Chapters 7

SI vs CI Performance Comparison

Performance Comparison of CI and SI Engines

- The CI engine cycle can be carried out in either 2 or 4 strokes of the piston, with the 4-cycle CI engine being more common.
- The air and fuel are not united in a CI engine until fuel is injected into the combustion chamber. The fuel injected into a CI engine (typically starting at about 20^o before TDC) has very little time to mix with air. Therefore, the mixture in the combustion chamber is heterogeneous (very rich within fuel spray plumes and very lean outside the plumes).

Performance Comparison of CI and SI Engines con't

- The air-fuel mixture of a SI engine has much more time to mix and is nearly homogeneous by the time of ignition in the combustion chamber. The fuel-air equivalence ratio of the homogeneous mixture in a SI engine must remain close enough to unity to be combustible.
- The compression ratio of a CI engine must be high enough to cause auto-ignition of the air-fuel mixture. The compression ratio of a SI engine must be low enough to prevent auto-ignition.

Performance Comparison of CI and SI Engines con’t

- The high compression ratio increases the stress on a CI engine, so it must be constructed more robustly than a SI engine.
- A spark ignites the mixture in a SI engine, and a flame front sweeps smoothly across the combustion chamber
- Initial combustion in a CI engine is rough and uncontrolled because the mixture may ignite spontaneously at more then one place in the combustion chamber.

Performance Comparison of CI and SI Engines con’t

- The power output of a CI engine is limited by it’s air-handling ability, which tends to limit the power output of the engine.
- A CI engine can produce about the same power output as a SI engine of equal displacement running at the same speed.

Table 7.1 Comparison of SI and CI engines.

Factor	SI Engine	CI Engine
Intake/compression	Air and fuel	Air only
Speed control	Throttled air-fuel mixture	Air unthrottled, fuel control only
Mixture uniformity	Nearly homogeneous	Very heterogeneous
Equivalence ratio	0.85 to 1.25	0 to 0.7
Exhaust temperature	Higher	Lower
Compression ratio range	7 to 10	14 to 20
Required strength	Lower	Higher
Relative efficiency at full load	1.0	1.4
Relative $P_b / (D_e N_e)$	1.0	$0.7 \times 1.4 = 0.98$

Goering et. al., 2003, Off-road Vehicles, ASAE

Performance Comparison of CI and SI Engines con’t

- CI engines are more efficient than SI engines at both full load and part load. The excess air supplied to the CI engine and its higher compression ratio help to increase the indicated thermal efficiency.
- The indicated thermal efficiency of a diesel engine improves at part load because fuel injection is ended sooner. The SI engine has no corresponding improvement in indicated thermal efficiency at part load.

Performance Comparison of CI and SI Engines con't

- The brake thermal efficiencies for the SI (gasoline) and CI (diesel) engines at full load are, respectively, 24.9% and 32.0%. Therefore, CI engines provide 28.5% better fuel economy at full load.
- At 30% load, the CI engine provides 73% better fuel economy than does the SI engine.

Brake Thermal Efficiencies

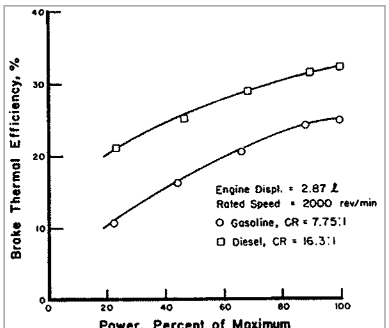


Figure 7.1. Typical brake thermal efficiencies of spark-ignition and compression-ignition engines.

Goering et. al., 2003, Off-road Vehicles, ASAE

Chapters 8

Intake and Exhaust Systems

Turbochargers

Supercharging an Engine

- The objective of supercharging an engine is to increase airflow, which allows greater fuel consumption and greater power output from an engine of given displacement. Superchargers may be mechanical driven or be driven by the engine exhaust; the latter are called turbochargers.

Supercharging an Engine con’t

- A turbocharger consists of an exhaust-driven turbine directly connected to a compressor wheel. The spinning compressor wheel receives air from the air cleaner, compresses it, and delivers it to the engine intake manifold.

