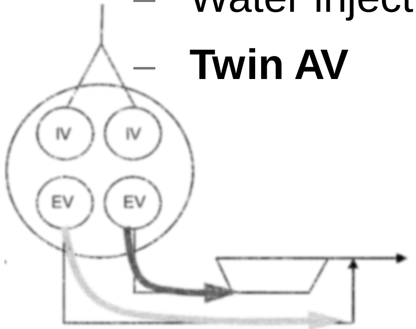
Here further improvement necessery

gofficient technology spectrum

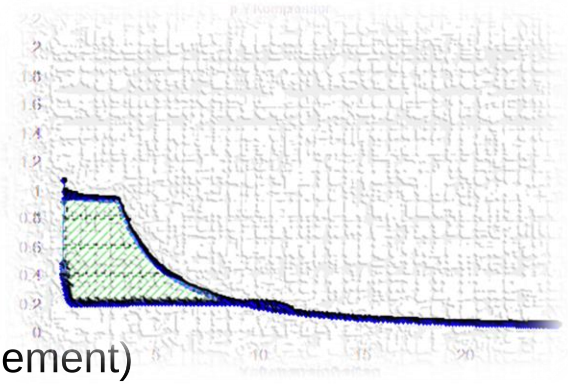
- Cold start/ Instationary optimization
  - Reduced heat capacity

- Waste Heat Recovery
  - Steam processes
    - Classic exhaust steam processes
    - **Combined water/exhaust cycle**
    - **Steam direct injection**

- Thermodynamic Efficiency Improvement
  - Increase of effective expansion ratio
    - VCR
    - Miller Cycle
    - Water injection
    - **Twin AV**



- Part Load Optimization
  - Reduction of Scavenging losses
    - Downspeeding
    - Dethrotteling by high EGR
    - Dethrotteling by lean combustion
    - Dethrotteling by Valvetrain
    - Downsizing (Reduction of Displacement)
    - **Variable Compressor/Expander unit**



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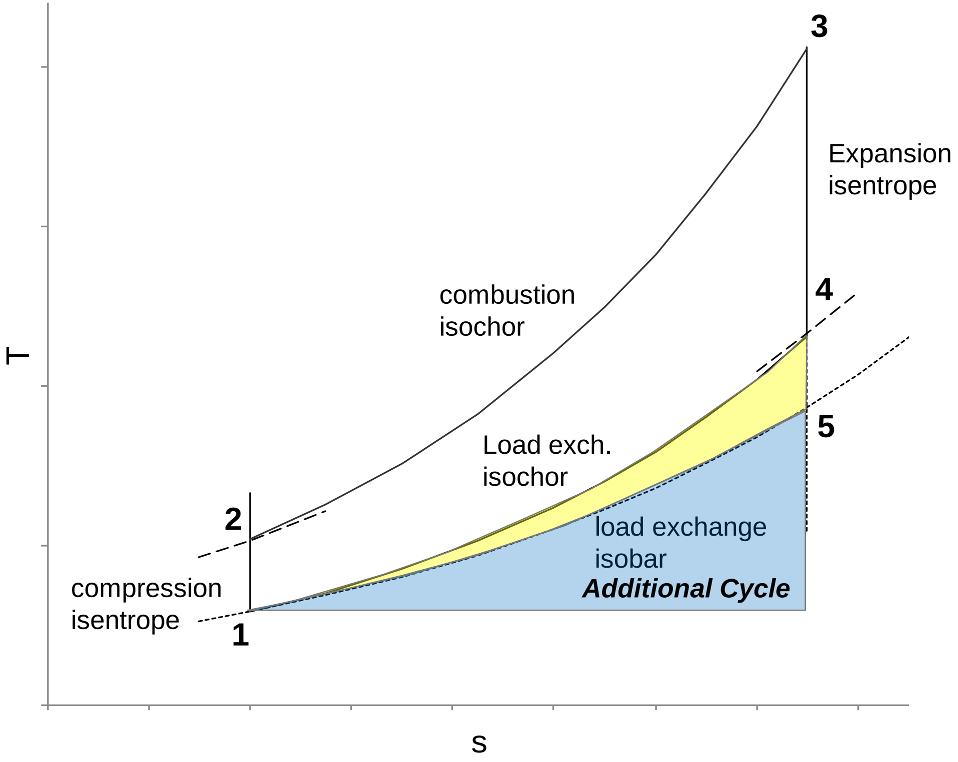
Gasoline engine optimization

Pushing a gasoline engine closer to Carnot

- Background/Reason for Technology development
- Increasing expansion
- Gain of Isochor/Isobar expansion triangle
  → TwinAV / Miller
- Using lower corner in T-s-diagram
  → Waste Heat Recovery
- Combination of Technologies



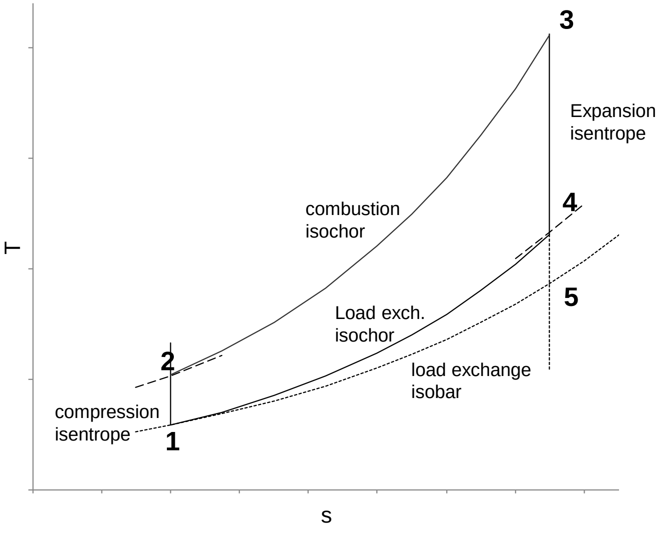
Gasoline engine optimization - Background

Pushing a gasoline engine closer to Carnot

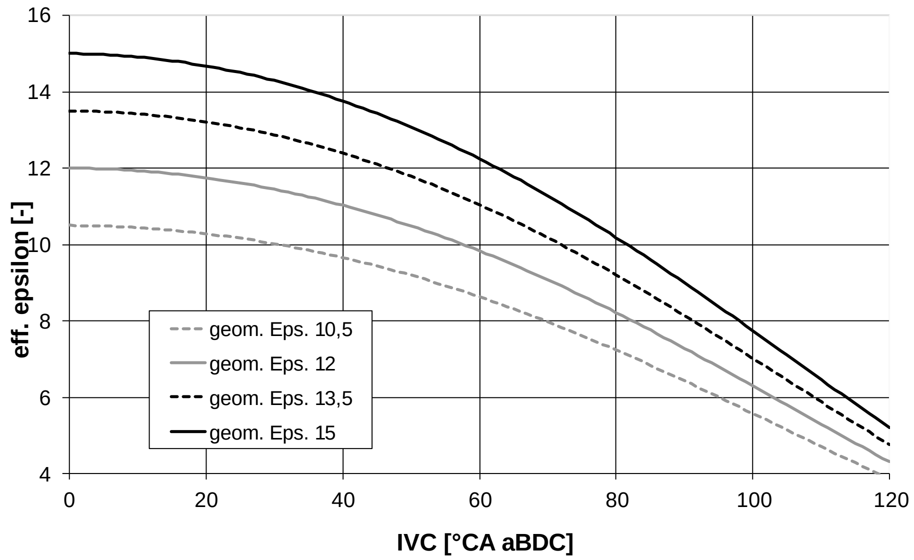
Background/Reason for Technology development

