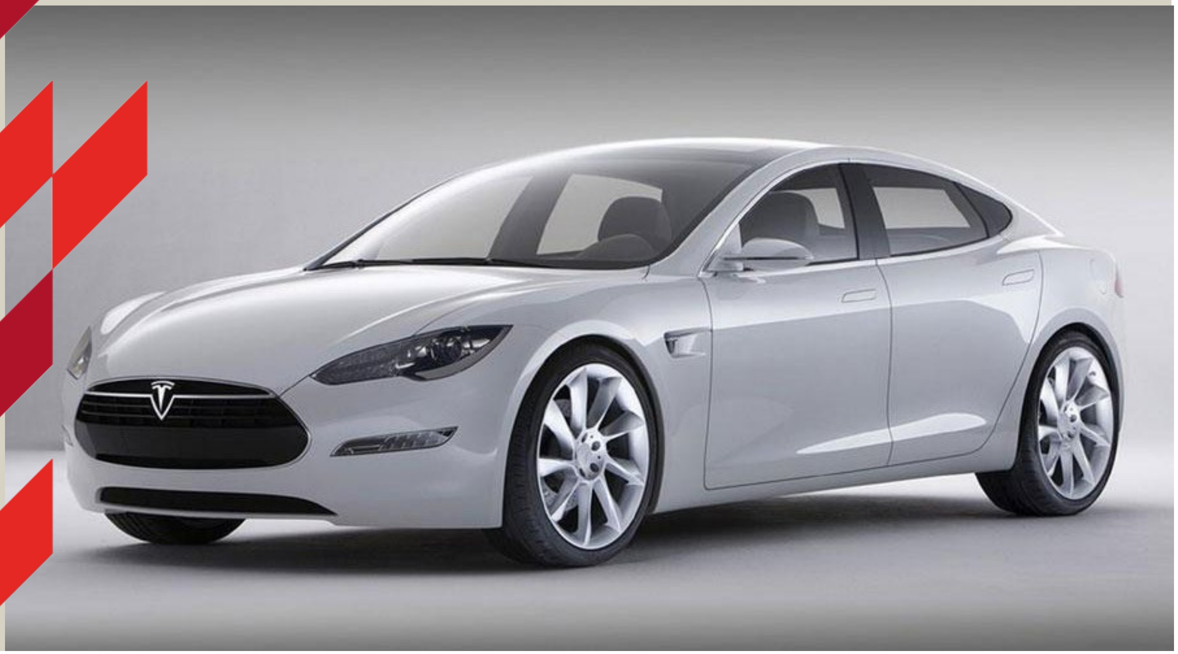
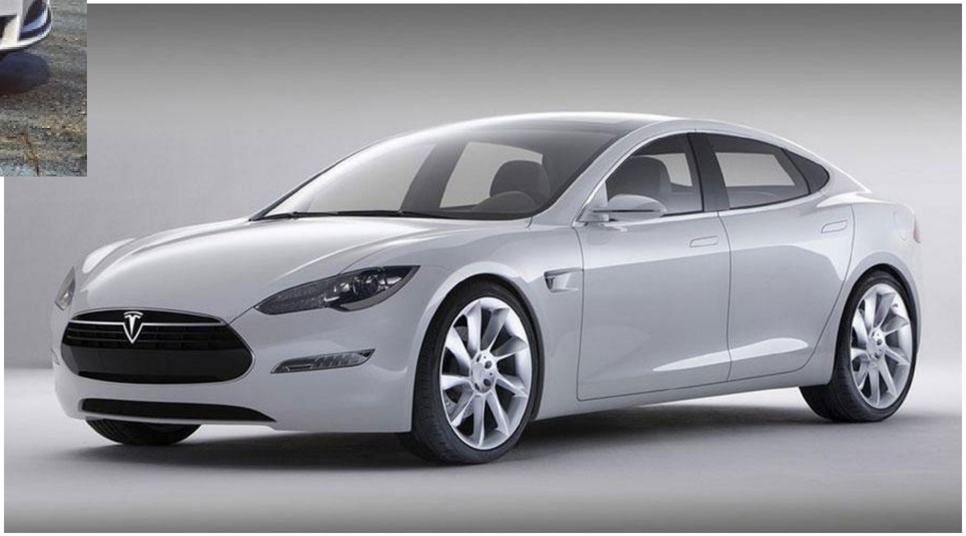
MECH2003, Mechanical Engineering Design

Motors and Motor Selection



Motors and Motor Selection

What is the most significant difference between these two cars?



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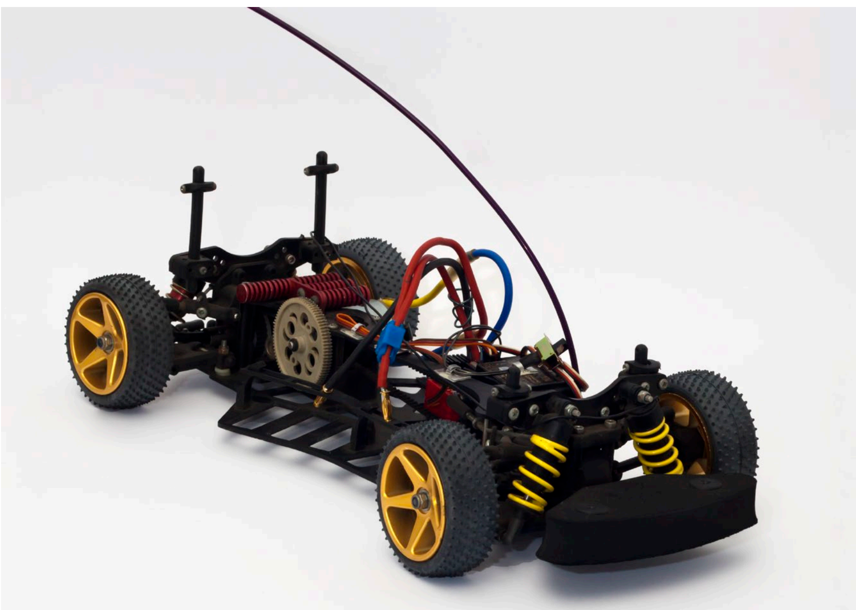
Motors and Motor Selection

There are an array of devices that can be powered by either electrical or chemical energy – toy cars



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Motors and Motor Selection

There are an array of devices that can be powered by either electrical or chemical energy – trains

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Motors and Motor Selection

There are an array of devices that can be powered by either electrical or chemical energy – Scooters

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Motors and Motor Selection

There are an array of devices that can be powered by either electrical or chemical energy – lawn mowers

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Motors and Motor Selection

There are an array of devices that can be powered by either electrical or chemical energy – chainsaws

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Motors and Motor Selection

There are an array of devices that can be powered by either electrical or chemical energy – aircraft

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Today we will learn about:

- Devices that convert either chemical or electrical energy into kinetic energy.
- How these devices operate and what supporting equipment they require.
- The advantageous and disadvantageous of using these devices in comparison to the alternatives presented here.
- How to calculate the influence that the torque characteristics will have on the desired output of a mechanical system.

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Motors and Motor Selection

How do we convert chemical energy into kinetic energy?

With the aid of an Internal Combustion Engine.

There are alternative methods for powering a machines, thankfully internal combustion engines are not the only option.

There are several different types of internal combustion engines that include:

- Four stroke engines
- Two stroke engines
- Rotary engines

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Internal Combustion Engines

All these engines have one thing in common, they produce a mixture of fuel and air at a ratio that is volatile. This mixture is compressed, and then ignited so that combustion occurs.

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Internal Combustion Engines

The resultant pressurised gas is used to drive a mechanism that transfers kinetic energy to the output shaft of the engine.

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Internal Combustion Engines

Each engine completed this process in there own unique way, but they all suck, squeeze, bang and blow…

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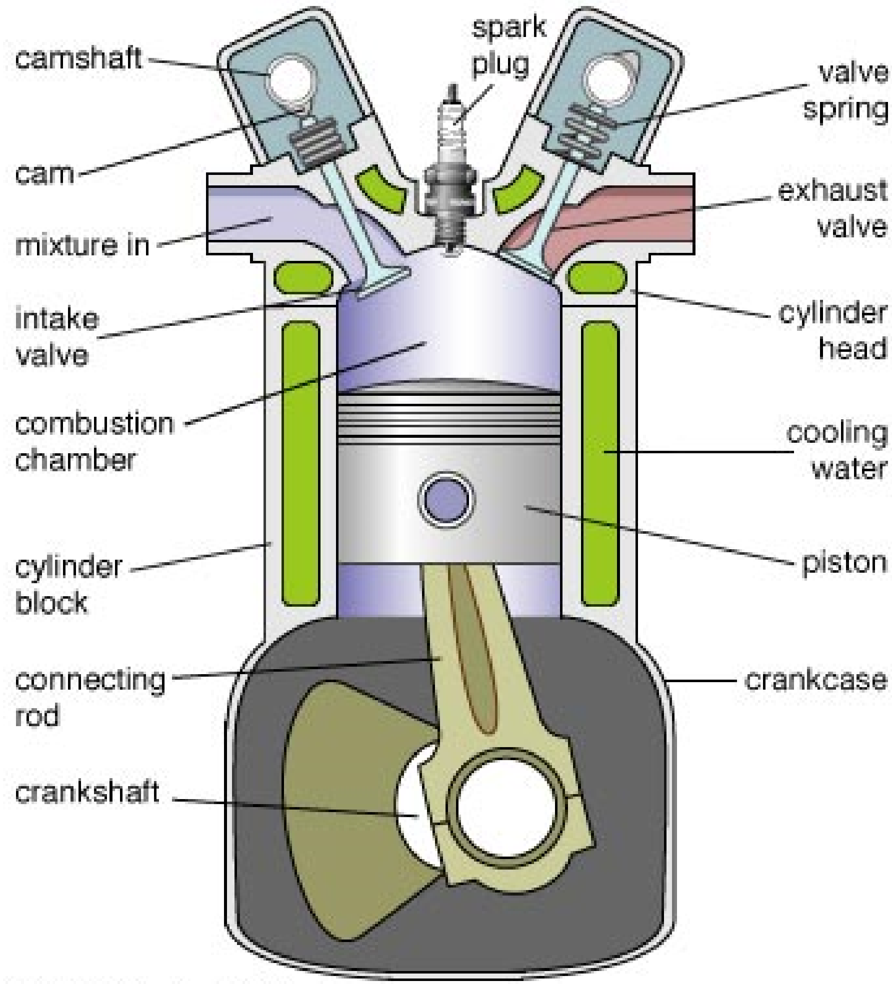
Internal Combustion Engines – Four stroke engines

The most common type of internal combustion engine is a four stroke engine. These are commonly used to power a large variety of vehicles.

Internal Combustion Engines – Four stroke engines

Each cylinder comprises of multiple moving components that allow the mixture to enter the cylinder, be compressed, ignite and then transfer the kinetic energy to the output shaft.



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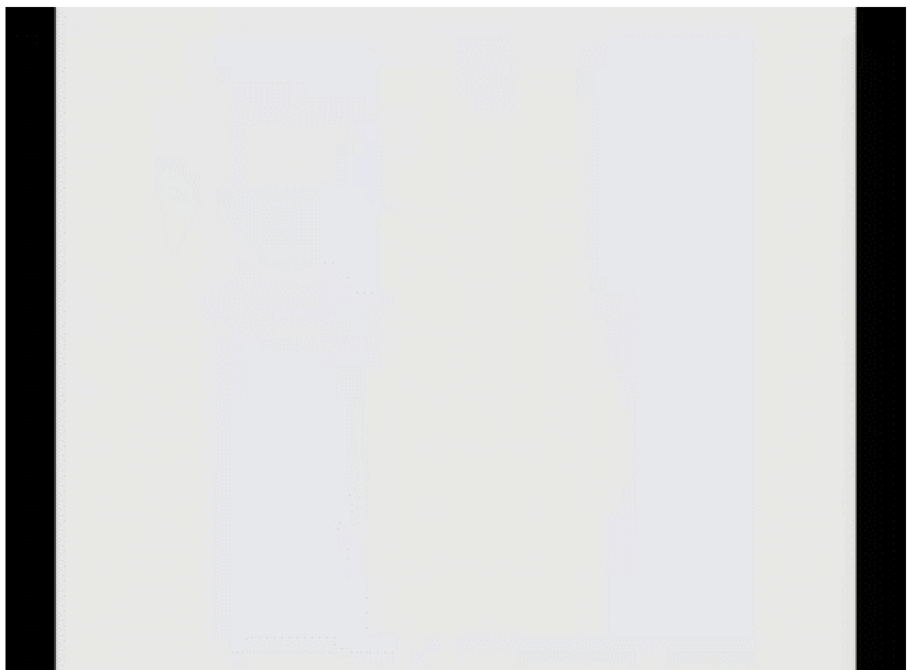
Internal Combustion Engines – Four stroke engines

They are referred to as four strokes engines as the piston passes either up or down four times in a single combustion cycle, note how critical the timing of opening or closing the valves is.



