2.61 Internal Combustion Engines
Spring 2008

# Engine Turbo/Super Charging

# Super and Turbo-charging

## Why super/ turbo-charging?

- Fuel burned per cycle in an IC engine is air limited
  - $(F/A)_{stoich} = 1/14.6$

$$\mathrm{Torq} = \frac{\eta_f m_f Q_{HV}}{2\pi n_R}$$

$$\mathrm{Power} = \mathrm{Torq} \cdot 2\pi N$$

$$m_f = \left(F/A\right) \eta_V \rho_{a,0} V_D$$

$\eta_f, \eta_V$ – fuel conversion and volumetric efficiencies
$m_f$ – fuel mass per cycle
$Q_{HV}$ – fuel heating value
$n_R$ – 1 for 2-stroke, 2 for 4-stroke engine
N – revolution per second
$V_D$ – engine displacement
$\rho_{a,0}$ – air density

**Super/turbo-charging: increase air density**

# Super- and Turbo- Charging

Purpose: To increase the charge density

- Supercharge: compressor powered by engine output
  - No turbo-lag
  - Does not impact exhaust treatment
  - Fuel consumption penalty
- Turbo-charge: compressor powered by exhaust turbine
  - Uses ‘wasted’ exhaust energy
  - Turbo- lag problem
  - Affects exhaust treatment
- Intercooler
  - Increase charge density (hence output power) by cooling the charge
  - Lowers $NO_x$ emissions

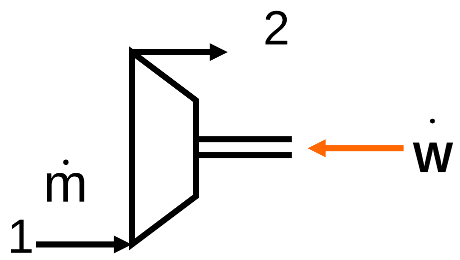
**Charge-air pressure regulation with wastegate on exhaust gas end.** 1.Engine, 2. Exhaust-gas turbochager, 3. Wastegate

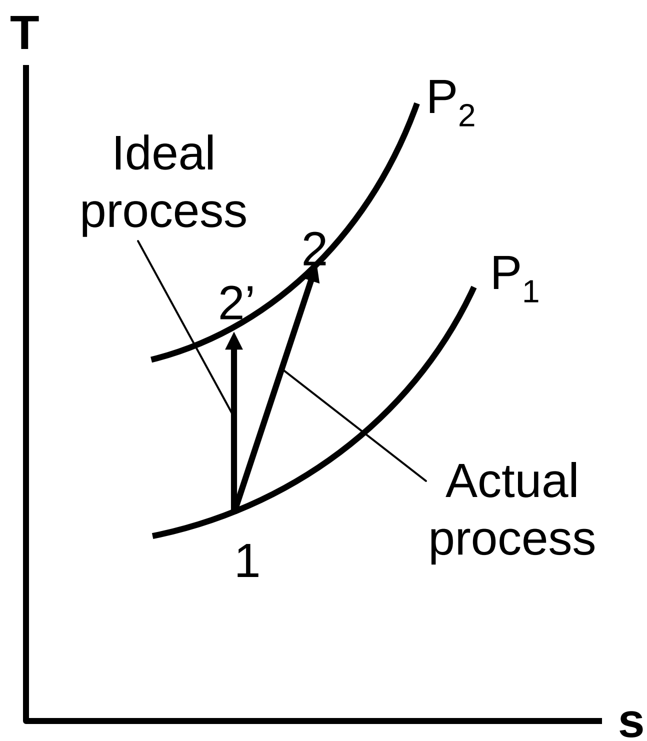
**Exhaust-gas turbocharger for trucks**
1.Compressor housing, 2. Compressor impeller, 3. Turbine housing, 4. Rotor, 5. Bearing housing, 6. inflowing exhaust gas, 7. Out-flowing exhaust gas, 8. Atmospheric fresh air, 9. Pre-compressed fresh air, 10. Oil inlet, 11. Oil return