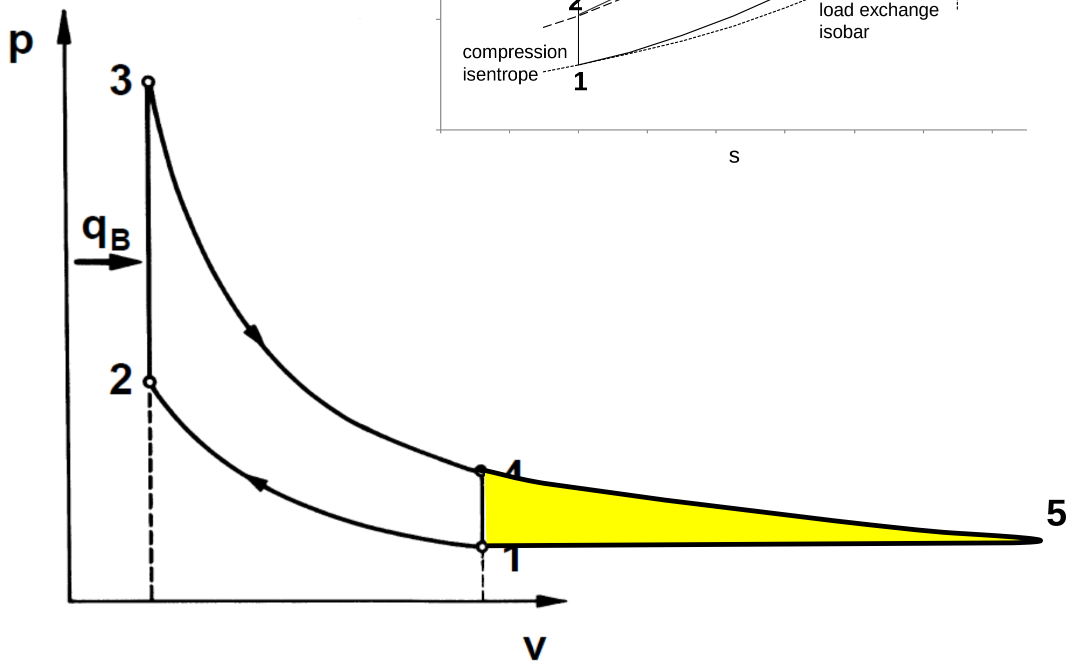
- Base thermodynamic efficiency of gasoline engine
- Efficiency of equal pressure process with fixed ε is $\eta_{th,\,v} = 1 - \frac{1}{\varepsilon^{\kappa - 1}}$
  - Typical ε is ~ 10.0 for TC engines
    and typical κ is ~ 1.28 for exhaust gas

→ $\eta_{ideal} = 47{,}5\%$



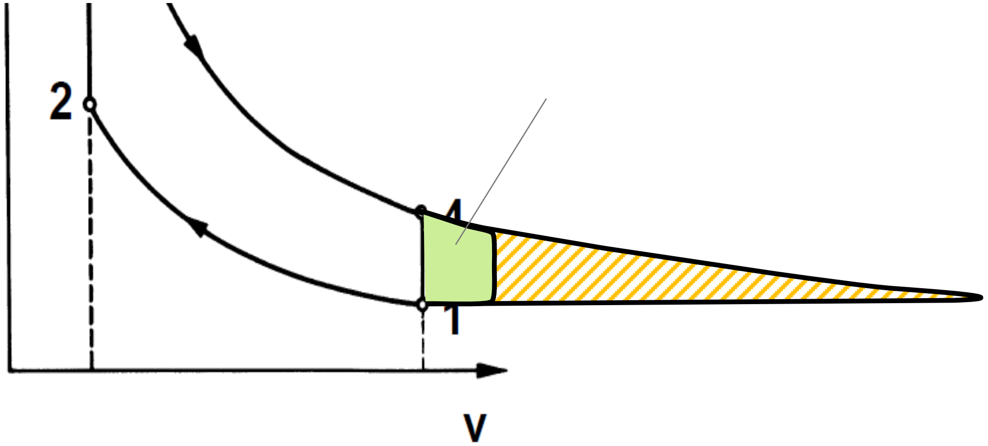
eff. compression rato Miller cycle

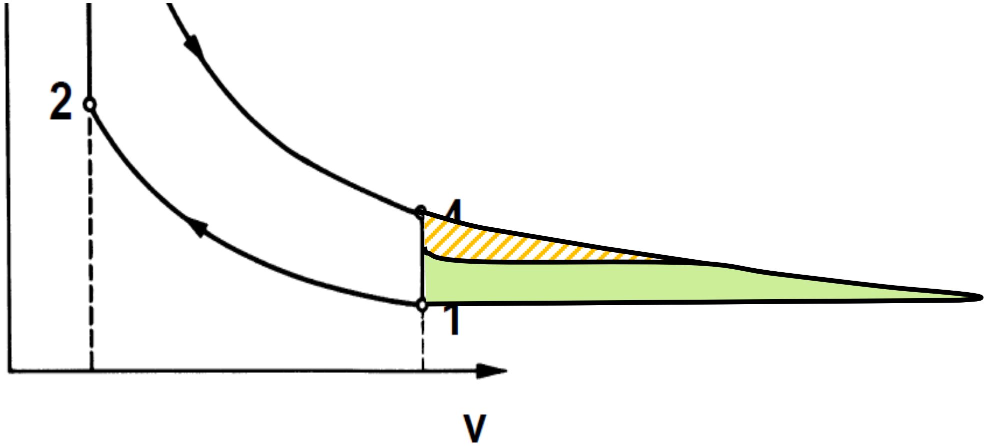




Gasoline engine optimization - Background

Two approaches to use „lower triangle“ exergy





Miller Cycle

- Increasing of geometric expansion by ~30%
- ε_{geo} = ~13 ; ε_{eff} = ~10
- → $\eta_{increase}$ ~ 5%
- Drawback is more total displacement

→ More relative friction, esp. at part-load

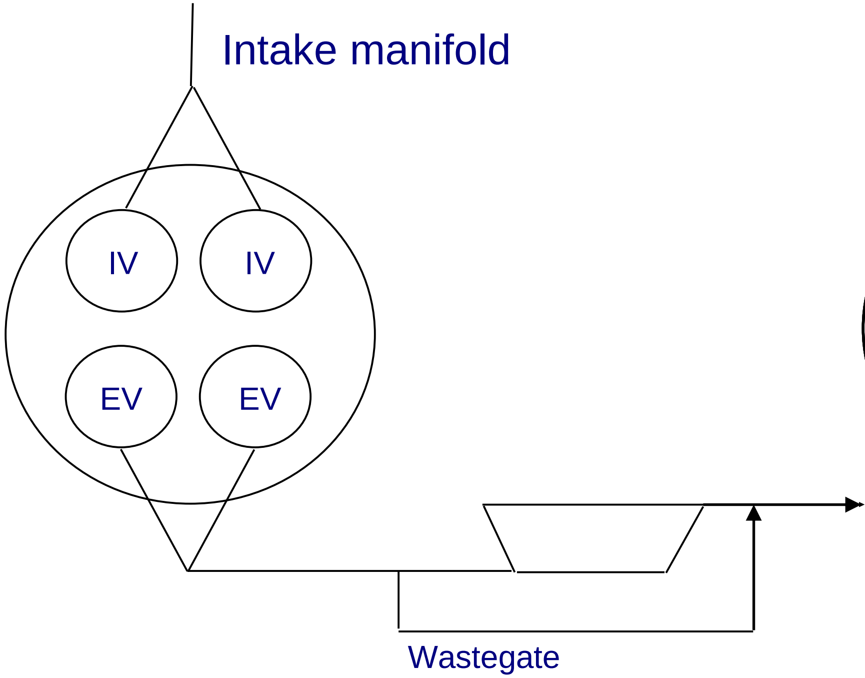
→ Worse warm-up behaviour

Twin AV

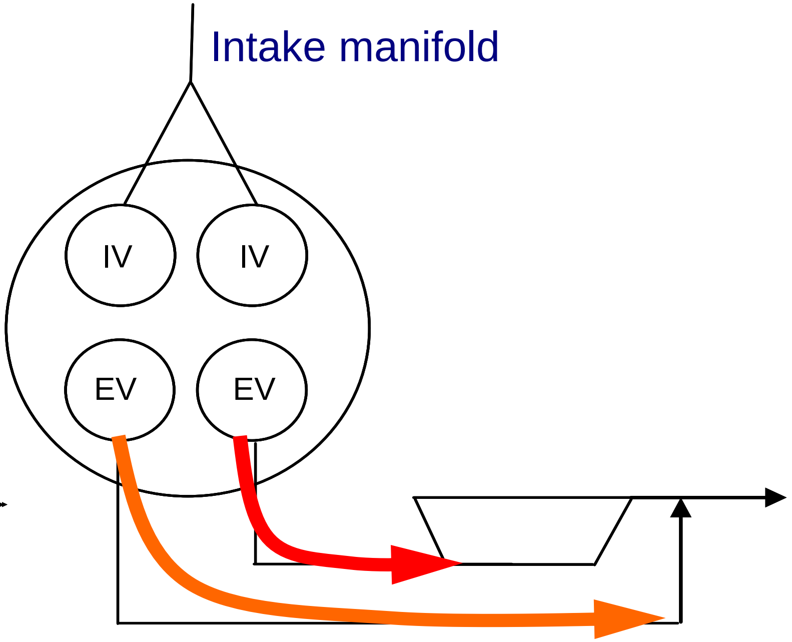
- Expansion at turbine until upstream cat pressure
- Usage of ~60% of exhaust gas mass
- → $\eta_{increase}$ ~ 7%
- Same engine displacement
- At high rpm (>5000) benefit reduces to ~0

