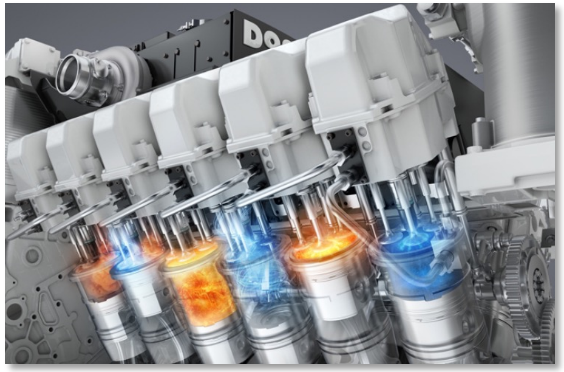
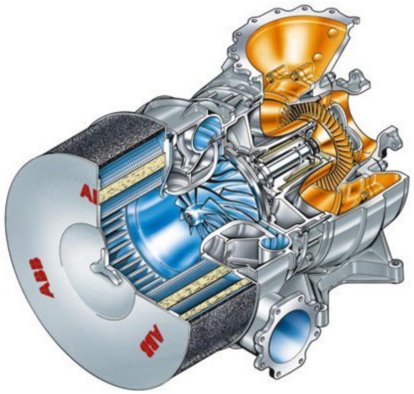
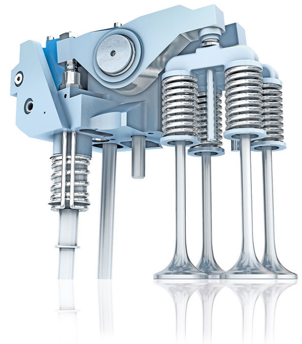
Internal Combustion Engines and Turbocharging

EPFL – 2021

J-F Tissot – Principal Expert Turbocharging & Engine Systems- ABB Turbo Systems



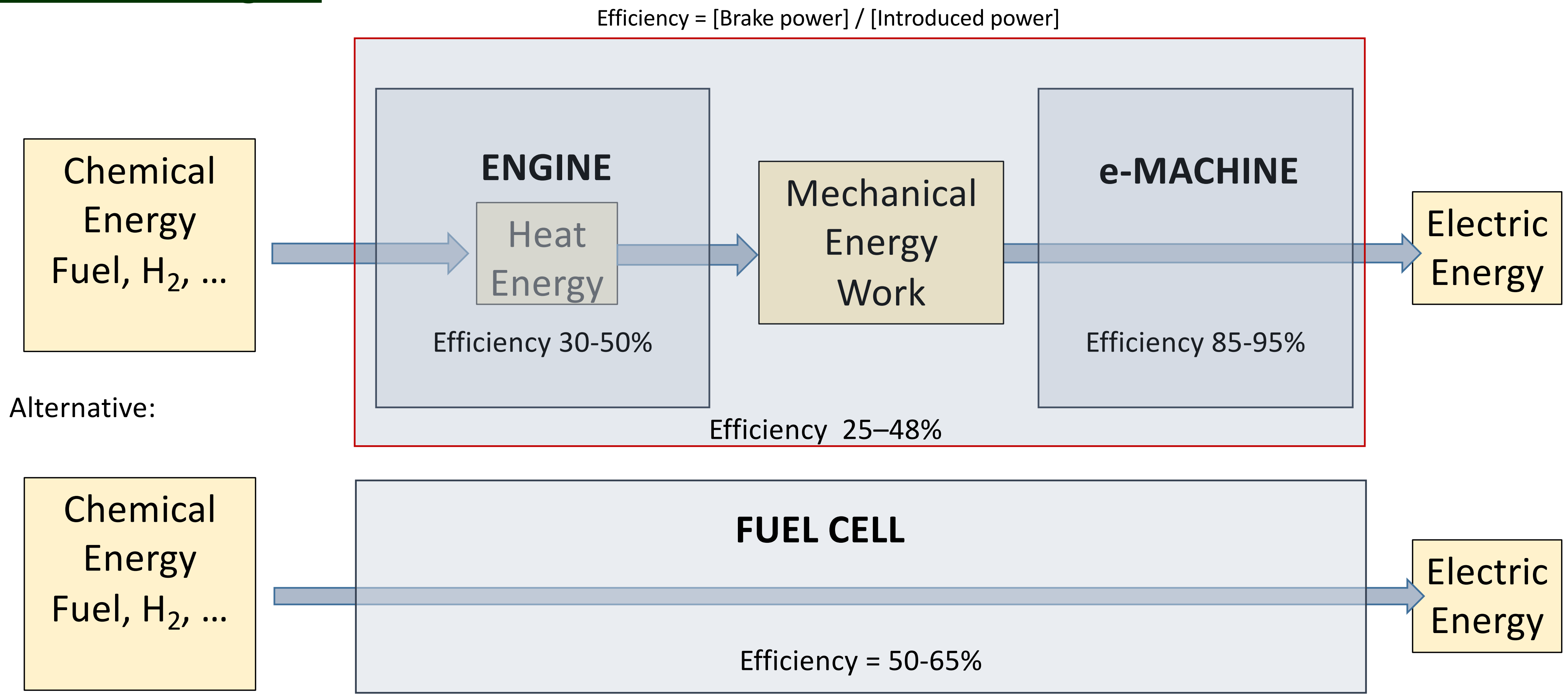




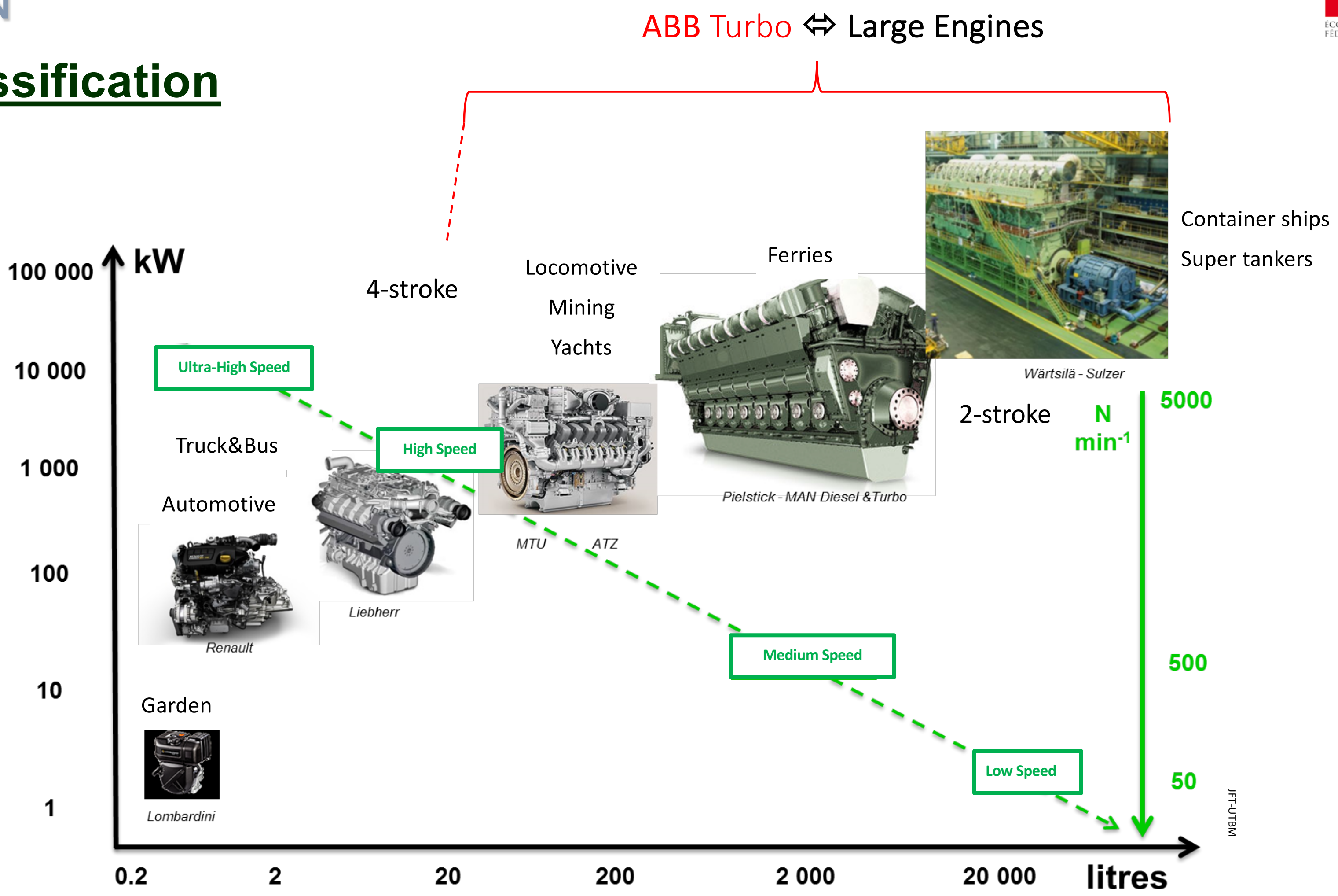
Content

Cover page illustrations (from left to right) : Liebherr; ABB Turbo; Peugeot; ABB Turbo

What is an Engine?

