Internal Combustion Engines

Internal and External Combustion Engine Classifications:

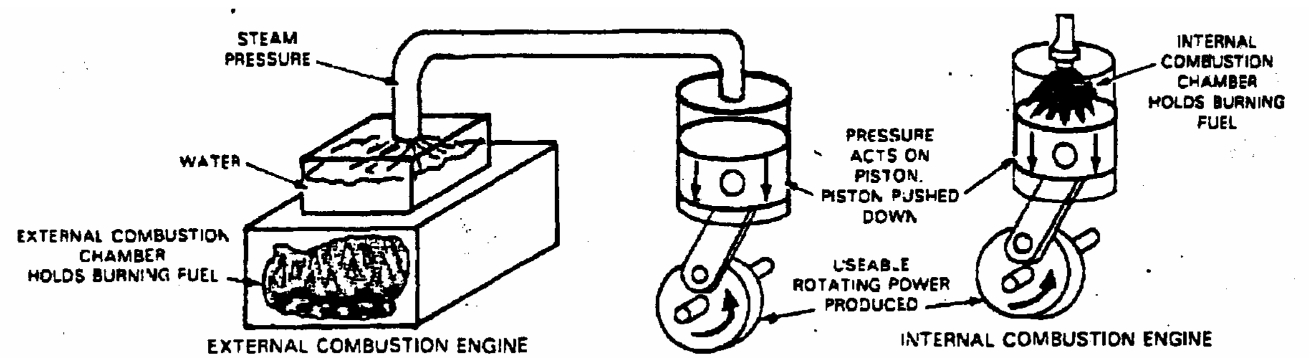


Fig. External combustion engine bums fuel outside cylinder. A steam engine is an external combustion engine. Internal combustion engine, like car engine, bums fuel inside cylinder.

Gasoline and diesel engine classifications:
A gasoline (Petrol) engine or spark ignition (SI) burns gasoline, and the fuel is metered into the intake manifold. Spark plug ignites the fuel. A diesel engine or (compression ignition Cl) bums diesel oil, and the fuel is injected right into the engine combustion chamber. When fuel is injected into the cylinder, it self ignites and bums.

Preparation of fuel air mixture (gasoline engine):

* High calorific value: (Benzene (Gasoline) 40000 kJ/kg, Diesel 45000 kJ/kg).

* Air-fuel ratio: A chemically correct air-fuel ratio is called ***stoichiometric*** mixture. It is an ideal ratio of around 14.7:1 (14.7 parts of air to 1 part fuel by weight). Under steady-state engine condition, this ratio of air to fuel would assure that all of the fuel will blend with all of the air and be burned completely.
A lean fuel mixture containing a lot of air compared to fuel, will give better fuel economy and fewer exhaust emissions (i.e. 17:1).
A rich fuel mixture: with a larger percentage of fuel, improves engine power and cold engine starting (i.e. 8:1). However, it will increase emissions and fuel consumption.

* Gasoline density = 737.22 kg/m^3, air density (at 20^o) = 1.2 kg/m3
The ratio 14.7 : 1 by weight equal to 14.7/1.2 : 1/737.22 = 12.25 : 0.0013564
The ratio is 9,030 : 1 by volume (one liter of gasoline needs 9.03 m^3 of air to have complete burning).

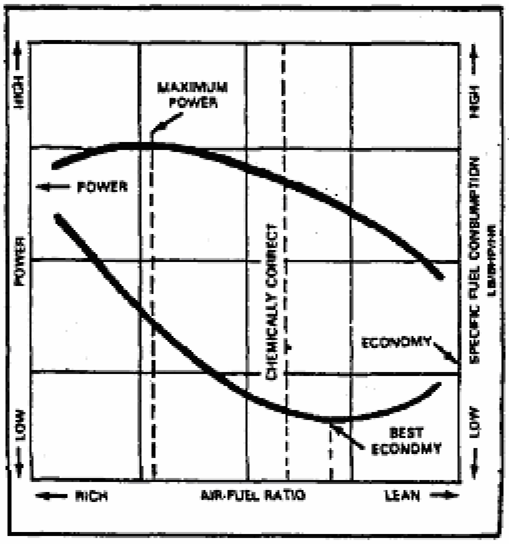


Fig. Note graph showing relationship of engine power, fuel consumption, and air-fuel ratio. Note how stoichiometric mixture or ideal mixture is between maximum power and best economy. (Ethyl Corporation)

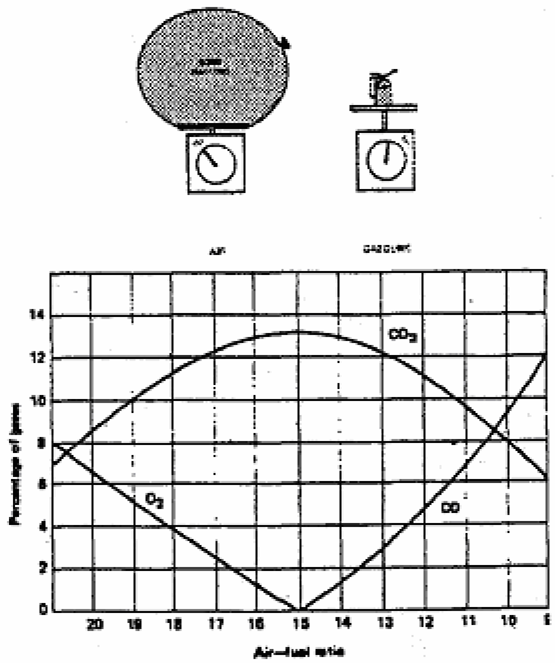


Fig. Air contains 23% O by weight or 21% by volume. Petrol contains 85% C and 15% H by weight.

<u>* Fuel atomization</u>: refers to how the fuel injector or carburetor breaks up liquid gasoline into tiny droplets.