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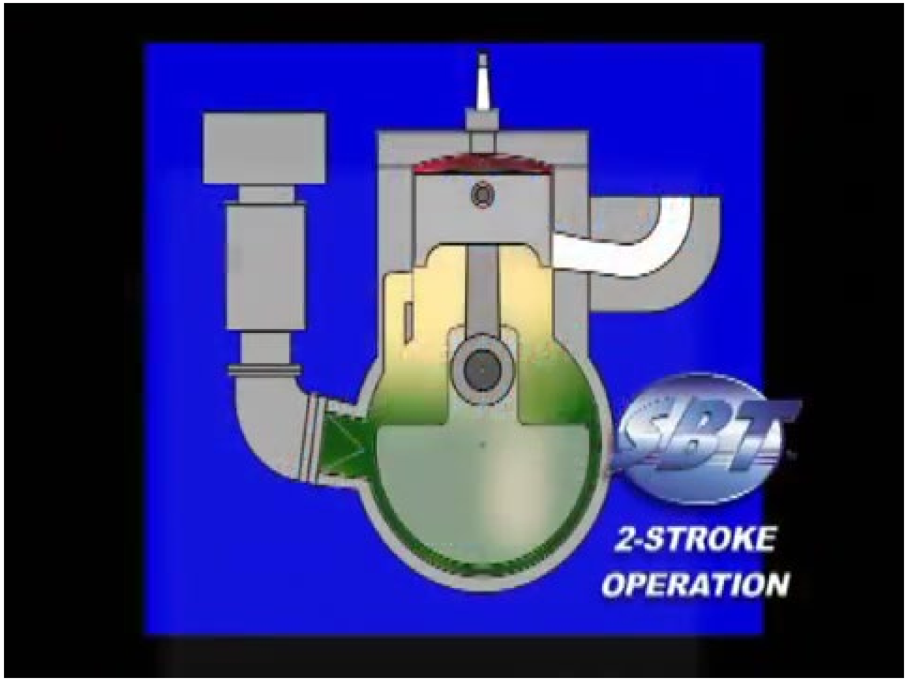
Internal Combustion Engines – Two stroke engines

Two stroke engines have similar components to a four stroke engine, but the cylinder only moves up and down once in each direction per cycle.



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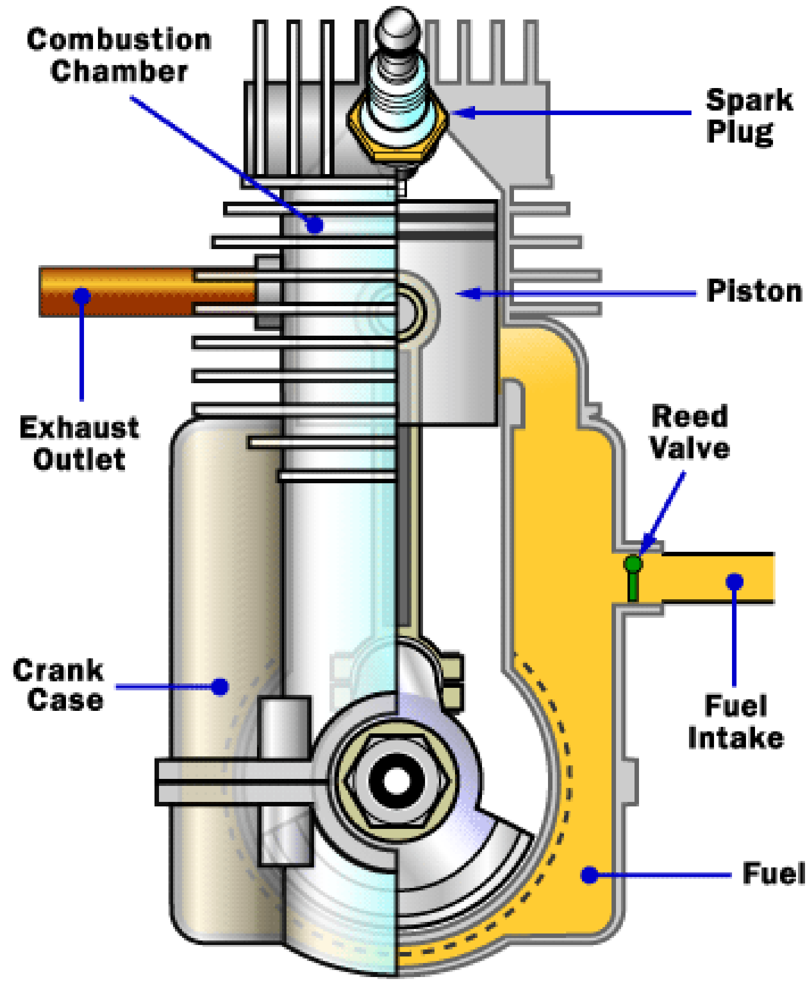
Internal Combustion Engines – Two stroke engines

As a result, there is no need to have exhaust and intake valves as the air/fuel mixture enters as the exhaust leaves while the piston is in its lowest position.



Internal Combustion Engines – Two stroke engines

Two stroke engines are typically found in remote control cars, lawnmowers, chainsaws and some scooters as they are less complex and cheaper to manufacture.

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Rotary engines are very unique internal combustion engines. They do not utilise pistons, instead they have an eccentrically mounted rotor that compresses the air fuel mixture and is also driven by the combusted and expanding gasses.

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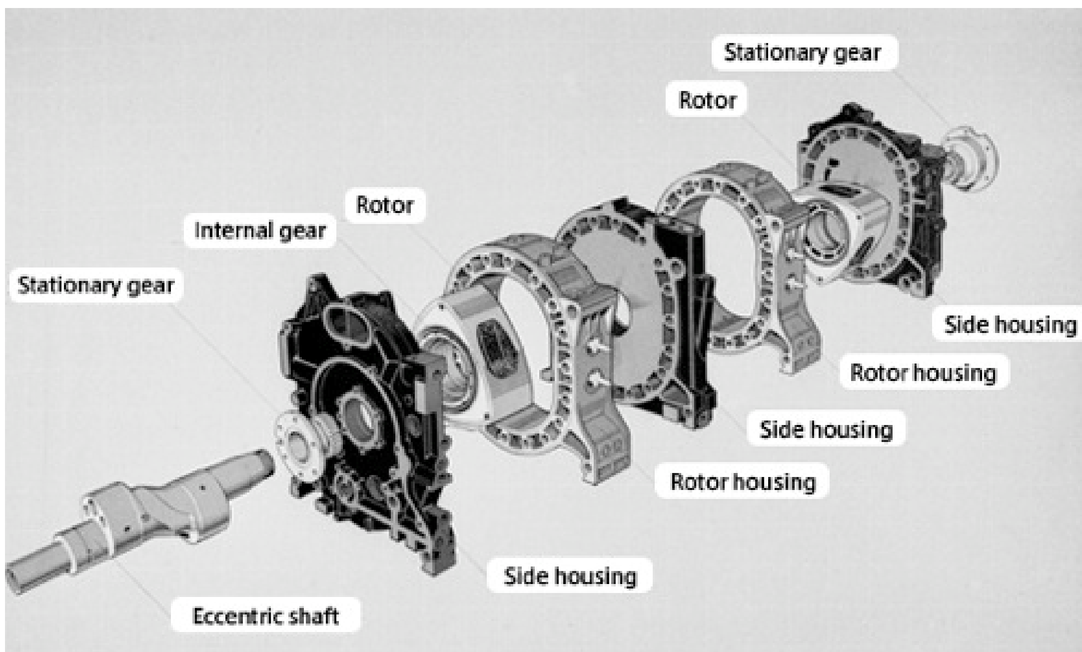
Internal Combustion Engines – Rotaries

The technique utilised by a rotary engine dictates that even less moving components are required in comparison to four or two stroke engines and they ignite fuel three times per revolution.



Internal Combustion Engines – Rotaries

They have been utilised in cars and motorbikes.

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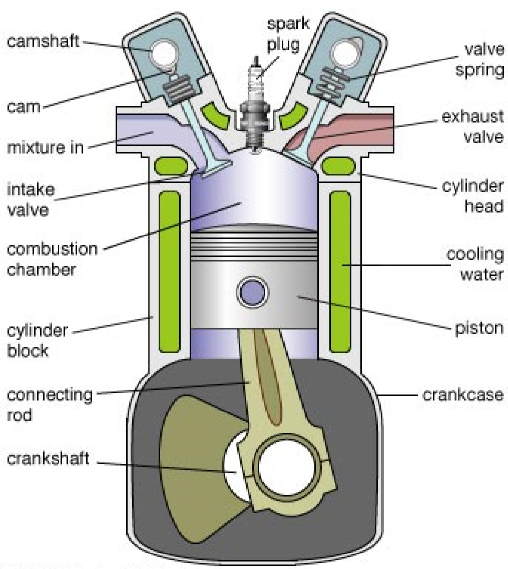
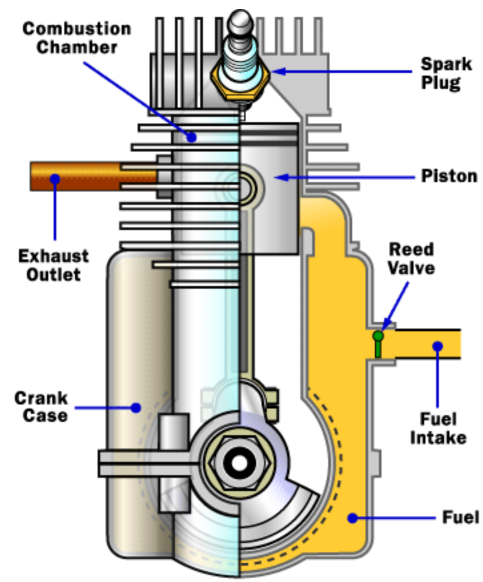
Internal Combustion Engines

Advantages and disadvantages exist for each type of engine that may make it suitable for different applications. In terms of cost, the engines with the least components would be cheapest making a 2 stroke engine the most cost effective.





Least expensive to most expensive

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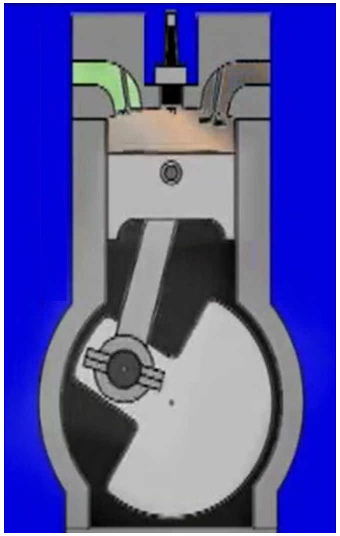
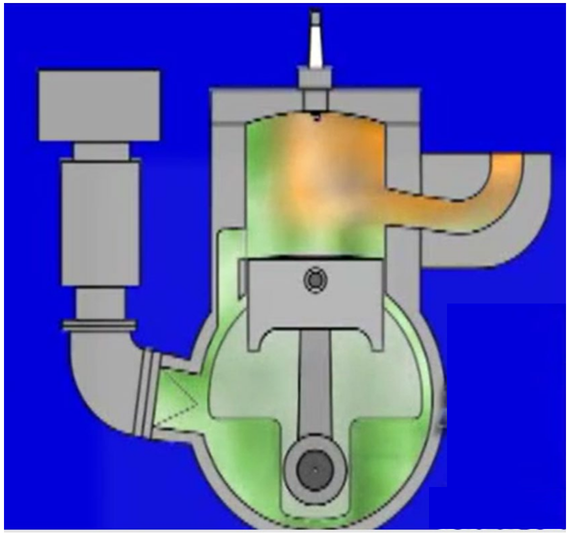
Internal Combustion Engines

Regarding efficiency and power output, the 4 stroke engine would be considered the best because its operation ensures that all the fuel in the cylinder is combusted and very little escapes through the exhaust unburnt.





Most to least efficient

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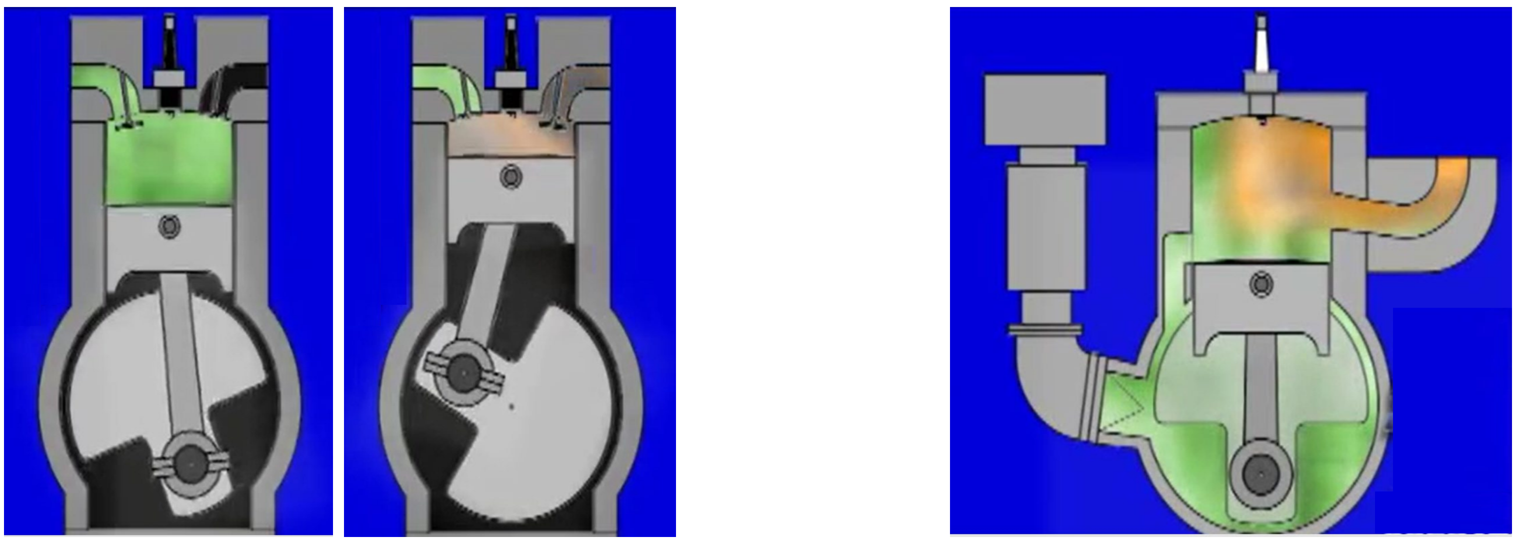
Internal Combustion Engines

All combustion engines produce carbon dioxide. Two stroke engines though produce additional pollutants because oil is added to the fuel to lubricate the crank which results in some oil being burnt in the process.



