Torque and Horse Power

Torque is one of those terms we use frequently, and it sits comfortably with us when talking about the performance of bikes and cars; E.G:

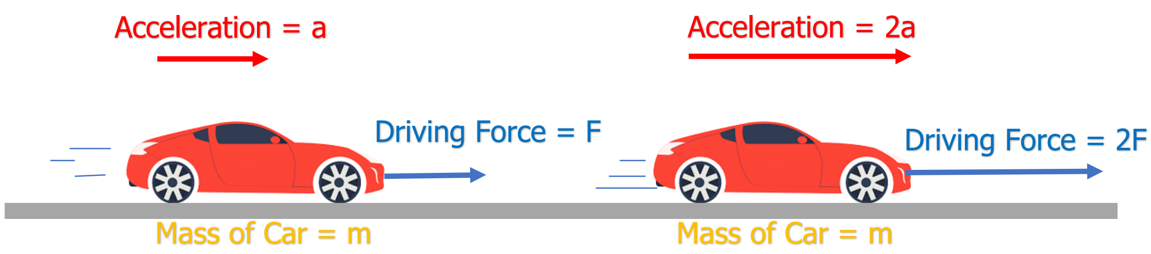
'The Hayabusa's acceleration is phenomenal, because it has tons of Torque.'

'A Range Rover's high Torque makes it a superb tow car!'

But what is Torque? Does it only apply to internal combustion engines, or do electric motors and bicycles also have Torque?

In this article I will explain what Torque is; how it is measured and how it relates to the Power output of an engine.

Let's start by looking at the components responsible for Torque: namely Force and Distance! Newton's Second Law tells us that an unbalanced Force (F) acting on a body with Mass (m), will result in Acceleration (a). For any given Mass, the size of the Acceleration increases proportionally with the Force responsible for the Acceleration; in other words, if you double the size of the Force you get twice as much Acceleration.



Stated mathematically, Newton's Second Law is given by the formula: $F = ma$

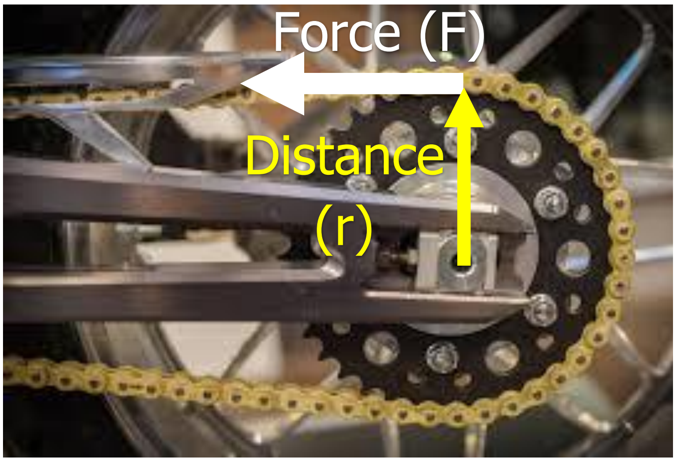
The Acceleration in the above diagrams is more correctly referred to as Linear Acceleration, as it is produced by a Linear Driving Force.

Force and Acceleration are quantities that have both 'size' and 'direction' components. The diagrams above show that both Force and Acceleration are acting to the right: they have 'direction' associated with them, as well as 'size'. Quantities that have both 'size' and 'direction' are referred to as *Vector Quantities*. Mass, on the other hand, is fully described by stating its 'size' alone. E.G. if the Mass of the car is 1500 kilograms, this is its Mass irrespective of the direction in which it moves. (For the 'purist' I am assuming speeds well below the speed of light!) Quantities that do not have a 'direction' component, are referred to as *Scalar Quantities*.

Definition of Torque:

Torque is defined as 'the turning effect of a Force'.

Torque is the product of Force and the Distance through which the Force is applied to generate turning motion.



In this diagram, the Force (F) pulls the chain to the left and the point of application of the Force is directly above the axis about which the wheel rotates, at a distance equal to the radius of the rear sprocket: shown as (r).

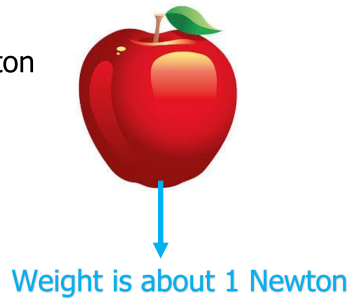
Torque = Force x Radius

$$T = F \times r$$

If the Radius of the sprocket increases, the Torque increases for any given driving Force (F): hence why low gears have a bigger radius than high gears, because they generate more Torque, making it easier for your car to move off from rest: especially on a hill.