From Bosch Automotive Handbook

# Compressor: basic thermodynamics




**Compressor efficiency $\eta_c$**

$$\eta_c = \frac{\dot{W}_{ideal}}{\dot{W}_{actual}}$$

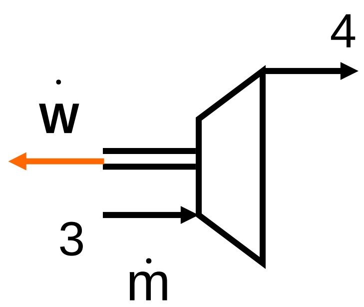
$$\dot{W}_{ideal} = \dot{m} c_p T_1 \left( \frac{T_2'}{T_1} - 1 \right)$$

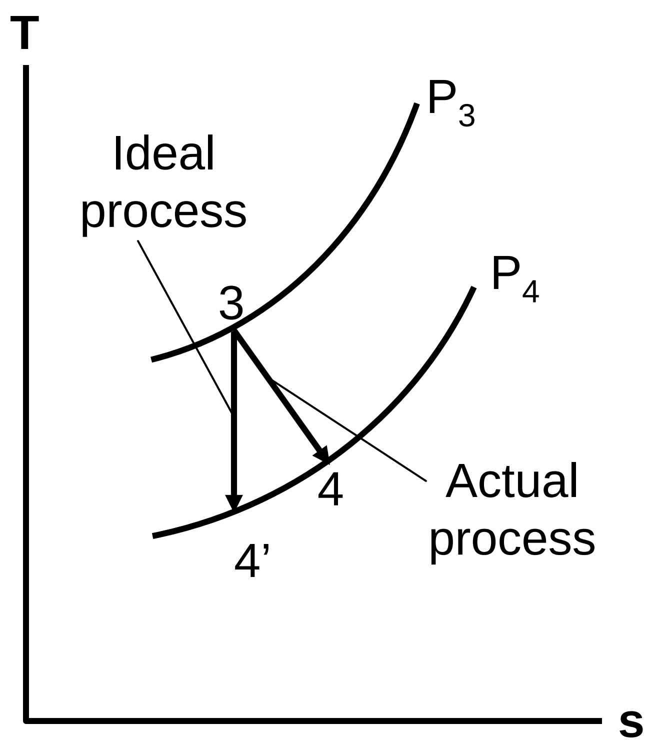
$$\frac{T_2'}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}}$$

$$\dot{W}_{actual} = \frac{1}{\eta_c} \dot{m} c_p T_1 \left( \left( \frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right)$$

$$T_2 = T_1 + \frac{\dot{W}_{actual}}{\dot{m} c_p}$$

# Turbine: basic thermodynamics




**Turbine efficiency $\eta_t$**

$$\eta_t = \frac{\dot{W}_{actual}}{\dot{W}_{ideal}}$$

$$\dot{W}_{ideal} = \dot{m} c_p T_3 \left(1 - \frac{T_4'}{T_3}\right)$$

$$\frac{T_4'}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\dot{W}_{actual} = \eta_t \dot{m} c_p T_3 \left(1 - \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}\right)$$

$$T_4 = T_3 - \frac{\dot{W}_{actual}}{\dot{m} c_p}$$

# Properties of Turbochargers

- Power transfer between fluid and shaft $\propto$ $RPM^3$
  - Typically operate at ~ 60K to 120K RPM
- RPM limited by centrifugal stress: usually tip velocity is approximately sonic
- Flow devices, sensitive to boundary layer (BL) behavior
  - Compressor: BL under unfavorable gradient
  - Turbine: BL under favorable gradient

## Typical super/turbo-charged engine parameters

- Peak compressor pressure ratio ≈ 3.5
- BMEP up to 22 bar
- Limits:
  - compressor aerodynamics
  - cylinder peak pressure
  - NOx emissions