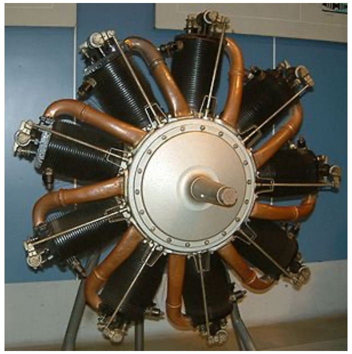


Engines Classification



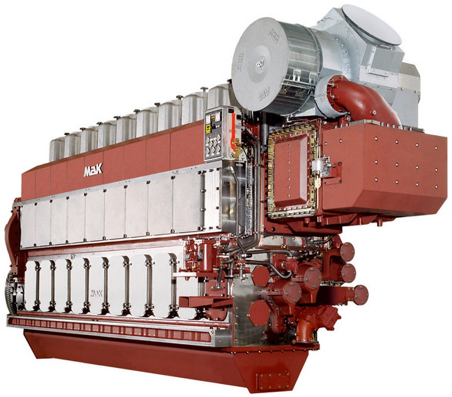
Engine Architectures

In-star



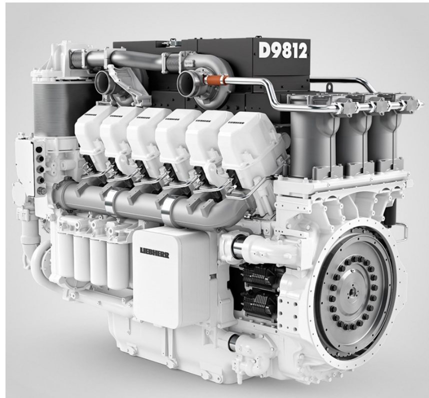
Wikipedia – Le Rhône

In-line



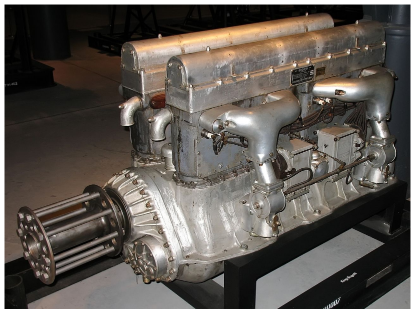
Zeppelin Power - MAK

V



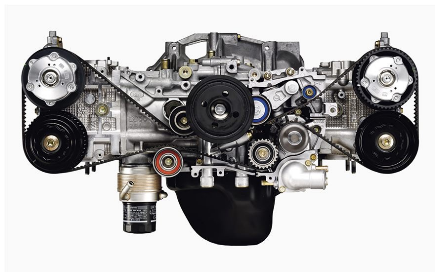
Liebherr

U



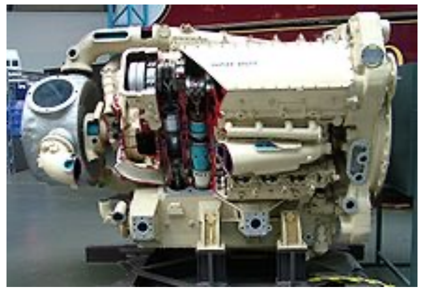
Wikipedia - Bugatti

Flat



Subaru

Delta



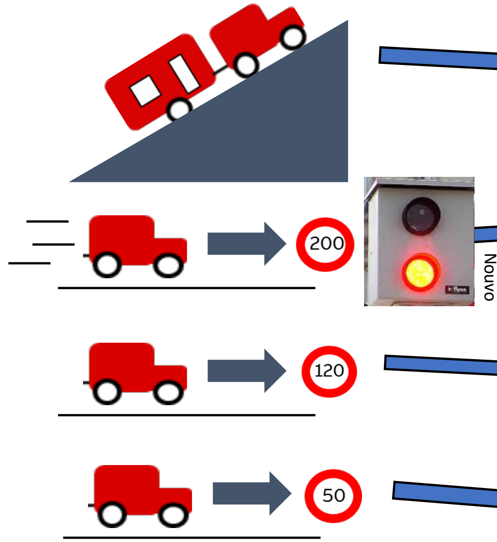
Wikipedia – Napier Deltic

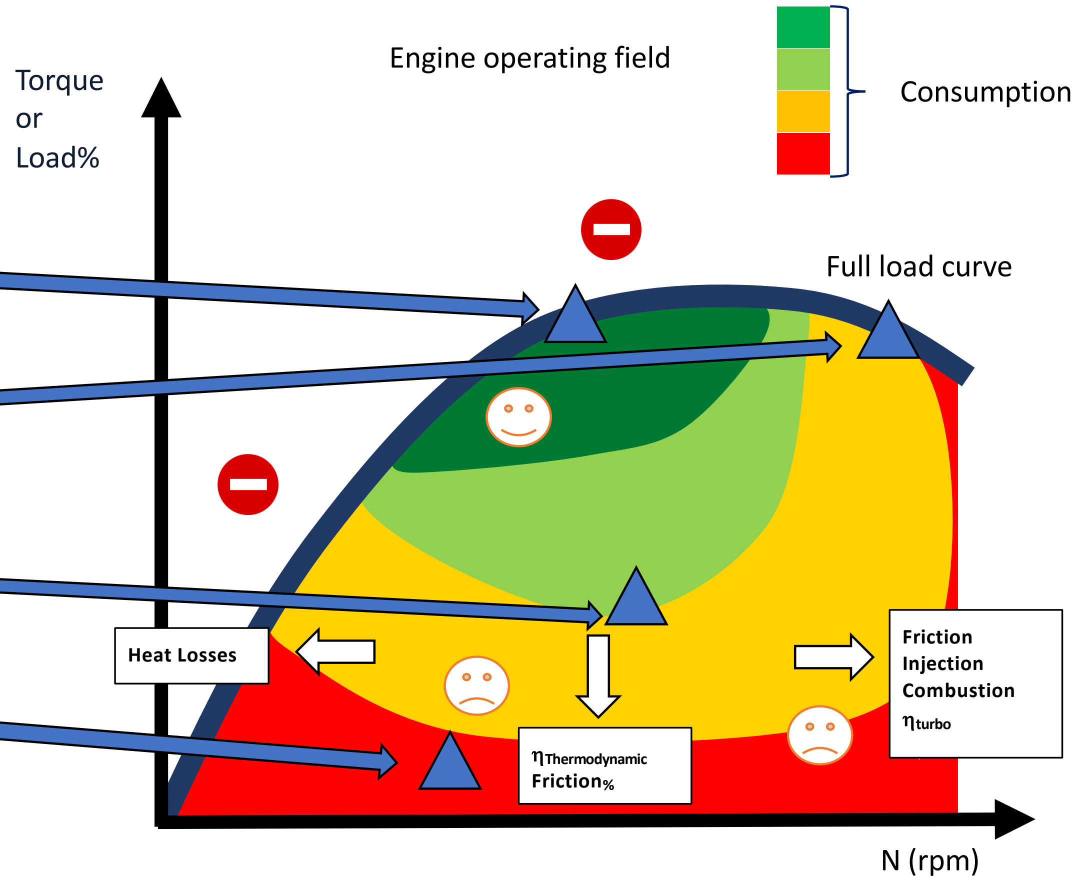
Principle and Cycles

Engine Operating Field

Wide – Variable Speed

Spark Ignition & Diesel



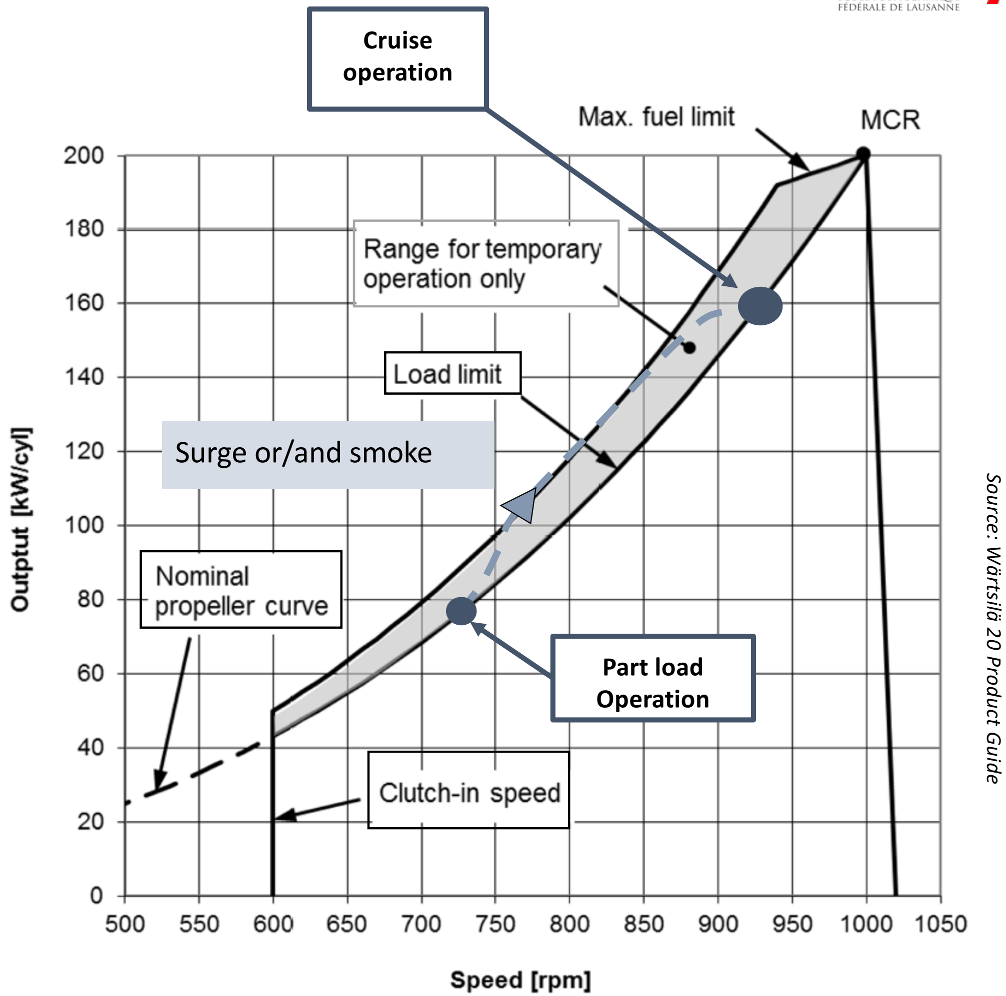


Principle and Cycles

Engine Operating Field

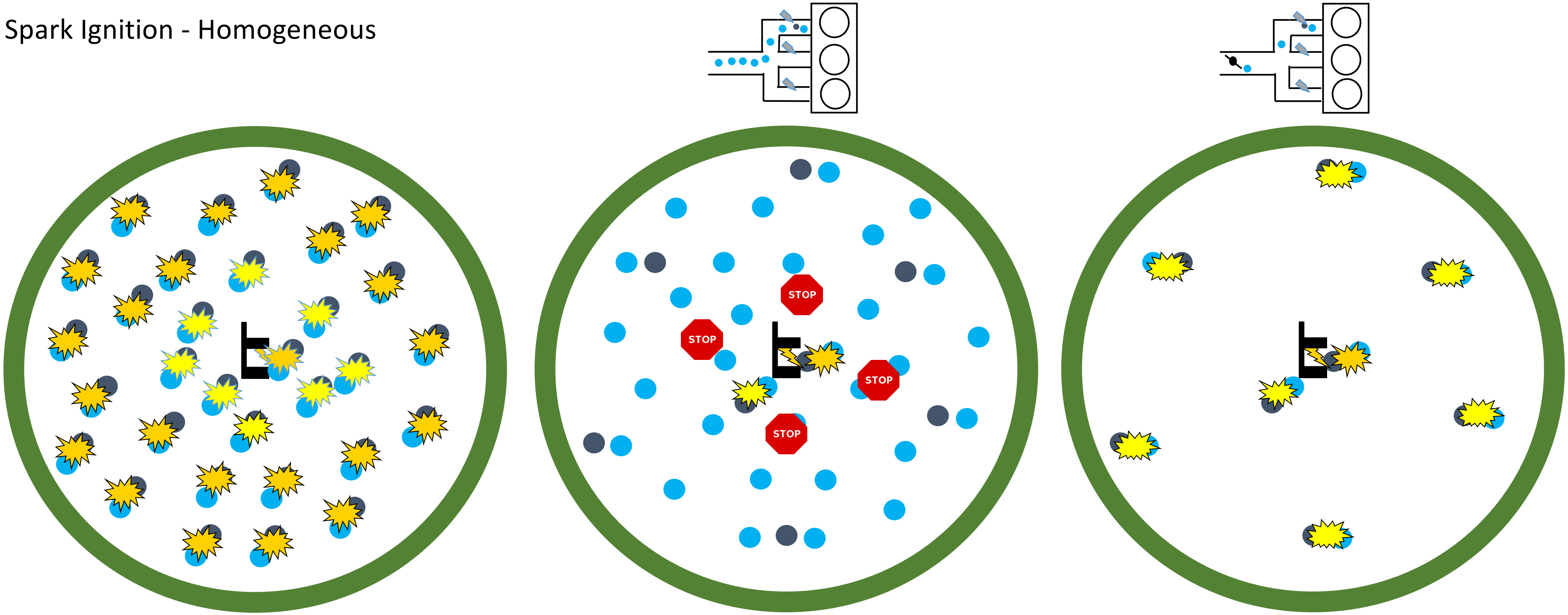
Fixed Pitch Propeller

Mainly Diesel



Combustion Process

Spark Ignition - Homogeneous



100% Load

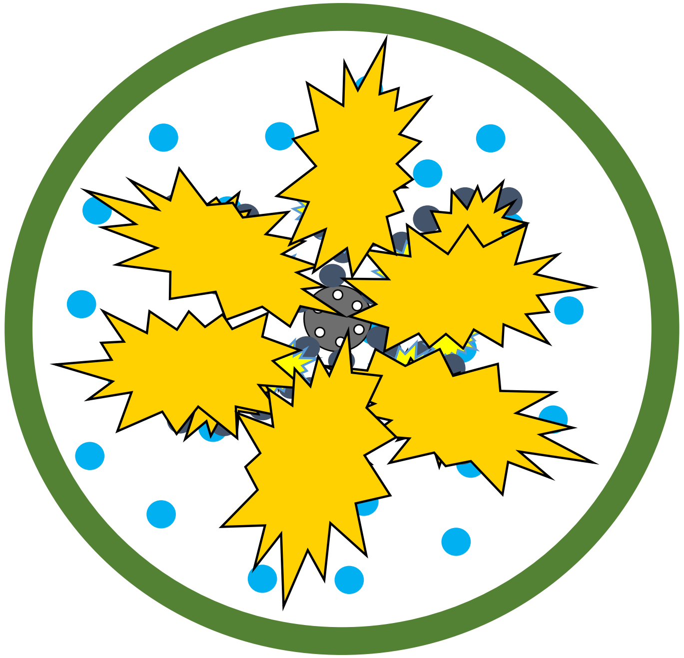
30% Load without air control

30% Load with air control

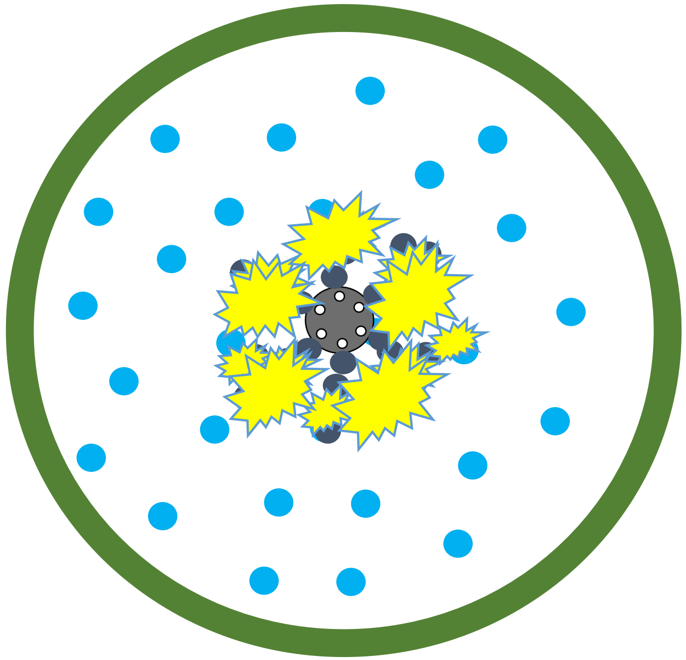
Combustion Process

Diesel - Heterogeneous

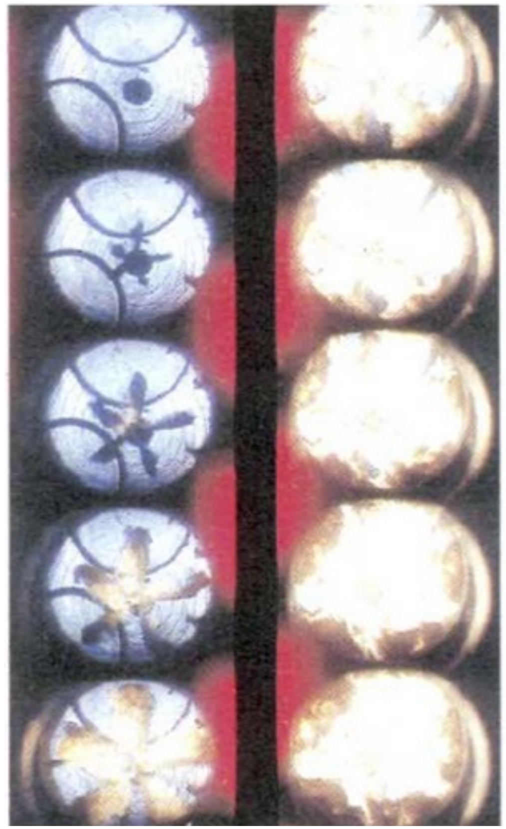
Source: MAHLE



100% Load



30% Load



Source: Combustion dans les moteurs Diesel - Alain HAUPAIS - Ed. Tech. De l'ingénieur B 2 700

Fuel Injection and Fuel-Air Mixture

Gas Spark Ignition – Homogeneous

Premix gas engine

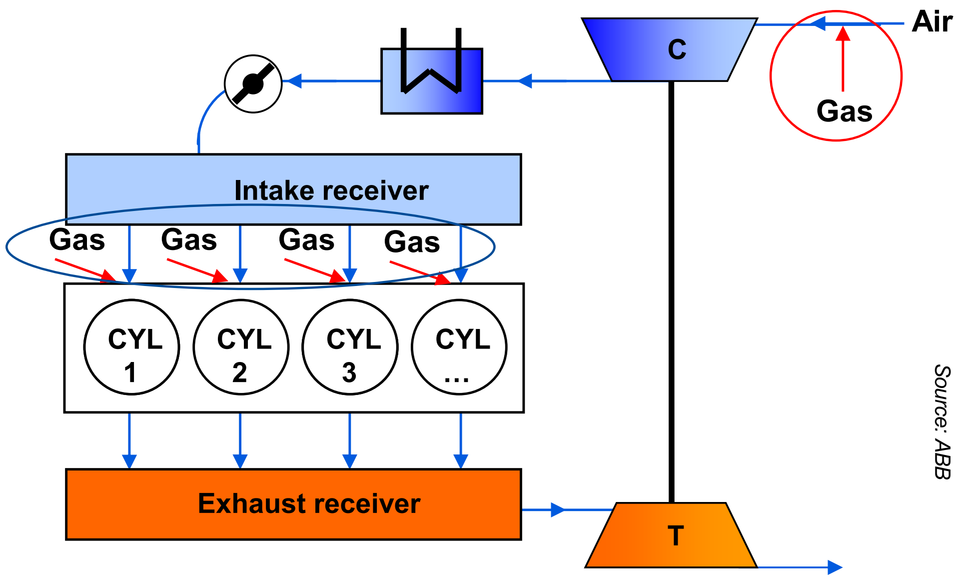