The units of Torque are the units of Force multiplied by the units of Distance.
The metric unit of Force is the 'Newton' and the metric unit of distance is the 'metre'; therefore, the metric units of Torque are 'Newton metres'; often abbreviated to 'Nm'.
The use of upper case 'N' for Newtons and a lower case 'm' for metres is the correct metric notation for these units.

Most of us will have a feel for how big a metre is, however, the Newton is a far less familiar unit in everyday life, so, it may help to consider that a Force of one Newton is approximately the weight of an apple!

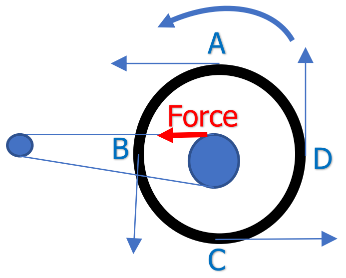


If a motorcycle has a Torque of 120 Nm (which is a lot!) it could have a Driving Force of 1200 Newtons pulling the chain under engine power and a rear sprocket radius of 0.1metres: I.E.

$$T = 1200N \times 0.1m$$
$$T = 120Nm$$

Is Torque a Vector or a Scalar quantity?

Linear Forces produce linear Acceleration in the direction of the Force, but when a Force results in 'turning motion', as in the case of a motorcycle or bicycle chain pulling on the rear wheel sprocket, the 'direction' in which the wheel rotates is a little more difficult to define.



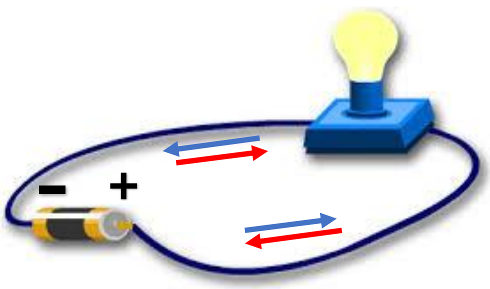
As the wheel rotates, Point A moves to the left; Point B moves down; Point C moves to the right and Point D moves up.

Furthermore, when viewed from this side the wheel rotates counter-clockwise from A to B to C to D; but if viewed from the other side of the wheel, the motion from A to B to C to D appears to be clockwise! The Force generates a turning motion and the resulting direction of rotation depends on where the observer stands to view the wheel; moreover, no one observer is any more correct when trying to describe the rotation, than any other observer: so how do we define the direction of rotation?

We defined Torque as 'the turning effect of a Force' and it has both 'size' and 'direction'. Furthermore, the 'direction' component of the Torque is related to the 'direction' of rotation of the wheel; which, as we have seen, depends on where you stand to observe the rotation. Hence the problem associated with defining the wheel's 'direction' of rotation, applies equally to defining the 'direction' in which Torque acts!

To solve this apparent dilemma, engineers and scientists adopted a convention to define the 'direction' in which Torque acts and if everyone in the World follows the convention, all calculations involving Torque will agree!

This is not unique, and a similar situation arose when electricity was discovered back in the mid 1700's by Benjamin Franklin, who proposed that it flowed through circuits from Positive to Negative.



Electron flow from – to +

Conventional current flow from + to -

When JJ Thomson discovered the Electron in 1887, it was apparent that electrical current must flow from Negative to Positive, as like charges repel and electrons are driven off by the negative terminal. Although the original convention was wrong, it made no difference to the 'size' of electrical currents and engineers can now use either convention by simply declaring whether they are using 'Conventional Current Flow' (Positive to Negative) or 'Electron Flow' (Negative to Positive) in their calculations.

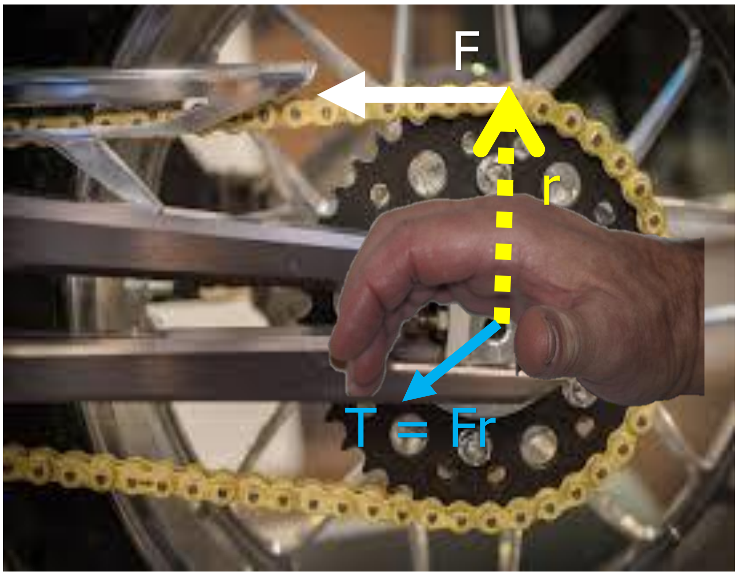
The Right Hand Rule:

The 'direction' in which Torque acts is given by the Right Hand Rule:

'Curl the fingers of the right hand in the direction of rotation and the right thumb will point in the 'direction' of the applied Torque'.