# Compressor/Turbine Characteristics

- Delivered pressure $P_2$
- $P_2 = f(\dot{m}, RT_1, P_1, N, D, \mu, \gamma,$ geometric ratios)
- Dimensional analysis:
  - 7 dimensional variables $\rightarrow$ (7-3) = 4 dimensionless parameters (plus $\gamma$ and geometric ratios)

$$\left(\frac{P_2}{P_1}\right) = f\Bigg(\frac{N}{\underbrace{\sqrt{\gamma RT_1}}_{\text{Velocity}}/D}, \frac{\dot{m}}{\underbrace{\left(\frac{P_1}{RT_1}\right)}_{\text{Density}}\underbrace{\sqrt{RT_1}}_{\text{Velocity}}D^2}, Re, \gamma, \text{geometric ratios}\Bigg)$$

High Re number flow $\rightarrow$ weak Re dependence

For fixed geometry machinery and gas properties

$$\left(\frac{P_2}{P_1}\right) = f\left(\frac{N}{\sqrt{T_1}}, \frac{\dot{m}\sqrt{T_1}}{P_1}\right)$$

# Compressor Map

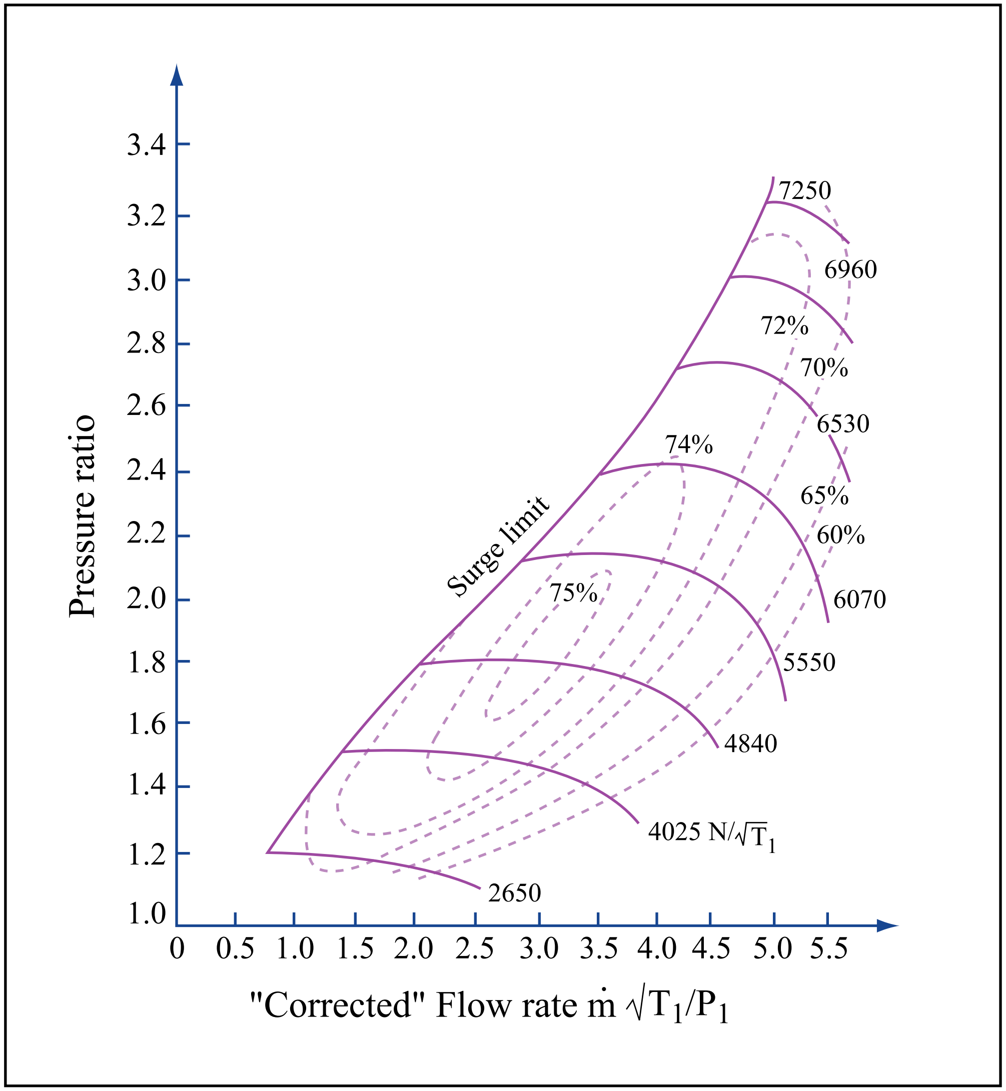



Figure by MIT OpenCourseWare. Adapted from Haddad, Sam David, and Watson, N. Principles and Performance in Diesel Engineering. Chichester, England: Ellis Horwood, 1984.