Twin AV
Basic concept Twin AV principle

- No wastegate – Exhaust gas which is not used for turbocharging is bypassed at separate exhaust valve
  → No exhaust backpressure at this LP exhaust valve
- Turbocharger has its own HP exhaust valve
- Small turbine with high typical pressure ratio can be applied



Conventional

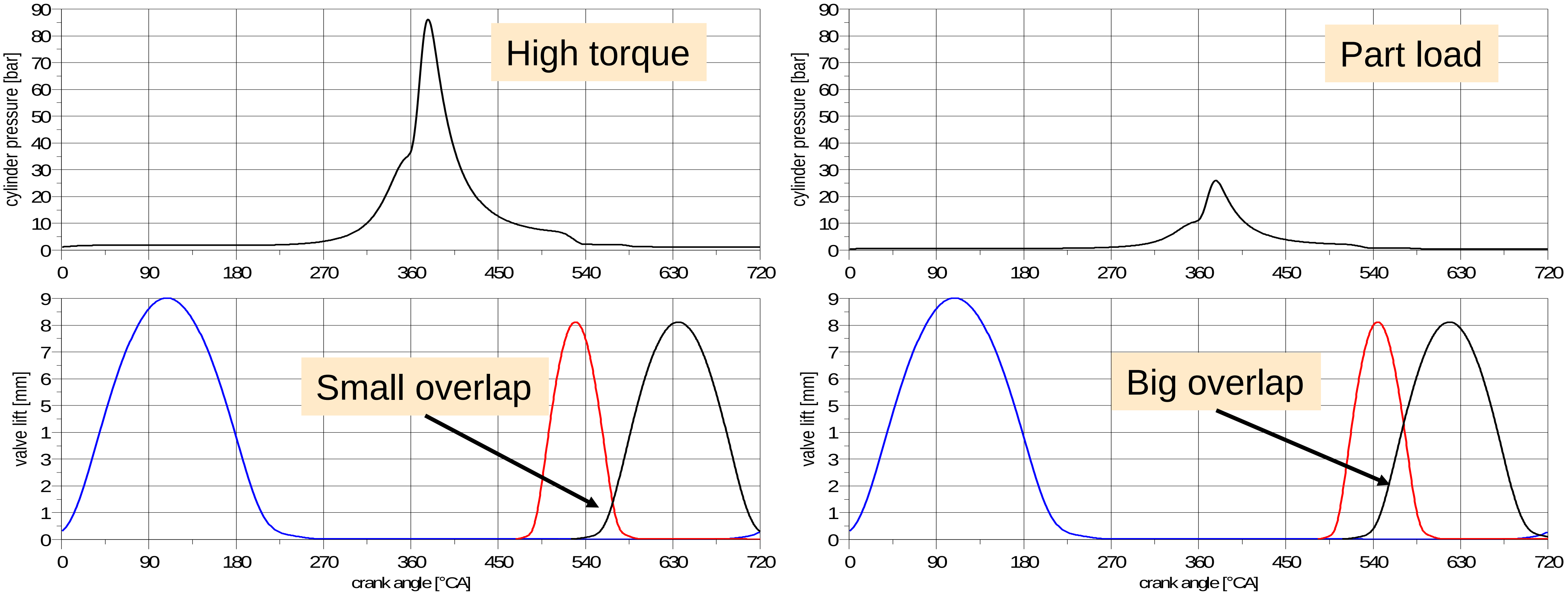


Twin AV

Twin AV

Control concept Twin AV principle

- Boost control is driven by relative movement between exhaust valves
- Just one additional camphaser necessary


High torque

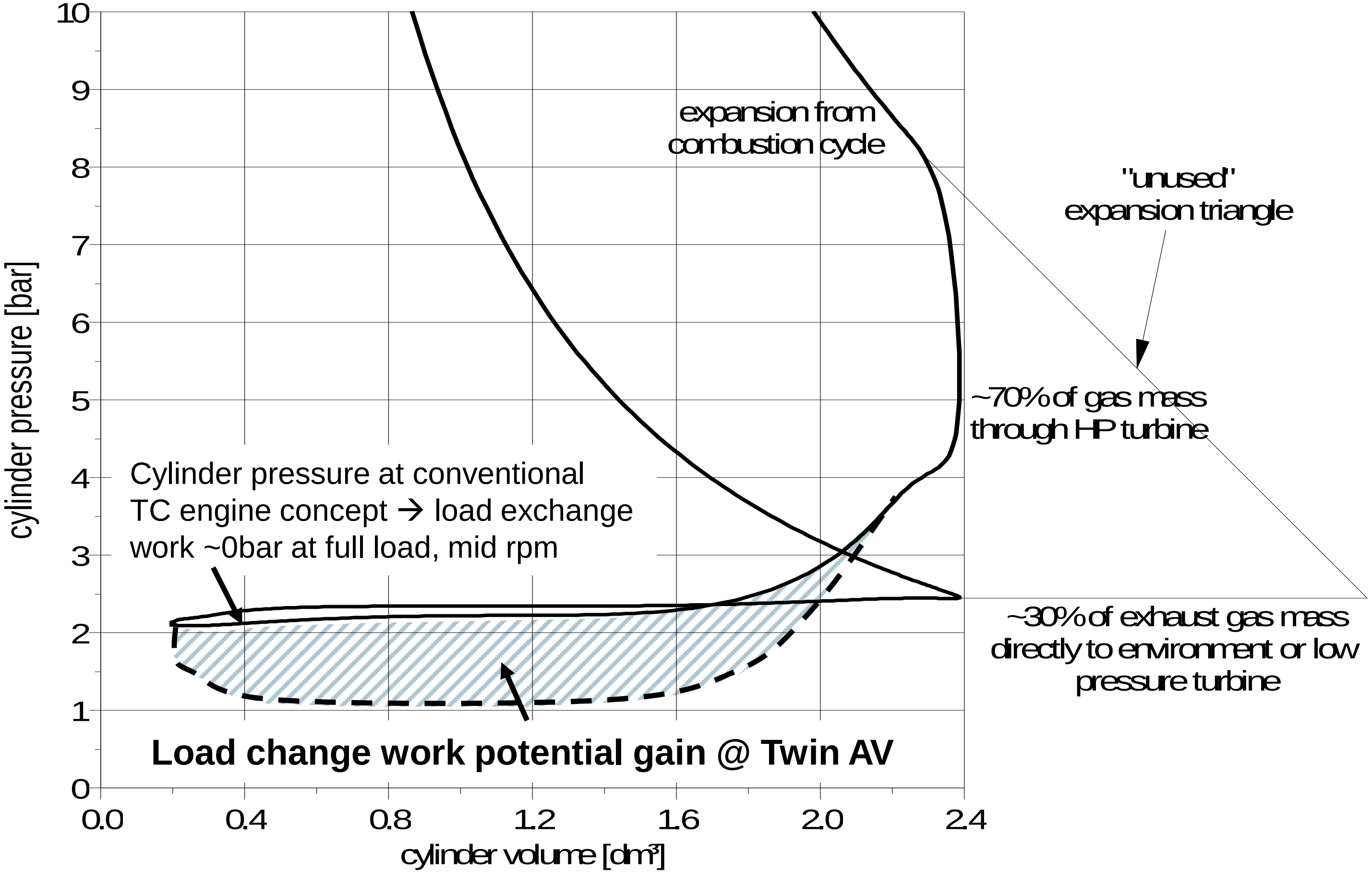
Part load

Small overlap

Big overlap

Twin AV

Basic concept Twin AV principle



expansion from combustion cycle

"unused" expansion triangle

~70% of gas mass through HP turbine

~30% of exhaust gas mass directly to environment or low pressure turbine

Cylinder pressure at conventional TC engine concept → load exchange work ~0bar at full load, mid rpm

Load change work potential gain @ Twin AV

Key facts:

- Almost no statical backpressure
- “lost” exhaust mass fraction can be compensated by smaller turbine (higher turbine pressure level)
- Thermodynamically increasing effective expansion ratio
- Always positive scavenging pressure ratio → low knock retard
- Efficiency gain up to 7%
- Increased exhaust gas temperatures at turbine

