Internal Combustion Engines

Operating Parameters

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Horsepower

- The term horsepower was invented by the engineer James Watt. Watt lived from 1736 to 1819 and is most famous for his work on improving the performance of steam engines. We are also reminded of him every day when we talk about 60-watt light bulbs.

- The story goes that Watt was working with ponies lifting coal at a coal mine, and he wanted a way to talk about the power available from one of these animals. He found that, on average, a mine pony could do 22,000 foot-pounds of work in a minute. He then increased that number by 50 percent and pegged the measurement of horsepower at 33,000 foot-pounds of work in one minute. It is that arbitrary unit of measure that has made its way down through the centuries and now appears on our cars, lawn mowers, chain saws and even in vacuum cleaner!
1 HORSEPOWER = 33,000 foot-pounds per minute
Horsepower

• **What horsepower means:** In Watt's judgement, one horse can do 33,000 foot-pounds of work every minute. A horse exerting 1 horsepower can raise 330 pounds of coal 100 feet in a minute, or 33 pounds of coal 1,000 feet in one minute, or 1,000 pounds 33 feet in one minute. Whatever combination of feet and pounds as long as the product is 33,000 foot-pounds in one minute, you have a horsepower.
Conversion of HP

• Horsepower can be converted into other units as well. For example:

• 1 horsepower is equivalent to 746 watts. So if you took a 1-horsepower horse and put it on a treadmill, it could operate a generator producing a continuous 746 watts.

• 1 horsepower (over the course of an hour) is equivalent to 2,545 BTU (British thermal units). If you took that 746 watts and ran it through an electric heater for an hour, it would produce 2,545 BTU (where a BTU is the amount of energy needed to raise the temperature of 1 pound of water by 1 degree F).

• One BTU is equal to 1,055 joules, or 252 gram-calories or 0.252 food Calories. Presumably, a horse producing 1 horsepower would burn 641 Calories in one hour if it were 100-percent efficient.
Engine Performance

- **Maximum Rated Power**: The highest power developed by an engine for short period of time/operation.

- **Normal Rated Power**: Highest power developed by an engine in continuous operation.

- **Rated Speed**: The crankshaft rotational speed at which rated power is developed.
Basic Terminology

- **Bore (B):** The diameter of the cylinder of an engine.

- **TDC:** The top-most position of the piston inside the cylinder of an engine.

- **BDC:** The bottom-most position of the piston inside the cylinder of an engine.

- **Stroke (L):** The distance through which the piston moves from TDC to BDC or BDC to TDC.
Remark

- Bore sizes of engines range from 0.5 m down to 0.5 cm (i.e., 20 inch to 0.2 inch).

- An engine with $B=L$ is called a square engine.

- If stroke length ($L$) is greater than the bore diameter ($B$), the engine is called an under square engine (Smaller diameter cylinder with shorter flame travel distance; Combustion chamber surface area will be smaller resulting less heat loss per cycle).

- If stroke length ($L$) is less than the bore diameter ($B$), the engine is called an over square engine.
Remark

- In an over square engine, the shorter stroke length gives lower average piston speed and hence lower frictional losses.

(a) Over square engine  (b) Square engine  (c) Under square engine
Basic Terminology - Contd.

- Clearance Volume ($V_c$): The space between the top dead center and the cylinder head.

- Swept or Displaced Volume ($V_d$): The volume that the piston displaces or sweeps out as it moves from one dead center to the other. This is equal to the cross-sectional area of piston multiplied by the stroke.
Clearance and Swept/Displaced Volumes

(a) Displacement volume

(b) Clearance volume
<table>
<thead>
<tr>
<th></th>
<th>Model Airplane Two-Stroke Cycle</th>
<th>Automobile Four-Stroke Cycle</th>
<th>Large Stationary Two-Stroke Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BORE (cm)</strong></td>
<td>2.00</td>
<td>9.42</td>
<td>50.0</td>
</tr>
<tr>
<td><strong>STROKE (cm)</strong></td>
<td>2.04</td>
<td>9.89</td>
<td>161</td>
</tr>
<tr>
<td><strong>DISPLACEMENT/cyl (L)</strong></td>
<td>0.0066</td>
<td>0.69</td>
<td>316</td>
</tr>
<tr>
<td><strong>SPEED (RPM)</strong></td>
<td>13,000</td>
<td>5200</td>
<td>125</td>
</tr>
<tr>
<td><strong>POWER/cyl (kW)</strong></td>
<td>0.72</td>
<td>35</td>
<td>311</td>
</tr>
<tr>
<td><strong>AVERAGE PISTON SPEED (m/sec)</strong></td>
<td>8.84</td>
<td>17.1</td>
<td>6.71</td>
</tr>
<tr>
<td><strong>POWER/DISPLACEMENT (kW/L)</strong></td>
<td>109</td>
<td>50.7</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>bme (kPa)</strong></td>
<td>503</td>
<td>1170</td>
<td>472</td>
</tr>
</tbody>
</table>
Basic Terminology - Contd.