gas admission before compressor

=> common configuration for large high speed gas engines

Port injection engines

gas admission in the inlet channel of the cylinder head

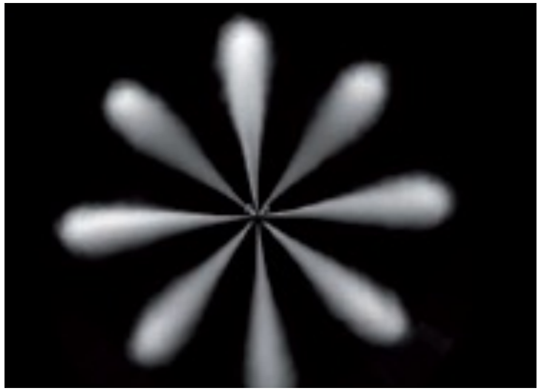
=> common configuration for medium speed gas engines



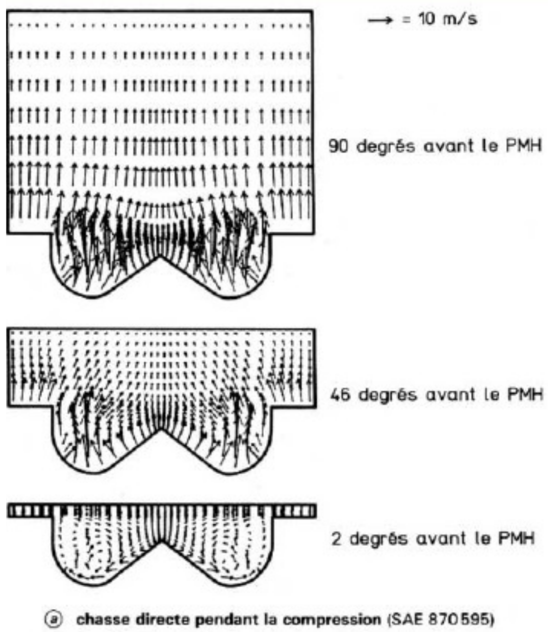
Fuel Injection and Fuel-Air Mixture

Diesel – Heterogeneous

Mixture is performed by air motion and injection pressure



Source: Liebherr Machine Bulle - CRS



Source: Combustion dans les moteurs Diesel - Alain HAUPAIS - Ed. Tech. De l'ingénieur B 2 700

Air Requirement

Spark ignition & Diesel

Stoichiometric chemical equation: $C_xH_y + (x+y/4)\,O_2 \rightarrow xCO_2 + (y/2)H_2O$

In **addition** to the stoichiometric Air/Fuel ratio, a physical correction is introduced : **lambda** ⇔ λ

$$\lambda = \frac{\left(\frac{Q_{mair}}{Q_{mfuel}}\right)_{real}}{\left(\frac{Q_{mair}}{Q_{mfuel}}\right)_{Stoichiometric}} = (Richness)^{-1}$$

14.5 to 14.7 for gasoline or Diesel fuel

⇒ Lambda is given as an input by the engine manufacturer for turbocharger(s) selection (requirement)

⇒ Lambda depends on:

=> injection, combustion capabilities of the engine

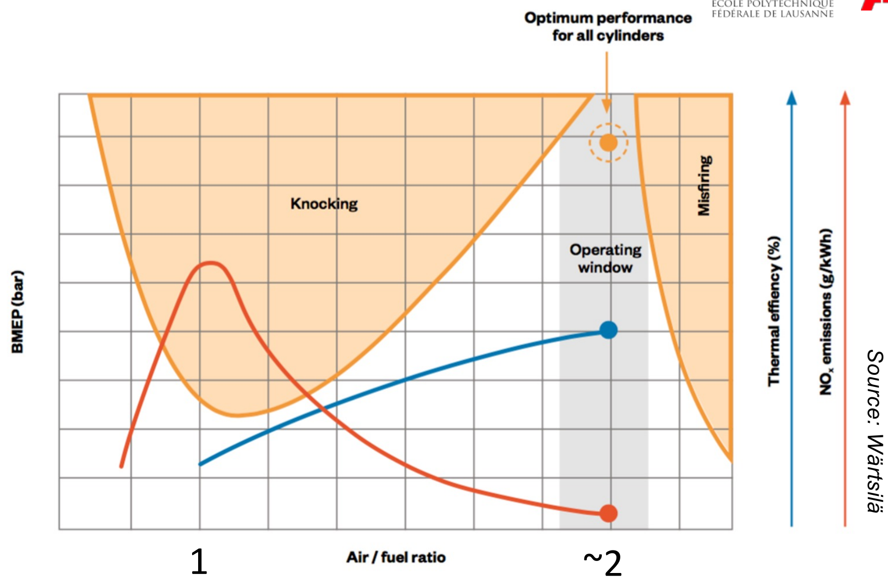
=> Internal component T°

Air Requirement

Why $\lambda >> 1$ on large engines, as it is ≤ 1 in automotive gasoline ?