<u>* Compression of the air-fuel mixture</u>: During this process the pressure and temperature of the gas rise. The ratio of volume before and after compression is called the compression ratio:

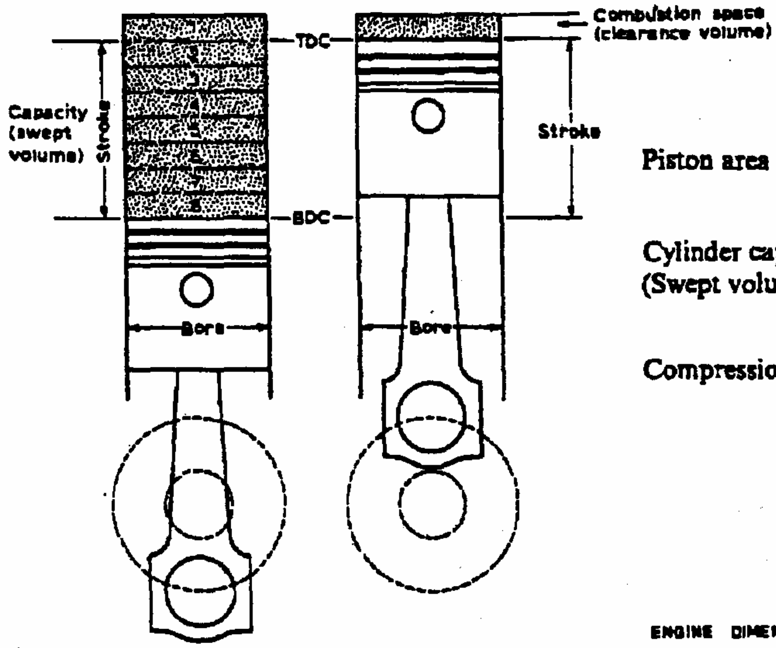
$$r = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c}$$

where:
r = compression ratio
V_s = Swept volume (cylinder volume),
V_c = clearance volume

<u>Engine swept volume (engine displacement, engine capacity):</u>

$$V_e = V_s \times n$$

where:
V_e = Engine swept volume -in liters or cubic centimeters (liter, or cm^3 (cc))
V_s = Cylinder swept volume
n = number of cylinders



$$\text{Piston area} = \pi\left(\frac{\text{bore}}{2}\right)\left(\frac{\text{bore}}{2}\right)$$

$$\text{Cylinder capacity (Swept volume)} = \pi\left(\frac{\text{bore}}{2}\right)\left(\frac{\text{bore}}{2}\right)\text{stroke}$$

$$\text{Compression ratio} = \frac{\text{total volume, piston BDC}}{\text{total volume, piston TDC}} = \frac{\text{capacity} + \text{combustion space}}{\text{combustion space}} = \frac{\text{swept volume} + \text{clearance volume}}{\text{clearance volume}}$$

ENGINE DIMENSIONS AND COMPRESSION RATIO

<u>Volumetric efficiency (η_v)</u>

Volumetric efficiency
= Volume of air taken into cylinder / Maximum possible volume in cylinder

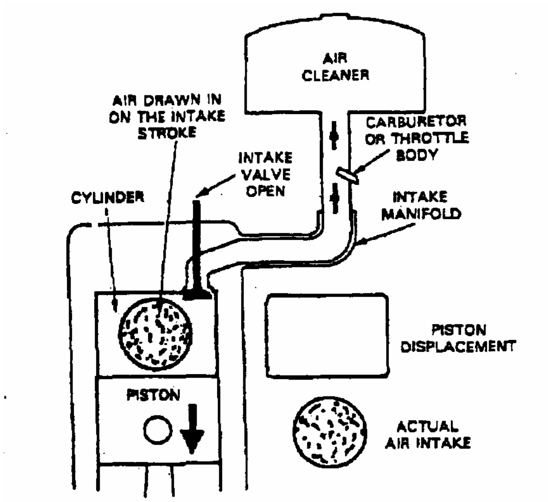


Fig. . Volumetric efficiency is comparison of actual air intake and theoretical potential for air intake. (Deere & Co.)

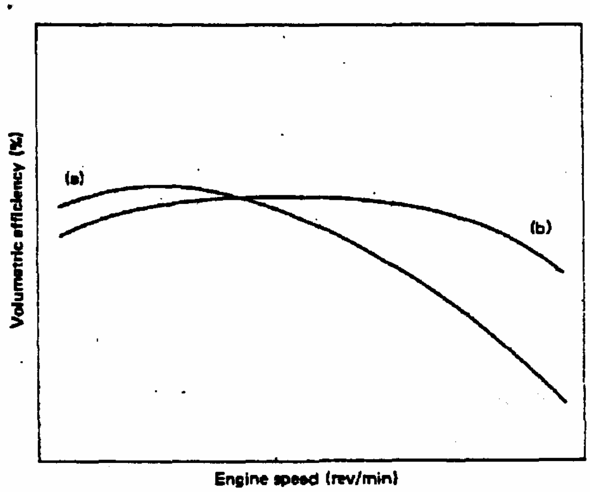


Fig. Volumetric efficiency and engine speed. (a) petrol engine, normally aspirated with carburettor. (b) compression ignition engine, normally aspirated.

* Volumetric efficiency depends upon throttle opening and engine speed as well as induction and exhaust system layout, port size and valve timing and opening duration.

IDEAL HEAT ENGINE GAS CYCLES:

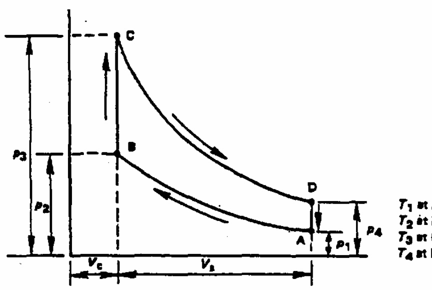


Fig. Constant volume cycle.

* Otto cycle

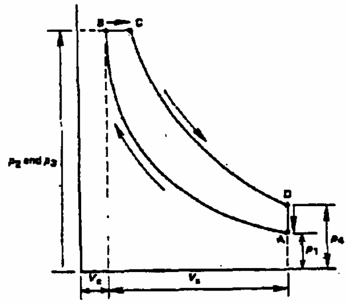


Fig. Constant pressure cycle.

* Diesel cycle

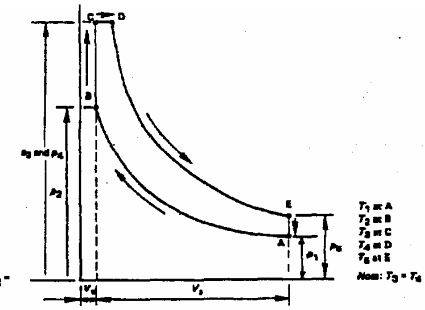


Fig. The dual combustion cycle.