Supercharging an Engine con’t

- The concept of a turbocharger is illustrated here.
- Points are numbered for identifying pressures and temperatures. Pt 1 is between air cleaner and compressor inlet; Pt 2 is between compressor outlet and intake manifold; Pt 3 is exhaust manifold; Pt 4 is between the turbine outlet and muffler.

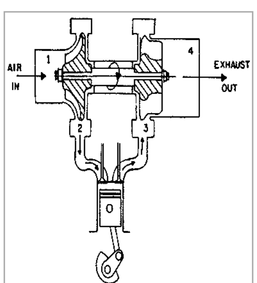


Figure 8.5. Illustration of the concept of a turbocharger.

Goering et. al., 2003, Off-road Vehicles, ASAE

Supercharging an Engine con't

- Air from the air cleaner enters the compressor at temperature T_1 and pressure p_1 and exits at temperature T_2 and pressure p_2. Absolute temperatures and pressures must be used in all turbocharger calculations.
- The exhaust gas enters the turbine at condition T_3, p_3, and exits at condition T_4, p_4. The increase in pressure across the compressor is referred to as *boost*.

Air Consumption and Air-Delivery Ratio

- The theoretical air consumption rate of a four-cycle engine is given by the following equation:
  - $\dot{m}_{at} = 0.03\ D_e\ N_e\ \rho_a$
    - Where $\dot{m}_{at}$ = theoretical air consumption rate, kg/h
    - D_e = engine displacement, L
    - N_e = engine speed, rpm
    - ρ_a = density of air entering compressor, kg/m3

Air Consumption and Air-Delivery Ratio con't

- The air-delivery ratio is the ratio of the measured over the theoretical air consumption of an engine
  - $e_v = \dot{m}_a / \dot{m}_{at}$
    - Where e_v = air-delivery ratio
    - $\dot{m}_a$ = actual air consumption, kg/h
    - $\dot{m}_{at}$ = theoretical air consumption, kg/h

Air Consumption and Air-Delivery Ratio con't

- For naturally-aspirated (NA) engines, e_v is called the volumetric efficiency of the engine because it is a measure of the efficiency of the combustion chambers in filling with air during the intake stroke.
- The condition, $e_v = 1$, would be achieved if each combustion chamber filled completely with air at ambient temperature during each intake stroke (each combustion chamber would be filled with air whose density was equal to that of the air in the environment around the engine).

Air Consumption and Air-Delivery Ratio con't

- For a NA engine running at rated load and speed, the volumetric efficiency is typically about 0.85.
- A turbocharger is able to increase the density of air entering the combustion chambers to well above that of the ambient air.

Air Consumption and Air-Delivery Ratio con't

- $\mathbf{E_v = (p_2 / p_1)(T_1 / T_2)}$ is used to compare the air density leaving the turbocharger compressor to that of the ambient temperature.
  - p_1, p_2 = absolute pressure of air entering and leaving the compressor, kPa
  - T1, T2 = absolute temperature of air entering and leaving the compressor, ^{o}K

Turbochargers

- On a compressor map, the compressor pressure ratio is on the y-axis and the compressor airflow is on the x-axis
- The oval-shaped contours are lines of equal compressor efficiency.Typical values range from 0.5 to 0.8.
- The other set of contours are lines of equal compressor speed.

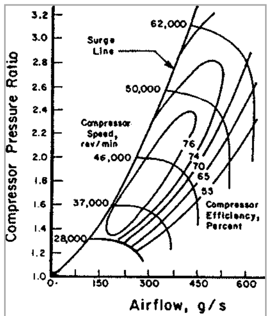


Figure 8.6. A compressor performance map.

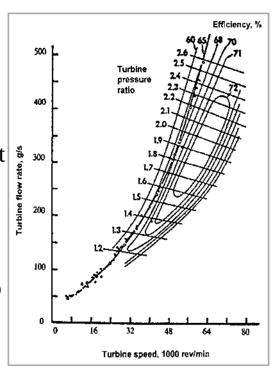
Goering et. al., 2003, Off-road Vehicles, ASAE

Turbochargers con't

- The speeds of compressors are measured in tens of thousands of revolutions per minute.
- The surge line on the last figure marks the region where the constant-speed contours begin to slope downward with increasing airflow. It can be shown that operation of a compressor to the left of the surge line is very unstable and results in air surges between the compressor and the intake manifold.