Spark ignition gas ⇔ [knock ; NO_x; Efficiency] trade-off

The excess of air plays a role of thermal capacity



Diesel ⇔ Heterogeneous process and limited time for [injection + mixture + combustion] => **Lean mixture**

RailPictures.Net

https://www.flickr.com/photos/jsjgeology/23028995706

Lambda is OK (Diesel)

http://industrialscenery.blogspot.com/2016/03/smoking-diesel-locomotives.html

Lambda is too low (Diesel)

Whatever spark ignition or Diesel, an engine should never smoke !

Air Requirement

Spark ignition & Diesel

What does the engine need?

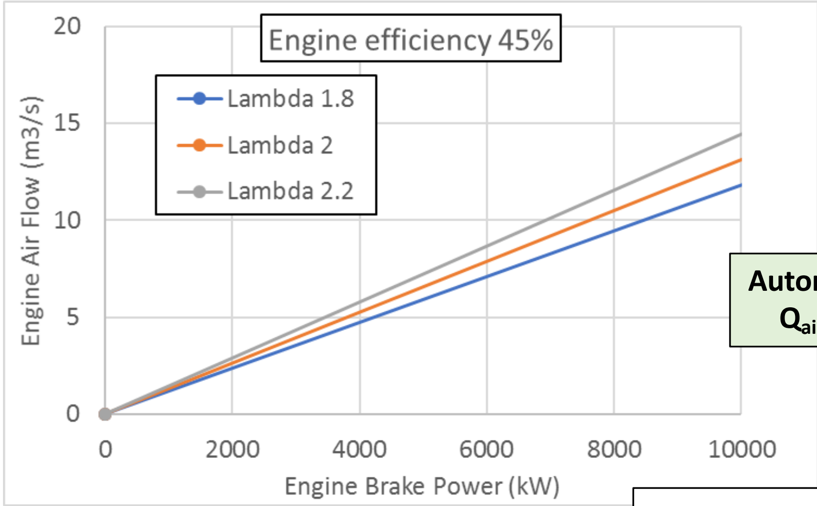
Engine Efficiency
Fuel LHV
(Lower Heating Value)

Stochiometric A/F ratio
Lambda

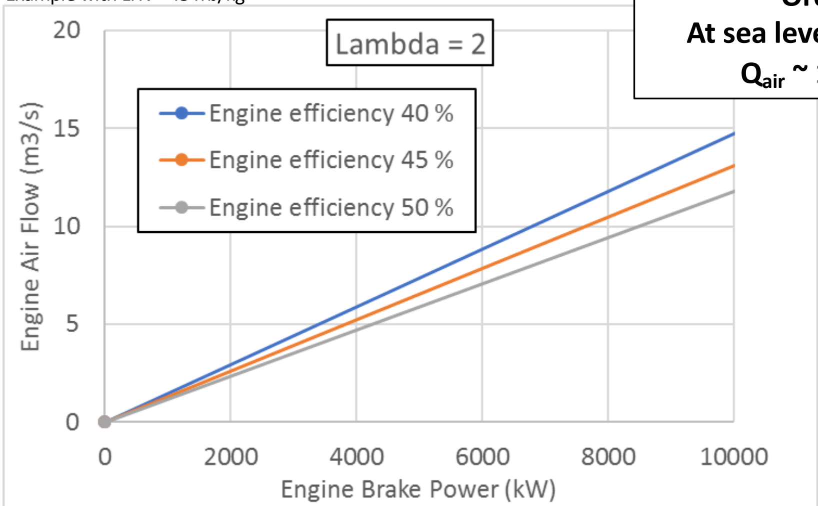
Required Brake Power → Required Fuel mass flow → Required Air mass flow

Efficiency = Brake power / Introduced power

$$\lambda = \frac{\left(\frac{Q_{mair}}{Q_{mfuel}}\right)_{real}}{\left(\frac{Q_{mair}}{Q_{mfuel}}\right)_{Stoichiometric}}$$



Example with LHV ~43 MJ/kg



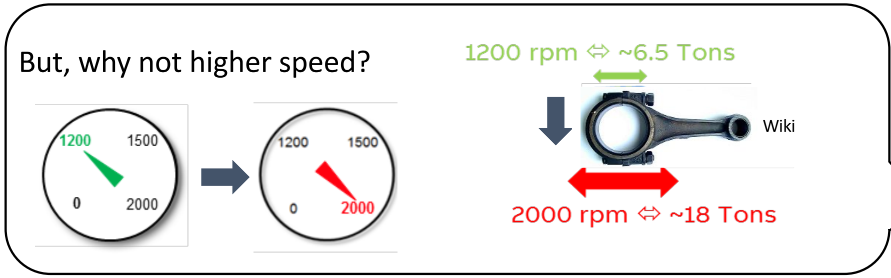
Automotive gasoline λ=1
Q_{air} ~ 1 g/s for 1 kW

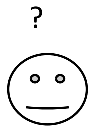
Order of magnitude:
At sea level, Diesel and gas «large»
Q_{air} ~ 1 to 2 m^3/s for 1 MW

Air Requirement

Spark Ignition & Diesel

How to breath this required air quantity ?



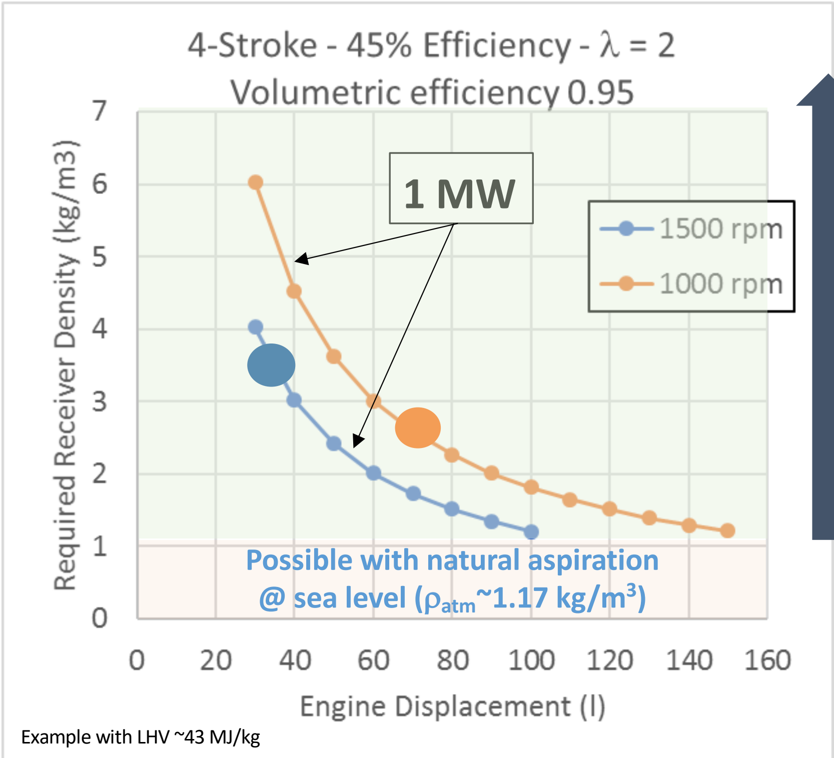


Engine Displacement
Engine speed
4-stroke or 2-stroke?
Volumetric efficiency

Required Air mass flow → Required Receiver Density

$$\text{Volumetric efficiency} = \frac{M_{air\ trapped\ per\ stroke}}{Displacement\ x\ \rho_{receiver}}$$

⇔ Breathing quality



Supercharging required

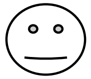
High Speed

Medium speed (small)

Current examples for 1MW

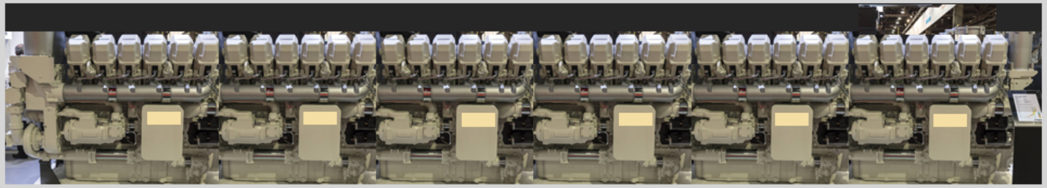
Air Requirement

To summarize: **No comment!**

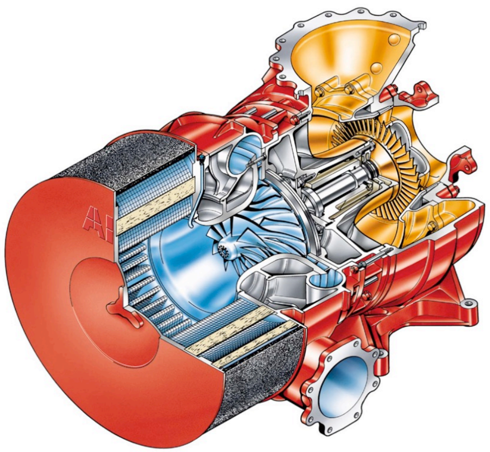


Diesel

Turbocharged versus Naturally Aspirated

3 MW Electrical High Speed Diesel 60Hz – 1800 rpm (example)	**Naturally Aspirated - Without Turbocharger(s) -**	**Turbocharged - With turbocharger(s) – Extreme case for 1-stage But still realistic**
Global Efficiency	30-35%	43%
Displacement	> 370 liters	60-65 liters
Mass	60T	10 T
N cylinders	72	12
Size		 *From: bauforum24.biz - Liebherr*