* Dual combustion cycle

Real cycle of SI Engine:

pV diagram

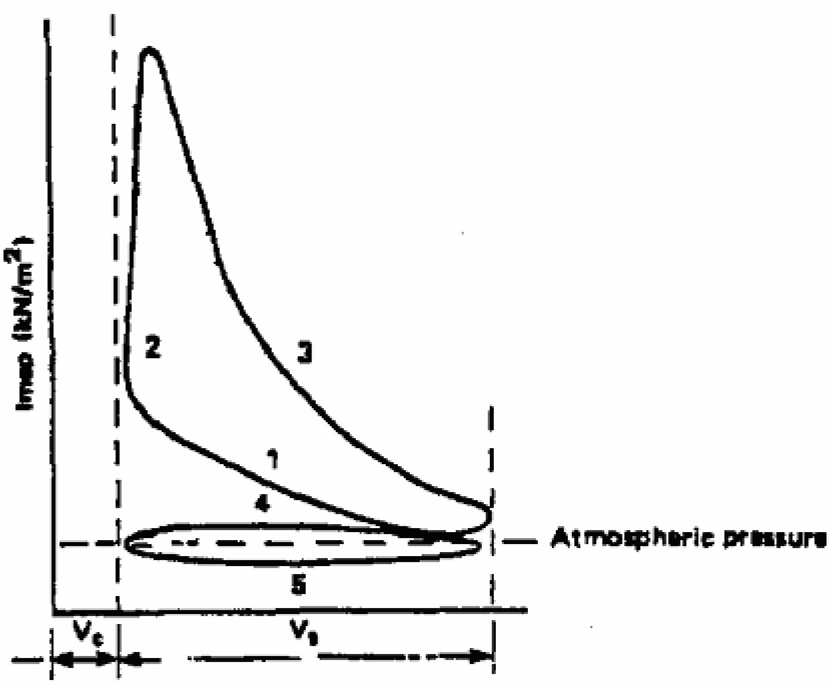
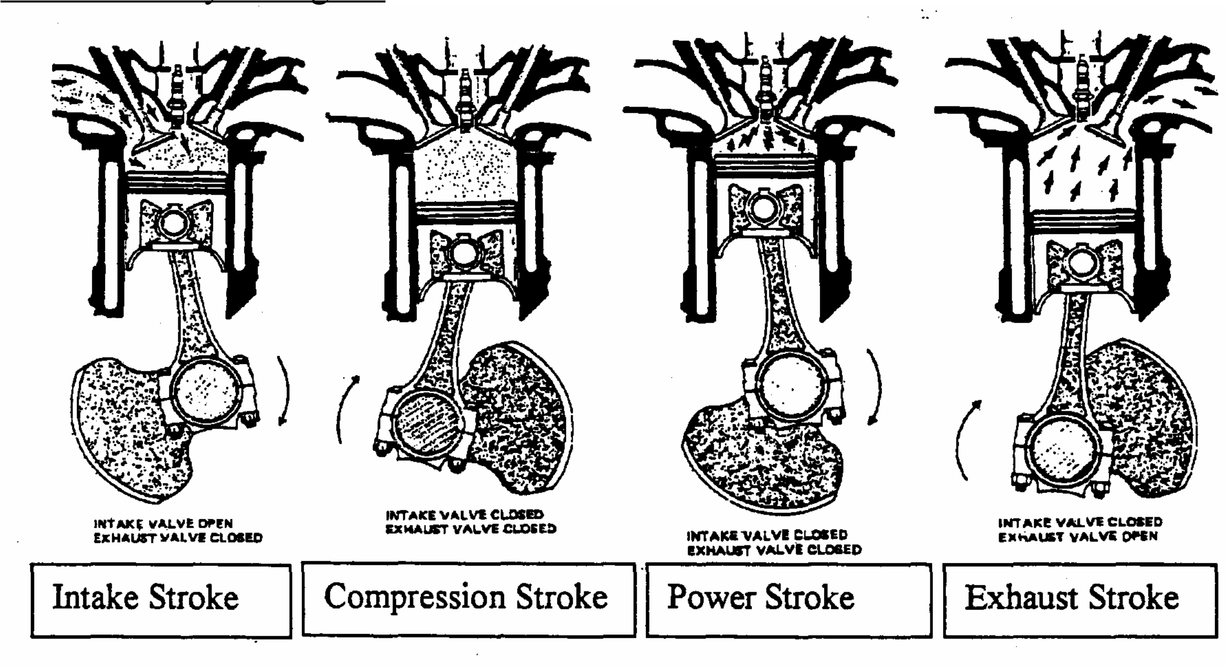


Fig. Pressure–volume indicator diagram. (1) compression, (2) combustion, (3) expansion, (4) exhaust, (5) induction.

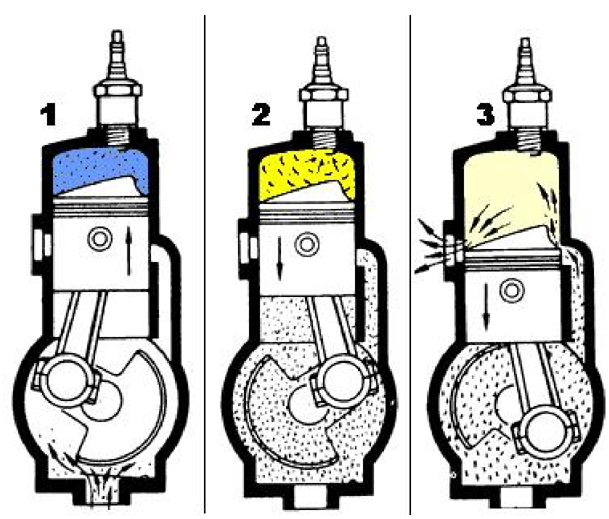
Engine cycles
*Two-stroke cycle *Four stroke cycle

Four-stroke-cycle engine:



* Intake (induction or inlet) stroke: The intake valve has opened. The piston is moving downward, drawing a mixture of air and gasoline vapor into the cylinder.
* Compression stroke: The intake valve has closed. The piston is moving upward, compressing the mixture.
* Power stroke: The ignition system has delivered a spark to the spark plug that ignites the compressed mixture. As the mixture burns, high pressure is created which pushes the piston downward.
* Exhaust stroke: The exhaust valve has opened. The piston is moving upward, forcing the burned gases from the cylinder.

Two-stroke-cycle engine:
A two-stroke cycle engine is similar to an automotive four-stroke engine, but it only requires one revolution of the crankshaft for a complete power-producing cycle. Generally, two-stroke cycle engines are NOT used in automobiles because they:
- Produce much exhaust pollution
- Have poor power output at low speeds
- Require more service than a four-stroke
- Are not as fuel efficient as a four- stroke
- Must have motor oil mixed into the fuel.