Most to least efficient

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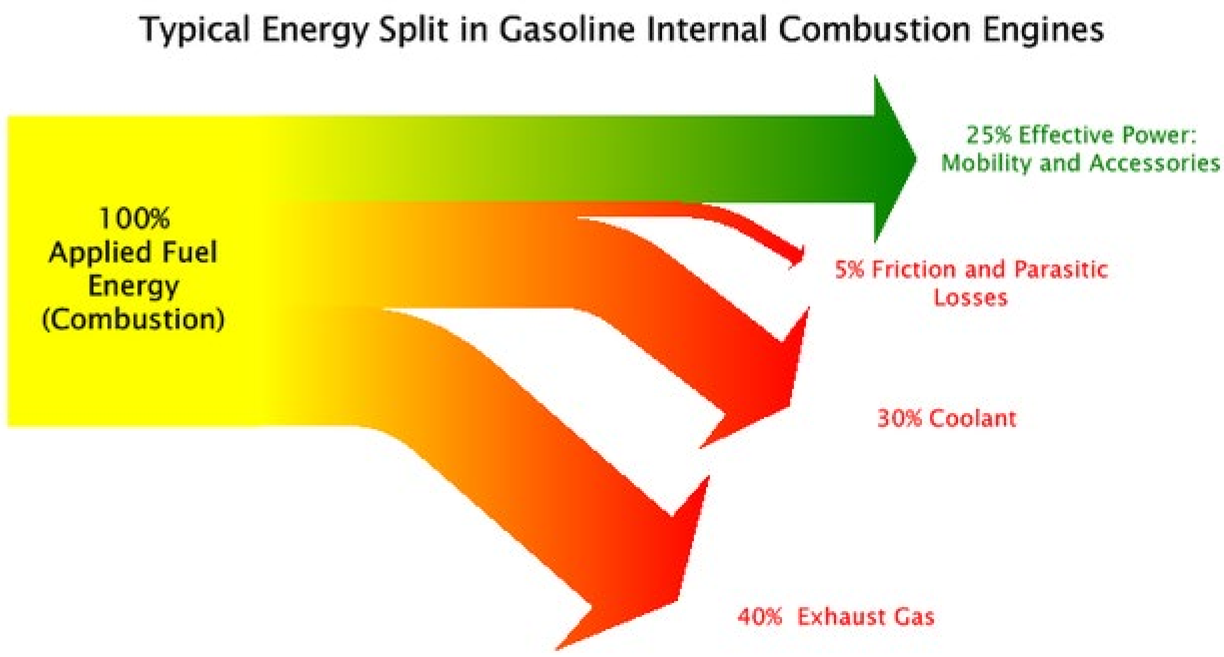
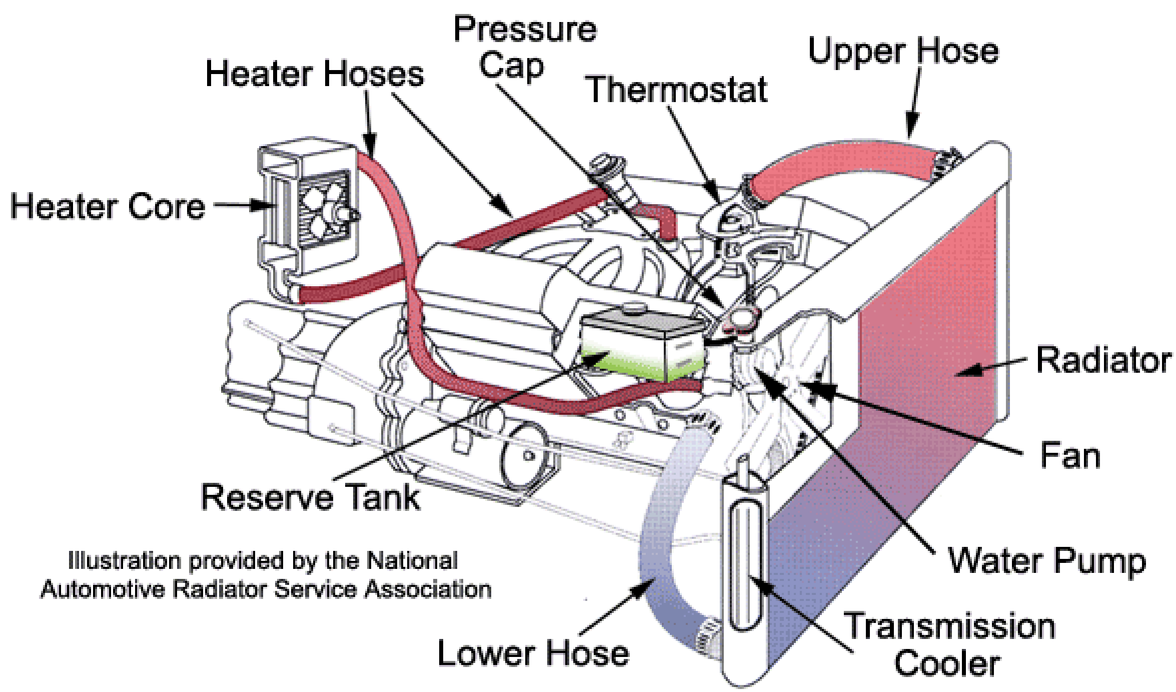
Internal Combustion Engines

The efficiency of an IC engine varies depending on the speed with which it is operated and can be anywhere between 25% and 30% efficient.

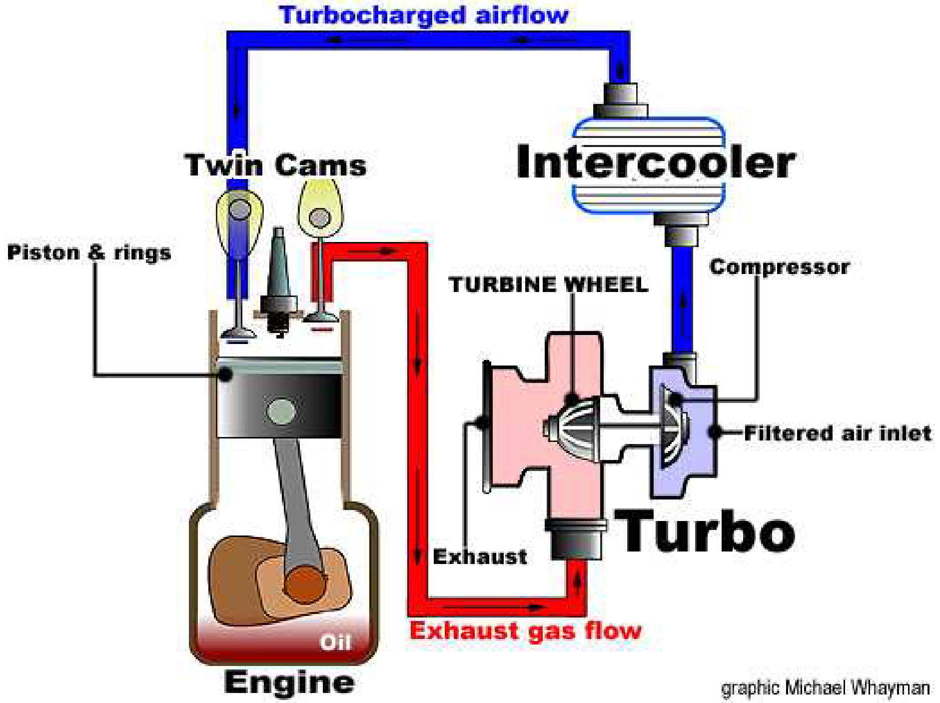


It should be noted that a significant portion of the power produced by an engine is converted to heat and noise. For this reason some IC engines require radiators or cooling fins to help dissipate the unwanted heat.



Internal Combustion Engines

Some engines incorporate turbos in an attempt to recover some of the energy lost through the exhaust gasses. This is used to pressurise the air entering the chamber increasing the quantity of fuel and air that can be combusted.



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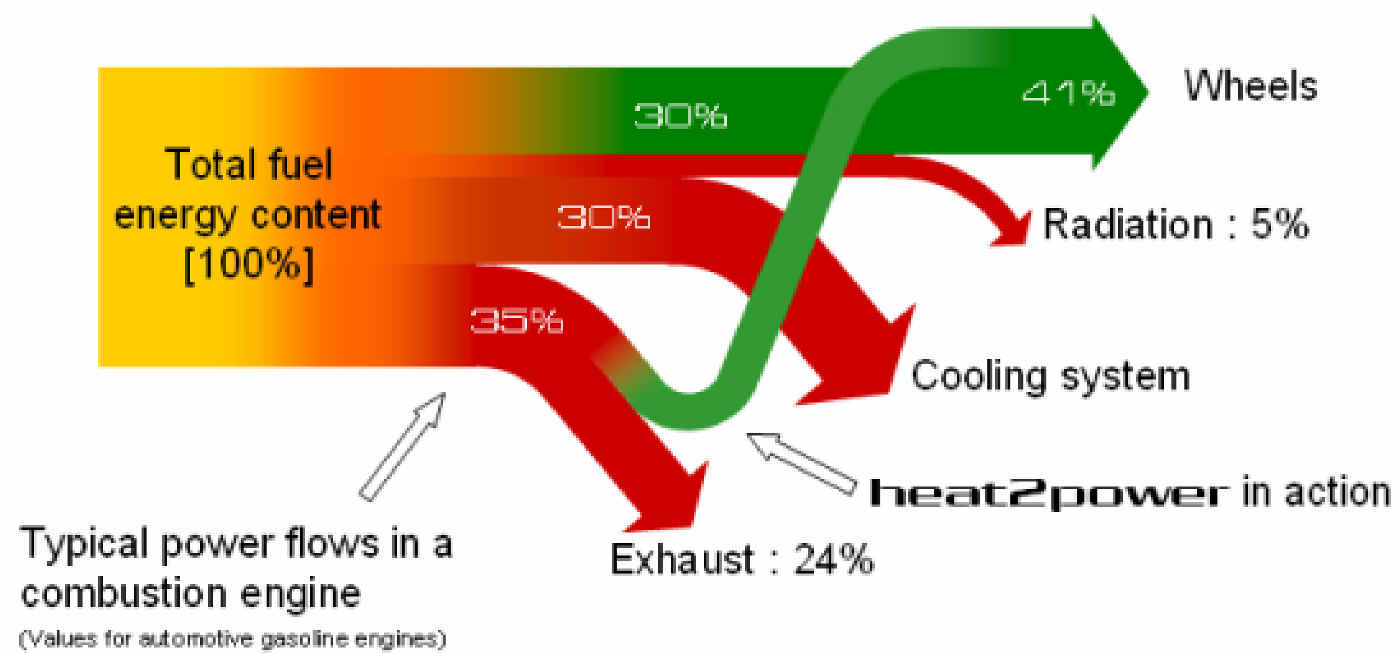
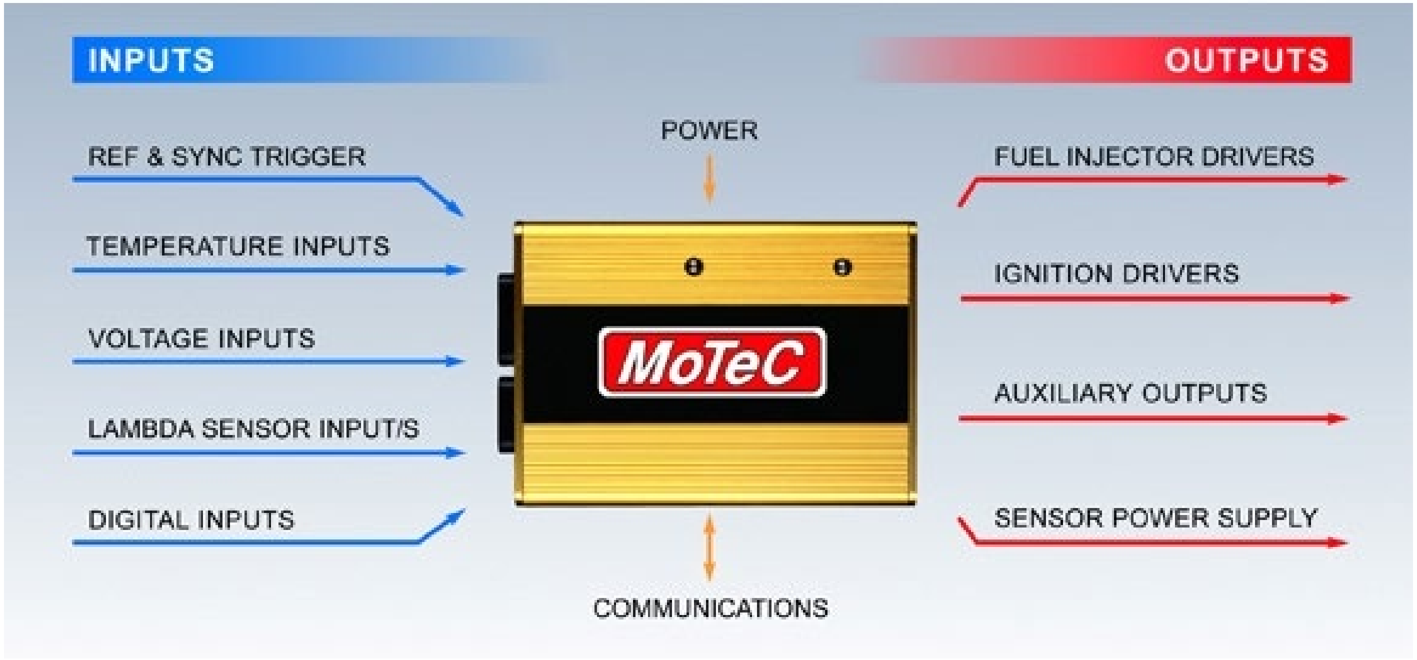
Internal Combustion Engines

As a result, the energy density and the efficiency of the system can be increased given that some of the wasted heat energy is being reutilised.