Turbocharging Principle

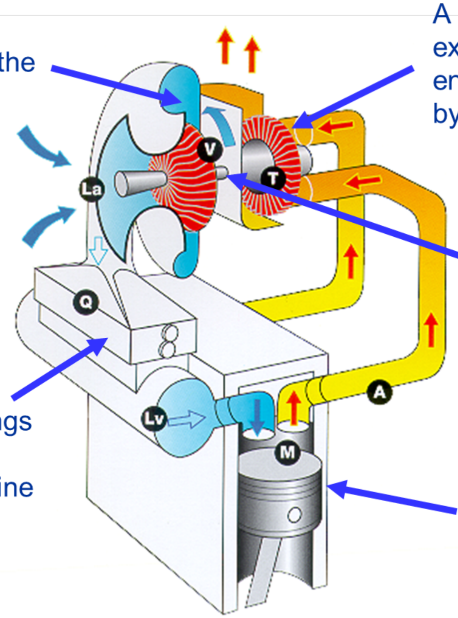


Source: ABB

Turbocharging basic Principle

The air is pressurized by the compressor

A part of the exhaust gas energy is treated by the turbine

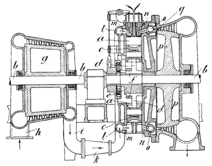


The turbine power is transmitted to the compressor through the rotating shaft

The air cooler brings the air to a high density to the engine by decreasing the temperature

The engine can work at a high power density without increase of the thermal load

Alfred Büchi 1905

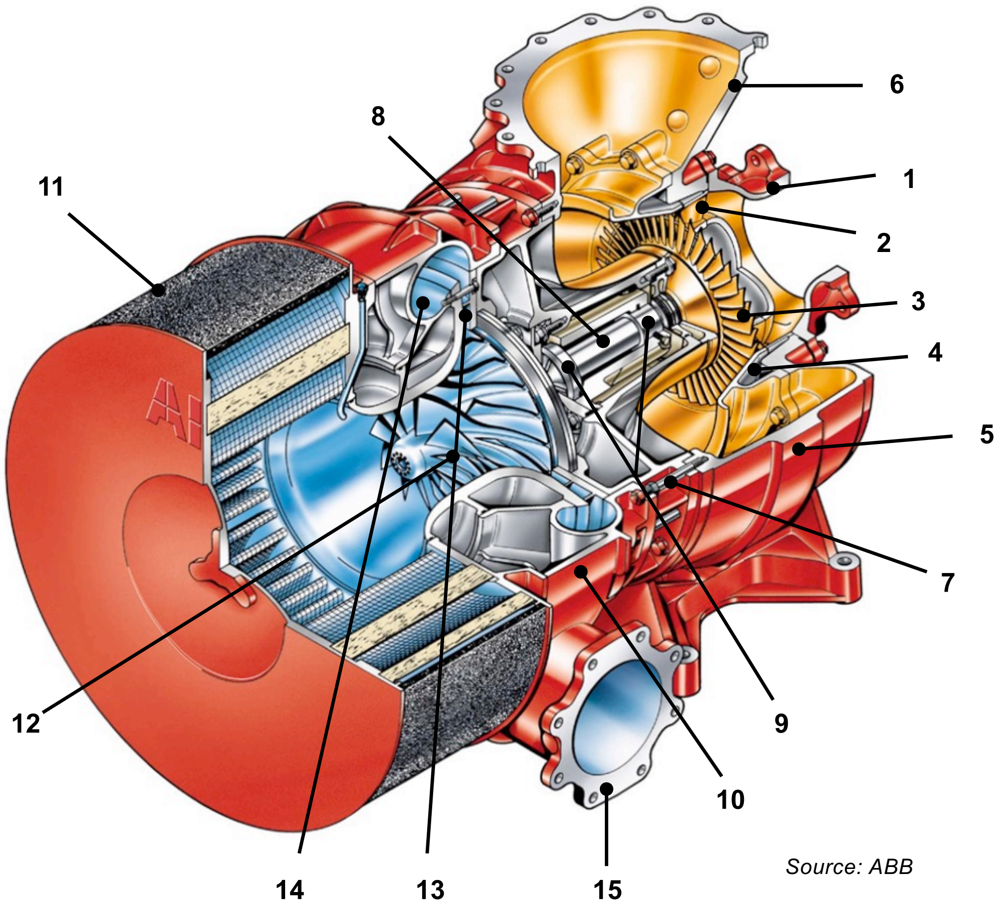


Exhaust gas energy is recovered to charge engine

Better engine efficiency & Higher engine power density

- 40% of introduced energy is originally wasted in exhaust
- Turbocharger recovers a fraction of this energy and sends it back to air compression in receiver

Turbocharger



Source: ABB

1. Gas inlet
2. Nozzle ring
3. Turbine wheel
4. Diffuser
5. Turbine casing
6. Gas outlet
7. Bearing housing
8. Shaft
9. Bearings
10. Compressor casing
11. Filter / Silencer (or air suction branch)
12. Compressor wheel
13. Compressor diffuser
14. Volute
15. Compressor outlet flange

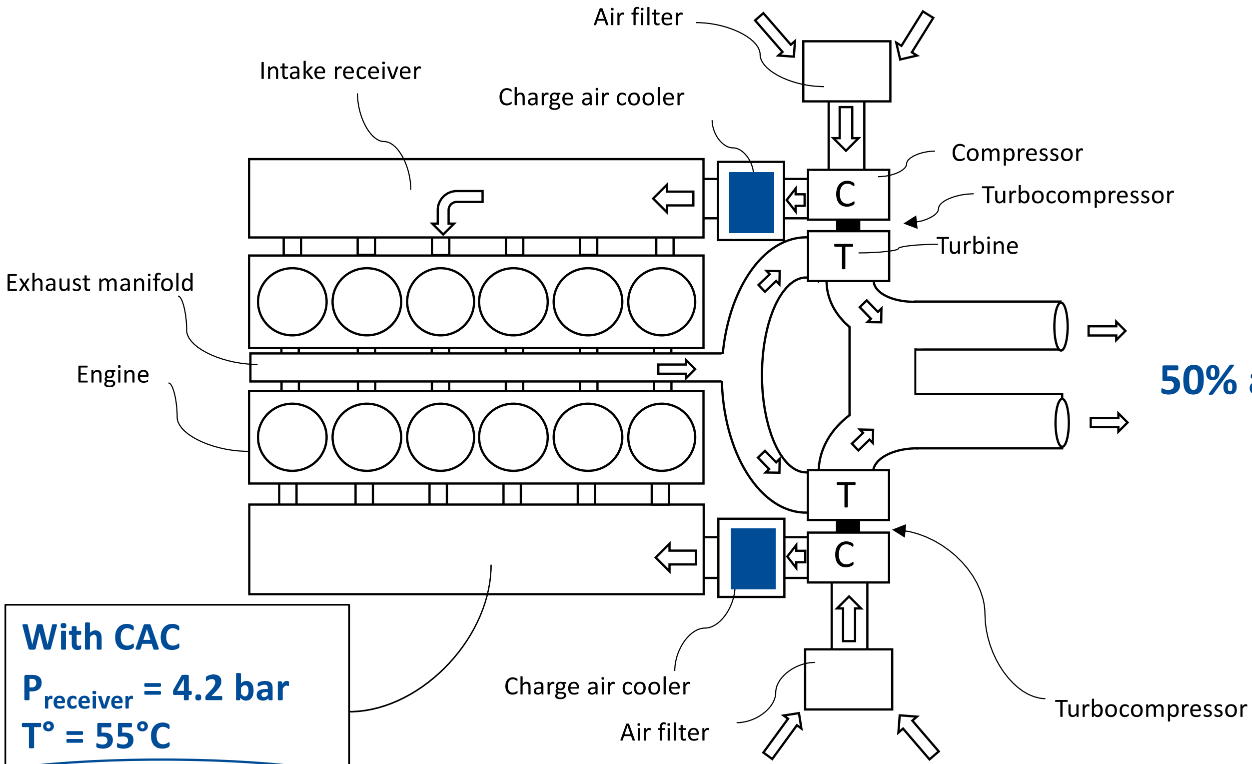
Charge Air Cooling (CAC)

With CAC

From Perfect Gas Law:

$$\rho = P/rT$$

kg.m^{-3} ← ρ; P → Pa; r → 288 J.K^{-1}.kg^{-1}; T → K



With CAC

$P_{receiver}$ = 4.2 bar

T° = 55°C

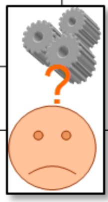
ρ = 4.4 kg/m^3

50% additional brake power

How do Engine and Turbocharger Match Together ?

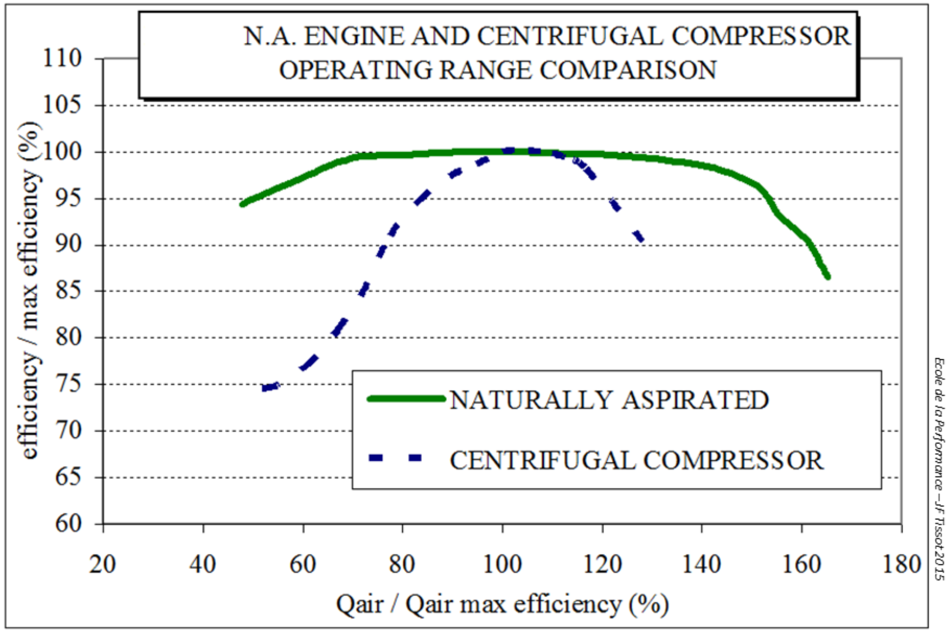
Reciprocating engine (Diesel and petrol) :

- Accepts important speed and air flow range
- High pressure ratio
- Low air flow rate



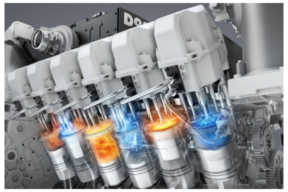
Turbocharger:

- Works generally on a focused operating point
- Low pressure ratio
- High air flow rate