Valve Timing:

Pressure-crank-angle diagram

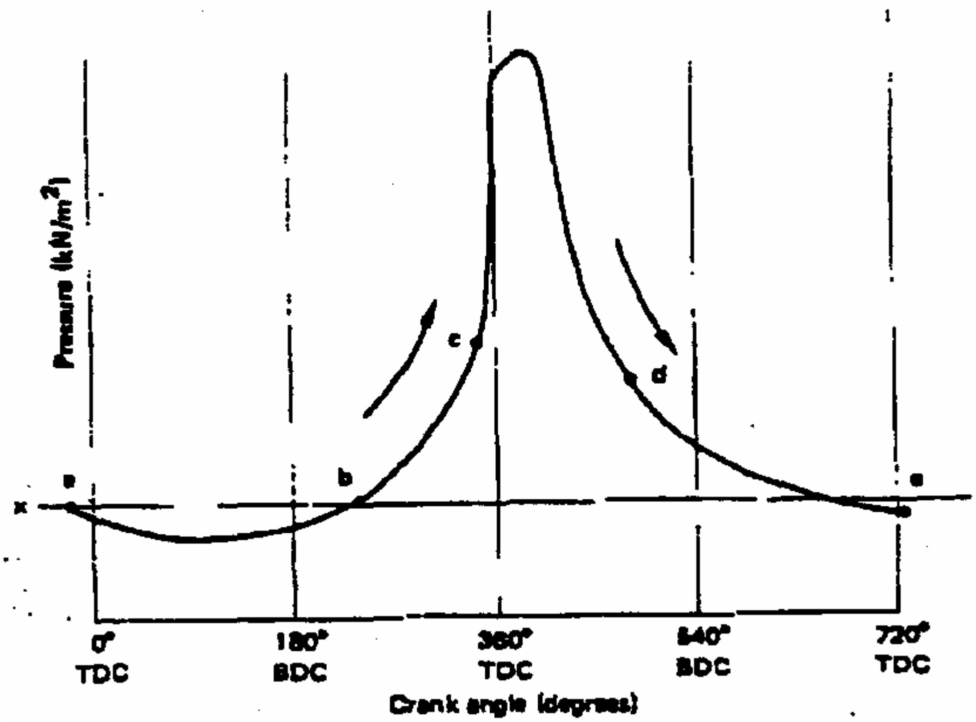


Fig. Rate of change of pressure diagram. (a) inlet valve commences to open, (b) inlet valve closes, (c) ignition commences, (d) exhaust valve opens, (e) exhaust valve closes. xx, atmospheric pressure.

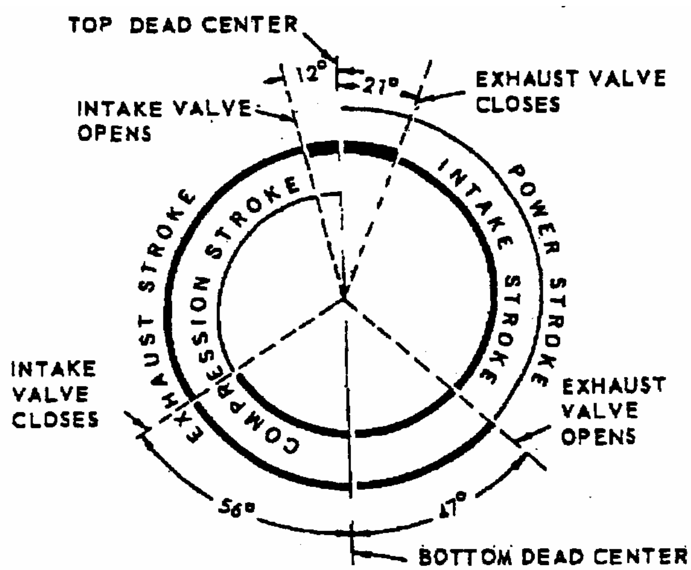


Fig Intake- and exhaust-valve timing. The complete cycle of events is shown as a 720° spiral, which represents two complete crankshaft revolutions. Timing of valves differs for different engines.

Engine indicator diagrams:

pV diagram

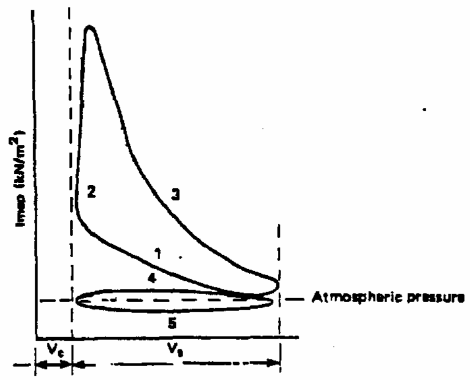


Fig. Pressure—volume indicator diagram. (1) compression, (2) combustion, (3) expansion, (4) exhaust, (5) induction.

Pressure-crank-angle diagram

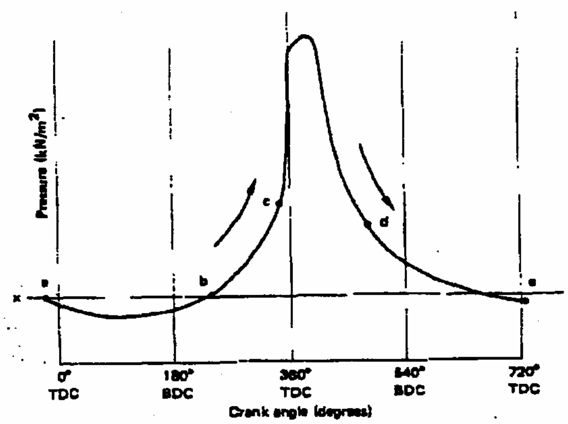


Fig. Rate of change of pressure diagram. (a) inlet valve commences to open, (b) inlet valve closes, (c) ignition commences, (d) exhaust valve opens, (e) exhaust valve closes. xx, atmospheric pressure.

Indicated mean effective pressure (imep):

This is the average pressure acting on the power stroke which creates the same amount of work as the varying pressure within the engine cylinder acting behind the piston. imep units are N/m^2, kN/m^2, and the Pascal (N/m^2) could be used.

* The highest mean effective pressure obtained without supercharging, and using petrol as fuel is between 896 and 1103.6 kPa (kN/m).

