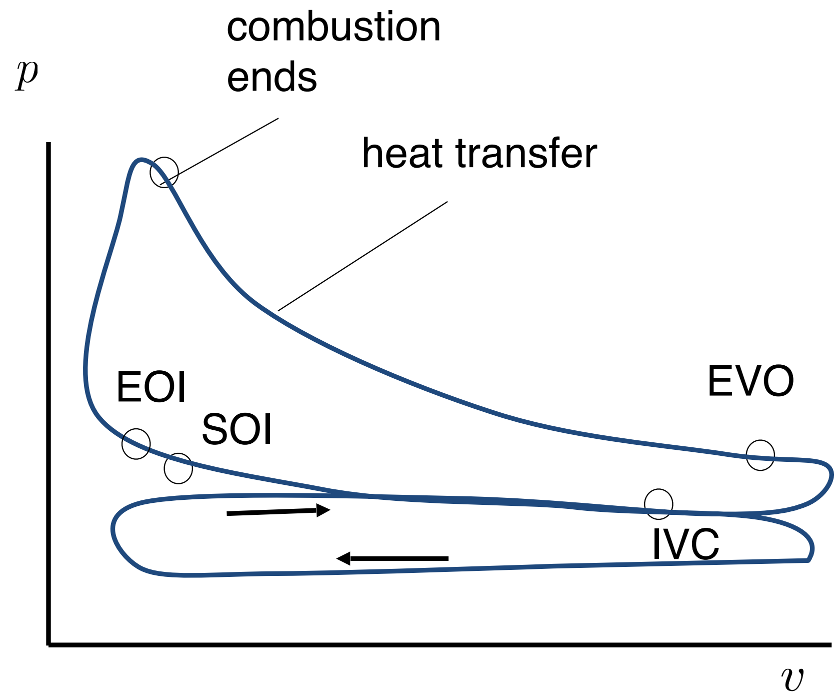
Real cycles – CI engines & turbochargers

4A13

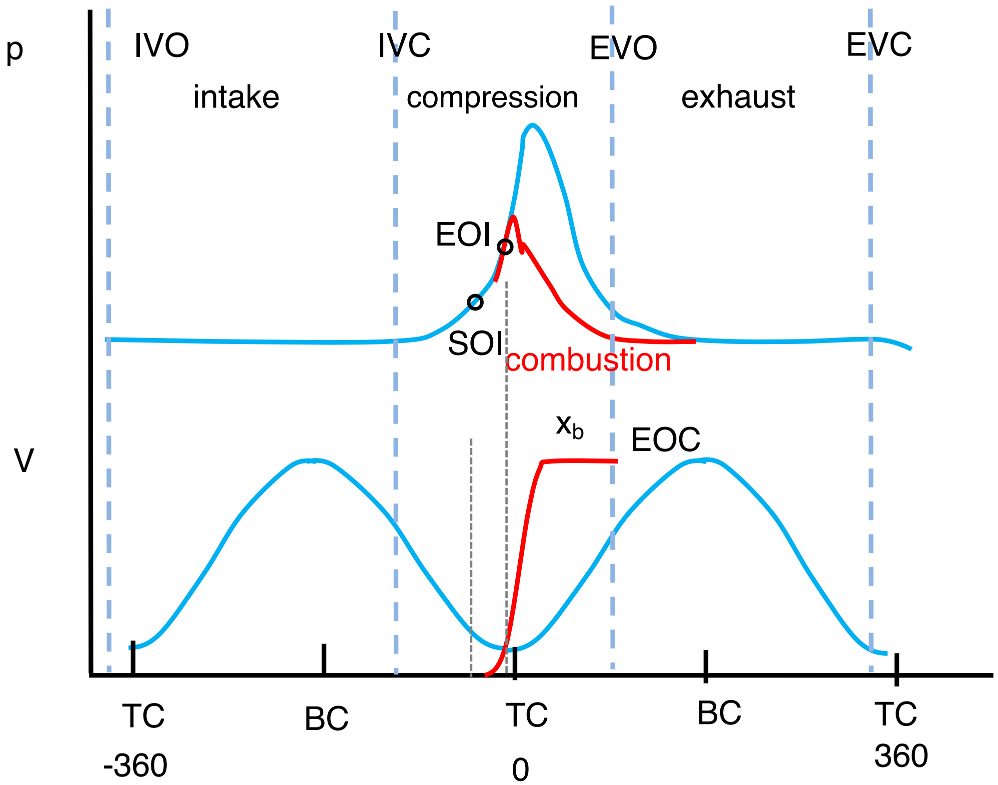
Heywood: Ch 10. Combustion in Compression Ignition Engines
Stone: Ch. 6. Compression Ignition Engines

Compression-ignition engines



- **Real gases:** fresh, residual and burned, variable properties with temperature
- **Gas exchange**: turbocharging + EGR
- **Heat transfer**: end of compression and combustion, exhaust enthalpy
- **Combustion phasing**: autoignition, heat release timing, noise and vibration
- **Emissions:** soot and NOx

Compression-ignition combustion



SOI/EOI: start/end of injection

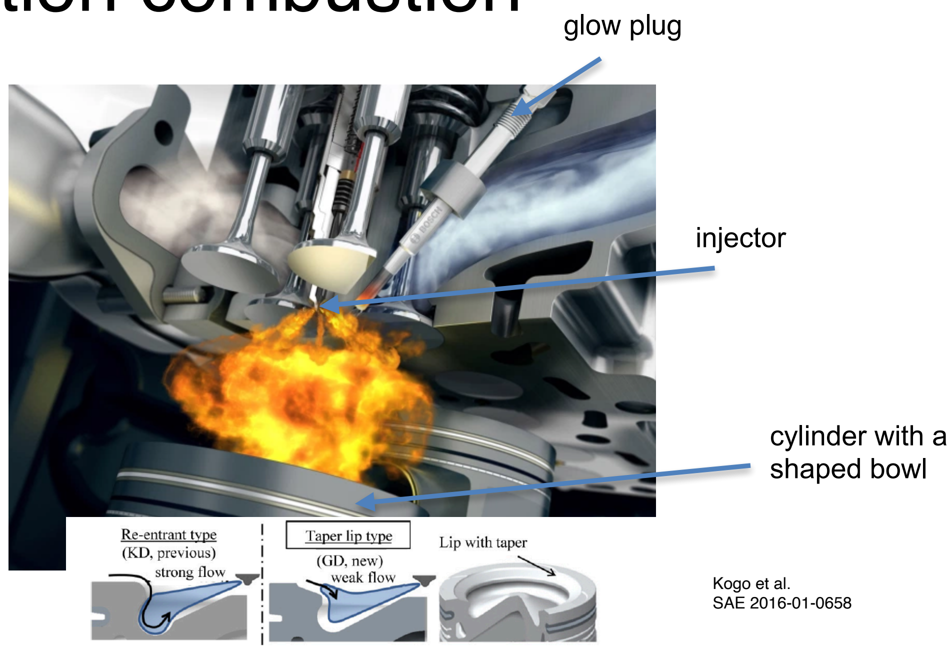


Figure 2. Newly developed bowl shape.