A critical factor for the most efficient operation of an internal combustion motor is the timing of the ignition and control of the air fuel mixture entering the cylinder. This is usually managed using an Engine Control Unit (ECU).



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Most internal combustion engines operate with a fuel to air ratio by mass of approximately 13%. This value is monitored in an engine with the quantity known as the lambda value.

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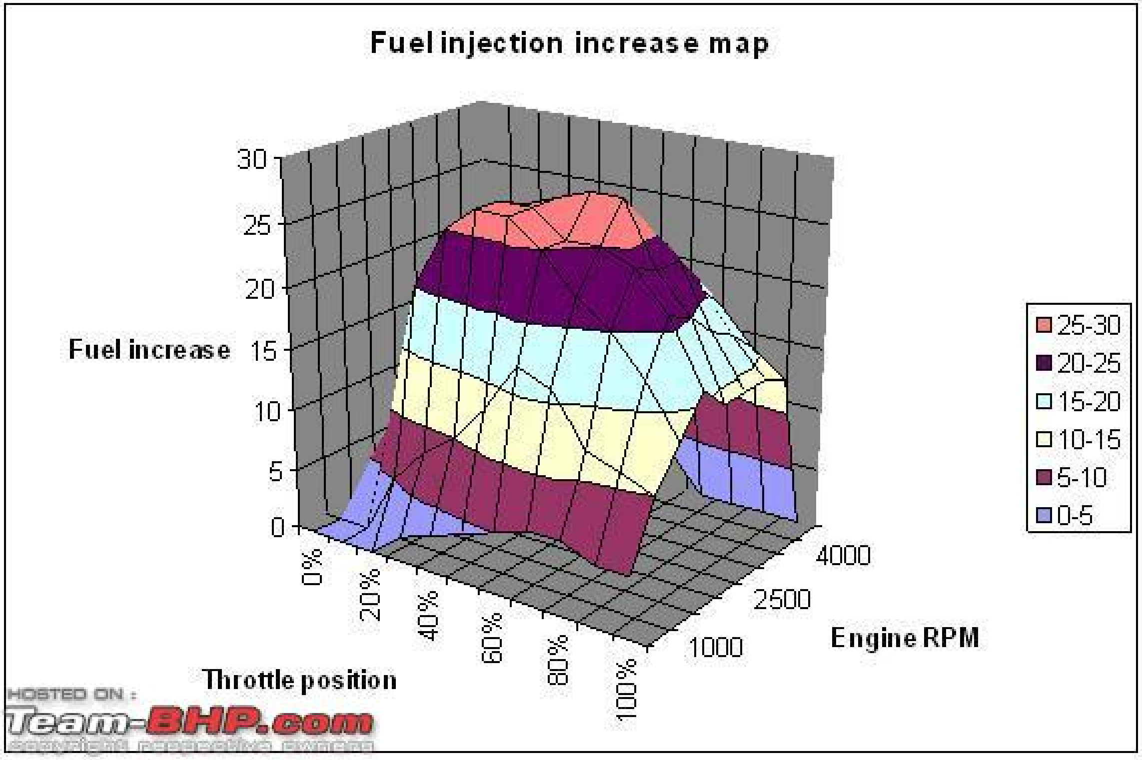
Internal Combustion Engines

An ECU will incorporate maps that relate when the optimum time to fire the ignition is and the desired air fuel mixture depending on the speed of the engine and the throttle position.



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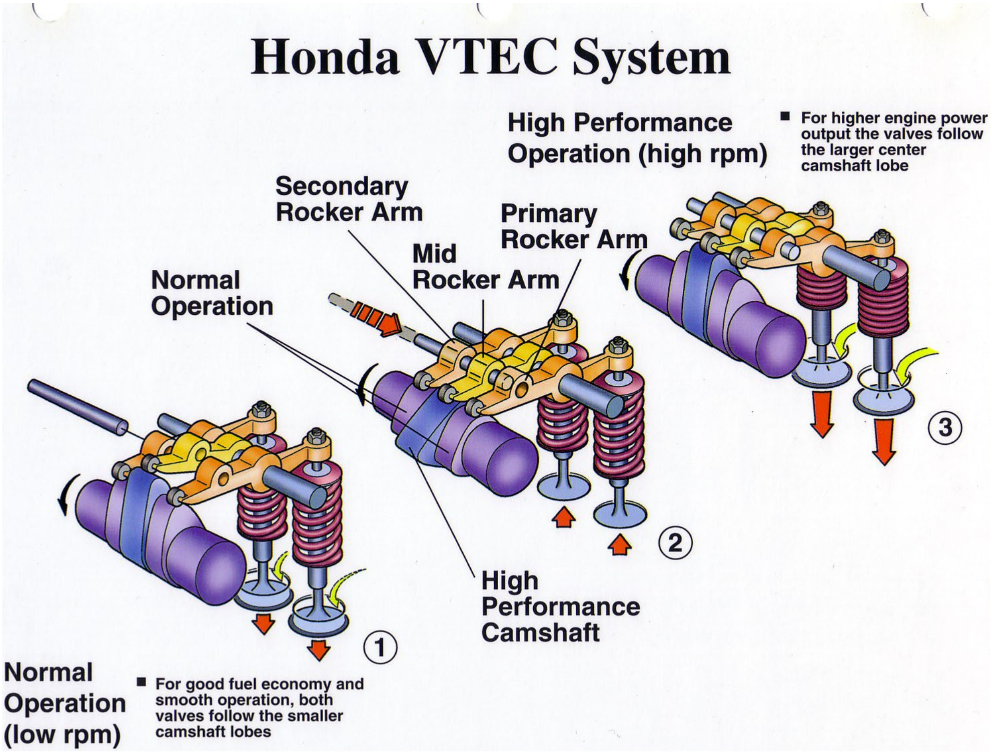
Internal Combustion Engines

More advanced four stroke motors also have the ability to alter when the intake or exhaust valves are opened to further enhance efficiency and performance.



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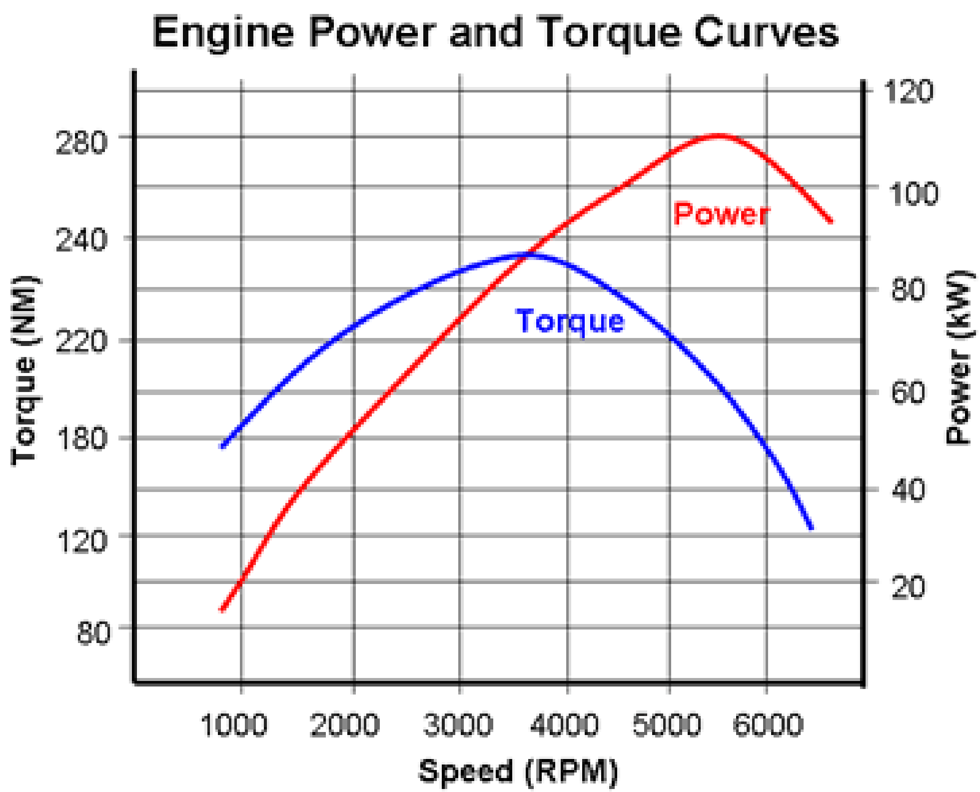
Internal Combustion Engines

The power and torque produced by a 4 stroke motor varies depending on the speed with which the motor is turning. The torque curve can be estimated as an inverted parabolic shape.



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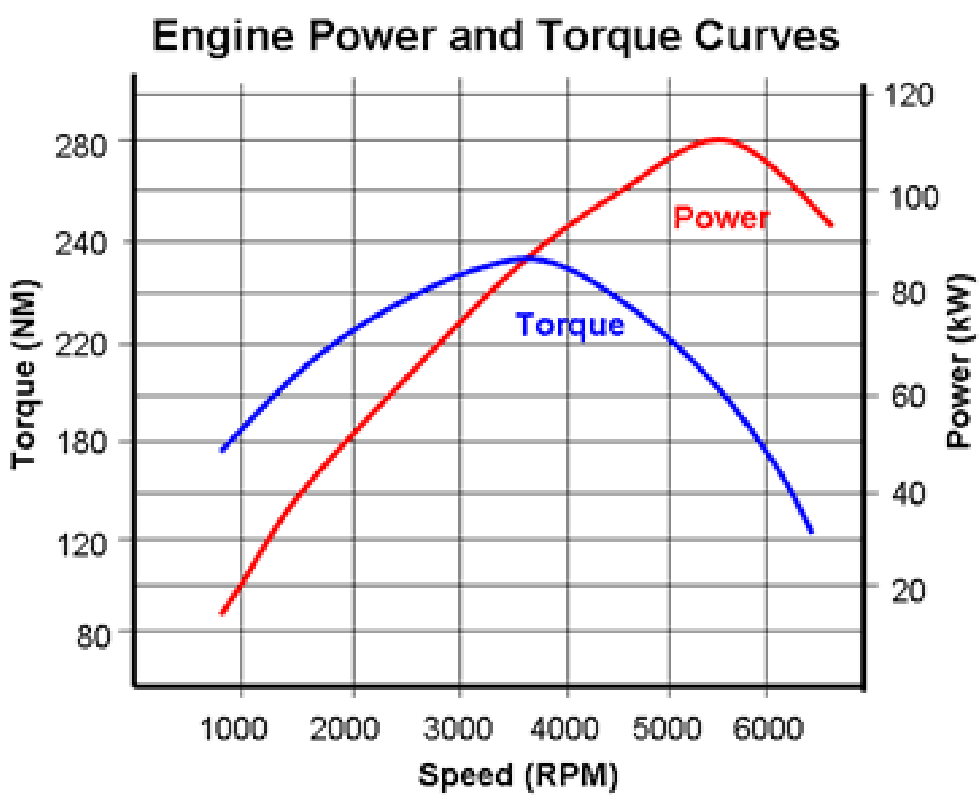
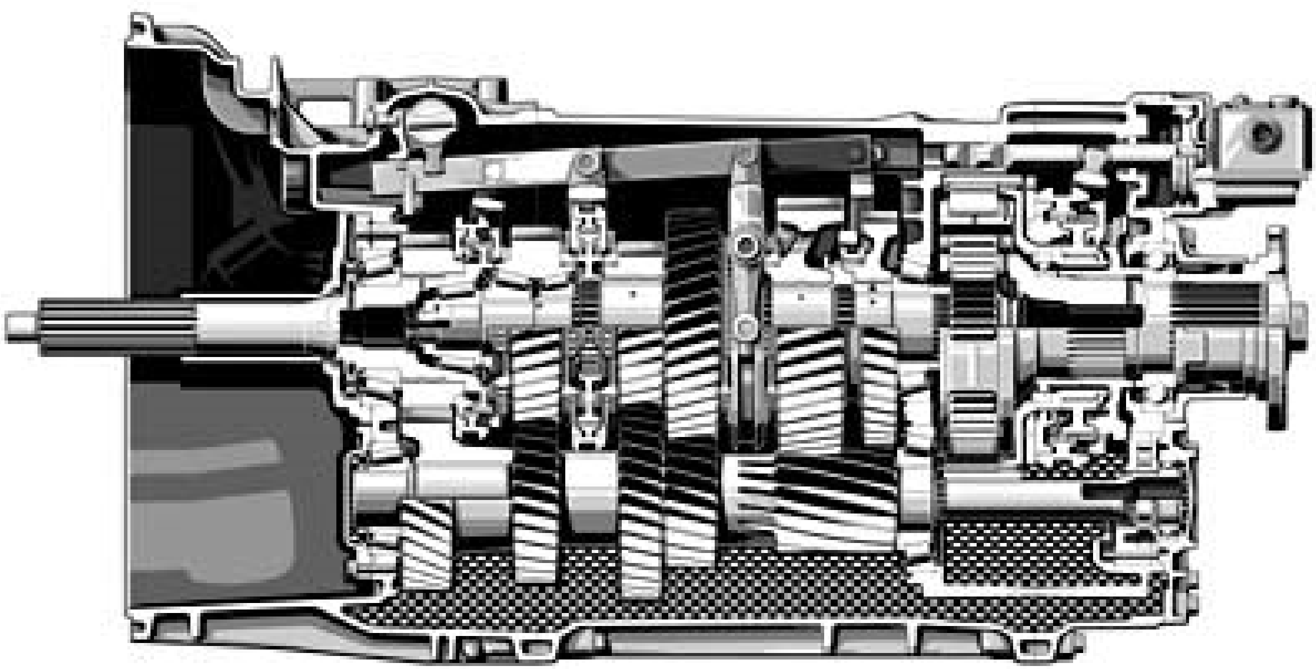
Internal Combustion Engines

The small "optimum" band with which an IC engine operates within causes an additional complication that often needs to be addressed.