- **Cylinder Capacity (V_E):** Engine sizes are compared on the basis of total cylinder swept volume known as engine cylinder capacity. Thus, it is equal to the swept volume of each cylinder times the number of cylinders. It is also known as the cubic capacity of the engine.

- **Compression Ratio (r):** It is the ratio of the maximum cylinder volume (when the piston is at BDC) to the minimum cylinder volume (when the piston is at TDC), i.e., the ratio of sum of swept and clearance volumes to clearance volume.
Compression ratio

Most cars: 8:1 - 12:1

High-performance cars: 15:1

Diesel: 20:1
Mean Piston Speed:

\[ \bar{U}_p = \frac{2LN}{60} \]

**Note:** If \( N \) is the rotational speed (RPM), \( 1/N \) is the time of 1 revolution. Now, half of this \( (1/2N) \) = time for 1 stroke.

\[ \therefore \bar{U}_p = \frac{L}{1/2N} \cdot \frac{1}{60} \]

Mean piston speed is often used as an appropriate parameter than crank rotational speed for correlating engine behavior as a function of speed.
Remark

- *Piston speed determines the instantaneous flow rate of air-fuel into the cylinder during intake and exhaust flow out of the cylinder.*

- *Higher piston speeds would require larger valves to allow for higher flow rates. In most engines, valves are at a maximum size with no room for enlargement.*
The cylinder volume at any crank angle is:

\[ V = V_c + A_c y = V_c + \frac{\pi B^2}{4} (l + a - s) \]

When the piston is at TC \((s = l+a)\) the cylinder volume equals the clearance volume \(V_c\).

The cylinder volume at any crank angle is:

\[ V = V_c + A_c y = V_c + \frac{\pi B^2}{4} (l + a - s) \]

Maximum displacement, or swept, volume:

\[ V_d = \frac{\pi B^2}{4} L \]

Compression ratio:

\[ r_c = \frac{V_{BC}}{V_{TC}} = \frac{V_c + V_d}{V_c} \]

For most engines \(B \sim L\) ("square engine")
Average and instantaneous piston velocity are:

\[ \bar{U}_p = 2LN \]
\[ U_p = \frac{ds}{dt} \]

where \( N \) is the rotational speed of the crank shaft in units revolutions per second.

Average piston speed for standard auto engine is about 15 m/s. Ultimately limited by material strength. Therefore engines with large strokes run at lower speeds than those with small strokes run at higher speeds.
The effect of $R$ on piston speed is shown in the figure.

$R$ is the ratio of connecting rod length to crank offset and usually has values of 3 to 4 for small engines, and increasing to 5 to 10 for large engines.
Basic Terminology – Contd.

- Torque (T): It is equal to the product of the force acting along the connecting rod and the perpendicular distance between this force and the center of rotation of the crankshaft.

\[ T = Fr \]

where,  
- \( T \) = engine torque (N-m)  
- \( F \) = force applied to crank (N)  
- \( r \) = effective crank-arm radius (m)

Torque is the turning effort about the crankshaft’s axis of rotation.

Modern automobile engines have maximum torque in the range of 200 to 300 N-m at engine speeds around 4000 to 6000 rpm.
Variation of torque during crankshaft rotation (p=gas pressure; F=connecting rod thrust; R=crank throw; r=effective crank radius; T=turning effort or torque).
Torque and Power

Torque is measured off the output shaft using a dynamometer.

The torque exerted by the engine is $T$:

$$T = F \cdot b \quad \text{units: } J$$

The power $\dot{W}$ delivered by the engine turning at a speed $N$ and absorbed by the dynamometer is:

$$\dot{W} = \omega \cdot T = (2\pi \cdot N) \cdot T \quad \text{units: } \left(\frac{\text{rad}}{\text{rev}}\right)\left(\frac{\text{rev}}{\text{s}}\right)(J) = \text{Watt}$$

Note: $\omega$ is the shaft angular velocity in units rad/s
Brake Power

- Torque is a measure of an engine’s ability to do work and power is the rate at which work is done.
- Note torque is independent of crank speed.
- The term brake power, $\dot{W}_b$, is used to specify that the power is measured at the output shaft, this is the usable power delivered by the engine to the load.
- The brake power is less than the power generated by the gas in the cylinders due to mechanical friction and parasitic loads (oil pump, air conditioner compressor, etc.).
- The power produced in the cylinder is termed the indicated power, $\dot{W}_i$. 