This diagram shows the fingers of my Right Hand curled in the direction of rotation of the bike's rear sprocket. My Right Thumb then points in the 'direction' of the Torque vector and the 'size' of the Torque vector is given by the formula:

T = Fr



In the case of a moving motorcycle, the Torque points out to the left, along the Axis of Rotation and at right angles to the plane of the wheel. You will see from the diagram that Torque is also associated with the front wheel of the motorcycle; despite the driving Force being applied to the rear wheel.

To see why this is, go back to the definition of Torque: I.E. *Torque is the turning effect of a Force.* If the front wheel turns, it does so under the action of Torque! It's a bit like a wheelbarrow: although you push from the back, the wheel rotates at the front and as such, the wheel of the barrow has an associated Torque.

The 'direction' of the Torque vector looks weird!

At this point, don't be confused between Force and Torque: although related, they are two separate quantities. The ***Force*** on the motorcycle chain pulls it in the direction in which the motorcycle moves; the ***Torque*** generated by the product of this Force and the Radius of the rear sprocket, points out to the left along the axis of rotation, at right angles to the vertical plane of the wheel, relative to the direction in which the rider faces!

Mathematically, the product of two Vector quantities, such as Force and Radius, must also be a Vector quantity acting in a 'direction' that is right angles to the two component Vectors: Torque must therefore point either to the left or right of the wheel's vertical plane.

Had everyone agreed on a convention stating that the 'direction' of Torque would be given by a Left-Hand Rule, it would be considered to point out to the Right; however, they agreed instead that it would be given by a Right-Hand Rule, so it is accepted that it points out to the Left. This may seem strange, but the concept of Torque is a mathematical description of the '***turning effect of a Force***' it is not the Force per se, the direction of which is clearly obvious from the resulting movement of the motorcycle! The concept of Torque is something that exists in our minds, although it has physical significance. If the calculations made involving Torque agree with observation -and they do- then the concept is good. Just as for electrical current, the convention used to show its direction of flow results in predictions that agree with observation; whether one assumes conventional or electron flow.

Torque and Power

To understand the relationship between Torque and Power we need an understanding of what we are referring to when talking about Power.

By definition: **Power is the Rate at which Work is Done**; so, we also need to understand what is meant by the term 'Work Done'.

Power; Work and Energy

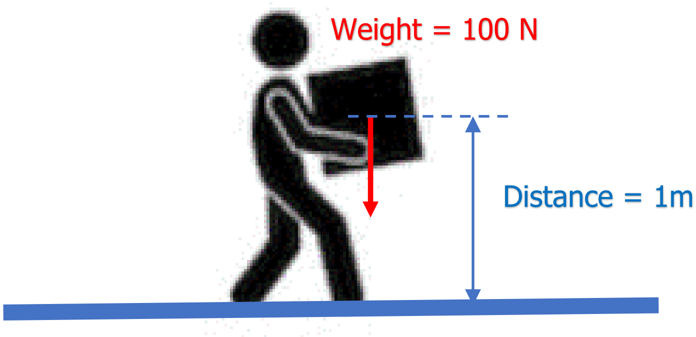
Work and Energy are two aspects of the same thing; I.E. Energy can be converted into Work Done and Work Done can be converted into Energy: therefore, they are both measured in the same units, which in the metric system are Joules; where one Joule equals one Newton metre.

Work Done (WD) in lifting the box:

WD = 100N x 1m

WD = 100 NM

WD = 100 Joules



If the man lifts the box in a time of 1 Second, the 'rate at which Work is Done' is 100 Joules Per Second. Power was defined as 'the rate at which Work is Done':

$$\text{Power} = \frac{\text{Work Done}}{\text{Time}} \quad \text{Nm/S or Joules/S}$$

In lifting the box in a time of 1 Second, the Power generated by the man is 100 Joules Per Second.

Another name for the 'Joule / Second' is the 'Watt'. I.E. 1 Watt = 1 Joule / Second; in lifting the box in a time of 1 Second, the Power generated by the man is 100 Watts.