$T_1$= inlet temperature (K); $P_1$= inlet pressure (bar); N = rev. per min.; $\dot{m}$ = mass flow rate (kg/s)
(From "**Principles and Performance in Diesel Engineering**," Ed. by Haddad and Watson)

# Compressor stall and surge

- Stall
  - Happens when incident flow angle is too large (large $V_\theta/V_x$)
  - Stall causes flow blockage
- Surge
  - Flow inertia/resistance, and compression system internal volume comprise a LRC resonance system
  - Oscillatory flow behave when flow blockage occurs because of compressor stall
    - reverse flow and violent flow rate surges

# Turbine Map

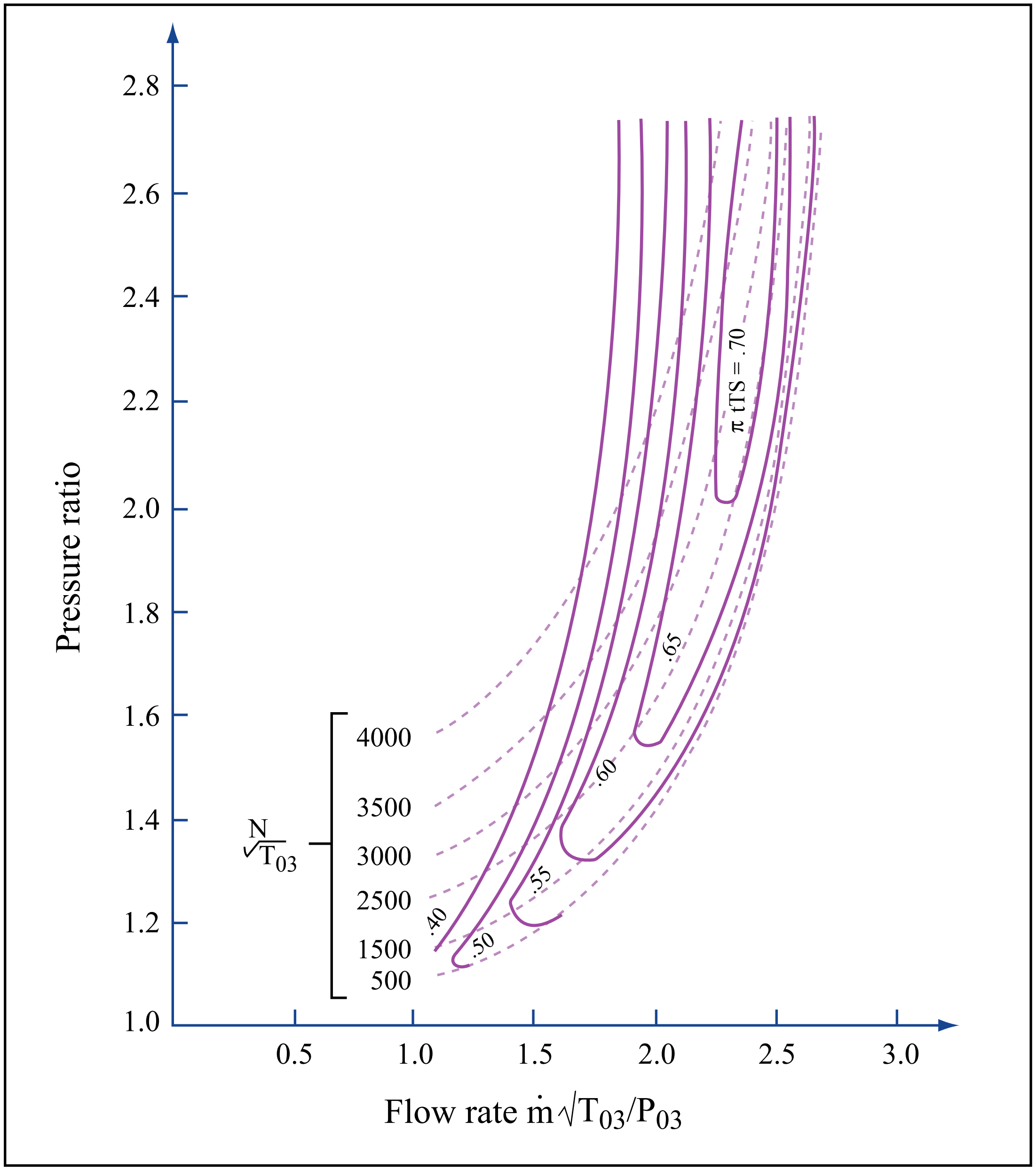


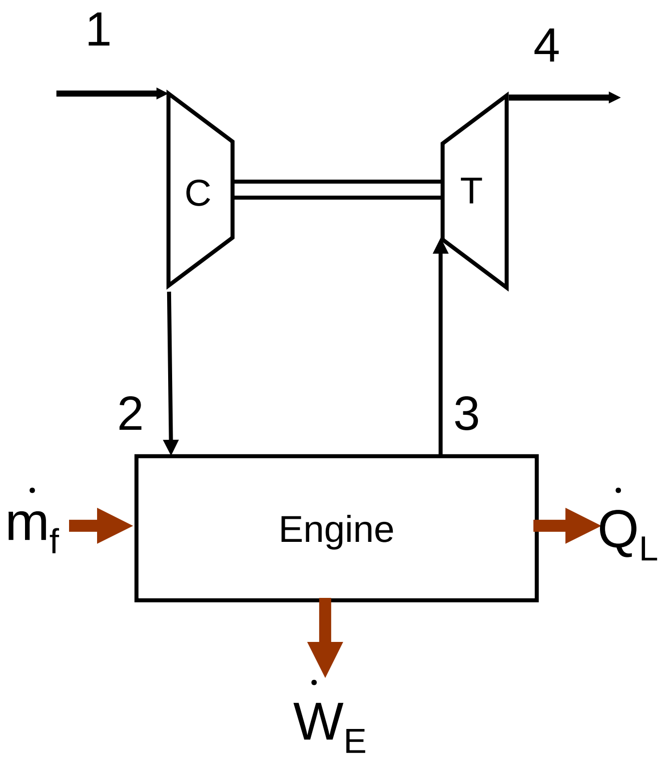

Figure by MIT OpenCourseWare. Adapted from Haddad, Sam David, and Watson, N. Principles and Performance in Diesel Engineering. Chichester, England: Ellis Horwood, 1984.