Kogo et al.
SAE 2016-01-0658

- high pressure fuel injection
- combustion starts by autoignition at high T, P
- high compression ratios (12-30) required
- combustion controlled by diffusion of fuel and air
- diffusion flame: high soot, NOx
- modern engines: higher pressure, multiple injections to minimise soot

Air-fuel ratio and CR in engines

$$AFR = \frac{\dot{m}_a}{\dot{m}_f}$$

CI: 18-70

CI: 1.2-1.6

$$\lambda = \frac{AFR}{AFR_s} = \frac{1}{\phi}$$

>1 fuel-lean
<1 fuel-rich

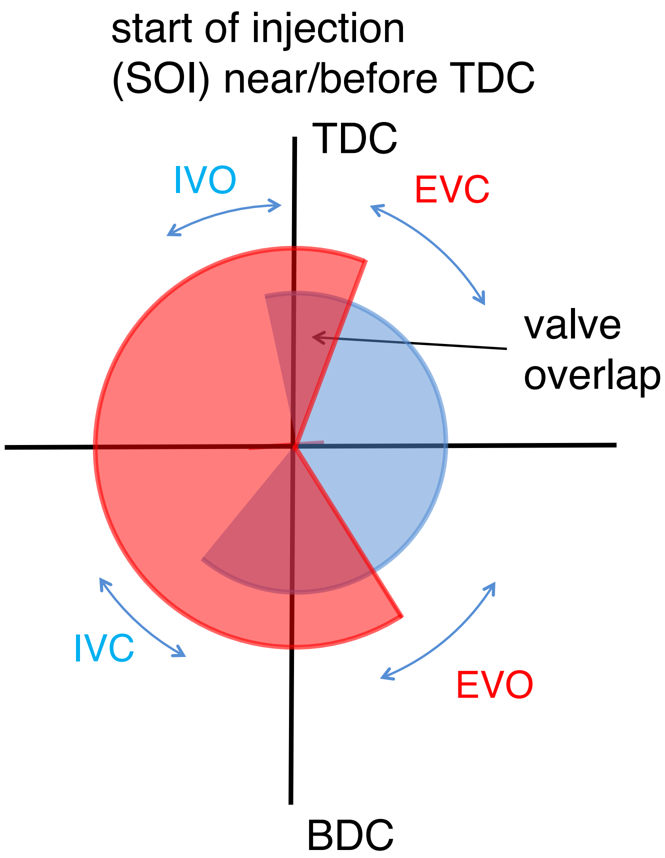
- CI engines must run at **fuel-lean ratios** to provide complete oxidation of the injected fuel, which would otherwise produce unacceptable amounts of **soot**.
- Mixture properties: unmixed air+fuel, products: very **heterogeneous**!
- Peak temperature: flame regions close to stoichiometric (non-premixed flame)
- Emissions: **NOx and soot** are key, and form in high temperature stoichiometric and rich conditions, respectively.

- CR ~16-20: **higher is better for efficiency,** but penalty is increase **in leakage through rings**, heat transfer, higher pressures and noise.

- CI engines are typically turbocharged to create **high enough temperatures and pressures for autoignition**
- larger engines typically also add an intercooler to better control of the load at reasonably low emissions.

Gas transfer processes: valve timing

IVO:
- Not so critical for CI engines
- Before BTC (large opening area)
- Earlier for for higher power/speeds
- Later for low residuals



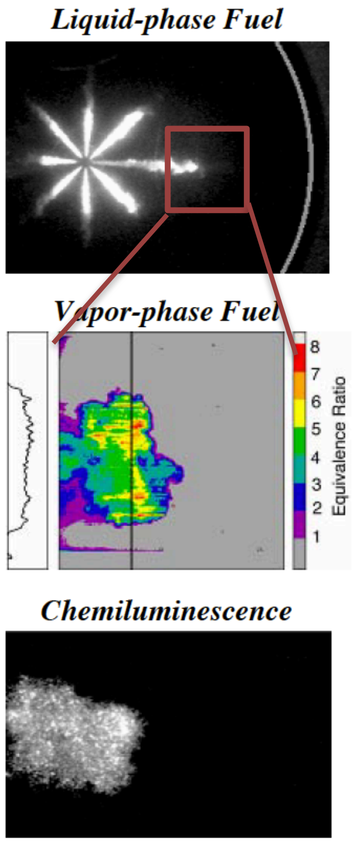
EVC:
- Avoid compression after EVC

IVC:
- Optimum for volumetric efficiency (with IVO) vs. speed

EVO:
- Too early: less gross work (but more turbo)
- Too late: poor overall scavenging/ breathing, but higher residuals (which can be good for low NOx).

Combustion process in CI engines

Tip of the jet
prior to ignition



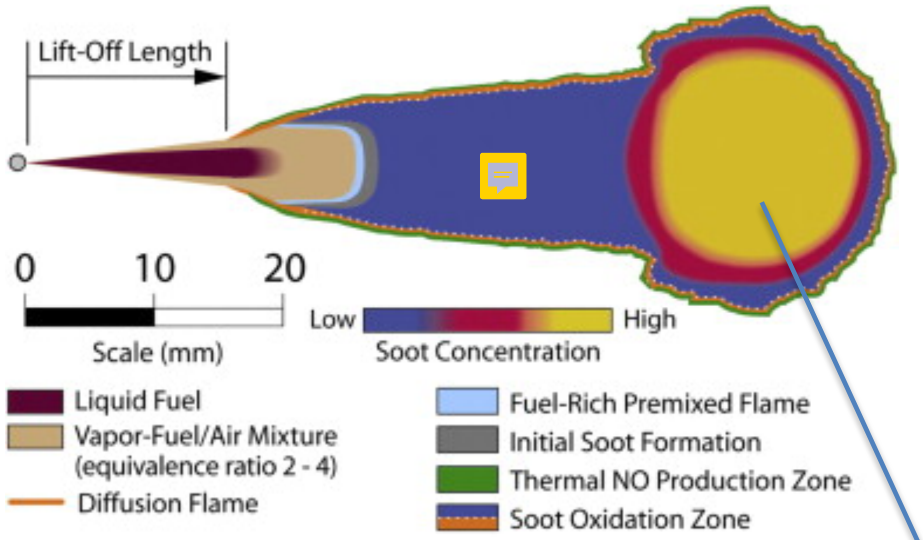
- Liquid fuel images show that all the fuel vaporizes within a characteristic length (~25 mm) from the injector.
- Vapor fuel images show that downstream of the liquid region, the fuel and air are uniformly mixed to an equivalence ratio of 3-4.
- Chemiluminescence images show autoignition occurring across the downstream portion of the fuel jet.

O_2=21%, SOI=-11 ATDC, T_{TDC} = 1000 K, ρ_{TDC} = 16.6 kg/m^3

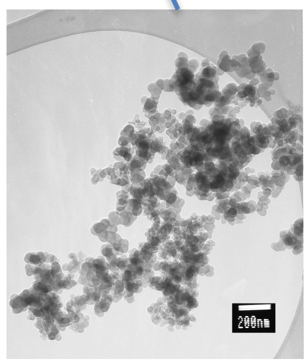
Dec, SAE980873

Dec & Espey, C. Espey, J.E. Dec, SAE Trans. 104 (4) (1995).