Internal Combustion Engines

To keep the engine operating close to the peak of the power curve, a gearbox is required to ensure that an adequately large speed range can be achieved which further reduces the efficiency.



Example 1: How many times will a cylinder belonging to a 2 stroke engine fire if it is operating at a constant 3000rpm over the duration of a second?

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$$\frac{3000}{60} = 50\,rev/s$$

Two-stroke engines fire every cycle, therefore it will fire 50 times.

Example 2: How many times will a cylinder belonging to a 4 stroke engine fire if it is operating at a constant 3000rpm over the duration of a second?

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Example 2: How many times will a cylinder belonging to a 4 stroke engine fire if it is operating at a constant 3000rpm over the duration of a second?

$$\frac{3000}{60} = 50\, rev/s$$

Four-stroke engines fire every second cycle, therefore it will fire 25 times.

Example 3: If an IC engine outputs 200kW and is 30% efficient, determine the heat that would have to be rejected by the radiator assuming that the parasitic losses are insignificant and equal amounts of heat was being rejected between the radiator and the exhaust?

Example 3: If an IC engine outputs 200kW and is 30% efficient, determine the heat that would have to be rejected by the radiator assuming that the parasitic losses are insignificant and equal amounts of heat was being rejected between the radiator and the exhaust?

$$P_{total} = P_{out} + P_{exhaust} + P_{radiator} + P_{parasitic}$$

Assuming no parasitic loss:

$$P_{exhaust} = P_{radiator} = 35\%$$

$$\frac{P_{out}}{P_{radiator}} = \frac{200\ kW}{P_{radiator}} = \frac{30\%}{35\%}$$

$$\therefore P_{radiator} = 233.3\ kW$$

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Example 4: A Formula One engine during the late 1990's was able to operate at up to 20000rpm. If these 3 litre V10 motors had a stroke of 150mm, what acceleration would the piston head experience at max rpm assuming its velocity was sinusoidal?

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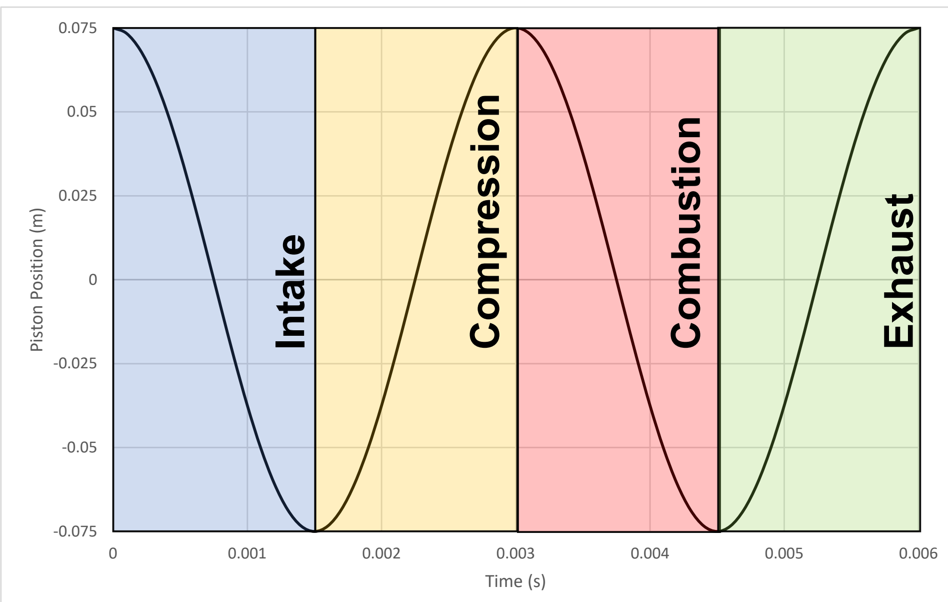
Motors and Motor Selection

Example 4: A Formula One engine during the late 1990's was able to operate at up to 20000rpm. If these 3 litre V10 motors had a stroke of 150mm, what acceleration would the piston head experience at max rpm assuming its velocity was sinusoidal?



166.67 cycles per second

1 cycle = 0.006s

Cycle can be expressed by

$$y = \alpha \cos bt$$

$$\text{Where } \alpha = \frac{150}{2} mm$$

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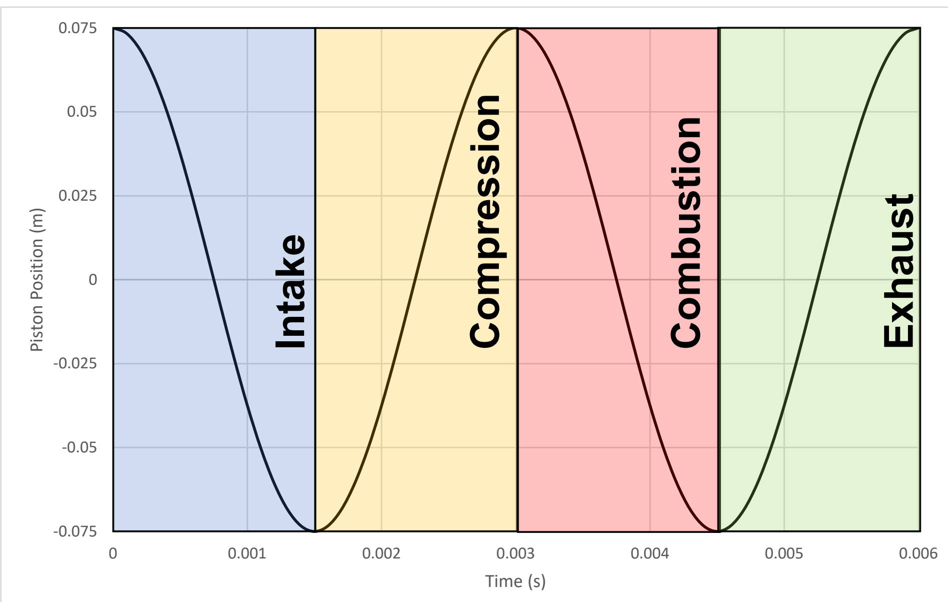

y=0 at t=0.00075s

$$7.5 \times 10^{-4} b = \frac{\pi}{2}$$

$$\therefore b = \frac{\pi}{1.5 \times 10^{-3}}$$

$$y = 0.075 \cos \frac{\pi}{1.5 \times 10^{-3}} t$$

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Example 4: A Formula One engine during the late 1990's was able to operate at up to 20000rpm. If these 3 litre V10 motors had a stroke of 150mm, what acceleration would the piston head experience at max rpm assuming its velocity was sinusoidal?

Remember $\mathrm{v} = \frac{dy}{dt}, \mathrm{a} = \frac{d^2y}{dt^2}$

$$y' = \frac{0.075\pi}{1.5 \times 10^{-3}} \sin \frac{\pi}{1.5 \times 10^{-3}} t$$

$$y'' = \frac{0.075\pi^2}{(1.5 \times 10^{-3})^2} \cos \frac{\pi}{1.5 \times 10^{-3}} t$$

Maximum acceleration at t=0

$$a = \frac{0.075\pi^2}{(1.5 \times 10^{-3})^2} = 328900 \frac{m}{s^2}$$

As mentioned previously, electric motors offer an alternative method of producing kinetic energy. Electric motors can belong to one of two main categories, either:

- Alternating Current (AC) motors
- Direct Current (DC) motors

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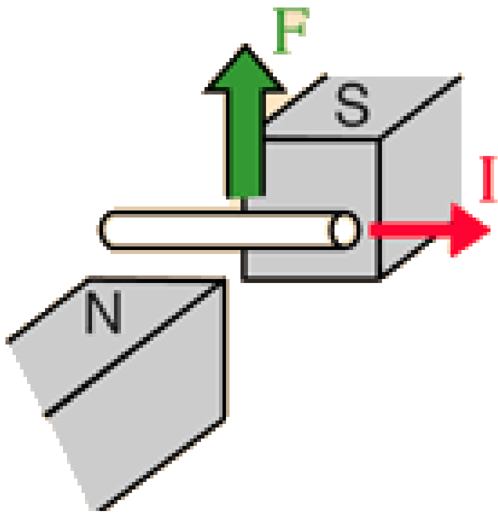
Electric Motors

They both take advantage of the fact that a conductor carrying current in a magnetic field will experience a force.



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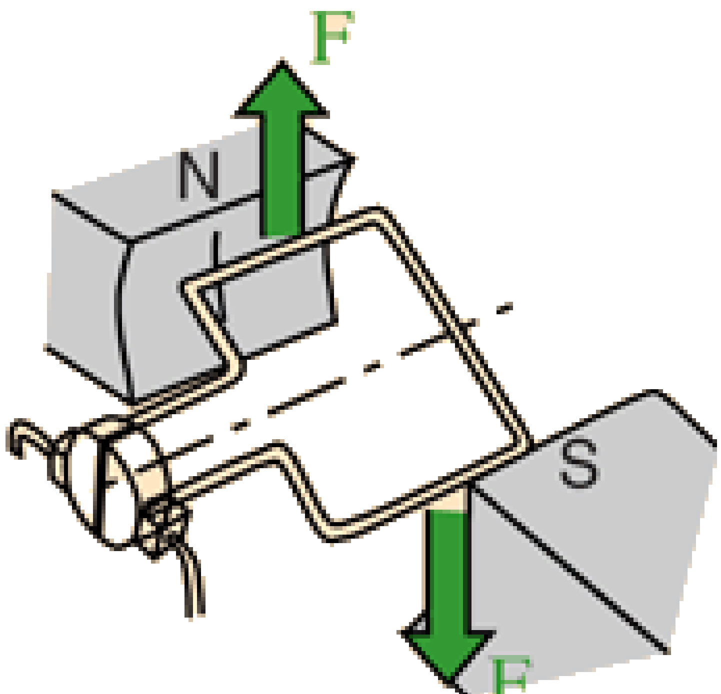
Electric Motors

If a conductor is bent into a coil shape, the two sides of the coil will experience forces acting in the opposite directions as the current is flowing in the opposite directions on each side of the coil.



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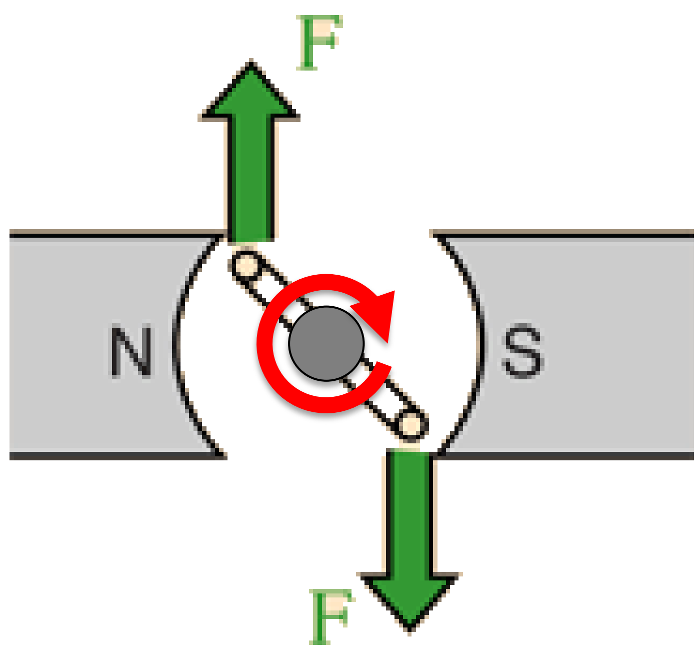
Electric Motors

The pair of forces are acting either side the output shaft of an electric motor which would result in a torque that would act on the output shaft.



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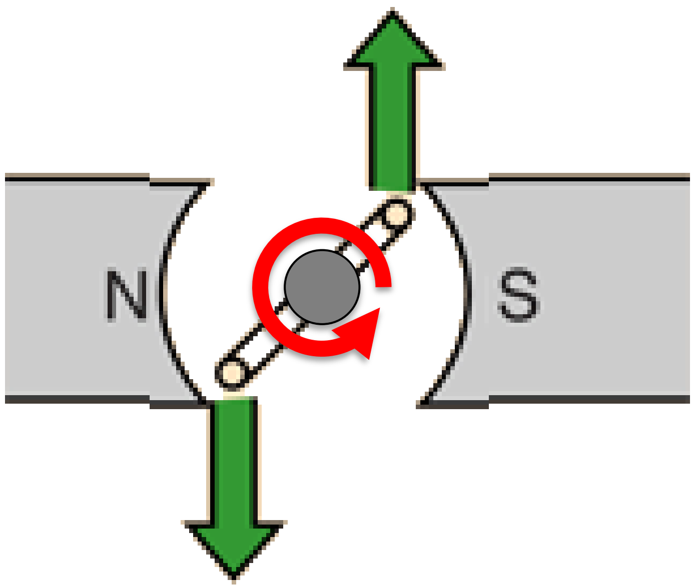
Electric Motors

Eventually the coil will rotate and if the current continued in the same direction through the coil, the direction of each force would result in a torque being created in the opposite direction to that previously.



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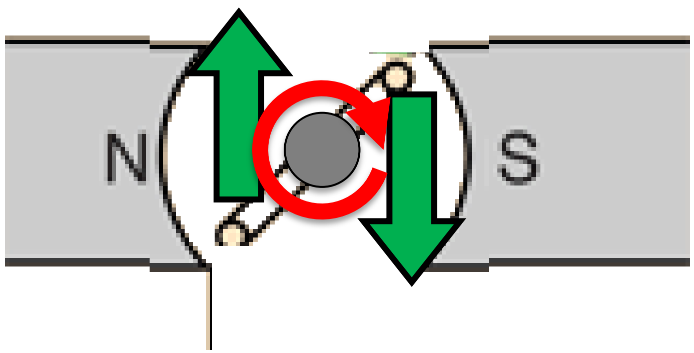
Electric Motors

Therefore a technique is required to reverse the forces acting on each side of the coil every time the coil travels through 180^{o}. This will produce a torque in a continuous direction and is achieved by changing the direction of the current through the coil.