→ Good combination with

  - Integration exhaust manifold
  - Water injection

Twin AV

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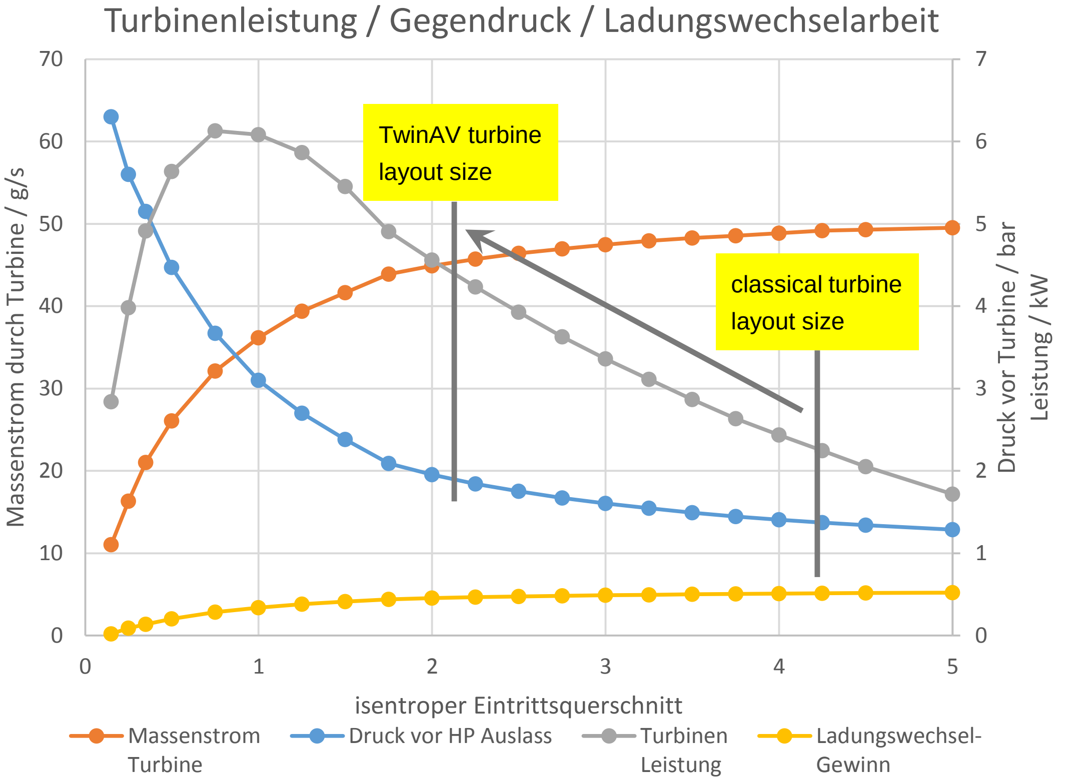
System Layout

- Smaller Turbine than conventional layout recommended
  → Less mass flow, higher backpressure
  → Same or more power than „base“ layout without TwinAV
- Combination with VTG could gain additional Turbo-Compound potential

Control concept Twin AV principle

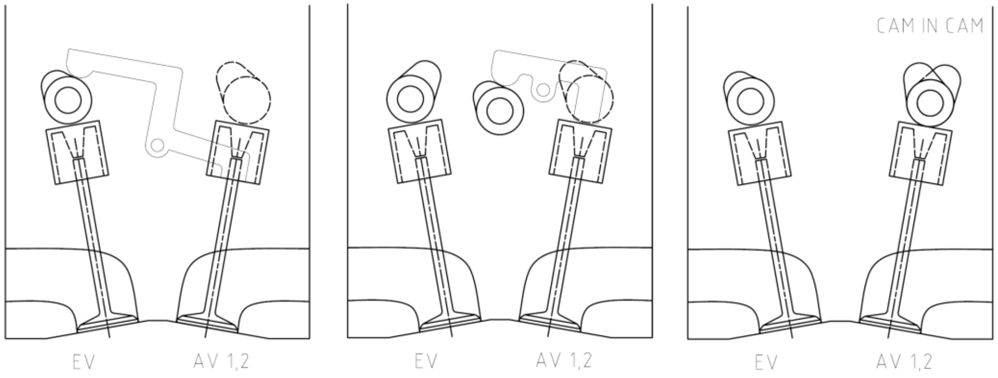
- Different mechanical approaches for camphaser integration
- Combination with main intake and outlet phasing possible
  3-way cam-phasing



TwinAV turbine layout size

classical turbine layout size

Diagram shows typical conditions upstream turbine at 2000 rpm / higher part load



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- Combination of Technologies

Steam Direct Injection

Technology Overview: Steam Direct Injection

Motivation

- Waste heat (exhaust and coolant) contains ~50% of total fuel energy, 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