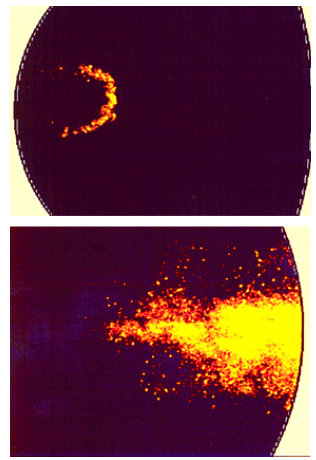
Combustion in CI engines



Musculus et al, Prog. Ener. Comb. Sci. 39, 246-283 (2013)



NO formation

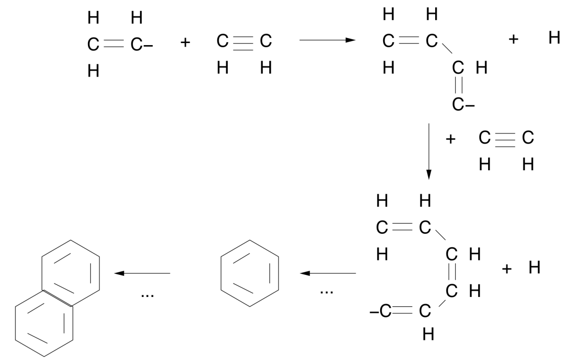


Immediately after ignition

Late in cycle

Dec & Zur Loye, SAE980873

Nitric oxide
(Dec, Sandia National Labs)



soot formation

Autoignition in CI engines

Autoignition:
- Hydrocarbon chain reaction during compressive heating
- Ignition time characteristic of the fuels: controlled by complex chain
- **Cetane** number: rating correlated with *ability to autoignite* (opposite of octane).
  100 = *n*-$C_{16}H_{34}$ (cetane), 0 =α-methyl-naphthalene: rating obtained in standard engine with standard operating conditions
- Air must be compressed, and sometimes heated to provide autoignition

Easy autoignition for higher temperatures

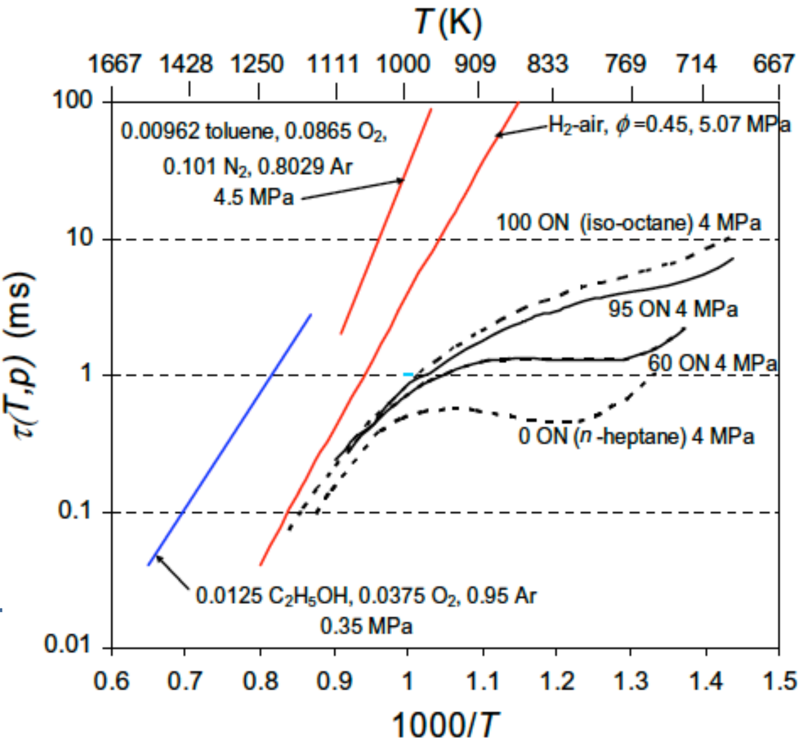
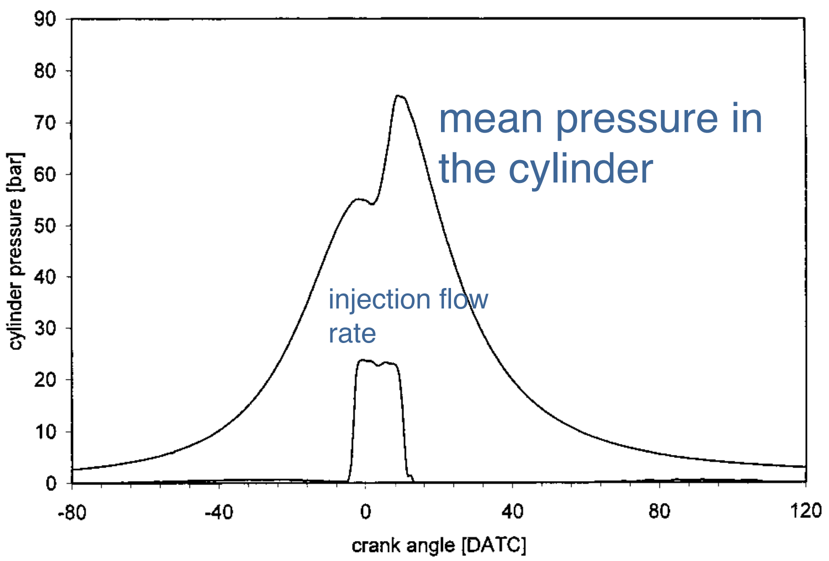


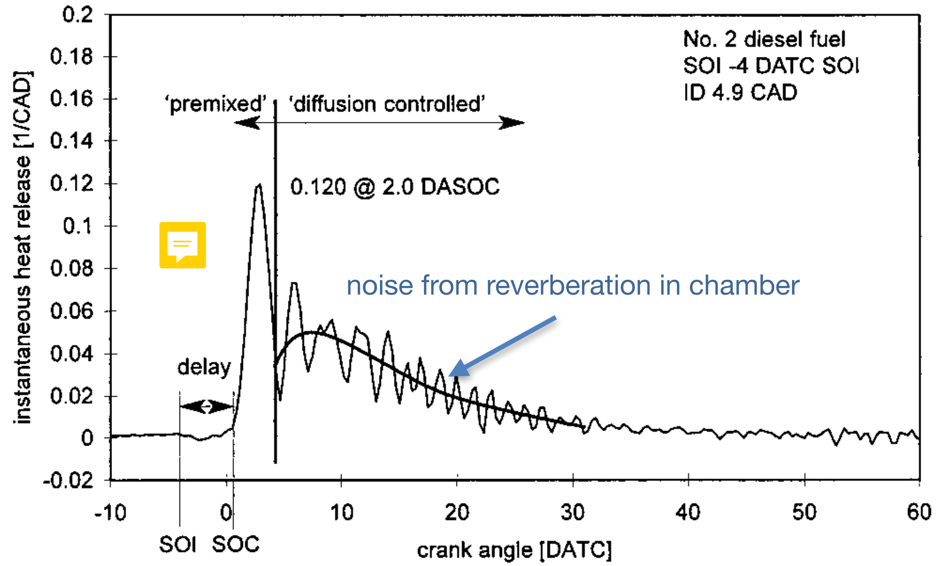
Fig. 2. Ignition delay times of various fuels with air at $\phi = 1.0$, unless otherwise stated. See Table 1 for source references.