Turbochargers con't

- This turbine map's flow rate is on the y-axis, while the turbine speed is on the x-axis.of the two contour lines plotted, one is for contours of constant turbine efficiency. The other is for contours of constant pressure ratio across the turbine.
- The turbine pressure ratio is defined as:
  - $K_{pt} = p_3 / p_4$



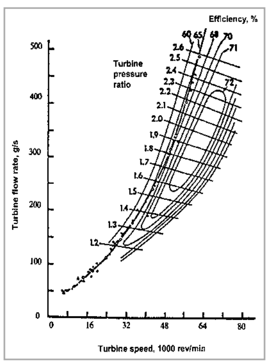
Goering et. al., 2003, Off-road Vehicles, ASAE

Turbochargers con’t

- The flow rates through the compressor and turbine are related through the fuel-air ratio of the engine. On a mass basis, the exhaust flow rate out of the engine must be equal to the sum of the air and fuel flow rates into the engine.

Turbochargers con’t

- The turbine flow rate is related to the air or compressor flow rate as: $\dot{m}_t/\dot{m}_c = 1 + FA$
  - Where $\dot{m}_t$ = mass flow rate through the turbine
  - $\dot{m}_c$ = mass flow rate through the compressor
  - FA = fuel-air ratio (inverse of the air-fuel ratio)



Goering et. al., 2003, Off-road Vehicles, ASAE

Selecting a Turbocharger

- The first equation is for the pressure ratio across the compressor:
  - $K_{pc} = p_2/p_1 = 1 + (\text{boost} / p_1)$
    - Where boost = pressure increase across the compressor.
- The temperature ratio across the compressor:
  - $T_2/T_1 = 1 + (\quad - 1)/e_c$
    - Where e_c = compressor efficiency, decimal

Selecting a Turbocharger con’t

- The compressor efficiency is defined as the theoretical temperature rise across the compressor divided by the actual temperature rise.
- The turbine efficiency is defined as the actual temperature rise across the turbine divided by the theoretical temperature rise.

Selecting a Turbocharger con’t

- The purpose of turbocharging is to increase the power output of an engine, and so the first step is to select the desired power output that would be appropriate for the engine at the desired rated speed and load.

Selecting a Turbocharger con’t

1. Select the desired, achievable power output, P_b; use Equation 2.6 to verify that the chosen power level does not require an excessive p_{bme}. Realistically, $p_{bme} \leq 1250$ kPa is possible.

2. Calculate $\dot{m}_f = P_b * BSFC$, using an achievable value for BSFC. Typically, for a well-designed engine, it is possible to achieve
$0.2 < BSFC < 0.25$ kg/kW h

Selecting a Turbocharger con’t

3. Calculate $\dot{m}_a = \dot{m}_f * (A/F)$, using the desired A/F ratio of the turbocharged engine. For a CI engine running on diesel fuel, typically $25 < (A/F) < 32$

4. Select the compressor and the point on the compressor map at which the compressor will operate at rated load and speed of the engine.

Selecting a Turbocharger con’t

- Reworked:
  - $\mathbf{(K_{pc}\, e_c\,)/\, (e_c + \quad -1) = (\dot{m}_a/(0.03 D_e N_e \rho_a))}$
  - Note that all the terms on the right side are known. By assuming a value for e_c, it can be iteratively solved to determine K_{pc}.
  - After a few iterations, values of e_c, K_{pc}, and $\dot{m}_a$ will be found that are compatible with the compressor map and this equation.

Selecting a Turbocharger con’t

5. Select the turbine and the operating point on the turbine map. Speed, flow, and power constraints must be met in matching the turbine to the compressor
   - The turbine and compressor must rotate at the same speed, the turbine flow must equal the compressor flow times (1+FA), and the turbine must supply enough power to drive the compressor while overcoming bearing friction

Selecting a Turbocharger con't

- The power available from the turbine (P_t) and the power needed to drive the compressor (P_c) are related through the mechanical efficiency of the turbocharger:
  - $E_m = P_c / P_t = (\dot{m}_c C_{pc}(T_2 - T_1)) / (\dot{m}_t C_{pt}(T_3 - T_4))$
    - Where P_c = power needed to drive the compressor
    - P_t = power available from the turbine