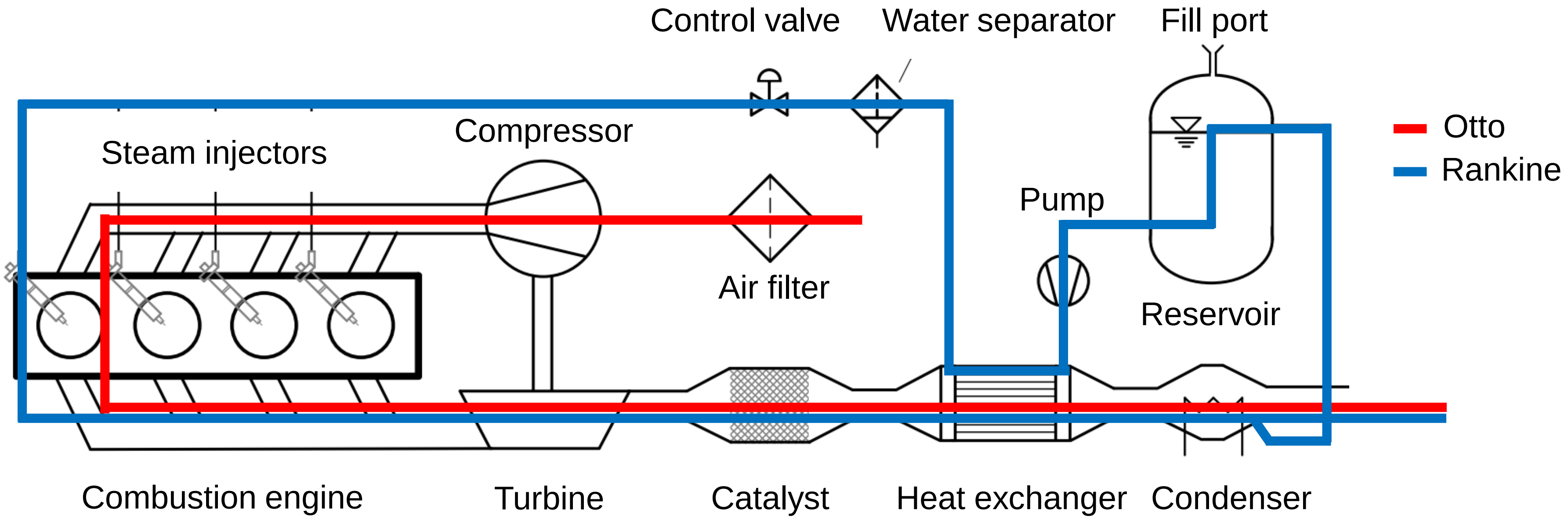
Solution

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

Concept
Combination of known processes in a single expansion machine is key

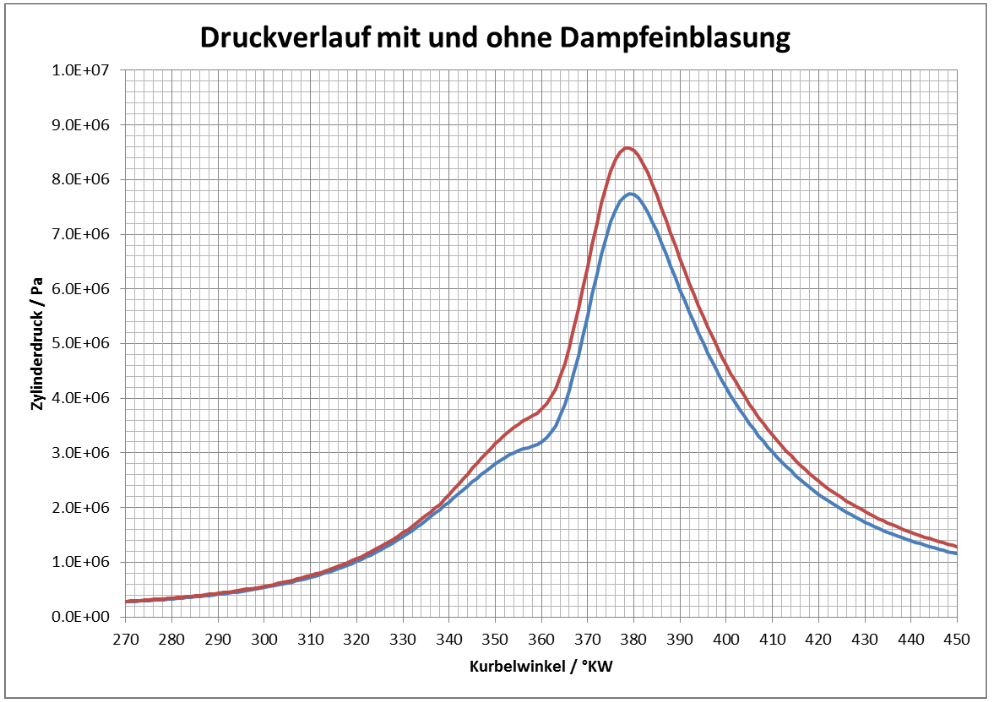
STEAM CONDITIONING AND DIRECT INJECTION

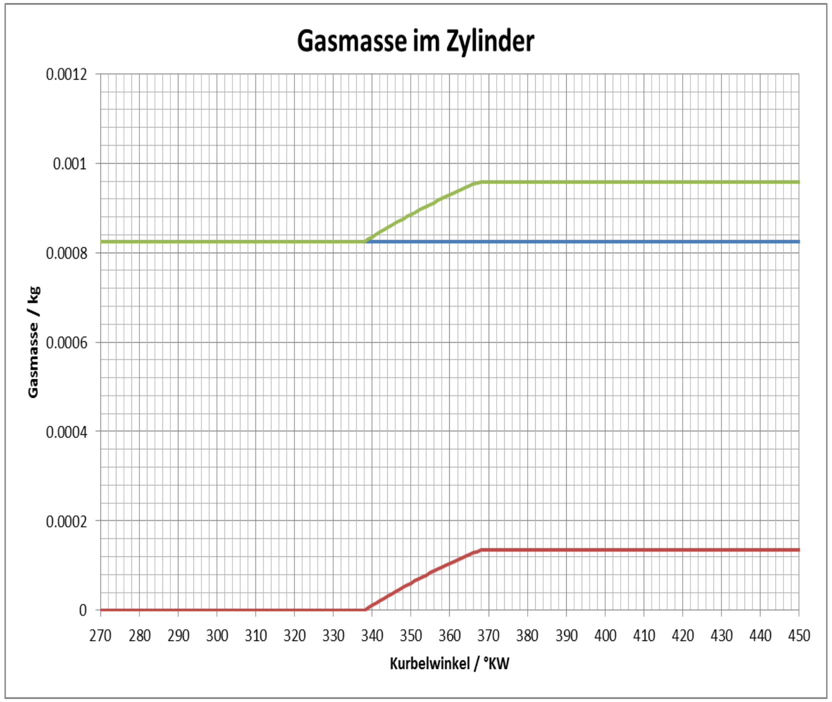
- Exhaust heat exchanger generates high pressure steam
- Steam pressure depends on waste heat energy, delayed heat up due to thermal inertia
- Steam injections depend on operating point, however it shows fast control characteristics
- Power increase and efficiency gain due to steam expansion and combustion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



Steam Direct Injection

- Generation of superheated steam based on exhaust energy recuperation
- Steam Direct Injection at a window close to TDC
  depending on operating point and actual cylinder pressure, steam pressure up to 20-100 bar
- In comparison to fluid water injection, low temperature drop (no evaporation) → increasing cyl. Pressure
- **Increasing cylinder pressure due to increasing mass and by this IMEP increase of up to 15%** more possible for short term (instationary)





Steam Direct Injection
Key facts

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Key facts Steam direct injection

- Steam generation by Exhaust heat exchanger up to 20-100bar
- Steam Power available on demand
- No additional expansion device necessary, steam injection into main engine
- Part-efficiency of bottom cycle up to 15..20%
- Maximum Power gain (for limited time) up to 10kW
- Additional positive influency to base engine
  - Soot reduction by agglomeration and peak combustion temperature reduction
  - Component protection included due to lower exhaust gas temperatures

Key facts Turbo Steamer

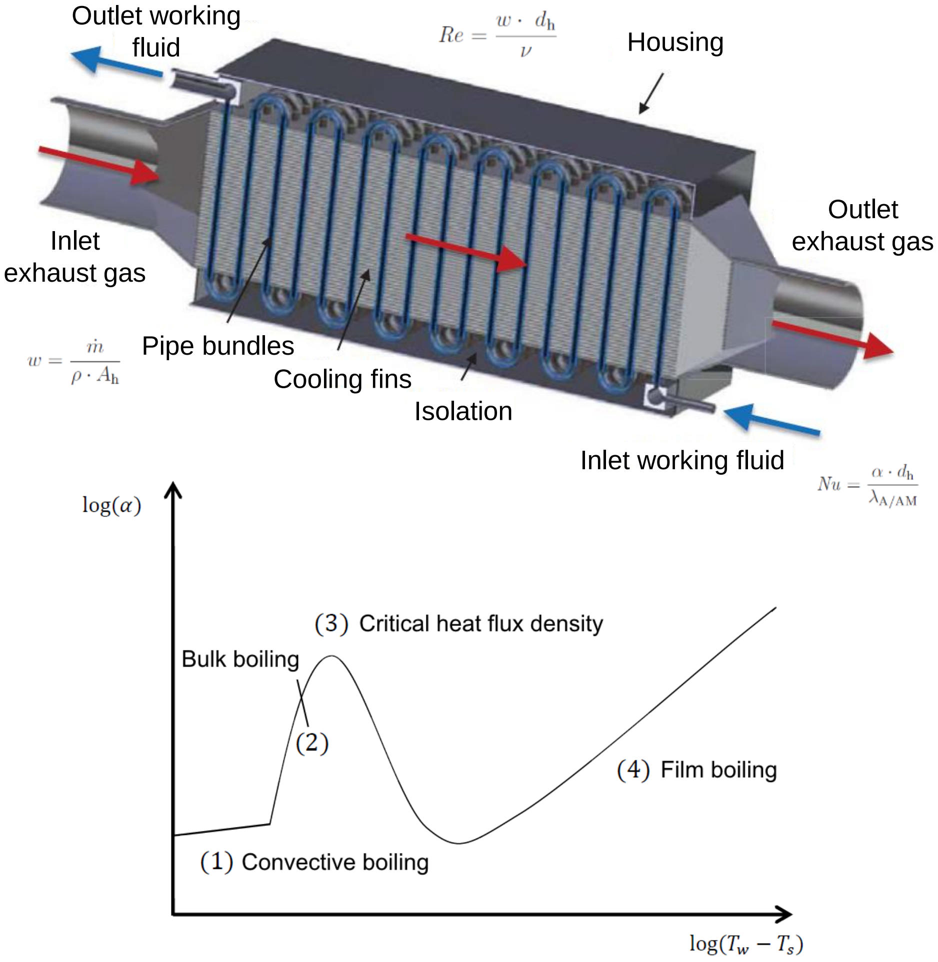
- Steam generation by Exhaust heat exchanger up to 5-50bar
- Continous steam power generation, independent from usage
  → needs to be buffered
- Expansion device is turbine or cell expander, efficiency strongly dependent on OP point
- Cycle efficiency including pinch-effect 10..12%
- Electrical power generation of max. 2kW

Component design
Rapid heat up vs. sufficient steam delivery rate

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	1.15 L
Max. Steam delivery rate	30 g/s