higher temperatures

D. Bradley, G.T. Kalghatgi / Combustion and Flame 156 (2009) 2307–2318

Heat release rate in CI engines



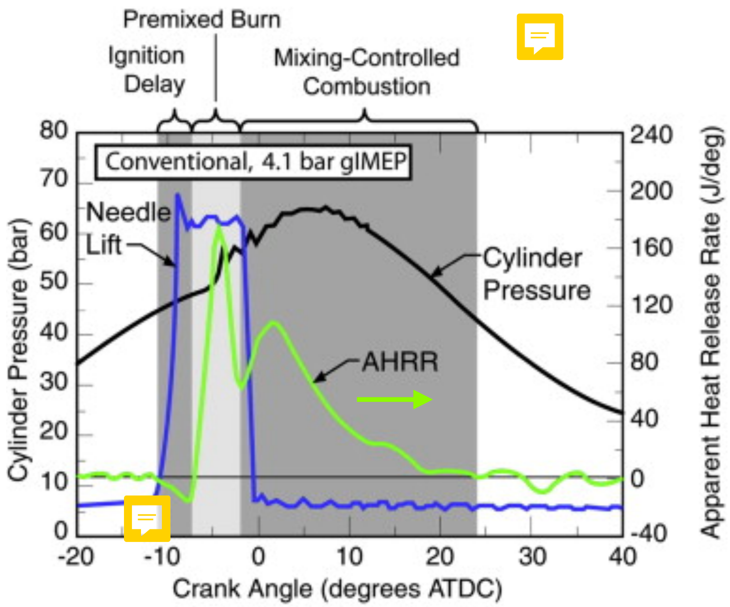


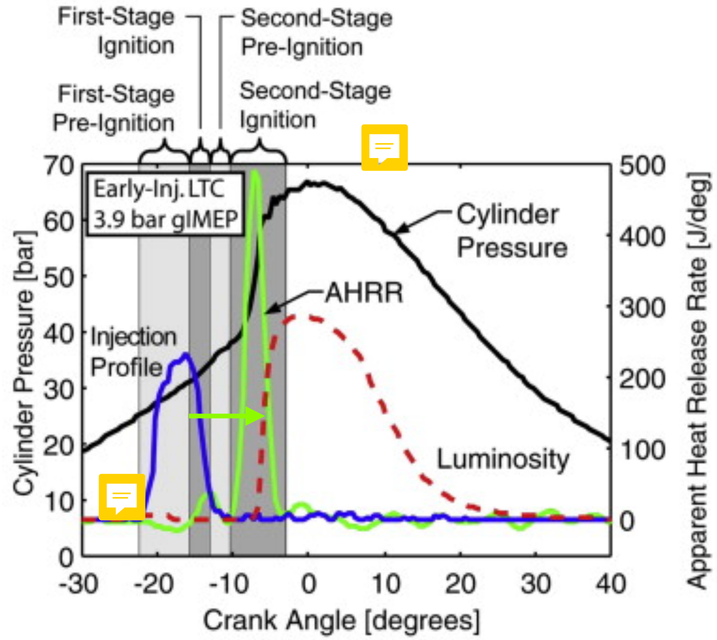
heat release rate obtained from the rate of pressure rise

Shihadeh et al, Energy & Fuels, Vol. 14, No. 2, 2000

Heat release for normal and early injection

Normal injection



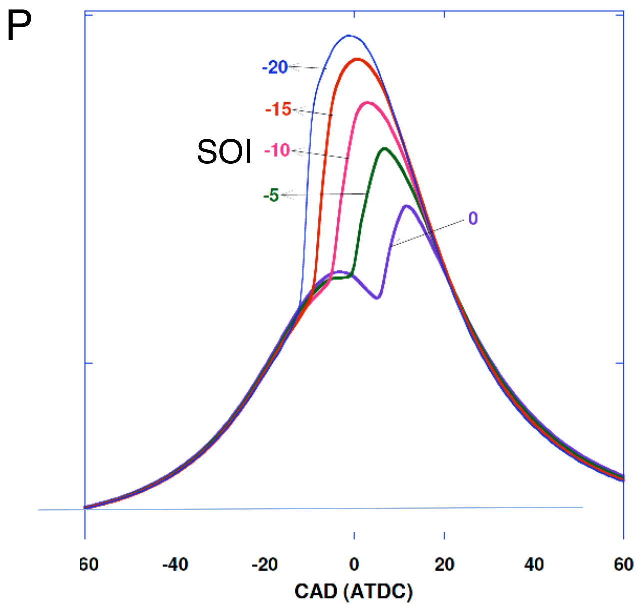


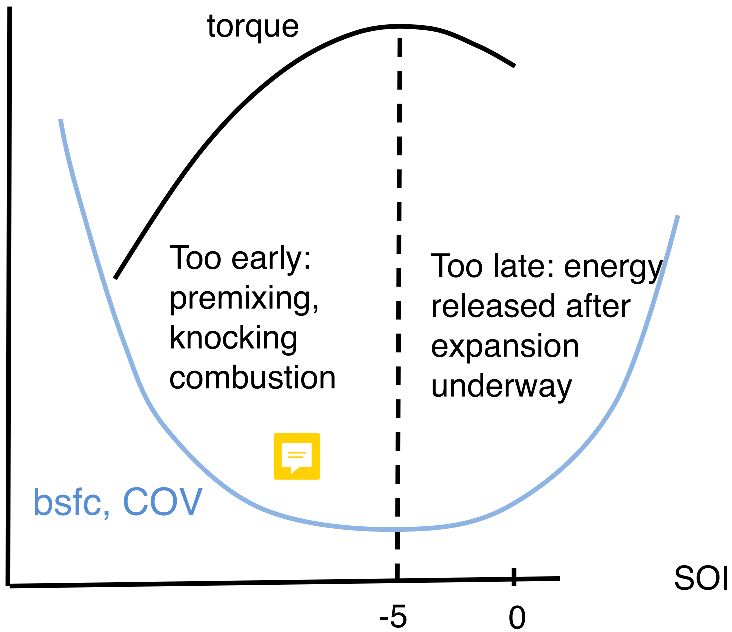
Early injection

SOI effects:

- Advancing injection provides more **premixing**, **lower emissions**, but typically a more pronounced heat release rate and pressure, leading to noise and vibration, unless the mixture is diluted with EGR.
- There are a number of **early injection, low temperature combustion (LTC)** concepts now deployed in commercial engines for control of NOx and PM, optimizing the balance between emissions, efficiency and noise and vibration.