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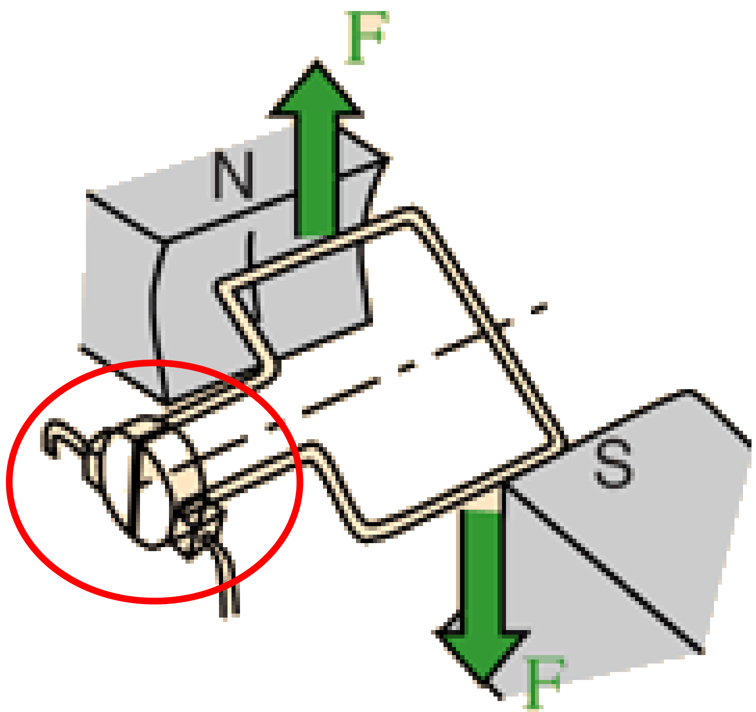
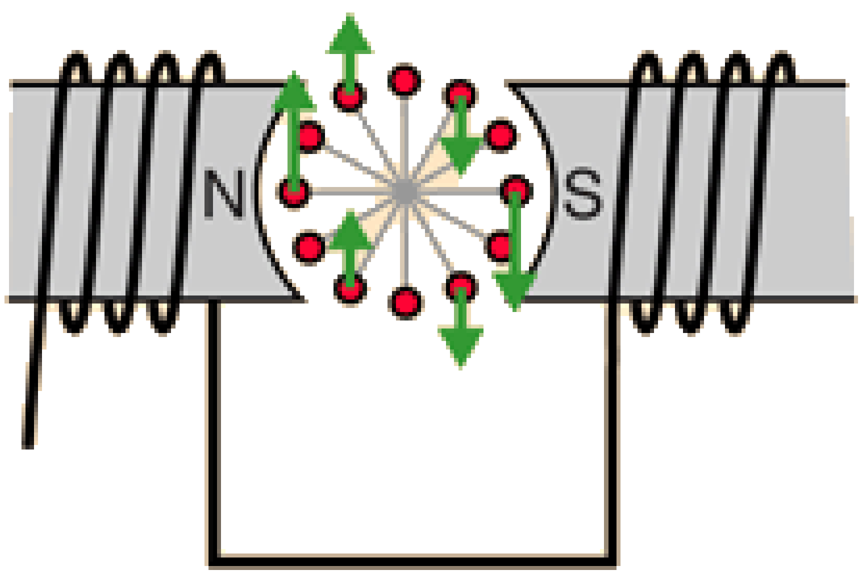
Electric Motors

For a motor that is supplied with direct current, this is achieved mechanically through the use of a commutator. The commutator comes in contact with brushes that switch the current flow in the coil.



Electric Motors

Combining a large number of coils, equaly spaced around a common output shaft allows the torque that is being produced to be more consistent.



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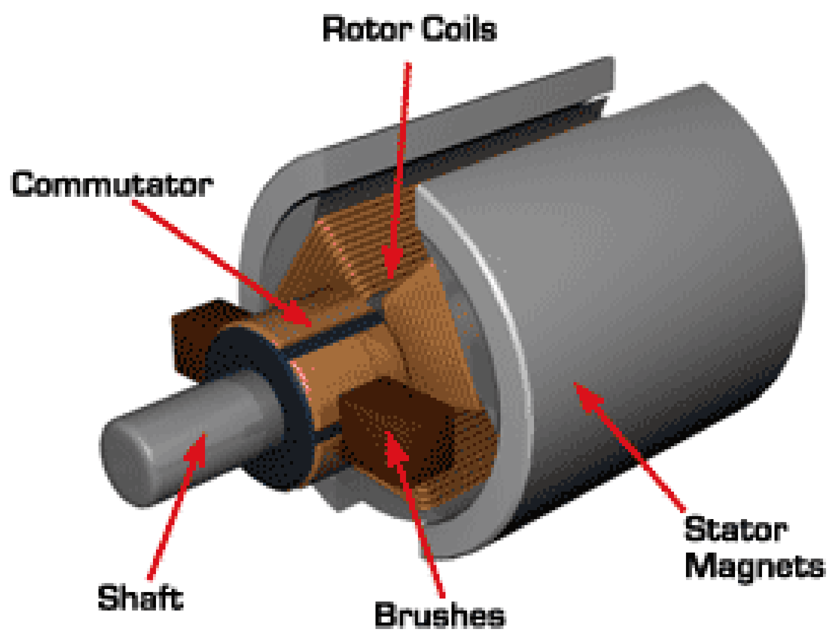
Electric Motors – DC Motors

Carbon or brass brushes are frequently used to provide the rotor coils with the current that is required to drive the motor.



Brushless DC motors exist that utilise electronics to switch the direction of the current as opposed to a commutator. The electronics that achieves this is referred to as the Drive.

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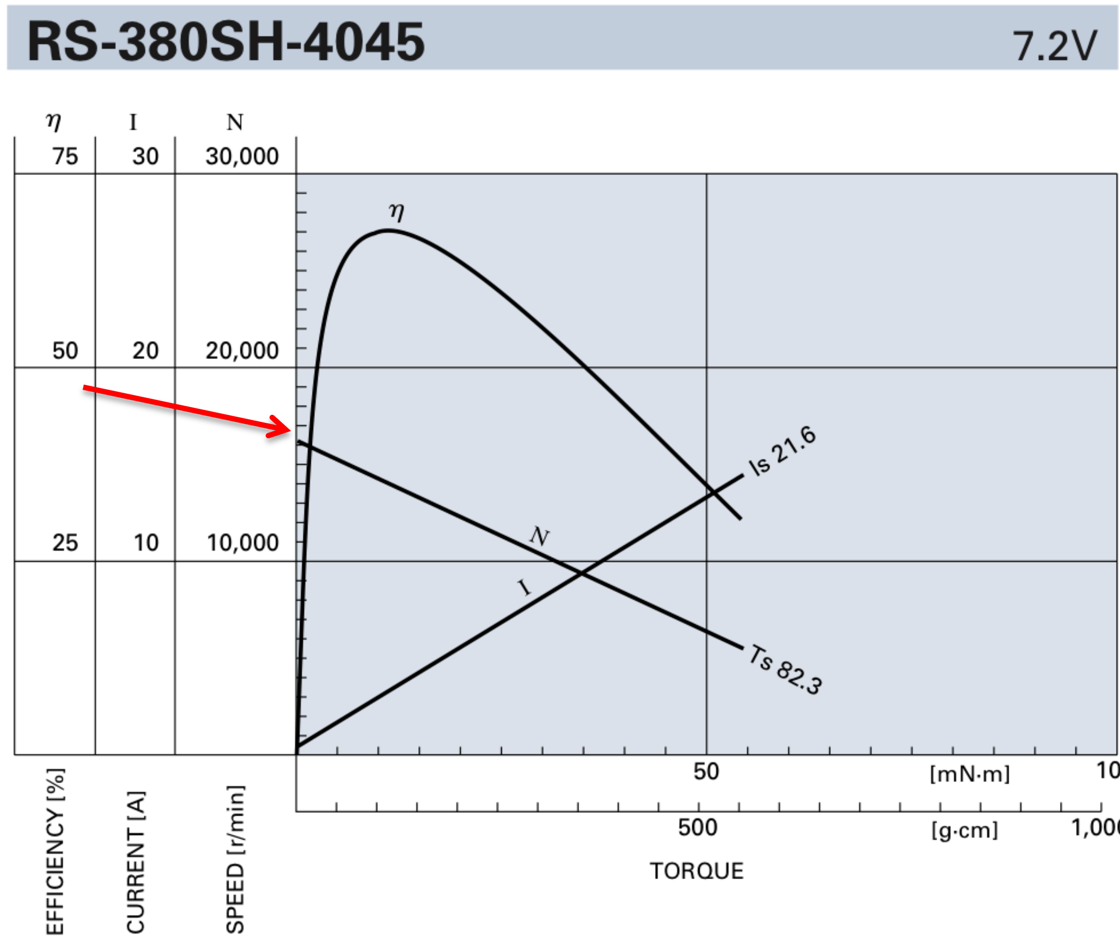
Electric Motors – DC Motors

The torque available from a DC motor is linearly proportional to its operating speed with decreasing torque as the speed increases.

Note how the DC motor peak torque is produced at 0 rpm!



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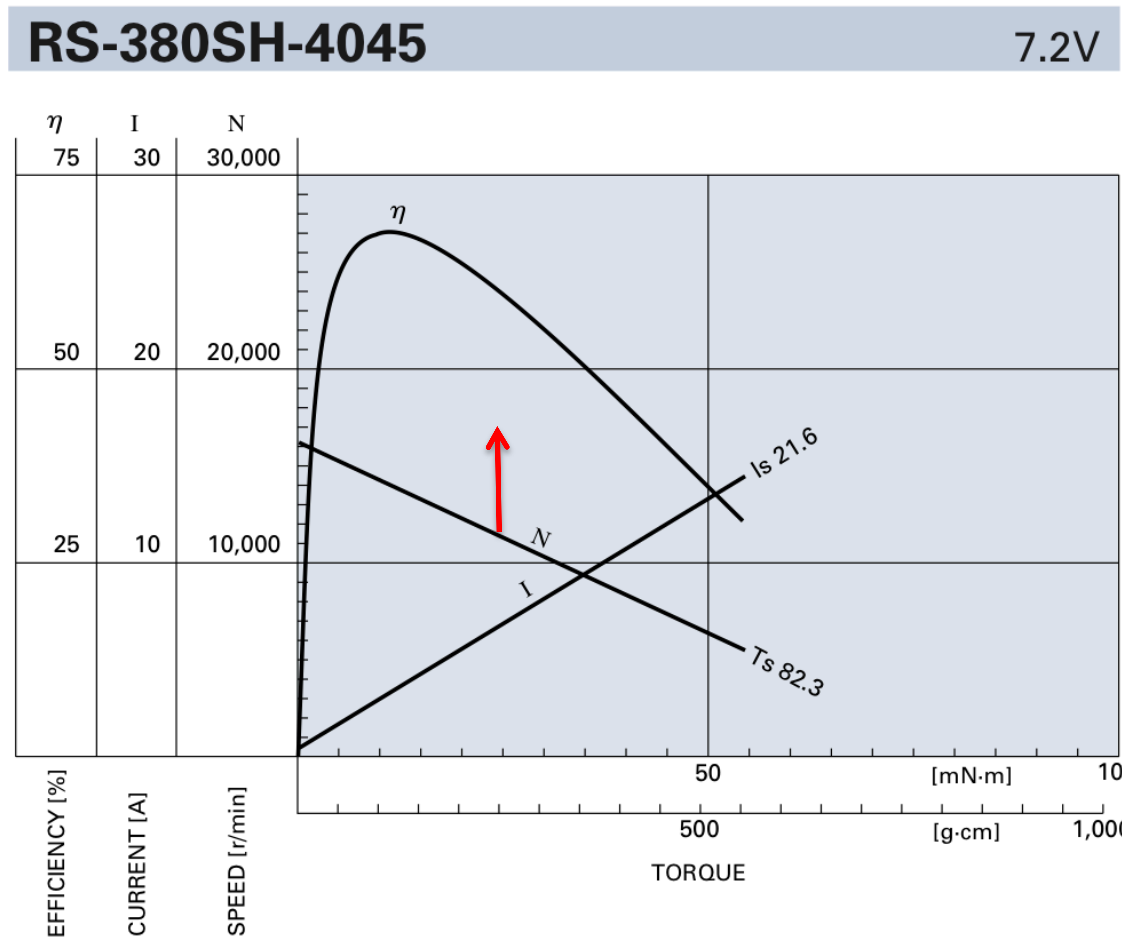
Electric Motors – DC Motors

The torque curve can be raised or lowered by altering the voltage of the electrical supply while maintaining the current.