Compressor…

…and Engine

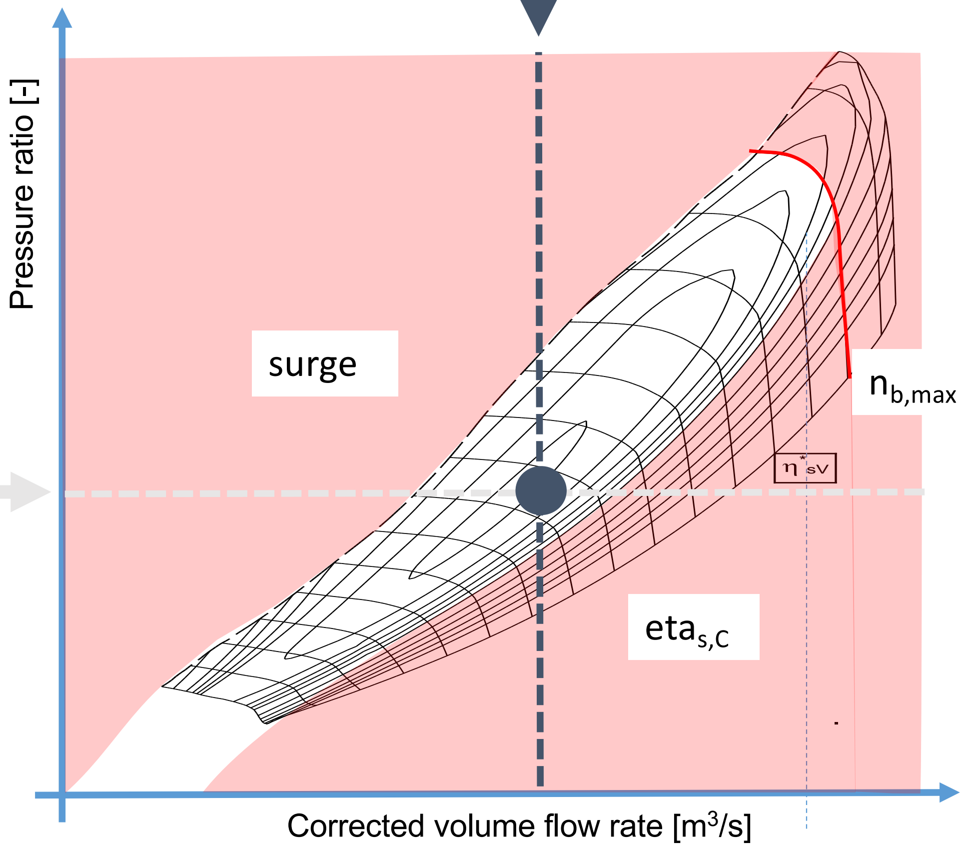


Liebherr

Required Brake Power → Required Fuel mass flow → Required Air mass flow

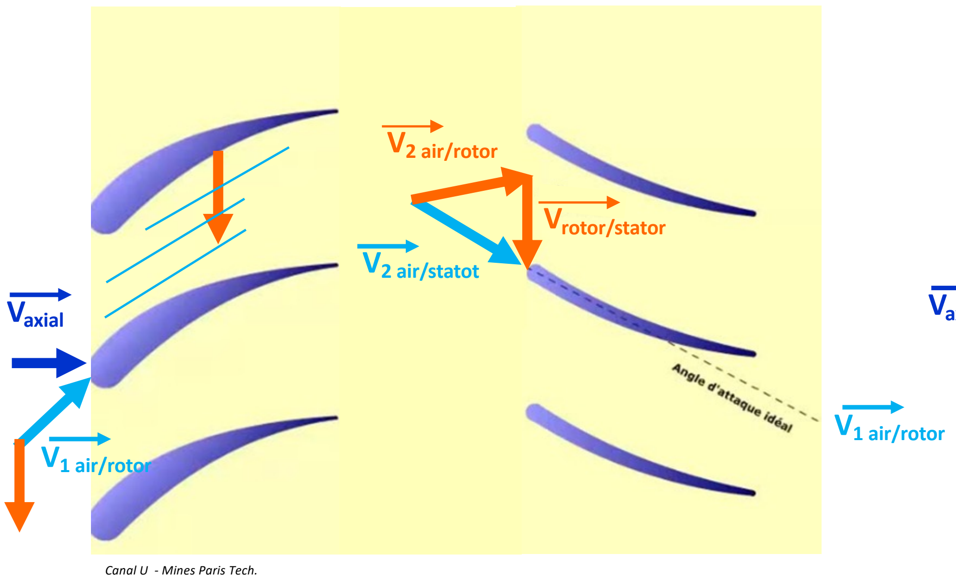
Required Air mass flow → Required Receiver Density → Required Pressure ratio π_c

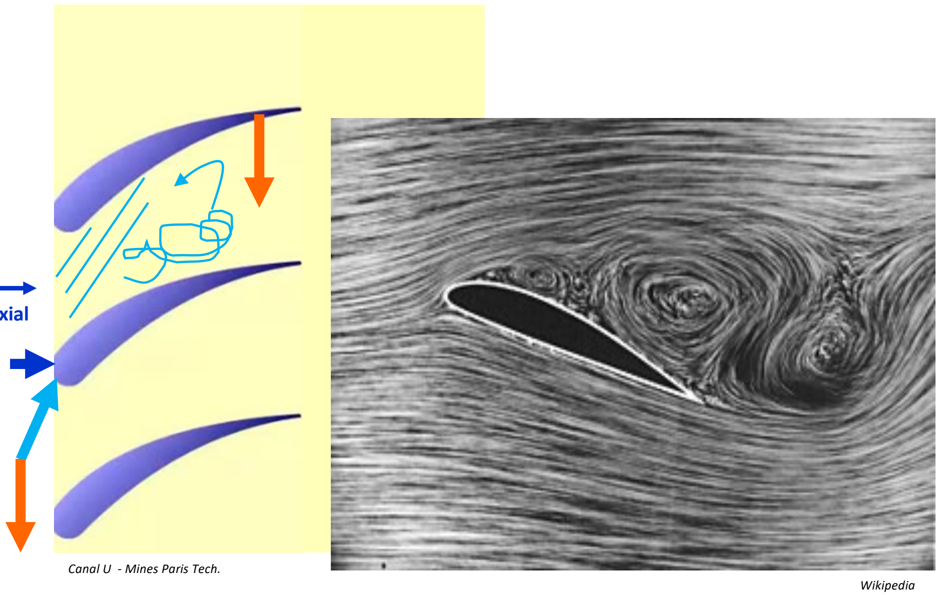
T° receiver
Pressure drops
$P = \rho.r.T…$



Compressor Surge

Low air volumic flow + high pressure ratio = mismatching => this is the starting point





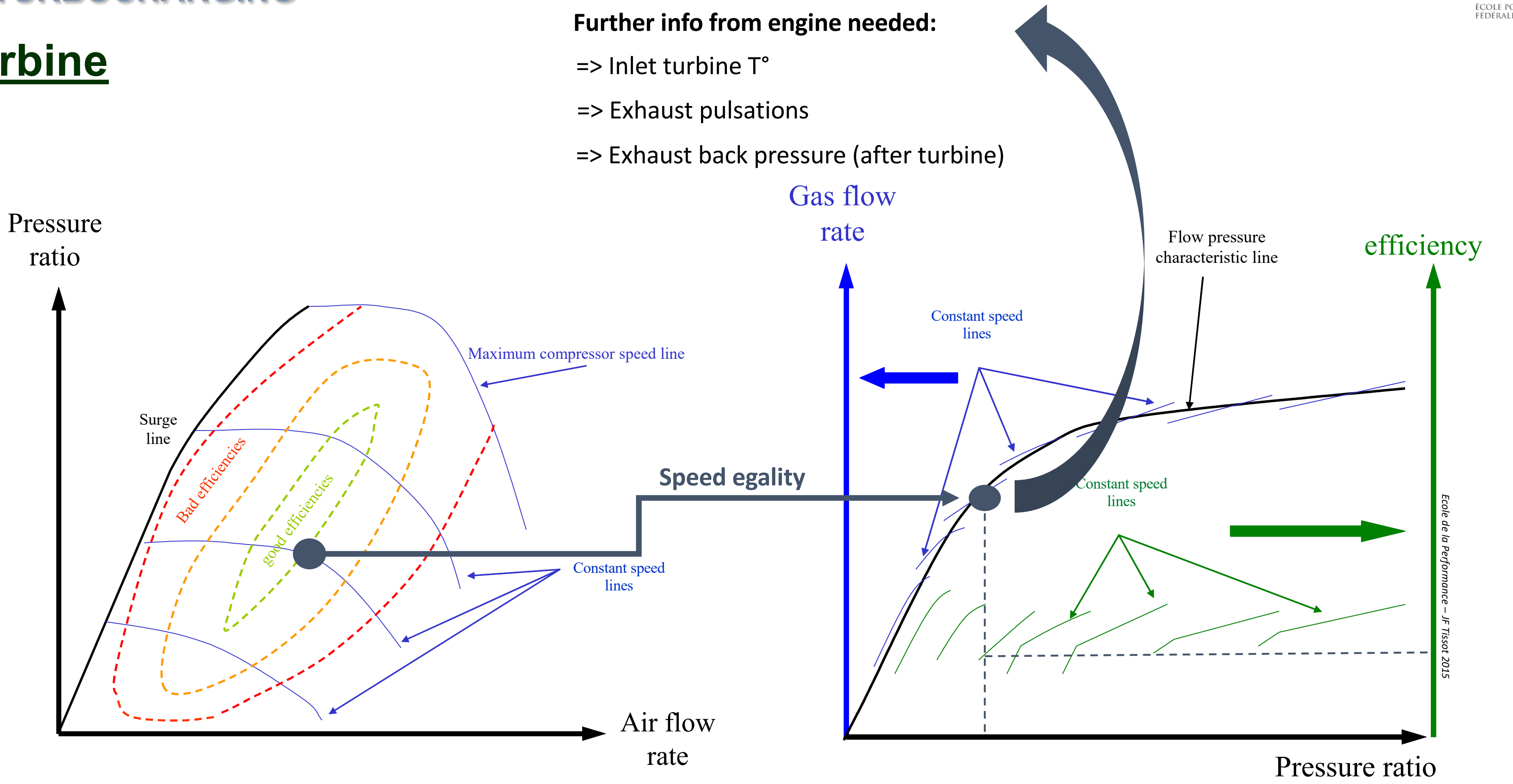
Turbine

Further info from engine needed:

=> Inlet turbine T°

=> Exhaust pulsations

=> Exhaust back pressure (after turbine)



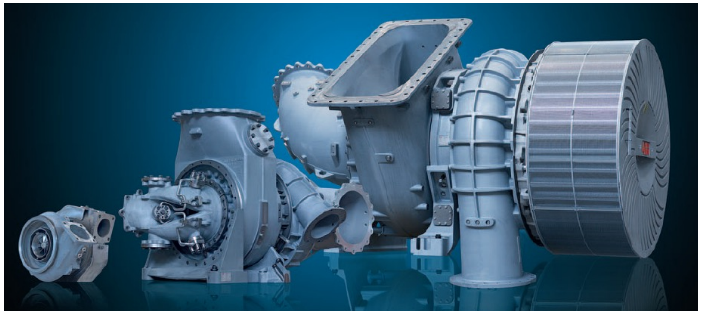
Turbocharger Size

How to select a TC Familly for a Large Engine?