Typical effect of start of injection (SOI) timing: normal CI

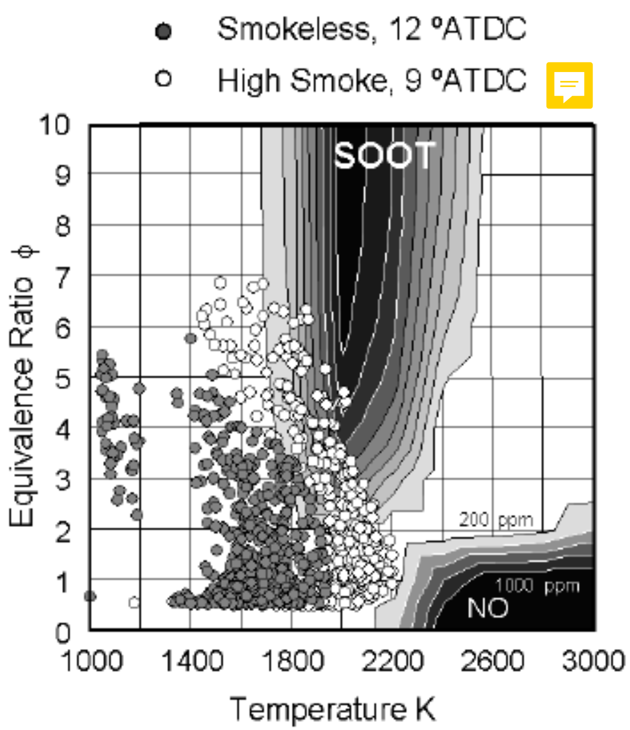


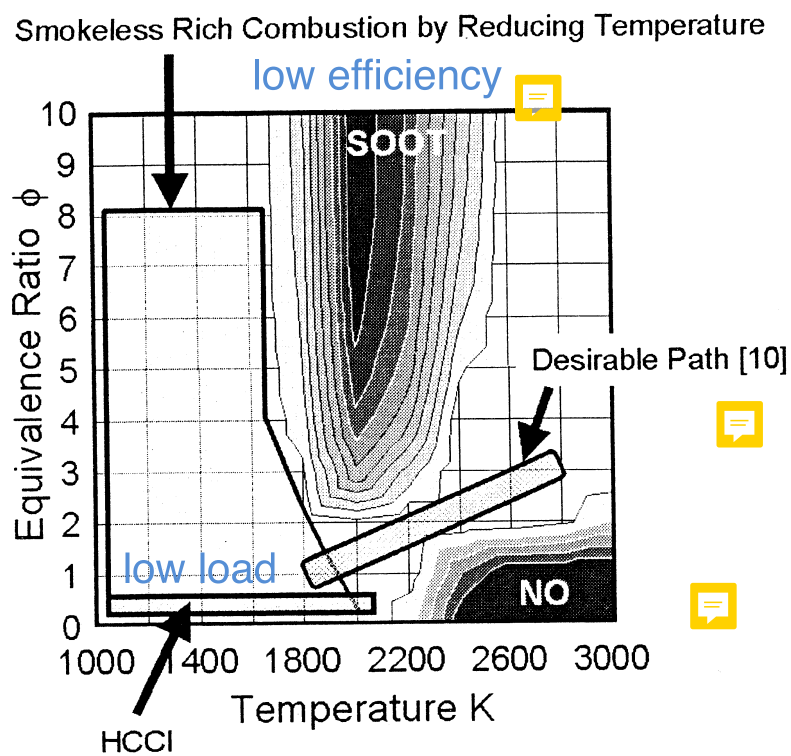


- For a given engine geometry and operating condition, there is an optimum SOI for maximum torque/ efficiency.
- This often must be traded off with emissions, as NOx is produced by the highest temperatures and efficiencies.
- Modeling heat release from CI engines is difficult, as it depends on the mixing rate. Semi-empirical rates are used for quick design purposes; CFD is increasingly used with careful calibration.

Simulated T-ϕ maps: controlling NOx and soot

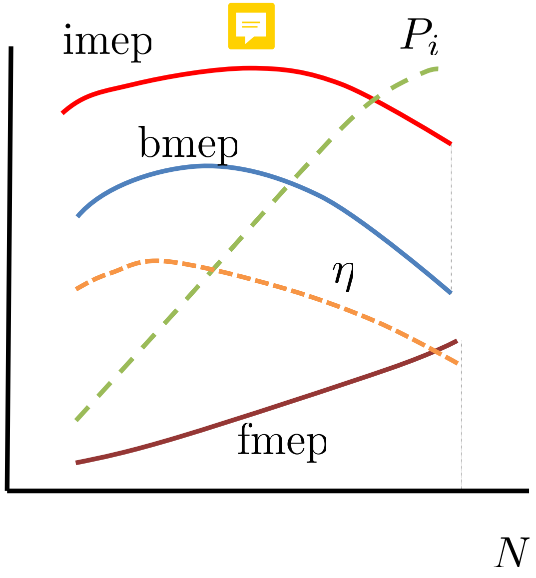
Non-premixed combustion produces high temperatures in the near stoichiometric regions produced in the mixing layer.
The high temperatures lead to **high NO formation** on the stoichiometric to oxidiser side, and high temperature pyrolysis of fuel, leading to and **soot formation** on the fuel side.





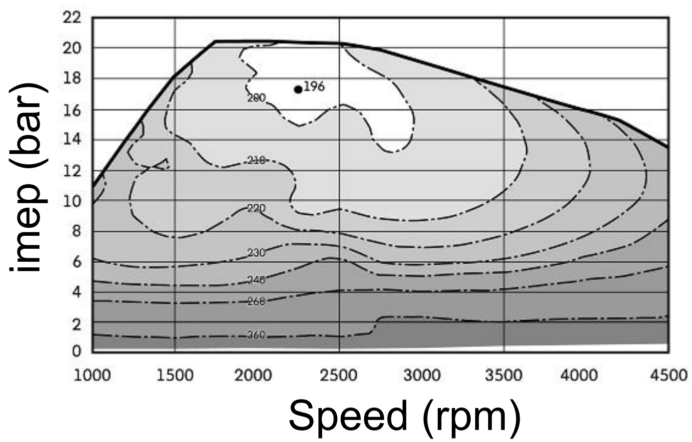
"Mechanism of the Smokeless Rich Diesel Combustion by Reducing Temperature"
SAE 2001 World Congress (2001-01-0655), K. Akihama, Y. Takatori, K. Inagaki, S. Sasaki, and A. M. Dean.

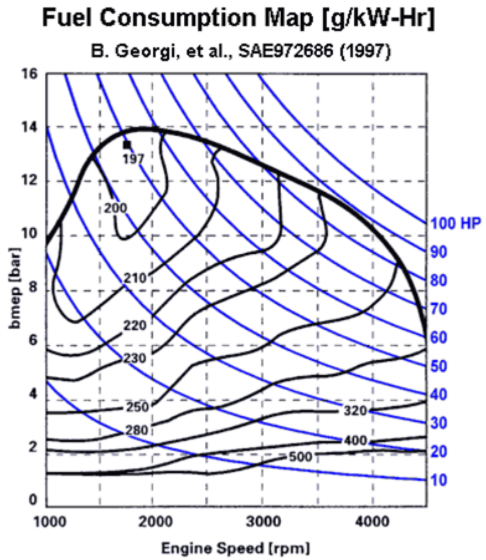
CI engine characteristics



higher imep/torque than SI engines for same displacement

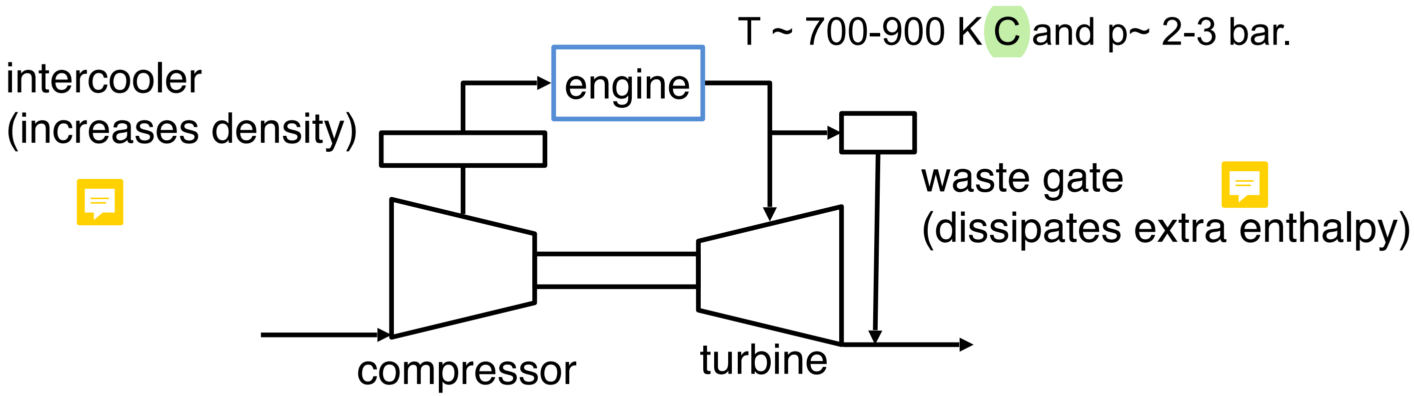
typically designed for high torque a low speed