$T_{03}$=Turbine inlet temperature(K); $P_{03}$ = Turbine inlet pressure(bar); $P_4$= Turbine outlet pressure(bar); N = rev. per min.; m = mass flow rate (kg/s)

(From **"Principles and Performance in Diesel Engineering,"** Ed. by Haddad and Watson)

# Compressor Turbine Matching Exercise

- For simplicity, take away intercooler and wastegate
- Given engine brake power output ($\dot{\mathbf{W}}_{\mathbf{E}}$ ) and RPM, compressor map, turbine map, and engine map
- Find operating point, i.e. air flow ($\dot{m}_a$), fuel flow rate ( $\dot{m}_f$ ) turbo-shaft revolution per second (N), compressor and turbine pressure ratios ($\pi_c$ and $\pi_t$) etc.



## Compressor/ turbine/engine matching solution

Compressor

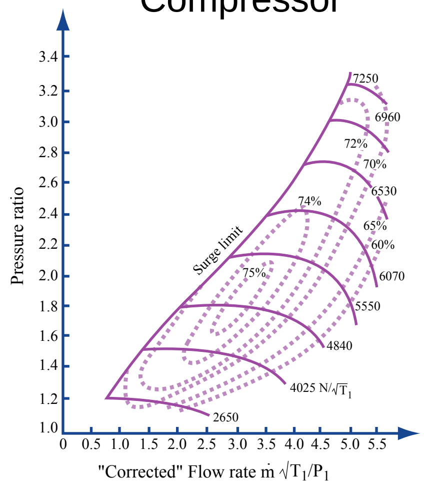



Figure by MIT OpenCourseWare. Adapted from Haddad, Sam David, and Watson, N. Principles and Performance in Diesel Engineering. Chichester, England: Ellis Horwood, 1984.