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



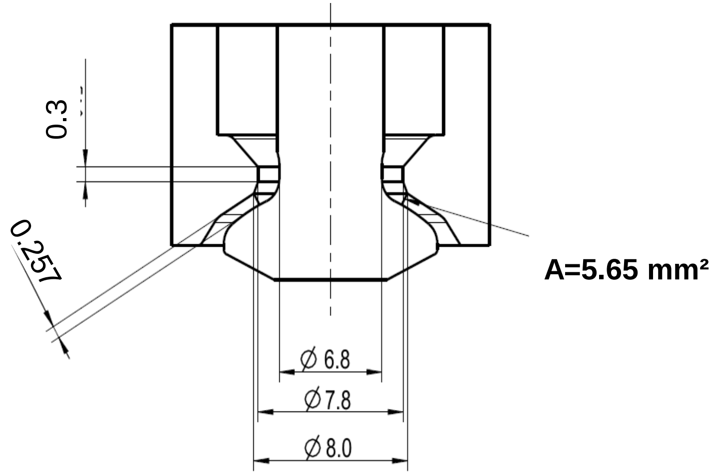
Component design
Sufficent Full-load with acceptable Part-load performance trade-off

INJECTOR

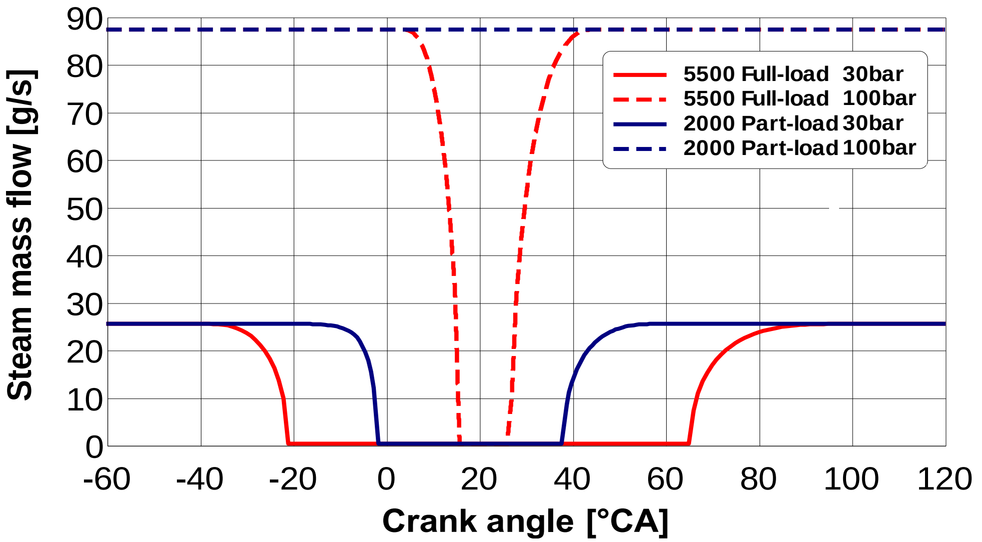
$$\dot{m}_{Inj} = A \cdot \mu \cdot \Psi(x,\kappa) \cdot \rho_{Steam} \cdot \sqrt{2 \cdot R \cdot T} \quad with \;\; x = \frac{p_{Cyl}}{p_{Inj}}$$

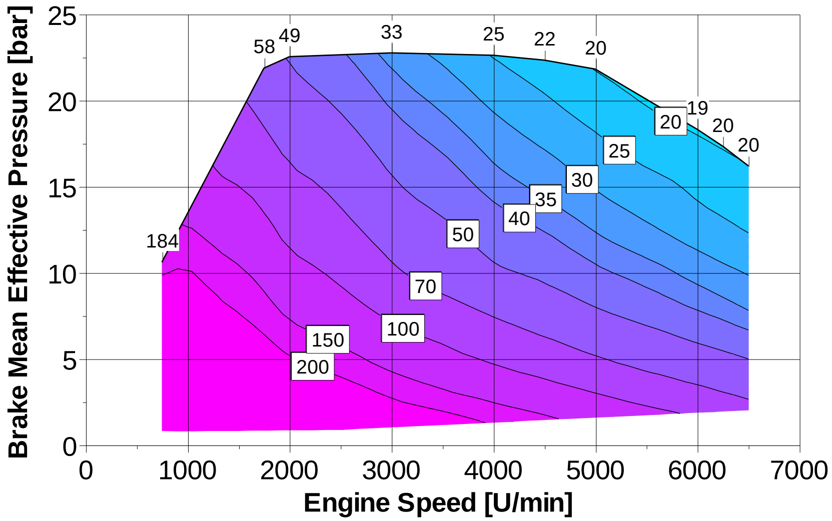
46 times more dense than air at 20°C

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



Max. rel. steam mass at $\Delta\alpha_{max}$= 80°KW
at operation with 100bar/311°C saturated steam





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

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

Steam injection

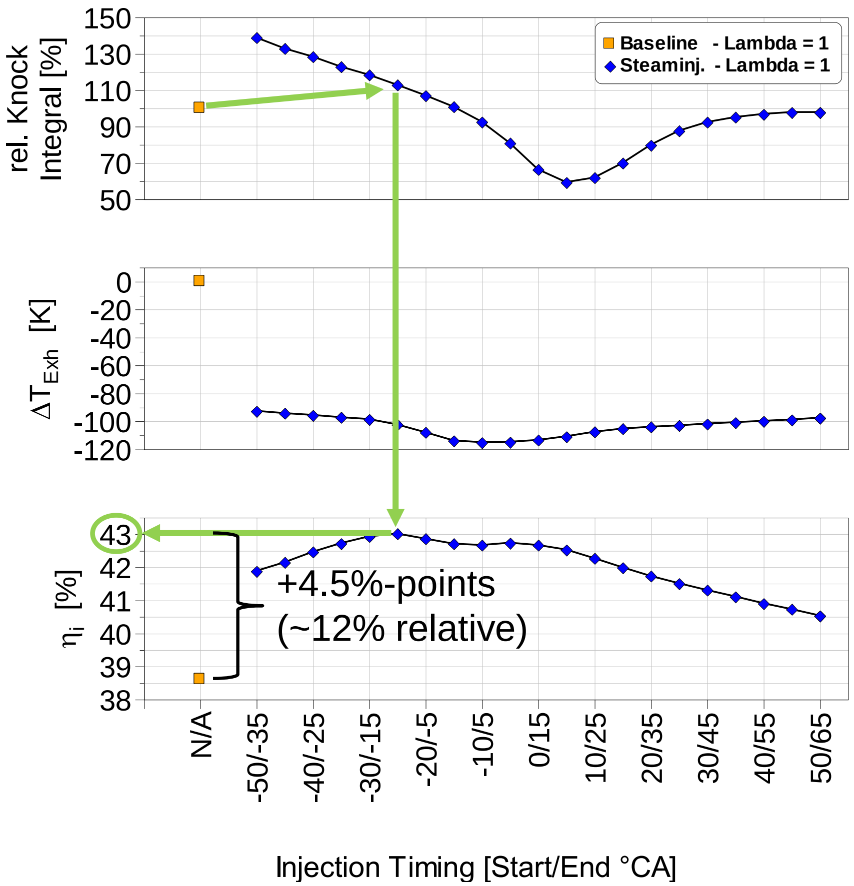
Simulation Results

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:	105 mg/cycle
Puls duration:	15 °CA



+4.5%-points
(~12% relative)

GT-Power Results

- Low rotational speed allows for short injection timing (15°CA)
- Load point stability enables pre p_{max} injections leading to higher efficiency
- Combustion peak temperature can be lowered significantly by 350 K
- 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
WLTP takes full advantage of fast heat up and torque boost