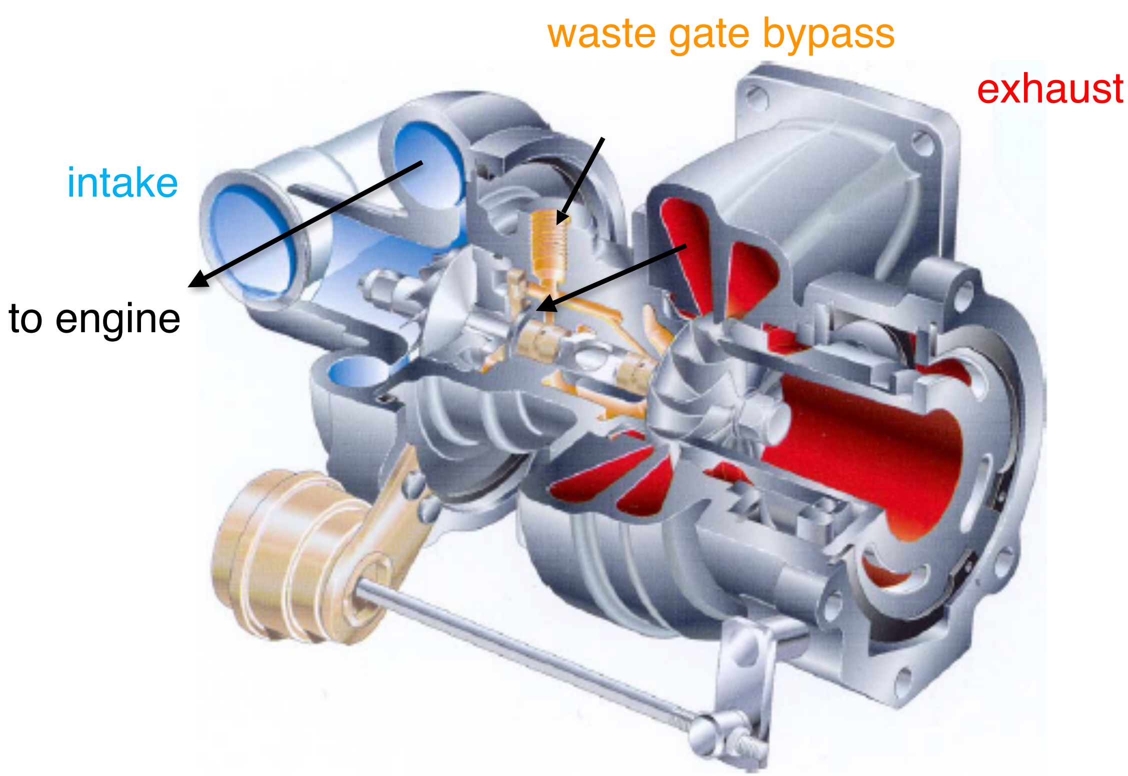
- CI engines can operate with a variety of fuels with little change, including natural gas, refinery oil, biofuels: used for generators, marine engines.
- Can be made from very small bore (80 mm) to very large bore (meter-size), and run with good torque at both high and low speeds.

Turbocharging



- Increases power in both CI and SI engines (higher density)
- Provides wider load range at low emissions for CI engines
- Must be matched to operating conditions: tricky balance of efficiency, weight and outlet temperature for aftertreatment

Turbocharger units



Typically single shaft: optimise speed
Turbo-lag (~ seconds) an issue at start up and transients

Variable geometry turbocharger:
allows more efficient operation over a wide range of flow rates

Dimensional analysis and performance maps: turbines and compressors

$$\dot{m}, \eta, \Delta T_0 = f(p_{0,in}, p_{0,out}, T_{0,in}, N, D, R, \gamma, \mu)$$

Dimensional analysis:

Fixed by geometry

Fixed by gas

$$\left(\frac{\dot{m}\sqrt{R T_{0,in}}}{p_{0,in} D^2}, \eta, \frac{\Delta T_0}{T_{0,in}} \right) = f\left(\frac{N D}{\sqrt{R T_{0,in}}}, \frac{p_{0,out}}{p_{0,in}}, \frac{\dot{m}}{\mu D}, \gamma \right)$$

mass flow rate

speed

Re

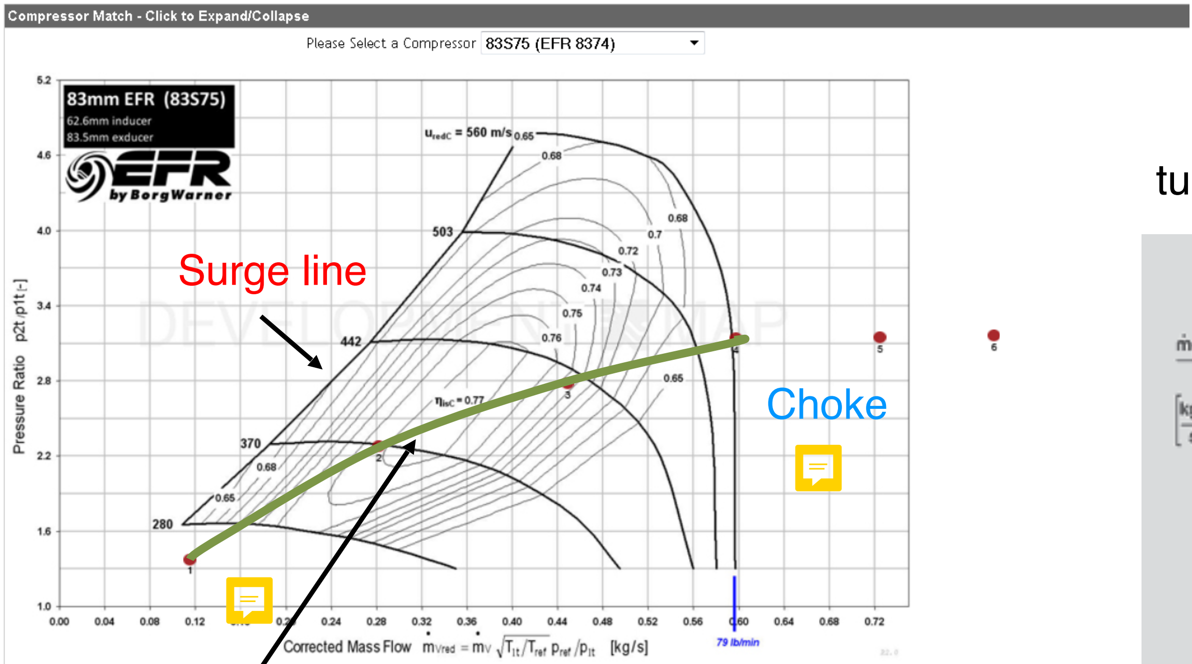
High Re: self-similar flows

$$\boxed{\left(\frac{\dot{m}\sqrt{R T_{0,in}}}{p_{0,in} D^2}, \eta, \frac{\Delta T_0}{T_{0,in}} \right) = f\left(\frac{N D}{\sqrt{R T_{0,in}}}, \frac{p_{0,out}}{p_{0,in}} \right)}$$

reduced mass flow rate (scaled by choking mass flow rate)