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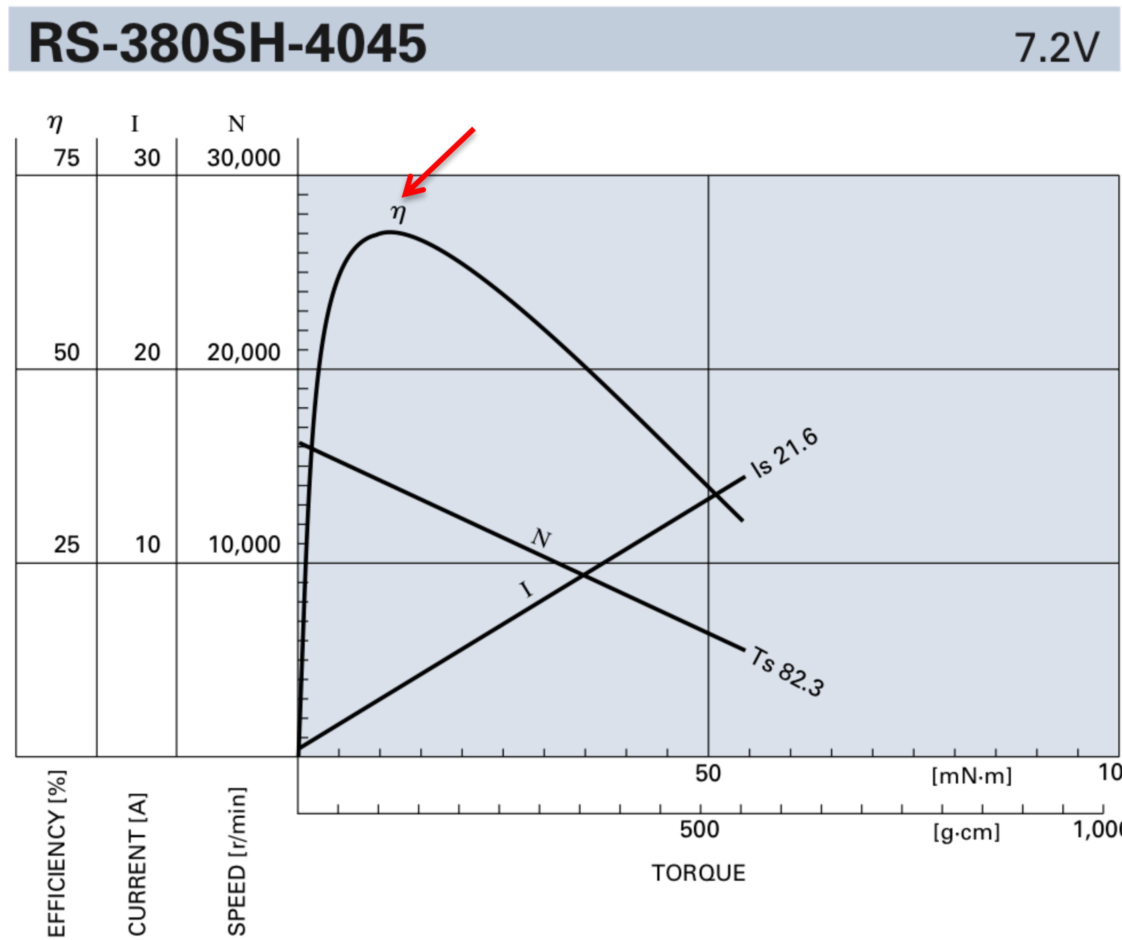
Electric Motors – DC Motors

The efficiency is also dependent on the operating speed. While this graph indicates a peak efficiency of 75%, greater efficiencies are possible for DC motors.



Large variety of DC motors exist that include:

- Permanent Magnet DC Motor
- DC Stepper Motors
- DC Servo Motors

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- Permanent Magnet DC Motor - (inexpensive up to 300 W). Requires large DC currents which may be difficult to get from common power supplies. Inexpensive and simple to control speed using a chopped DC supply from a battery.
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- DC Stepper Motors - common up to a 200 W. Give simple and reliable open loop position control. Have high inertia and can be under-damped. Require sophisticated drive electronics.
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All the above options can be considered to be low to medium power options.

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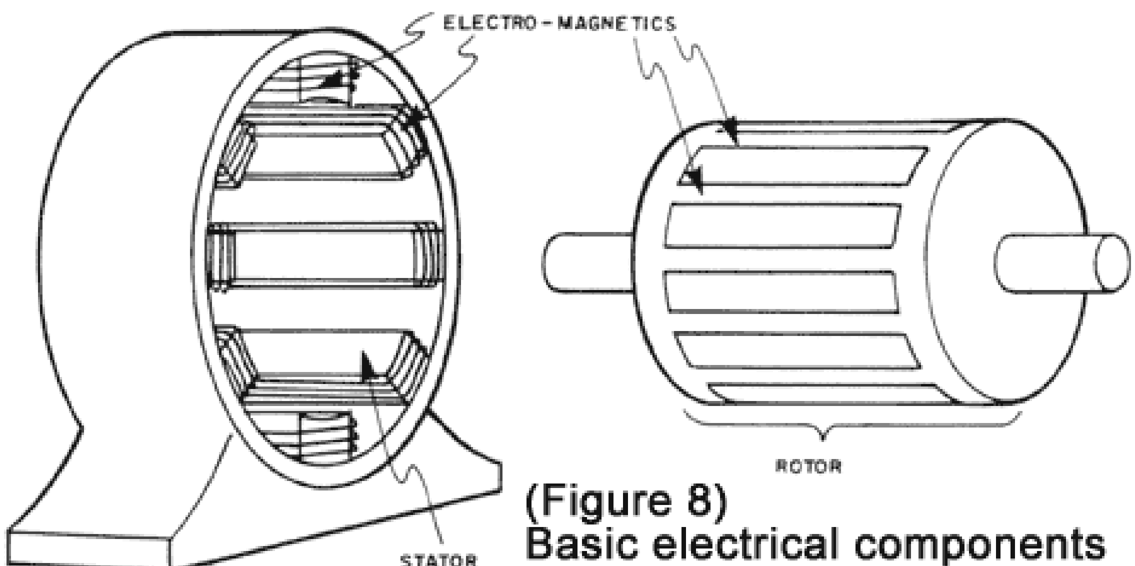
Electric Motors – AC Motors

AC motors are the best option for high powered drives (>300W) and are inexpensive when required to operate a single speed. There large power output is possible as they use induction coils in both the stator and the armature increasing the magnetic field strength.



(Figure 8)
Basic electrical components of an AC motor

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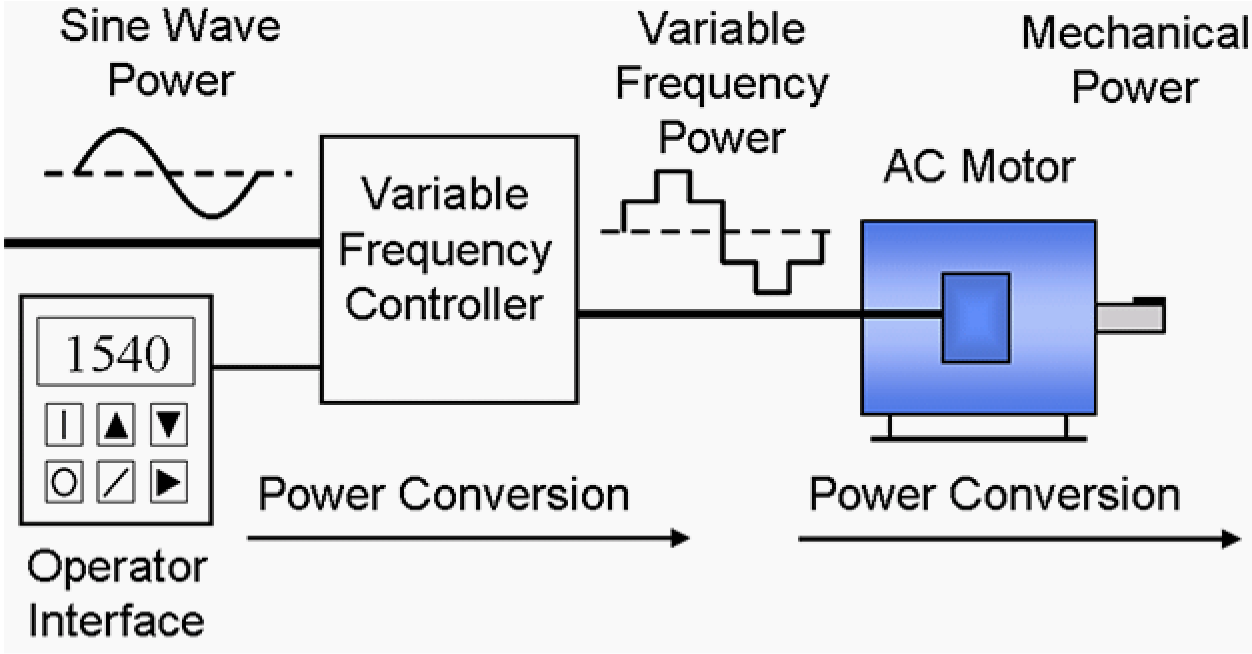
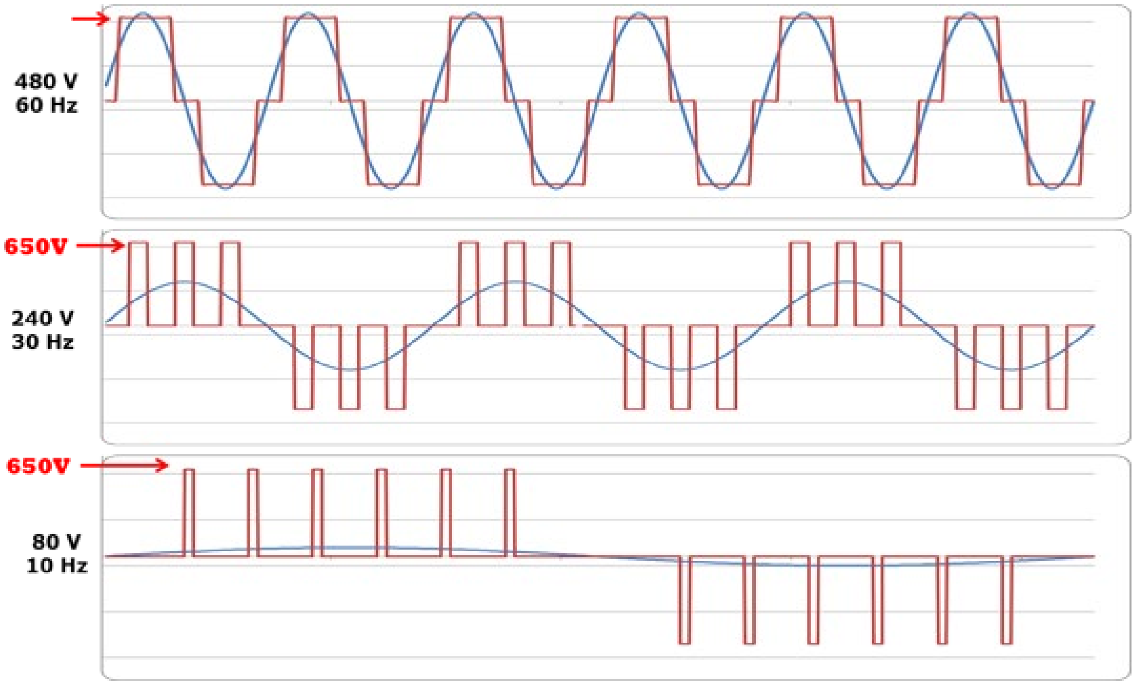
Electric Motors – AC Motors

Coupled with a modern variable frequency drive, they have excellent speed and torque control. This is because the power being sent to the AC motor is stepped (or processed).



Electric Motors – AC Motors

By doing this, the pulse duration can be spread out to provide an effectively lower or higher current supply while the switching can be adjusted to control the frequency.



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Electric Motors – AC Motors

The torque characteristics differ to that of a DC motor, but both are capable of producing torque at no rotation!

Start up current (Large AC motors are started slowly by ramping up the voltage/current)

Start up Torque

Breakdown torque

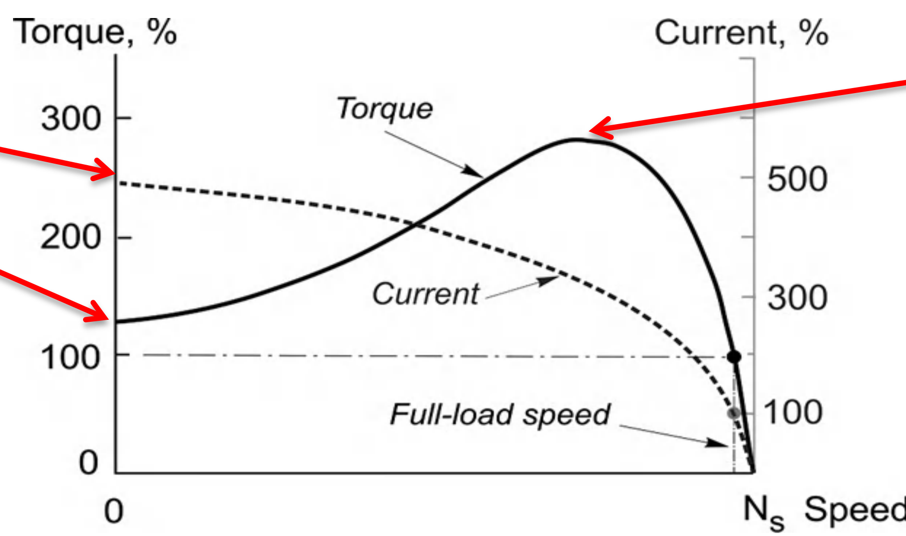

Figure 5.23 Typical torque–speed and current–speed curves for a cage induction motor. The torque and current axes are scaled so that 100% represents the continuously rated (full-load) value.