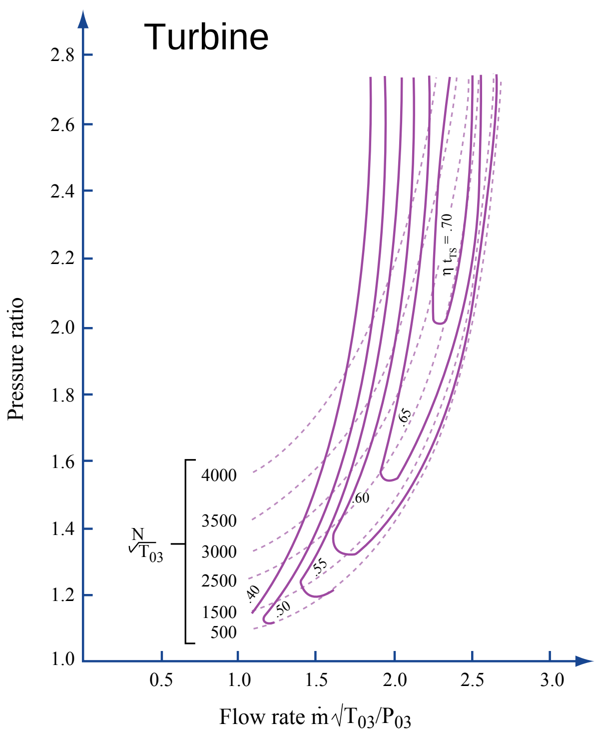



Figure by MIT OpenCourseWare. Adapted from Haddad, Sam David, and Watson, N. Principles and Performance in Diesel Engineering. Chichester, England: Ellis Horwood, 1984.

Procedure :

1. Guess $\pi_c$; can get engine inlet conditions :

$$P_2 = \pi_c P_1 \qquad T_2 = \frac{T_1}{\eta_c}\left[(\pi_c)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

2. Then engine volumetric efficiency calibration will give the air flow $\dot{m}_a$ that can be 'swallowed'
3. From $\dot{m}_a$ and $\pi_c$, the compressor speed N can be obtained from the compressor map
4. The fuel flow rate $\dot{m}_f$ may be obtained from the engine map :

$$\dot{W}_E = \dot{m}_f \; LHV \; \eta_f(RPM, \dot{W}_E, A/F)$$

5. Engine exhaust temperature $T_3$ may be obtained from energy balance (with known engine mech. eff. $\eta_M$)

$$(\dot{m}_a + \dot{m}_f)c_p T_3 = \dot{m}_a c_p T_2 + \dot{m}_f LHV - \frac{\dot{W}_E}{\eta_M} - \dot{Q}_L$$

6. Guess $\pi_t$, then get turbine speed $N_t$ from turbine map
7. Determine turbine power from turbine efficiency on map

$$\dot{W}_t = \eta_t\left[1 - \left(\frac{1}{\pi_t}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