Turbocharger units and efficiency maps

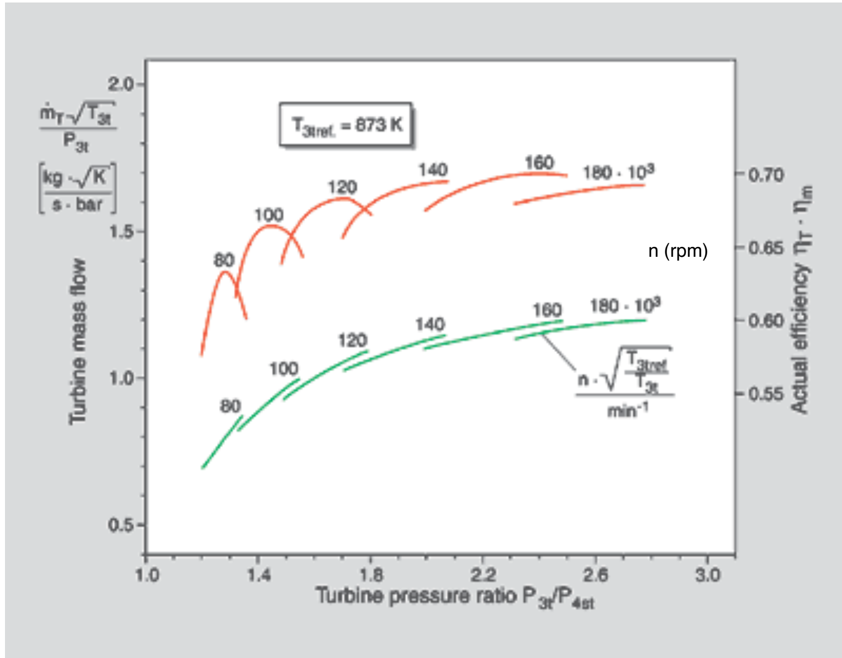
compressor



operating line

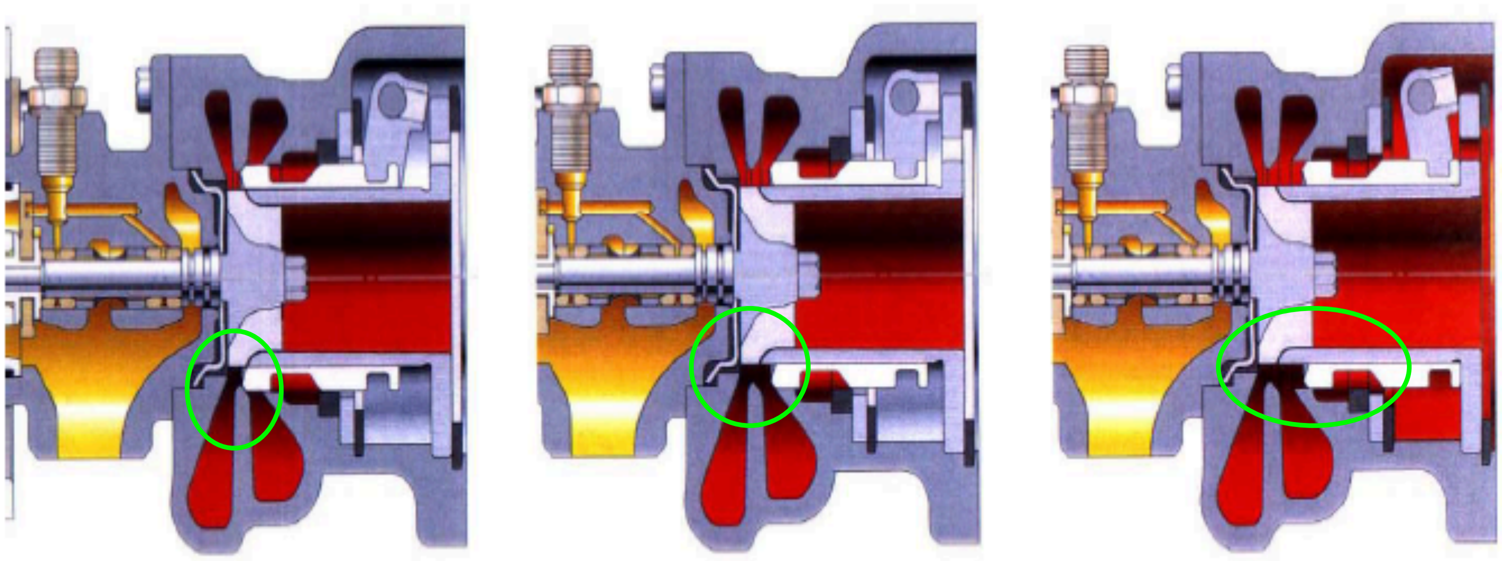
Pressure ratio: 2-4

turbine



Surge: instability when flow is too low to provide smooth flow over the blades
Choke: choked conditions at the outlet

Variable geometry exhaust turbocharger



first pass open | both passes open | both passes and bypass open

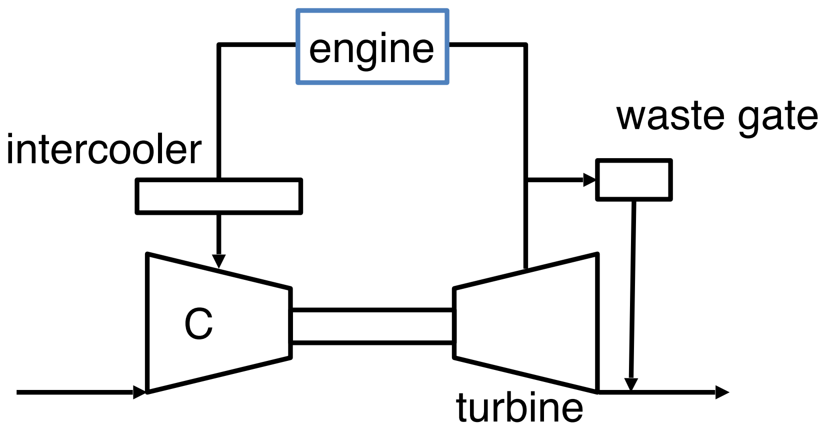
The variable inlet area arrangement maintains high velocity at high/
low flow rates for maximum efficiency over a range of flow rates