1/ Engine power

2/ number of TC's per engine

3/ «family matching»



ABB

Order of magnitude:
At sea level, Diesel and gas «large»
Q_{air} ~ 1 to 2 m^3/s for 1 MW

500 kW

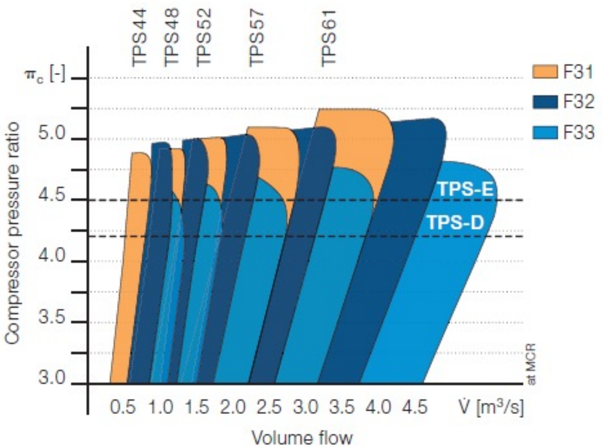
Krone

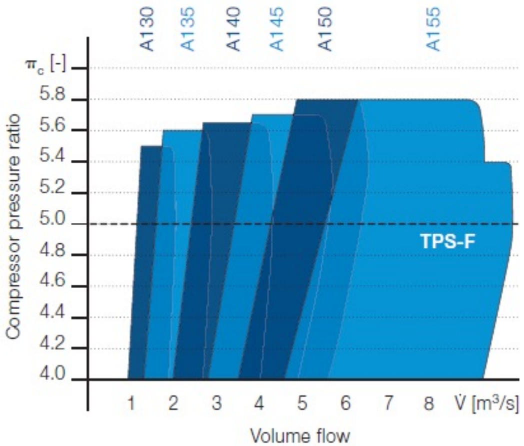
2 500 kW

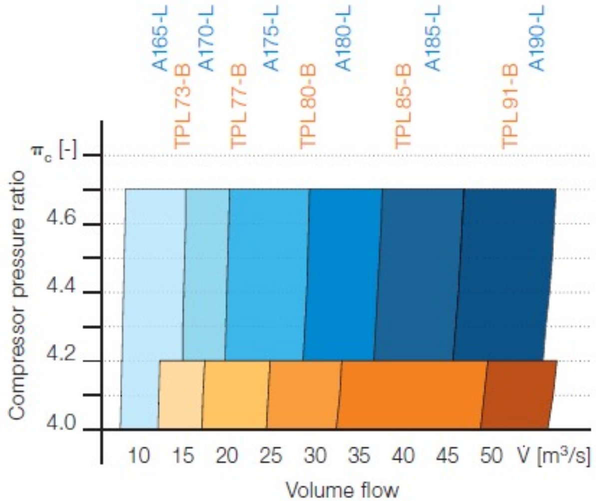
ABB

100 000 kW

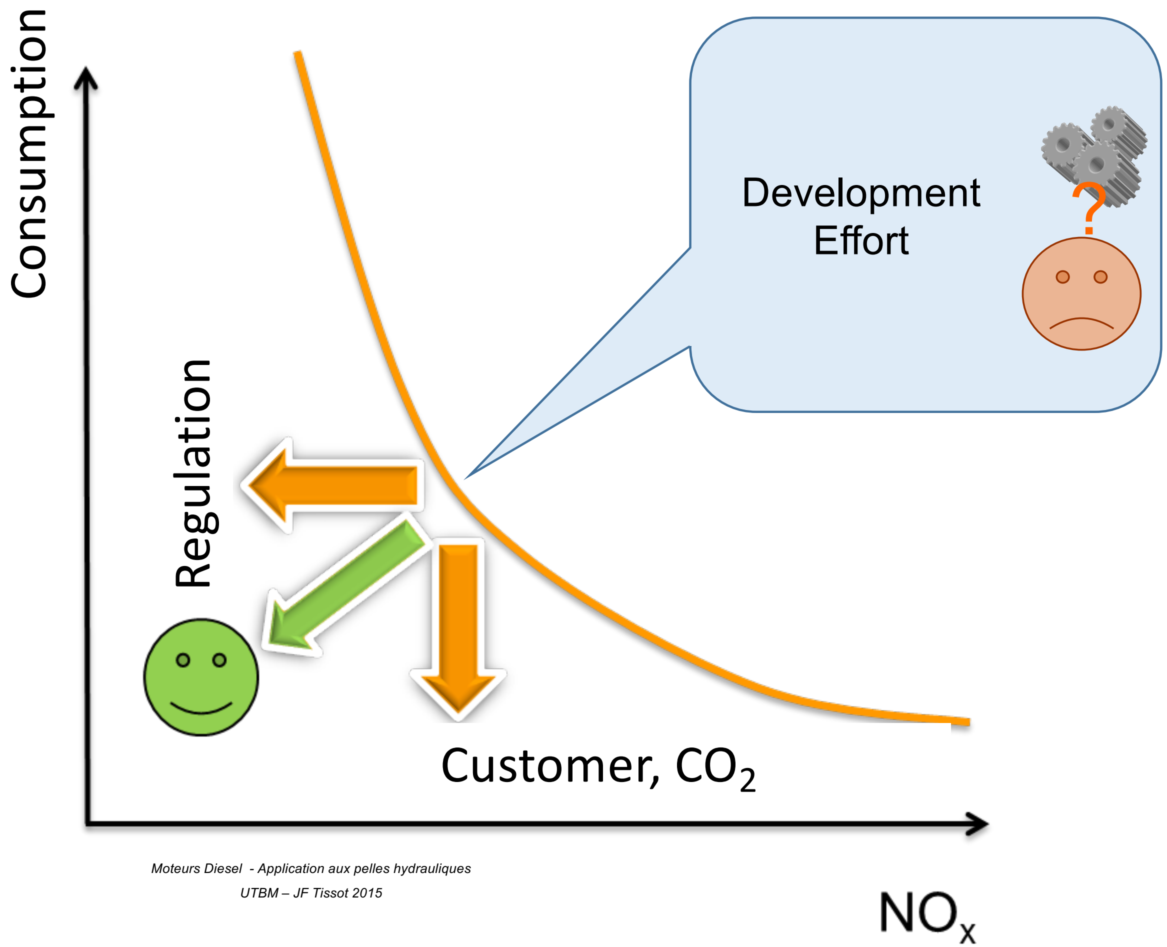
https://www.meretmarine.com







Consumption and Emissions



Moteurs Diesel - Application aux pelles hydrauliques
UTBM – JF Tissot 2015

$$\eta_{max} = 1 - \frac{T_{cold}}{T_{max}}$$

High maximal T°
=>
Thermodynamic Efficieny

+

Enough O_2
=>
Good combustion without smoke

=

High max T° + high O_2 rate
=> **NO_x**

Consumption and Emissions

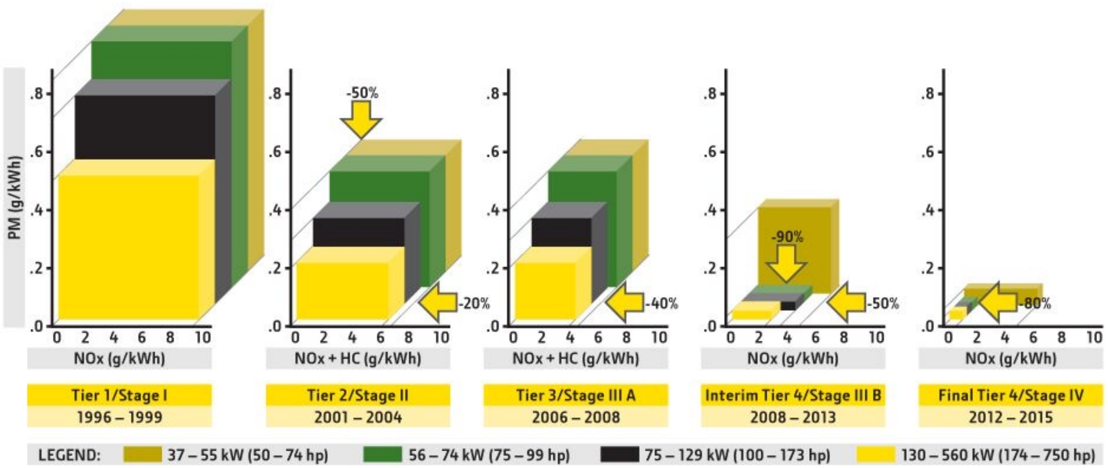
Emissions are reduced down to 0 through regulations

Tier 4 emission standards—Engines above 560 kW, g/kWh (g/bhp-hr)

Year	Category	CO	NMHC	NO_x	PM
2011	Generator sets > 900 kW	3.5 (2.6)	0.40 (0.30)	0.67 (0.50)	0.10 (0.075)
	All engines except gensets > 900 kW	3.5 (2.6)	0.40 (0.30)	3.5 (2.6)	0.10 (0.075)
2015	Generator sets	3.5 (2.6)	0.19 (0.14)	0.67 (0.50)	0.03 (0.022)
	All engines except gensets	3.5 (2.6)	0.19 (0.14)	3.5 (2.6)	0.04 (0.03)

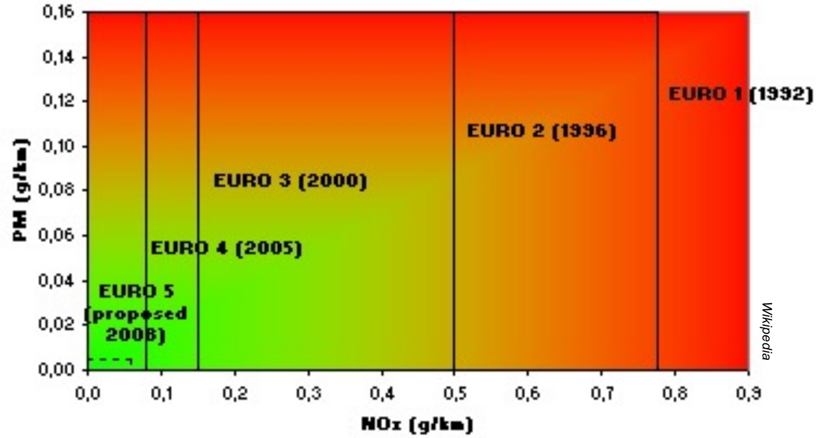
DieselNet

EPA and EU nonroad emissions regulations: 37 – 560 kW (50 – 750 hp)