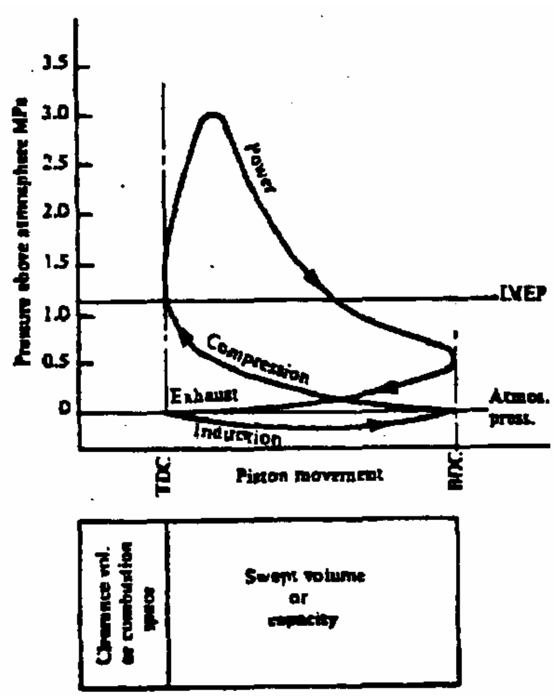


Figure Indicator diagram

Indicated power (P_i):

This is the power that would be available at the crankshaft if a mechanical efficiency of 100% was possible. The term "indicated" is derived from the use of engine indicators and their diagrams from which indicated power could be calculated.

Total average force per revolution [F] (N or kN) = (imep . A) n /2 (4-stroke cycle)
Total work done per revolution [W] (N m or J, kN m, kJ) = F . L = imep . A n L /2
Total work done per second (power) [P] = J/sec (W) = imep . A n L . (N/2) /60

Indicated power (P_i) [4-stroke cycle] = imep x L A n (N/2) /60 (N m/s) or W
Indicated power (P_i) [2-stroke cycle] = imep x L A n N /60 (N m/s) or W
Where:

imep = average or indicated mean effective pressure (N/m^2) or kN/m^2
A = area of the piston crown (m^2)
n = number of engine cylinders
L = piston or engine stroke (m)
N/2 = number of firing impulses per minute per cylinder (4-stroke cycle)
n N/2 = engine number of firing impulses per minute (4-stroke cycle)
n N = engine number of firing impulses per minute (2-stroke cycle)
L A n = total swept volume of engine, or engine capacity (m^3)
P = indicated power (N m/s or W)

Engine friction:

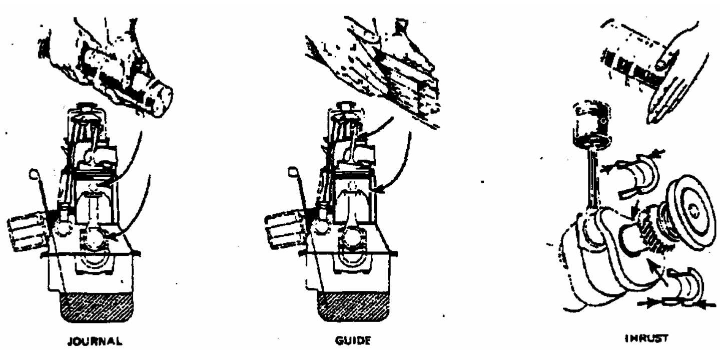


Fig. Three types of friction-bearing surfaces in an automobile engine.

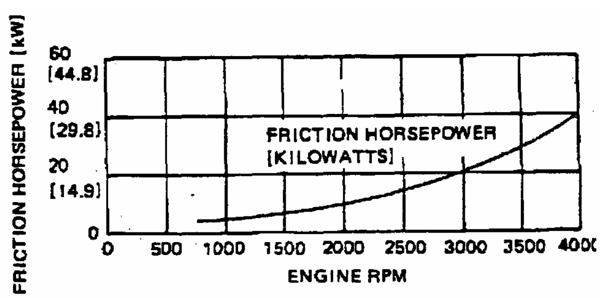


Fig. Friction-horsepower curve showing the relationship between frictional horsepower and engine speed (rpm).

Brake power (P_b):

The brake power (net power) is the engine's power as measured at the crankshaft at a specified rpm. The engine brake power is obtained using a brake dynamometer at engine full throttle.

Mechanical efficiency (η_m):

Mechanical efficiency (η_m) = brake power (P_b)/indicated power (P_i)

Thus

brake power = η_m . indicated power, ($P_b = P_i \eta_m$)

brake power = η_m . imep L A n (N/2) /60 (W)

The pumping losses of the engine pistons, and the friction between their rings and the cylinder walls, account for the greater part or percentage of the lost work and power.

The main factors which contribute to the lost power are:

1. the type of materials used and their surface finish;
2. the loading between materials in contact under boundary lubrication conditions;
3. the rubbing speeds.
4. the engine compression ratio;
5. revolution per minute;
6. the throttle position;
7. windage. Air resistance increases in proportion to the square of the speed. The flywheel, clutch, generator and engine-operated cooling fan all introduce windage;
8. the churning of the lubricating oil.

* From the figure it can be seen that the indicated power (P_i) is somewhat higher than the brake power (P_b) throughout the rev/min range, but not proportionally higher. If the vertical distance between the two curves is measured at each revolution point, this distance will represent the power lost to pumping and friction at that engine speed (friction power P_f). As engine speed rises so the losses increase, hence the increasing divergence between the brake power and indicated curve lines.

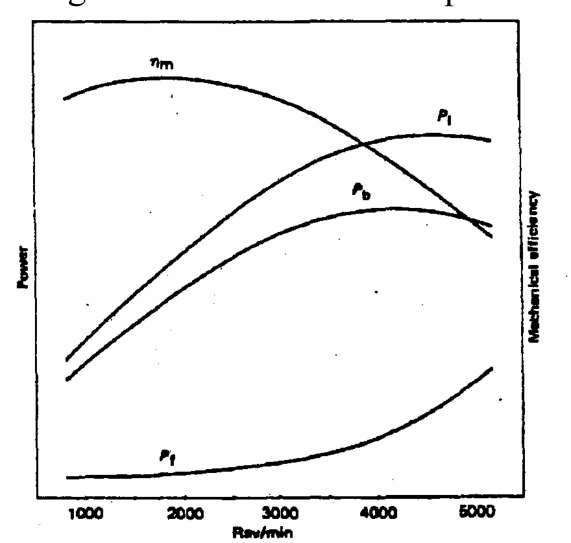


Fig. Indicated power (P_i), brake power (P_b), mechanical efficiency (η_m) and frictional power (P_f) plotted on a rev/min base.