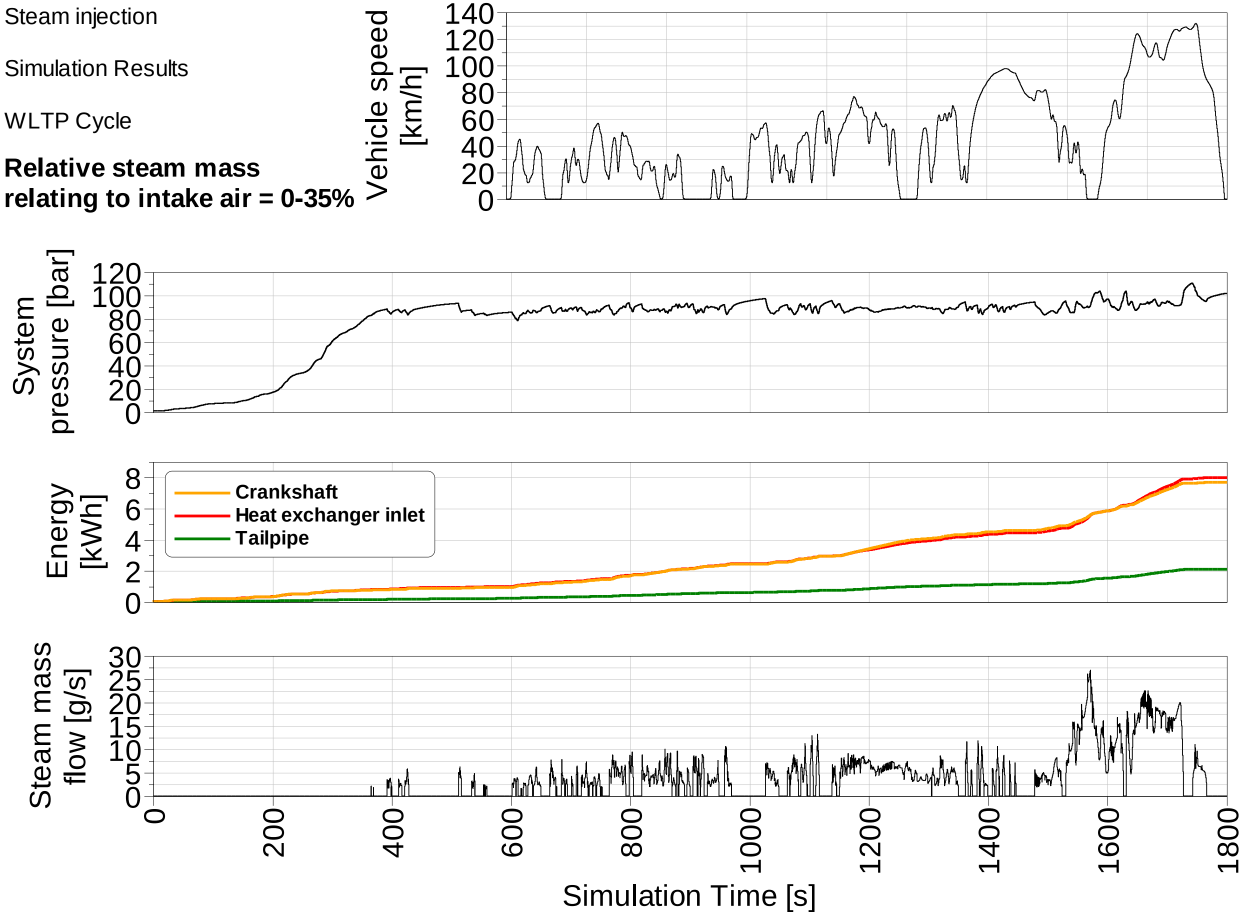
ZYKLUSSIMULATION WLTP

Steam injection

Simulation Results

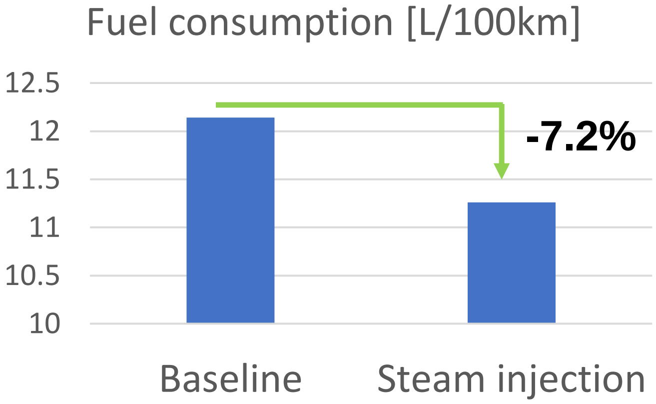
WLTP Cycle

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.



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Variable Compressor/Expander unit

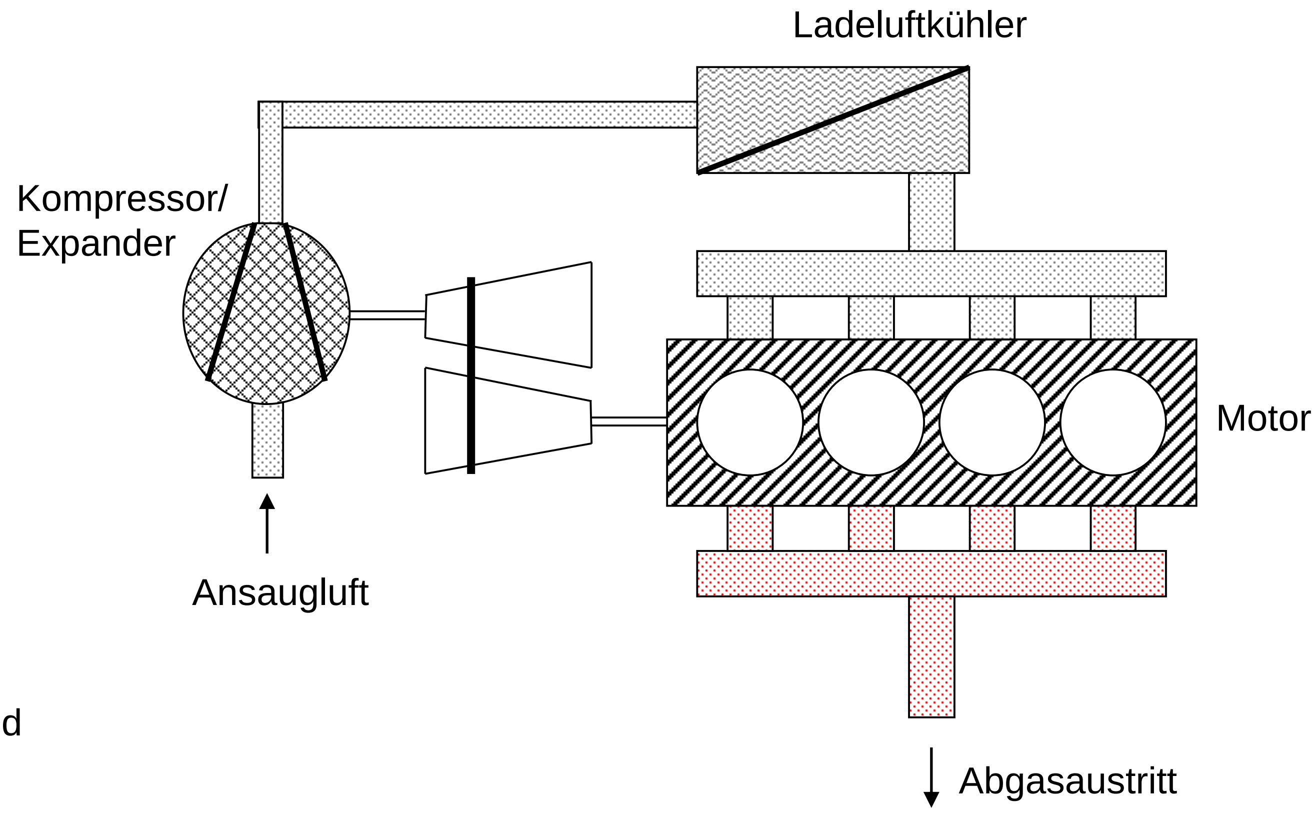
Variable Compressor/Expander unit

General Idea

- Use a piston based compressor for supercharging a combustion engine
- Directly coupled to the engine crankshaft
- The compressor can vary its mass flow
  - A) By changing geometry
  - B) By changing transmission ratio
- No leakage air occurs

Benefits

- Throttling of engine can be done by compressor geometry → No throttle valve necessary
- Load exchange work from engine is gained back at compressor, when operating with underpressure at part load