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Electric Motors – AC Motors

So what does this result in? A vehicle fitted with AC motors, like the Tesla, has excellent ability to accelerate:

Example 5: Calculate the maximum torque that can be produced by a single coil carrying a current of 5 A in a constant magnetic field of 20 T that has dimensions, 40mm by 30mm with the longer side parallel to the axis of rotation and perpendicular to the magnetic field.

$$F = 20 \times 5 \times 0.04 \sin 90 = 4N$$

$$T = 2Fd = 2 \times 4 \times 0.015 = 0.12\ Nm$$

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Example 6: If the same coil was duplicated 3 times and equally spaced, what would the maximum torque now be that they could deliver?

$$F = 20 \times 5 \times 0.04 \sin 90 = 4N$$

$$T = 2Fd + 2Fd \sin 30 + 2Fd \sin 30$$
$$T = 2 \times 4 \times 0.015 + 4 \times 4 \times 0.015 \sin 30$$
$$T = 0.24\ Nm$$

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When deciding during the synthesis stage of your design process if a motor or engine will be used to drive your mechanical device several factors would have to be considered:

- Power delivery required
- The weight of the final system
- Duration which power is required for
- How the energy will be provided and/or stored
- Safety
- The necessary supporting infrastructure
- The environmental impact
- Public perception

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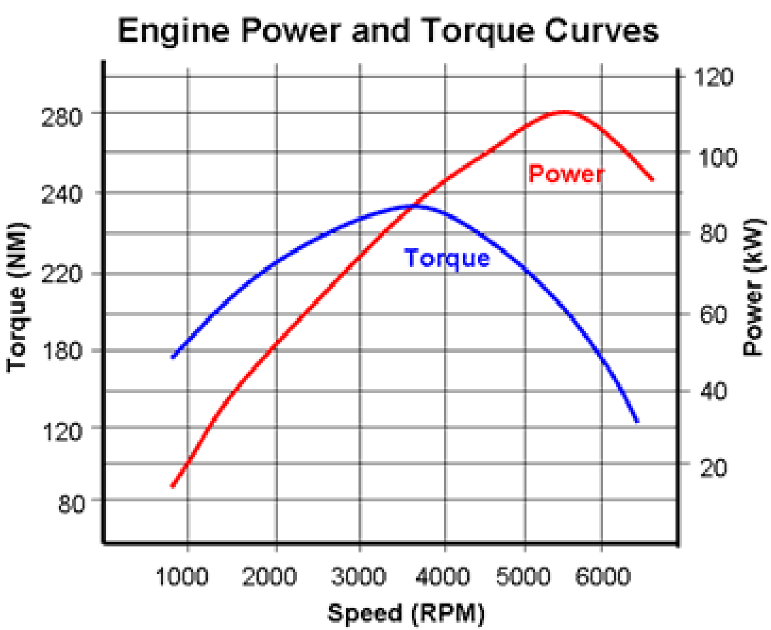
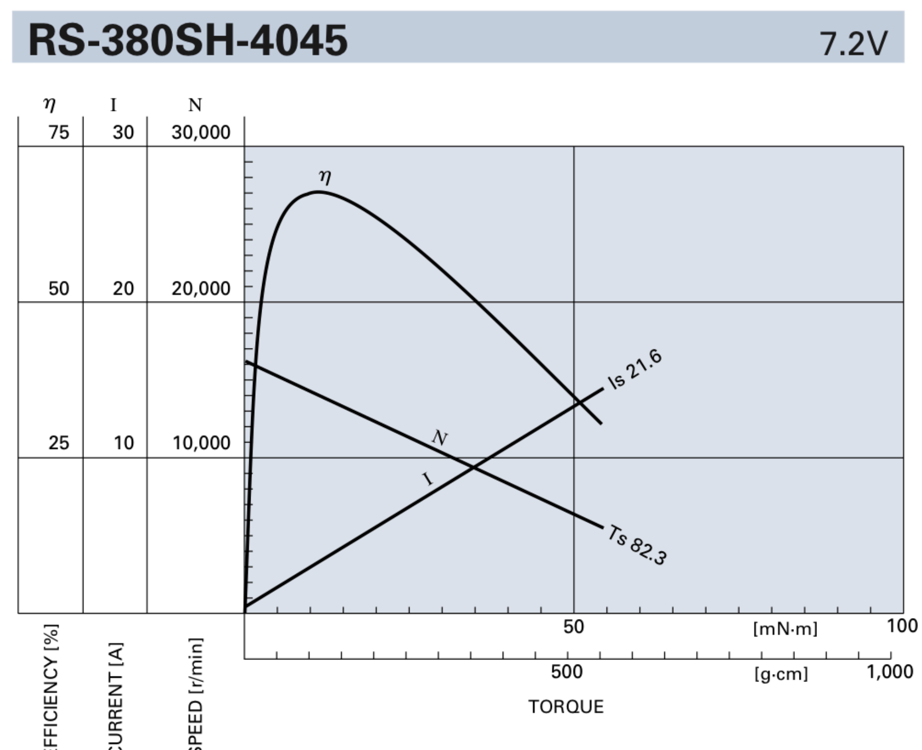
Making the correct selection – Power delivery

We have seen that an IC engine and an electric motor provide peak torque at different speeds making there power delivery very different.





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Making the correct selection – Power delivery

The initial peak torque produced by a DC motor would make it very suitable for controlling with high precision the position of a device (ie, a steper motor).

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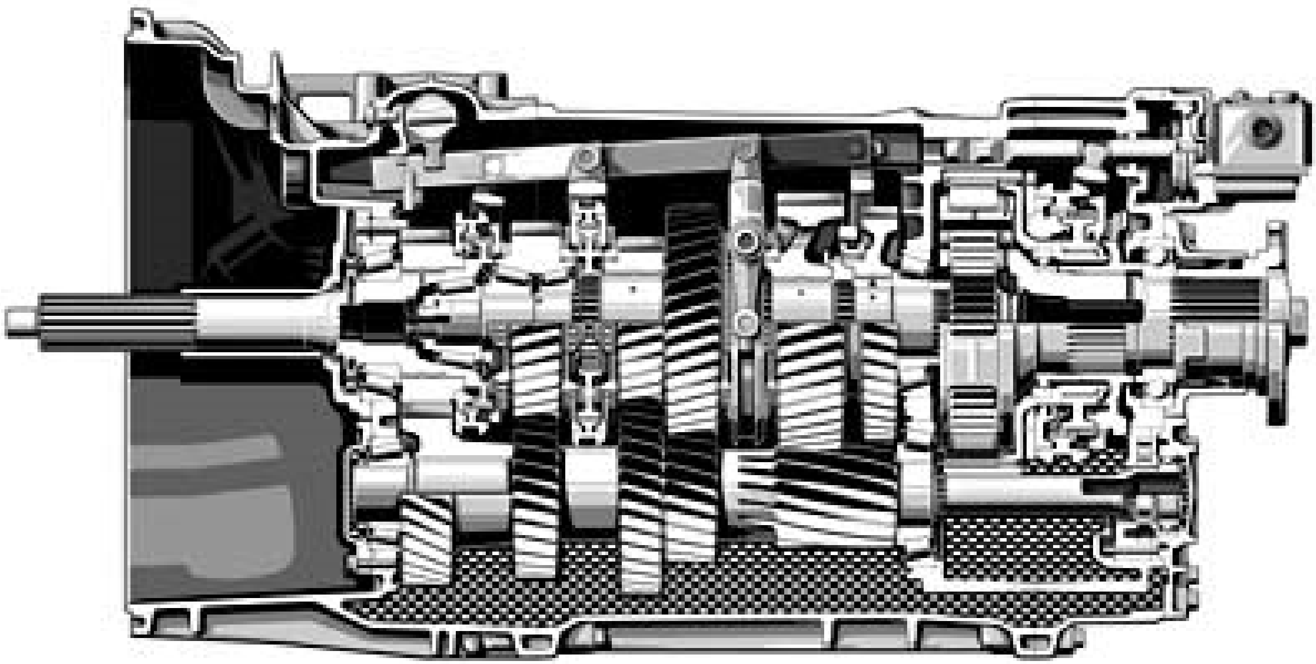
Making the correct selection – Weight

The power delivery, and the operating speed range that is required could also affect the mass of the system. If an IC motor is selected, a gearbox may also have to be included.



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Making the correct selection – Longevity/Energy Source

The duration with which an IC engine will be required to operate for will determine the amount of fuel that is required and therefore the size of the fuel tank that will have to be included in the mechanical system.

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Making the correct selection – Longevity/Energy Source

If an AC or DC motor is utilised in a device that is intended to be mobile, energy storage will most likely be batteries. Depending on the longevity required, this will also have an impact on the mass.

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Making the correct selection – Longevity/Energy Source

Batteries would not be required though if the device was stationary and a mains power supply was available. The Duty cycle will also impact the duration that a motor can be operated for.

Start up current (Large AC motors are started slowly by ramping up the voltage/current)

Start up Torque

Breakdown torque

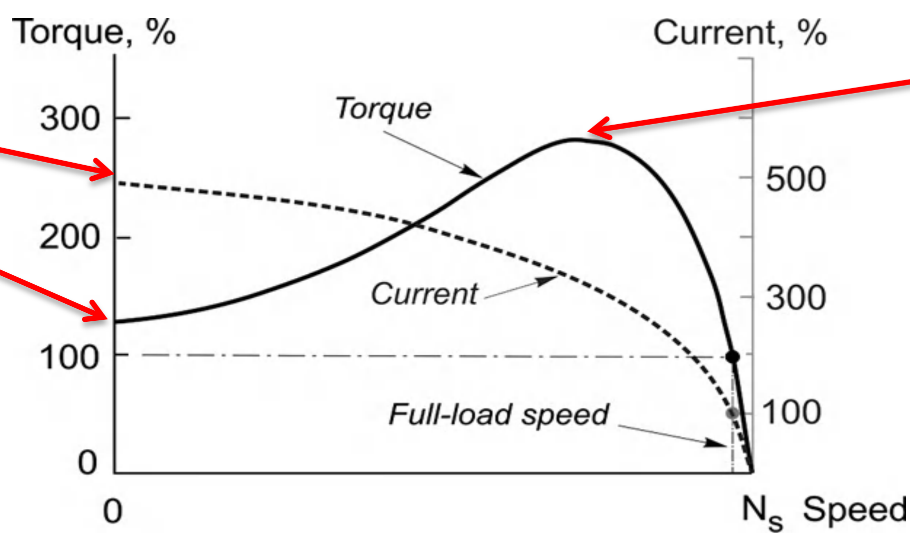

Figure 5.23 Typical torque–speed and current–speed curves for a cage induction motor. The torque and current axes are scaled so that 100% represents the continuously rated (full-load) value.

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Making the correct selection – Safety

If batteries or a fuel tank were being used to store energy, considerations must be made for safety. Fuel is flammable which is a risk while some batteries have very high energy densities making them sensitive to there operating conditions.

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Making the correct selection – Supporting Infrastructure

The biggest challenge for alternative fuel vehicles is the existing infrastructure that exists. Changing to electricity or Hydrogen requires significant investment in infrastructure to make viable.

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Making the correct selection – Supporting Infrastructure

In most locations, electrical power is available making this option suitable for immobile mechanical systems.

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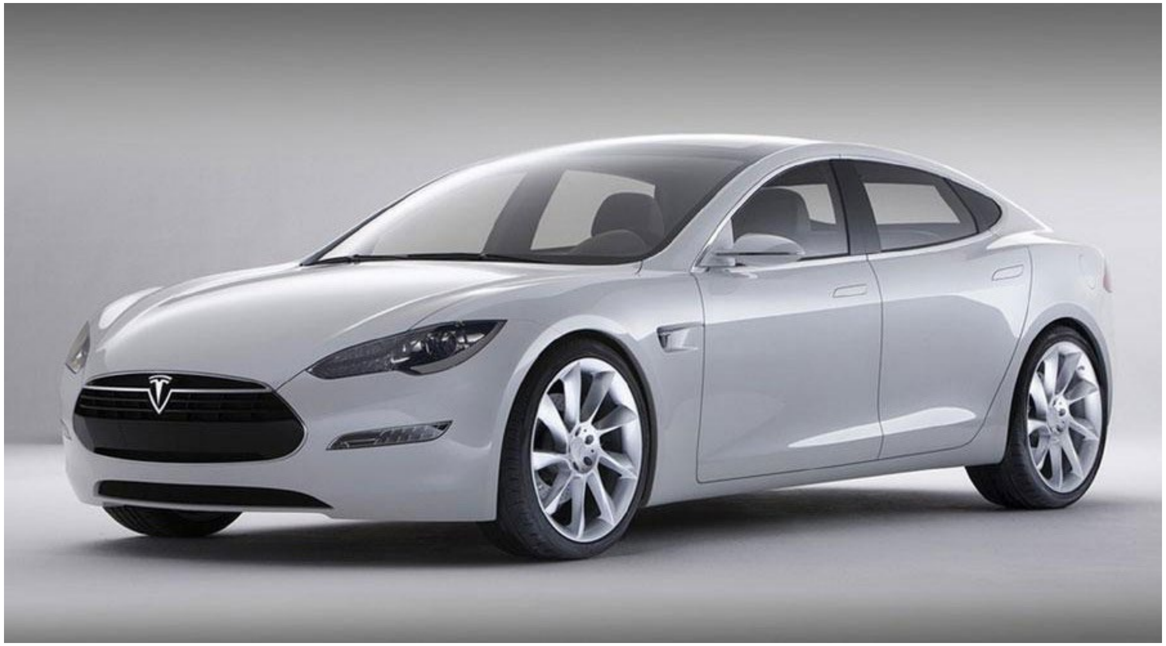
The choice being made will certainly have an impact on the cost of the mechanical system either to manufacture, operate or maintain the system.

The selection will also have some impact on the environment. This should not only consider the impact of operating the system, but also during the manufacture and disposal of the item.

Making the correct selection – Public Perception

If the system needs to be sold to the public, then public perception also needs to be overcome. For example, do electric car's really have insignificant range?



426km

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Making the correct selection – Public Perception

For example, do electric car’s really have poor performance?

0 to 100km/h 2.3s

0 to 100km/h 2.5s

Example 7: If I was designing this toy car which is required to be inexpensive and allow for children to play indoors, what type of motor or engine would I use to power the toy and why?

Example 8: I intend to design a truck that will be used to transport goods between capital cities of Australia. What type of engine/motor would you recommend that I use and why?

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Example 9: The wind tunnel at 44WR requires an upgrade to increase the speed with which can be achieved in the test section. What type of motor/engine would you consider using for such an application and why?

Example 10: A drilling machine is being designed by a mining company to collect soil samples in remote locations. It is intended that surveys could last at these remote locations for several months with all supplies being air lifted to the desired location. It is very likely that the equipment will be damaged on these expeditions and would therefore have to be inexpensive to replace. What type of motor/engine would you propose for this device?