8. Iterate on the values of $\pi_c$ and $\pi_t$ until $\dot{W}_t = \dot{W}_c$ and $N_t = N_c$

# Compressor/ Engine/ Turbine Matching

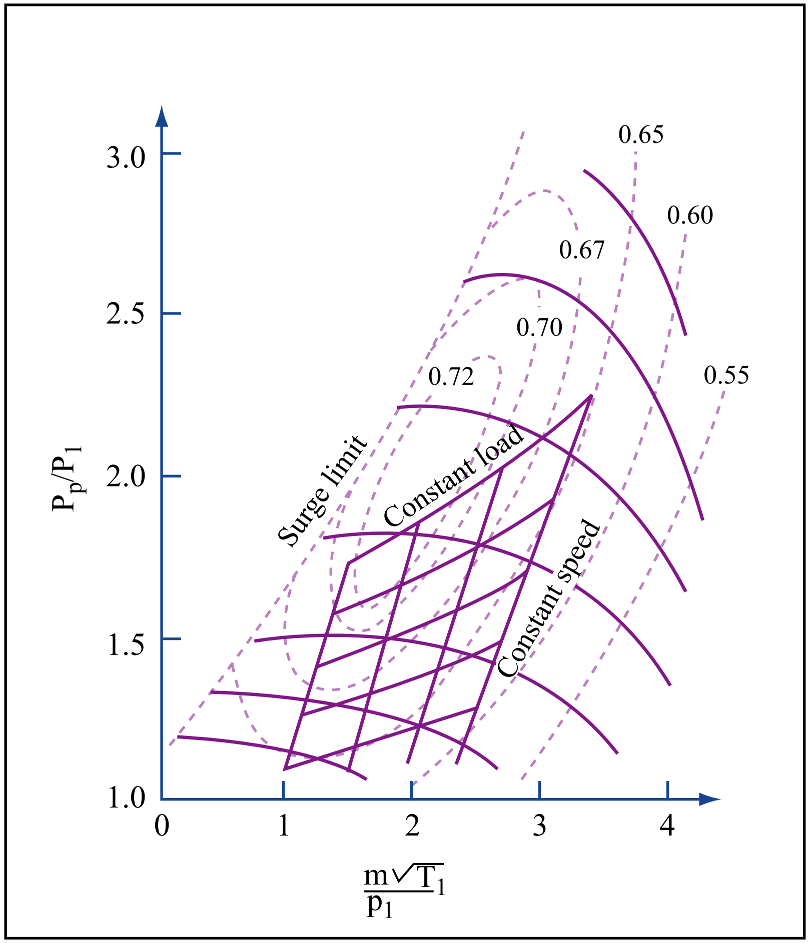
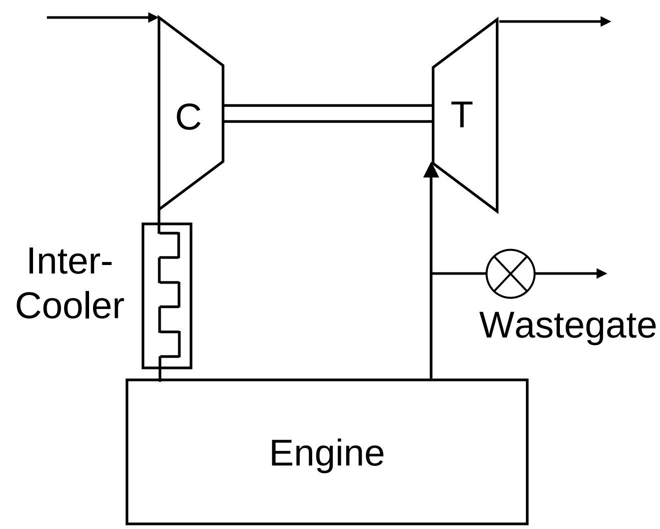



Figure by MIT OpenCourseWare. Adapted from Haddad, Sam David, and Watson, N. Principles and Performance in Diesel Engineering. Chichester, England: Ellis Horwood, 1984.

Compressor characteristics, with airflow requirements of a four-stroke truck engine superimposed.

(From **"Principles and Performance in Diesel Engineering,"** Ed. by Haddad and Watson)