Variable Compressor/Expander unit

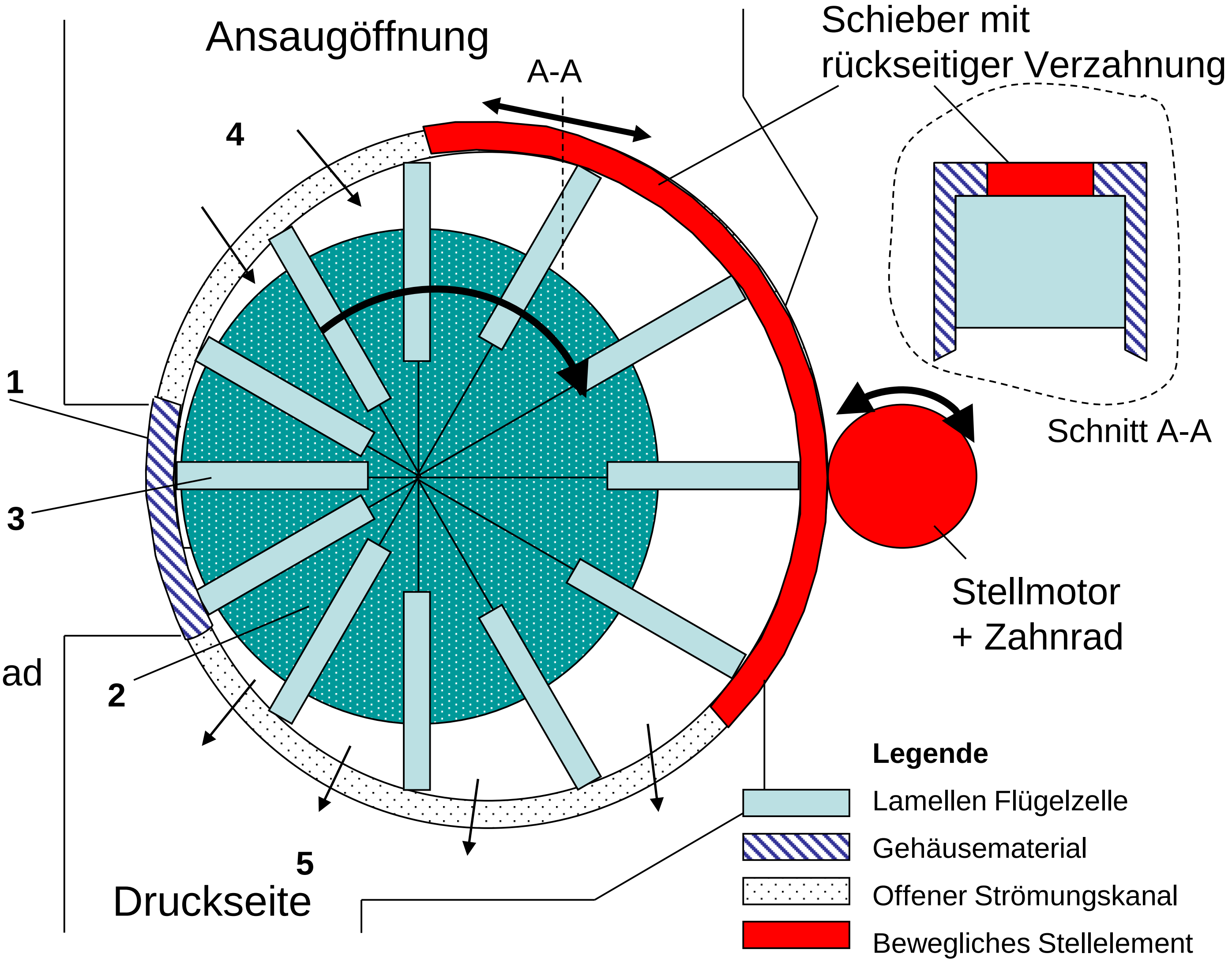
Variable Compressor/Expander unit

Design example

Variant A) Variable geometry

Exhaust volume
of compressor unit almost
equal to cylinder displacement

Variable intake volume
- Smaller than exhaust for part load
- Larger for high load/full load



Legende

🟦 Lamellen Flügelzelle

▨ Gehäusematerial

⬚ Offener Strömungskanal

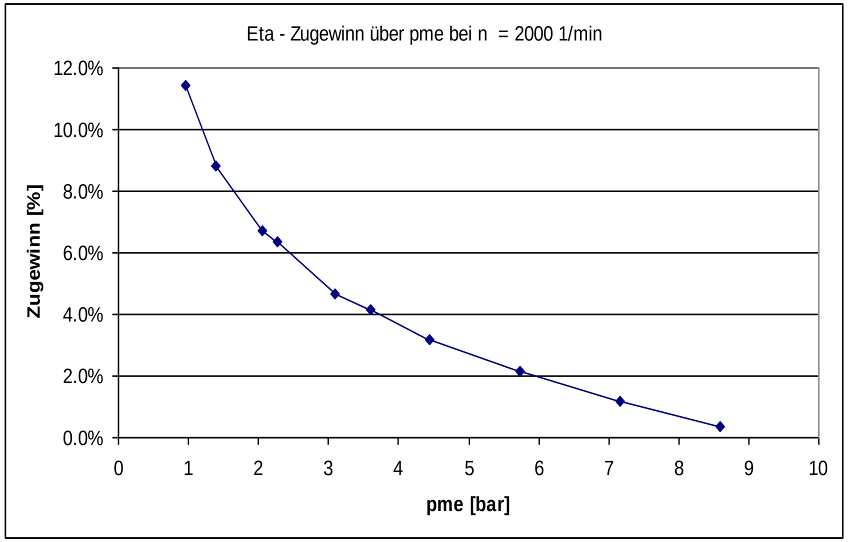
🟥 Bewegliches Stellelement

Variable Compressor/Expander unit

Variable Compressor/Expander unit

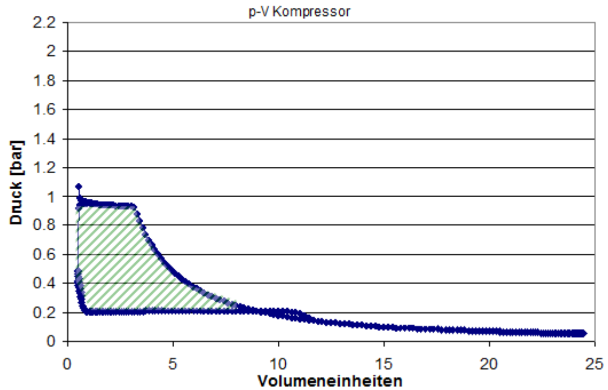
pV Diagram at different OP points shown right →

Overall efficiency increase compared to **N/A** engine shown below (much higher when comparing to turbo- or supercharged engine due to missing backpressure)



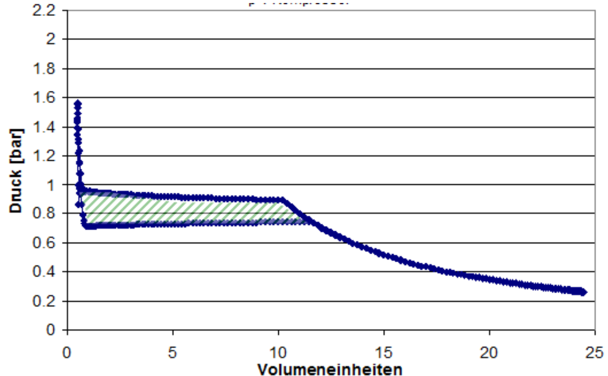
- **Lower part load**

→ pV diagram shows **big gain** at Compressor unit



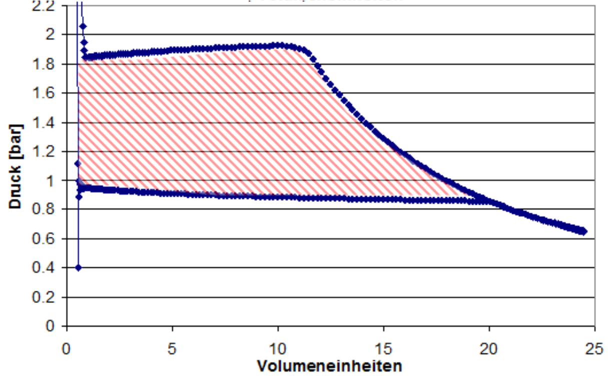
- **Middle load**

→ pV diagram ~neutral work at Compressor unit Benefit against Turbo (no backpressure) and Supercharger (no losses)



- **Full Load**

→ pV diagram comparable to conv. Supercharger



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Combination of bsfc-opt specific approaches

Which technologies should be combined ?

- Twin AV used potential of full expansion → no parasitic interaction with other methods
- Simplest and most effective method for Waste Heat Recovery is Steam Direct Injection
- Water Injection has minor additional benefit, however very low additional effort to above's config

With additional effort also reasonable

- 2-stage turbocharging+supercharging, especially TwinAV + Compressor/Expander

Not reasonable for combination

- Miller cycling (competes with Twin AV)
- VCR (competes with water injection)

Combination of be-opt specific approaches

Combination of Technologies

- Discussed Technologies can be combined with the effect of additive benefits
- Achievable specific fuel consumption with combination in optimum operation point

  → 185 g/kWh

  (η_{ges} = 46%)
- → Better than Diesel engines
  State of the art 2016
- Still more potential possible by combination with other principles
- Additional costs of proposed methods moderate, especially when compared to high degree of electrification