Brake power and torque of a typical automobile reciprocating engine as a function of engine speed.

Indicated power increases with engine speed while brake power increases to a maximum and then decreases. This is because friction power increases with engine speed to a higher power and becomes dominant at higher speeds.
Mean Effective Pressure (mep): The pressure inside the cylinder of an engine varies considerably during the cycle. Peak pressure occurs just after TDC, and it drops as the piston moves toward BDC. When quoting cylinder pressure, it is therefore, more helpful to refer to the average or mean effective pressure throughout the whole power stroke.

For brake work, the corresponding term used is brake mean effective pressure (bmeₚ), and for indicated work the corresponding term is the indicated mean effective pressure (imₚ).

\[ bmeₚ = \frac{4 \cdot \pi \cdot \tau}{V_d} \]  
(4 stroke)  

\[ bmeₚ = \frac{2 \cdot \pi \cdot \tau}{V_d} \]  
(2 stroke)
Maximum BMEP

\[ bmep = \frac{W_b}{V_d} = \frac{2\pi \cdot T \cdot n_R}{V_d} \]

- The maximum bmep is obtained at WOT at a particular engine speed.
- Closing the throttle decreases the bmep.
- For a given displacement, a higher maximum bmep means more torque.
- For a given torque, a higher maximum bmep means smaller engine.
- Higher maximum bmep means higher stresses and temperatures in the engine hence shorter engine life, or bulkier engine.
- For the same bmep 2-strokes have almost twice the power of 4-stroke.
The maximum bmep of good engine designs is well established:

**Four stroke engines:**

- **SI engines:** bmep = 850 - 1050 kPa*
- **CI engines:** bmep = 700 - 900 kPa

**Turbocharged SI engines:** bmep = 1250 - 1700 kPa
**Turbocharged CI engines:** bmep = 1000 - 1200 kPa

**Two stroke engines:**

- **Standard CI engines comparable bmep to four stroke**
- **Large slow CI engines:** 1600 kPa

*Values are at maximum brake torque and WOT
Note, at the rated (maximum) brake power the bmep is 10 - 15% less

Can use above maximum bmep in design calculations to estimate engine displacement required to provide a given torque or power at a specified speed.
## Typical 1998 Passenger Car Engine Characteristics

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Engine type</th>
<th>Displ. (L)</th>
<th>Max Power (HP@rpm)</th>
<th>Max Torque (lb-ft@rpm)</th>
<th>BMEP at Max BT (bar)</th>
<th>BMEP at Rated BP (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mazda Protégé LX</td>
<td>L4</td>
<td>1.839</td>
<td>122@6000</td>
<td>117@4000</td>
<td>10.8</td>
<td>9.9</td>
</tr>
<tr>
<td>Honda Accord EX</td>
<td>L4</td>
<td>2.254</td>
<td>150@5700</td>
<td>152@4900</td>
<td>11.4</td>
<td>10.4</td>
</tr>
<tr>
<td>Mazda Millenia S</td>
<td>L4 Turbo</td>
<td>2.255</td>
<td>210@5300</td>
<td>210@3500</td>
<td>15.9</td>
<td>15.7</td>
</tr>
<tr>
<td>BMW 328i</td>
<td>L6</td>
<td>2.793</td>
<td>190@5300</td>
<td>206@3950</td>
<td>12.6</td>
<td>11.5</td>
</tr>
<tr>
<td>Ferrari F355 GTS</td>
<td>V8</td>
<td>3.496</td>
<td>375@8250</td>
<td>268@6000</td>
<td>13.1</td>
<td>11.6</td>
</tr>
<tr>
<td>Ferrari 456 GT</td>
<td>V12</td>
<td>5.474</td>
<td>436@6250</td>
<td>398@4500</td>
<td>12.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Lamborghini Diablo VT</td>
<td>V12</td>
<td>5.707</td>
<td>492@7000</td>
<td>427@5200</td>
<td>12.7</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Both torque and power are functions of engine speed. At low speed, torque increases as engine speed increases. As engine speed increases further, torque reaches a maximum and then decreases. Torque decreases because the engine is unable to ingest a full charge of air at higher speeds.

Indicated power increases with speed, while brake power increases to a maximum and then decreases at higher speeds. This is because friction losses increase with speed and become the dominant factor at very high speeds.
For automobile engines, maximum brake power occurs at about 6000 to 7000 rpm, about one and a half times the speed of maximum torque.

Greater power can be generated by increasing displacement, mep, and/or speed. Increased displacement increases engine mass and occupies more space, and both of these are undesirable. For this reason, most modern engines are smaller but run at high speeds, and are often turbocharged or supercharged to increase mep.
References

# Web Resources

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