Engine torque (Nm):
Torque (T) is a turning moment (N m) and is dependent on the pressure produced within the engine cylinders, the piston crown area upon which the effective pressure (bmep) is applied, and the crankshaft angle or effective radius. Engine capacity thus plays a large part in torque production. Doubling the engine's capacity (swept volume V_e) will almost double the engine torque.
When engine testing with a dynamometer, the load lifted is situated at end of the dynamometer torque arm:
thus torque $T = w \cdot R$ (Nm)
The work done in one revolution is calculated as follows (see figure). If the brake load w was moved through one revolution (2π) 3600^o with the radius or torque arm of R (m), the work done in one revolution:

$W = w \cdot \pi R$ (N m) or J
$= T \cdot 2\pi$ (N m) or J

where:
$T = w \cdot R$

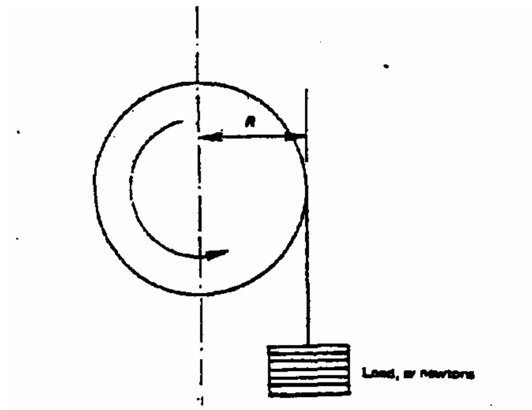


Fig.

Torque and the crankshaft angle
Work is also accomplished when the torque is applied through an angle. Distance xy (see figure, is equal $r\theta$) where θ is the angle through which the crankshaft moves, in radians.
torque = force . radius =F. r
work done = F . distance xy =$F \cdot r\,\theta = T \cdot \theta$
work done per one revolution (2π) = $T \cdot 2\pi$ (J) or N m

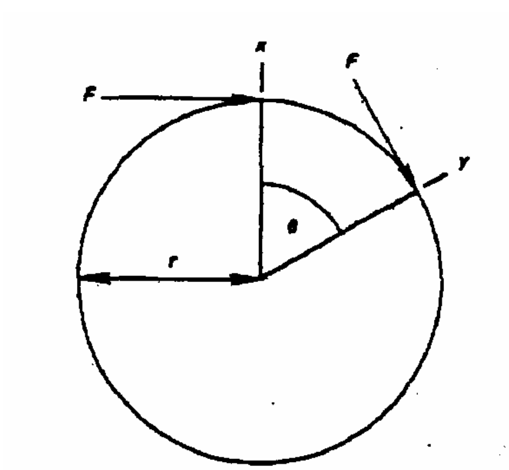


Fig.

Engine brake power (P_b):
This is the power developed at the crankshaft or flywheel. The term brake originated from the method used to determine an engine's power output by measuring the torque using some form of friction dynamometer. In early days of engine design the flywheel was often used for the brake dynamometer. Often quoted brake power figures do not indicate whether they are gross or net.
An engine connected to a modern test bench is generally without such items as cooling fan, coolant pump and radiator, dynamo and clutch unit and is connected to the large test bench exhaust system. Thus some 10-15% more power is often possible under these conditions (gross power) compared to the 'under the bonnet' performance (net power).

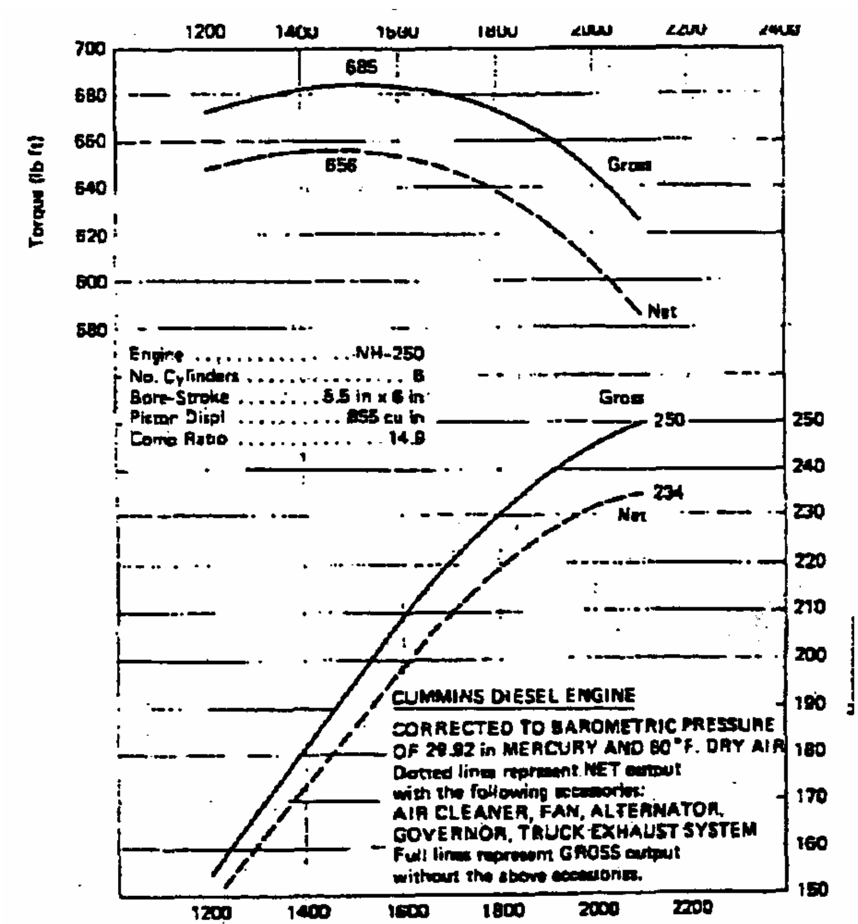


Figure A typical engine power curve.

* On the Continent, the DIN rating is used, which confirms the engine's performance with all its accessories as fitted to the chassis together with correction for normal temperature and pressure. in the USA the SAE rating method is adopted which in effect is the gross engine output.