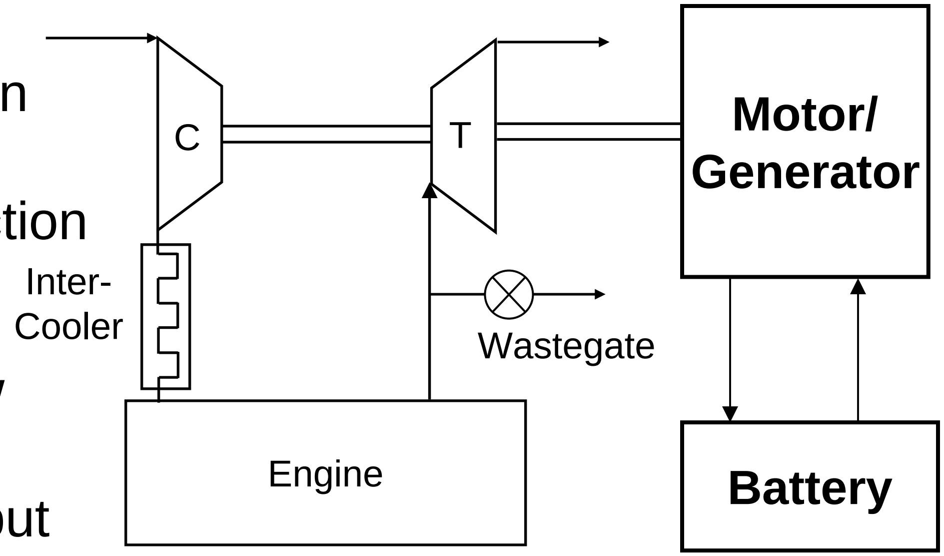
- Mass flows through compressor, engine, turbine and wastegate have to be consistent
- Turbine inlet temperature consistent with fuel flow and engine power output
- Turbine supplies compressor work
- Turbine and compressor at same speed



# Advanced turbocharger development

## Electric assisted turbo-charging

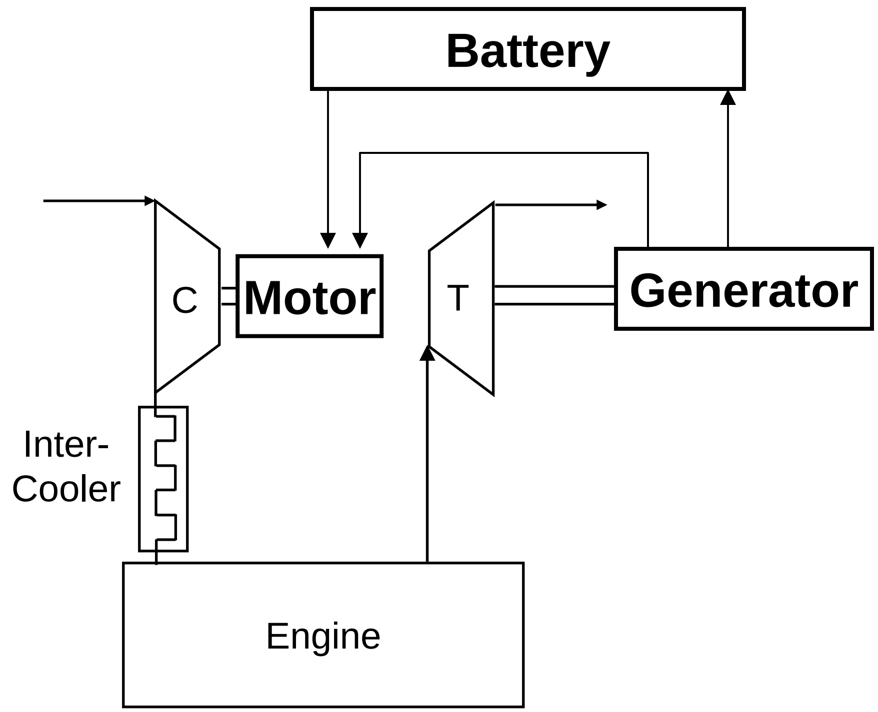
- Concept
  - Put motor/ generator on turbo-charger
  - reduce wastegate function
- Benefit
  - increase air flow at low engine speed
  - auxiliary electrical output at part load



# Advanced turbocharger development

## Electrical turbo-charger

- Concept
  - turbine drives generator; compressor driven by motor
- Benefit
  - decoupling of turbine and compressor map, hence much more freedom in performance optimization
  - Auxiliary power output
  - do not need wastegate; no turbo-lag



# Advanced turbocharger development

## Challenges

- Interaction of turbo-charging system with exhaust treatment and emissions
  - Especially severe in light-duty diesel market because of low exhaust temperature
- Cost