Turbocharger analysis: steady state

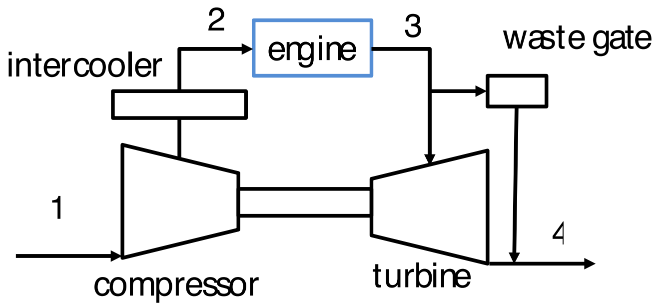
Steady flow energy equation: $$\dot{Q} - \dot{W} = \dot{m}\left[\left(h + \frac{v^2}{2} + gz\right)_{out} - \left(h + \frac{v^2}{2} + gz\right)_{in}\right]$$

Adiabatic: $$-\dot{W} = \dot{m}\left[h_{0,out} - h_{0,in}\right]$$

Stagnation conditions: $$T_0 = T + \frac{v^2}{2c_p} \qquad p_0 = p\left(\frac{T_0}{T}\right)^{\gamma/\gamma-1}$$



Turbocharger analysis: compressor



Compressor efficiency

$$\eta_{CTT} = \frac{h_{02s} - h_{01}}{h_{02} - h_{01}} = \frac{T_{02s} - T_{01}}{T_{02} - T_{01}}$$

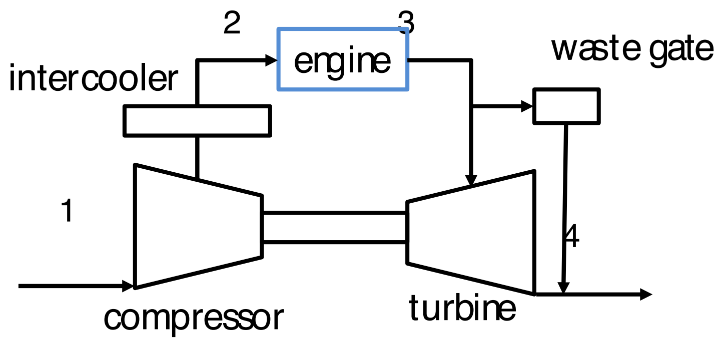
Final state

$$T_{02s} = T_{01}\left(\frac{p_{02}}{p_{01}}\right)^{(\gamma-1)/\gamma}$$

Compressor power (ex-mech. eff.)

$$-\dot{W}_C = \dot{m}_i\, c_{p,i}\left(T_{02} - T_{01}\right) = \frac{\dot{m}_i\, c_{p,i}\, T_{01}}{\eta_{CTT}}\left[\left(\frac{p_{02}}{p_{01}}\right)^{(\gamma-1)/\gamma} - 1\right]$$

Turbocharger analysis: turbine



Turbine efficiency

$$\eta_{TTT} = \frac{h_{03} - h_{04}}{h_{03} - h_{04s}} = \frac{T_{03} - T_{04}}{T_{03} - T_{04s}}$$

Final state

$$T_{04,s} = T_{03} \left(\frac{p_{04}}{p_{03}} \right)^{(\gamma-1)/\gamma}$$

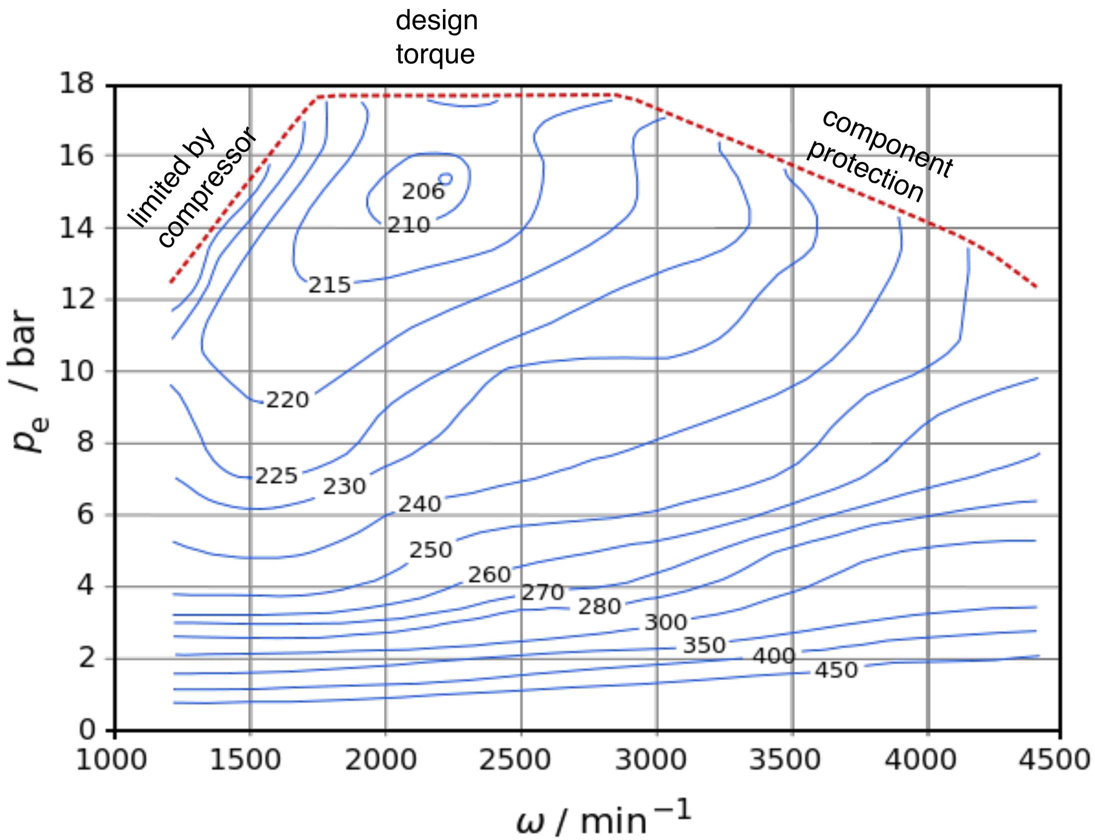
Turbine power (ex-mech. eff.)

$$\dot{W}_T = \dot{m}_e c_{p,e}(T_{03} - T_{04}) = \dot{m}_e c_{p,e} \eta_{TTT} T_{03} \left(1 - \left(\frac{p_{04}}{p_{03}} \right)^{(\gamma-1)/\gamma} \right)$$

Matching: $\dot{W}_c = \eta_m \dot{W}_T$

Any excess energy → wastegate

Overall CI engine map including turbocharging



bsfc (g/kWh) for a 3-cylinder diesel motor
with 1.5 l displacement (incl. turbo)

IC engines in numbers

	SI	**CI**
Compression ratio	6-11 (limited by onset of knock and NOx production)	12-24 (limited by noise and mechanical stresses)
Equivalence ratio φ	1.0 (to allow operation of 3-way catalytic converter)	0.3-0.7 (limited by smoke production)
Throttling	Yes (associated pumping losses)	Unthrottled (usually turbocharged)
Efficiency	Max. 35%	Max. 45%
Bore (mm)	50-450 (70-100 for light duty)	70-400 (70-100 for light duty)
Maximum speed (rpm)	4500-7500 (limited by heat transfer and stresses)	2100-5000 (lower end for high torque applications)
Maximum bmep (bar)	7-12	5-20
Weight/power ratio (kg/kW)	2-6	2.5-10
Power densities (kW/litre)	20-60	5-26

https://www.vle.cam.ac.uk/mod/quiz/view.php?id=11783192