Power is the rate of doing work = work done/time taken (Joules/sec) or Watts

= force . distance / time taken (t seconds)

= F . xy/t =F . rθ/t =T . θ/t = Tω

Note:

$\omega = \theta/t$ = angular velocity in radians/second = $2\pi N/60$

where:

N = engine rev/min

Brake power per one revolution = Work done per one revolution =T 2π

Work done was previously stated as equal to (imep η_m LAn/2) therefore

$T\,2\pi = (\text{imep } \eta_m)\ LAn/2$

$T = \ . LAn/4\pi = (\text{imep } \eta_m)$. engine swept volume / 4π

also brake power $P_b = T\omega = T\ .\ 2\pi N/60 = (\text{imep } \eta_m)\ .\ LAnN/(60\ .\ 2)$

P_b = bmep . engine swept volume . number of effective stroke / s

* indicated power = brake power + friction power

$P_i = P_b + P_f$

Mechanical efficiency % = η_m = brake power/indicated power = $(P_i/P_b)\ .\ 100\ \%$

* bmep (imep η_m) is an indication of engine efficiency regardless of capacity or engine speed; 1000 kPa represent high efficiency.

Fuel consumption and thermal efficiency:

The fuel an engine consumes can be measured by volume or by mass. By volume the units are cm liters per second, minute or hour (1000 cm = 1 liter). By mass the units are kg per second, minute or hour (1 liter of water = 1 kg).

Liters x relative density of the fuel = kg of fuel

Specific fuel consumption (SFC):

Specific fuel consumption represents the mass or volume of fuel an engine consumes per hour while it produces 1 kW of power. It is an indication of the engine's thermal or heat efficiency and is one of the most important engine characteristics. Comparisons can be made between engines of widely different capacities and characteristics, providing similar fuel and test conditions are arranged for each test.

A mirror reflection of the specific consumption curve shows the shape of the engine's thermal efficiency curve. The lowest point on the consumption curve becomes the highest point on the thermal efficiency curve.

If the consumption = kg/(kW h), (h = hour)

=(kg/h)/kW or L/(kW h)

SFC = (mass of fuel consumption/h) / engine brake power

SFC_i = (mass of fuel consumption/h) / engine indicated power

* Motorists assess fuel consumption in terms of kilometer per liter (km/L), (mile/gallon)

Thermal efficiency (η_{th}):

The efficiency of an engine in converting the heat energy contained in the liquid fuel into m energy is termed its thermal efficiency. A study of the results taken from heat balance tests shows clearly that internal combustion engines are inefficient at this conversion. The petrol engines particularly inefficient and at its best may reach 25% efficiency.

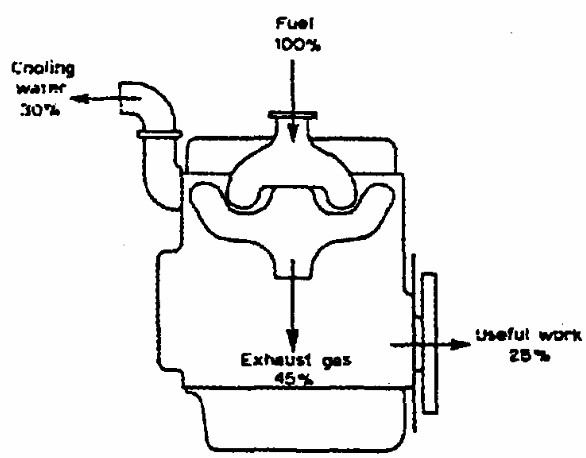
$$\text{brake thermal efficiency} = \frac{\text{output (heat units)}}{\text{input (heat units)}} = \frac{\text{brake power}}{\text{fuel power}} = \frac{P_b}{(\text{kg/h}) \, . \, CV}$$

where: CV is the calorific or heat value of 1 kg of the fuel (J/kg, kJ/kg or MJ/kg).

$$\text{brake thermal efficiency } (\eta_{th}) = \frac{P_b \, . \, 60 \, . \, 60}{(\text{kg/h}) \, . \, CV}$$

$$\text{brake thermal efficiency } (\eta_{th}) = \frac{3600 \, P_b}{(\text{L/h}) \, . \, \rho \, . \, CV}$$

where ρ is the relative density (kg/L) of the fuel.



Engine performance curves:

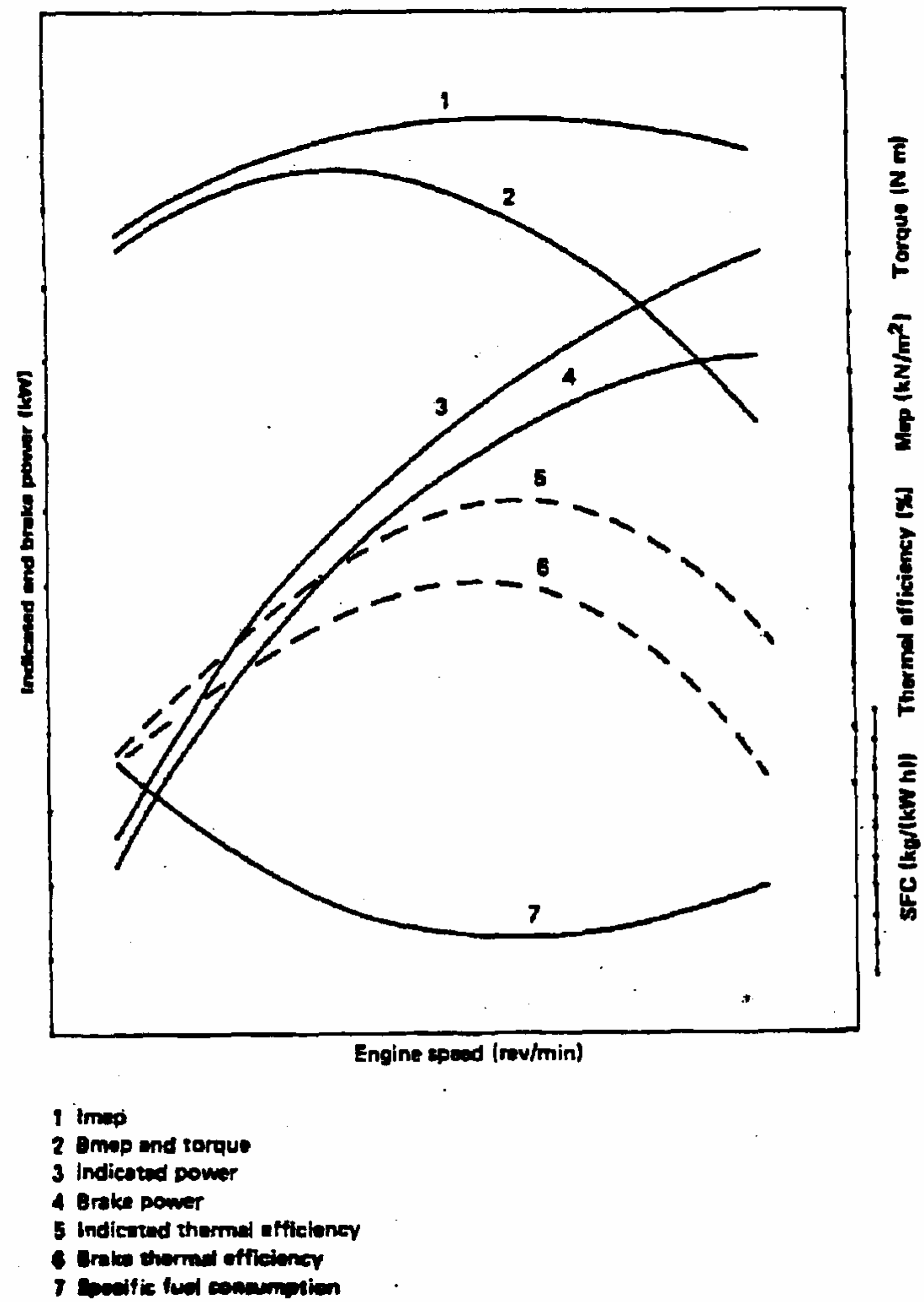


Fig. Graphs of engine performance curves.

$$\text{bmep} = \text{imep}\ \eta_m$$

$$\eta_{th\,i} = \frac{P_i}{(kg/h)\,CV}$$

Factors affect the engine torque and power:
Pre -ignition, detonation, retarded ignition, weak mixture, engine load, piston speed, ignition timing, camshaft advanced or crankshaft retarded, tappet clearances, variation of compression ratio, fuel pump injection timing, supercharging.

Retarded ignition:

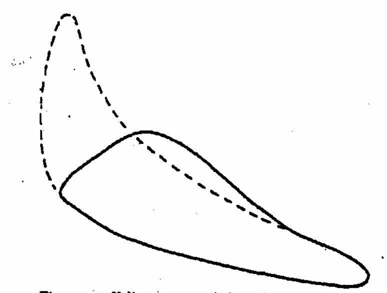


Fig. pV diagram: retarded ignition

Weak mixture:

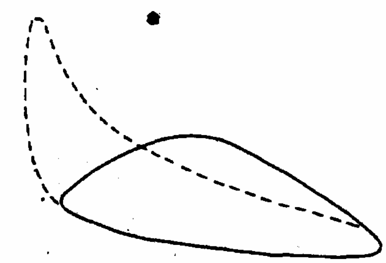
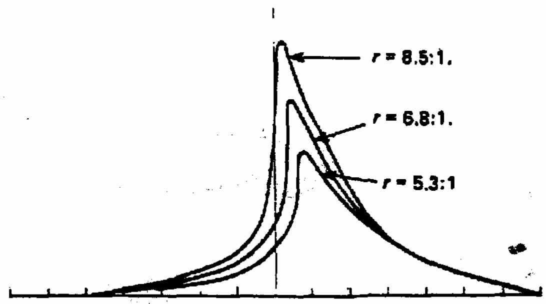


Fig. pV diagram: weak mixture

Variation of compression ratio:



(a)

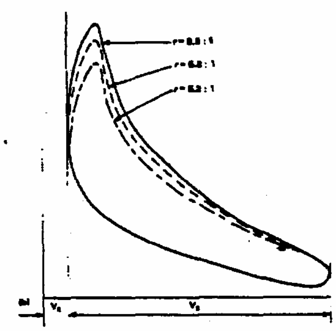
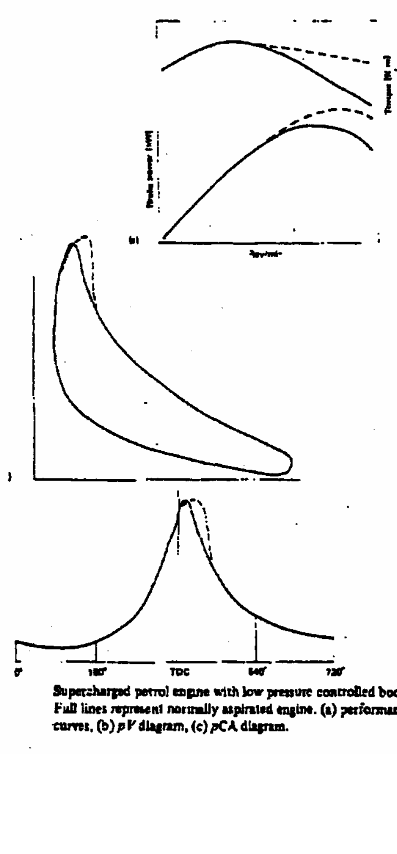


Fig. Petrol engine diagrams. (a) pCA diagram, (b) pV diagram.



Supercharged petrol engine with low pressure controlled boost. Full lines represent normally aspirated engine. (a) performance curves, (b) pV diagram, (c) pCA diagram.

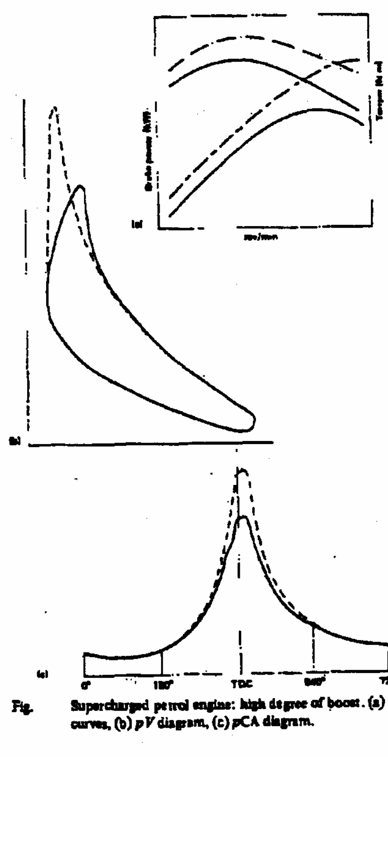


Fig. Supercharged petrol engine: high degree of boost. (a) perfc curves, (b) pV diagram, (c) pCA diagram.

Power to weight ratio (single-and multi-cylinder engines):

The engine power varies as the square of the bore (piston area) but the mass varies as the square of the bore (that is with the volume used). Increasing power by using a large cylinder therefore results in a low power/weight ratio, where as increasing the number of cylinders maintains power to weight in the same proportion.