John-Deere

NOx and PM emission standards for petrol cars

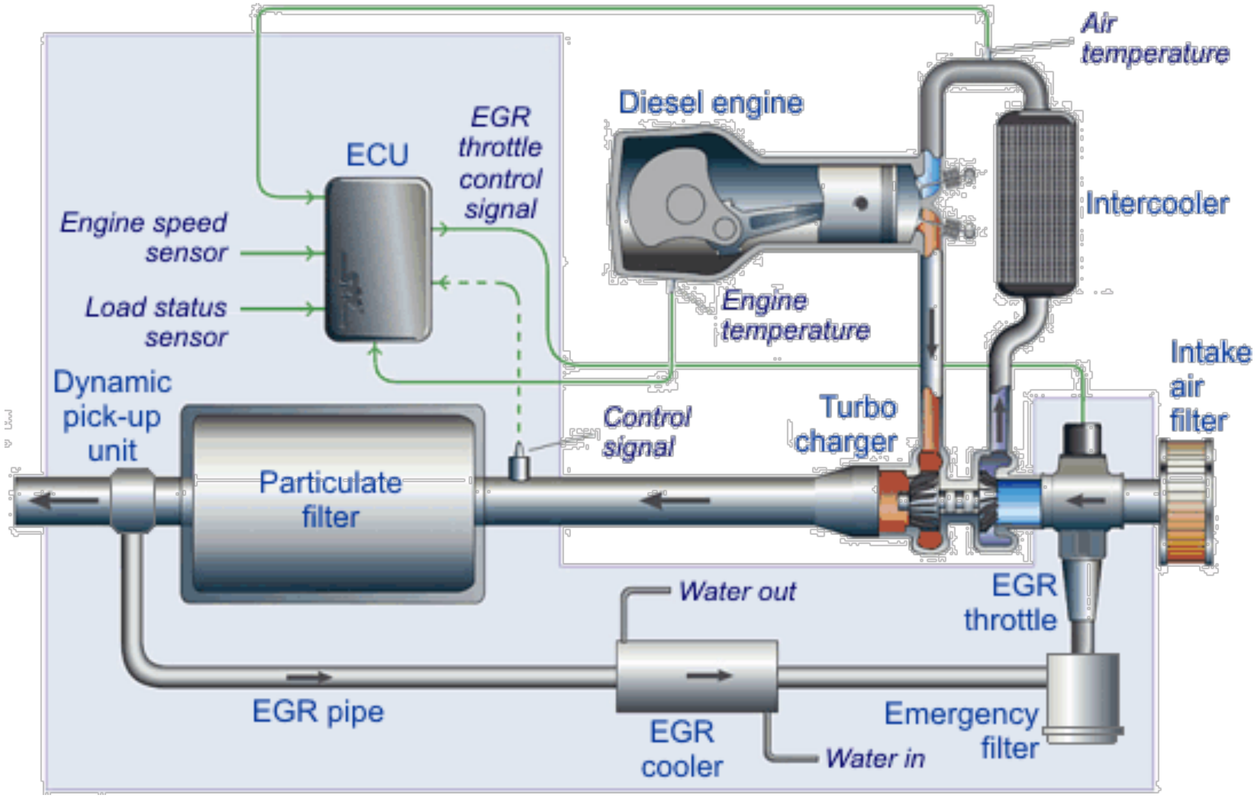


Wikipedia

Consumption and Emissions

Raw emissions reduction

Example of considered measure for automotive and large engines : Low Pressure EGR

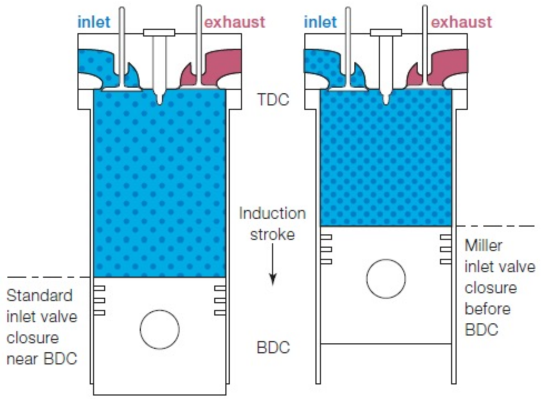


DieselNet

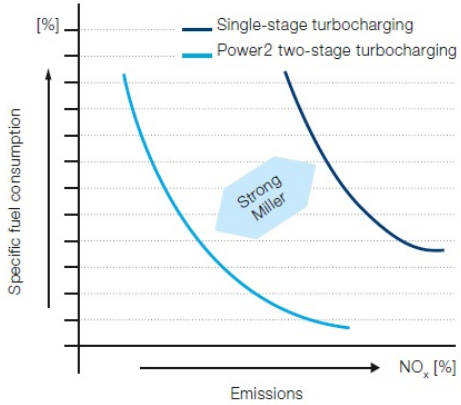
Consumption and Emissions

Raw emissions reduction

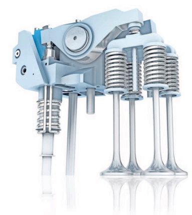
Example of considered measure for large engines : Miller Timing + Variable valve timing + 2-Stage Turbocharging

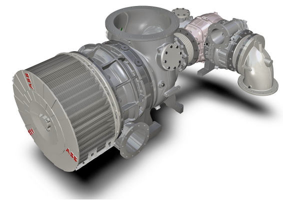


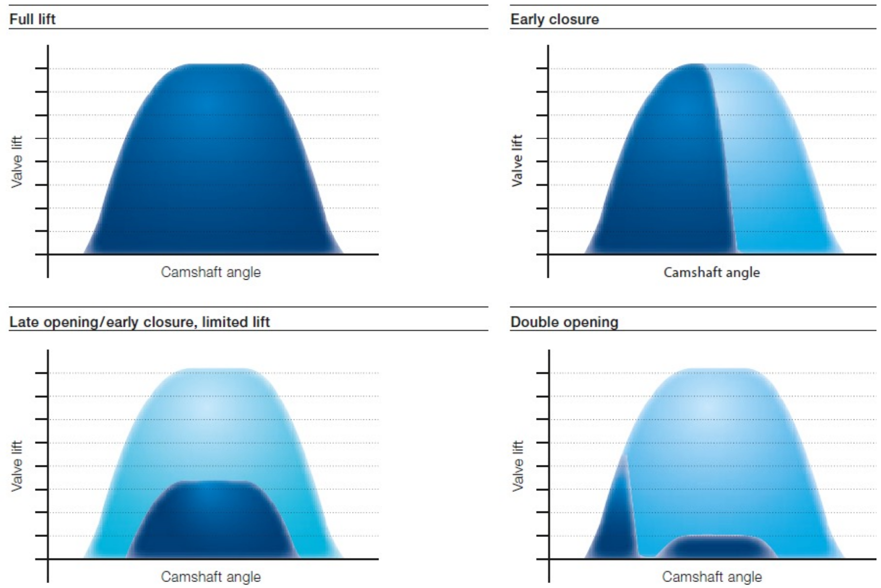
Early Miller cycle and standard induction at the moment of inlet valve closure.



Shifting the curve – fuel consumption and NO_x reduction potential using two-stage turbocharging to achieve strong Miller Cycles on further developed diesel engines.



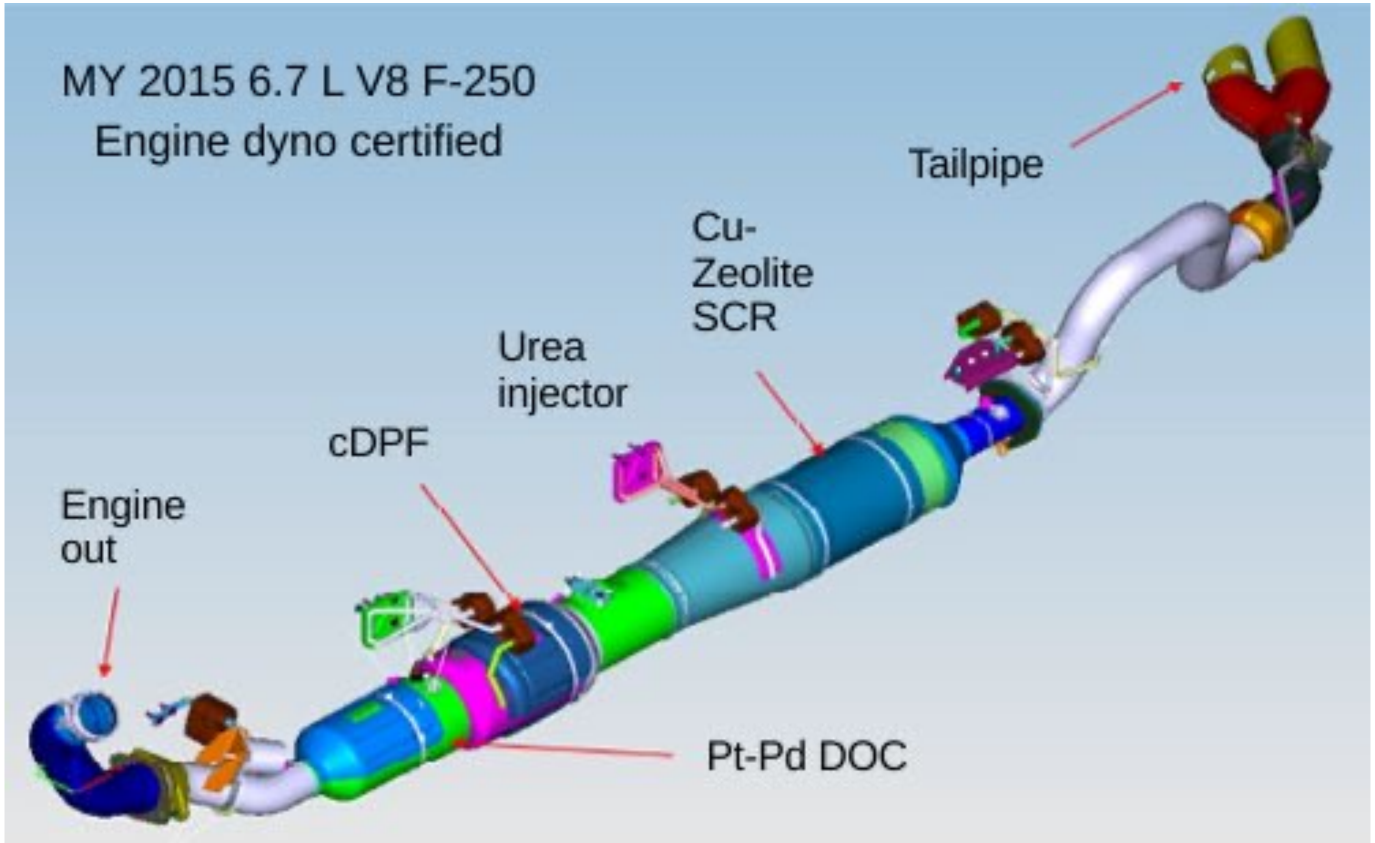




Valve Control Management (VCM®)
Flexibility to meet future challenges
ABB Turbo Systems

After-treatment

From raw emissions to tailpipe emissions



DieselNet

THANK YOU FOR YOUR ATTENTION!