However, if the man took 2 Seconds to lift the box; the Work Done and the Energy expended are both the same: 100 Joules; but this time the Power is 100 Joules / 2 Seconds; which is 50 Joules / second or 50 Watts. Although the same amount of Work was Done by the man and the same amount of Energy was expended, because he took twice as long to do the Work, he generated half the Power!

Summarising the units of Work Done; Energy and Power:

	Work Done	**Energy**	**Power**
Unit of measurement	Newton metre	Newton metre	Newton metre / Second
Equivalent unit	Joule	Joule	Joule / Second
	-	-	Watt

The final bit of the jigsaw is to determine the relationship between Torque and Power and this can be achieved by examining the Units used to measure these quantities:

Torque is measured in 'Newton metres'
Power is measured in 'Newton metres / Second'

By analysing these Units, we can say that Power is a measure of the Torque generated / Second. (This is a simple example of a mathematical technique called 'Dimensional Analysis') When dealing with internal combustion engines, we don't measure the rotational speed in 'Revolutions / Second', we measure it 'Revolutions / minute'.

A useful formula for Power is therefore:

Power = Torque x RPM x Constant

The 'constant' is simply a dimensionless number that allows us to convert RPM to Seconds, hence in this case the Constant = (1÷60) I.E. if the engine rotates at 600 RPM, that is 600÷ 60; which is 10 Revolutions / Second.

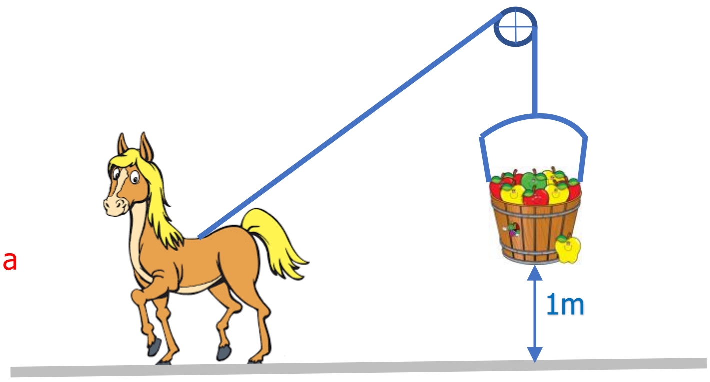
Horse Power:

This is a fabulous term with historic origins! A Horse is a powerful animal that can 'Work' harder than a man. The amount of Work that can be done by a Horse is the origin of the term 'Horse Power'. Horses come in all shapes and sizes, so there had to be a bit of imagination when deciding just how much Work the 'average' horse could do!

However, Horse Power is simply another measure of Power and as such, it has a metric equivalent allowing us to determine how much Work can be Done by a horse in Watts. When converting Horse Power to Watts, the following rate of exchange is used:

1 Horse Power = 735.5 Watts
= 735.5 Joule / Second
= 735.5 Nm / Second

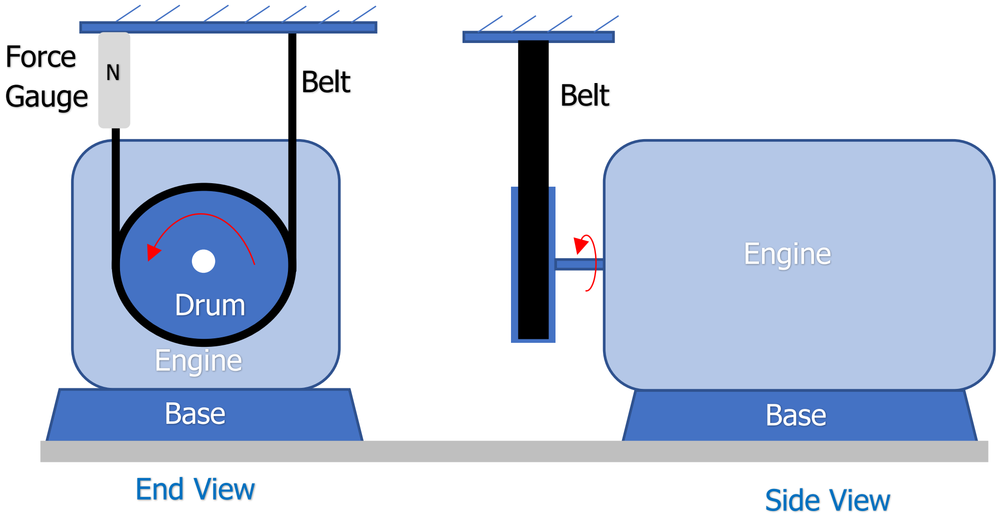
Which means that the average horse can lift 735.5 apples through a height of 1 metre in a time of 1 second!



Brake Horse Power

The term Brake Horse Power (BHP) is often used when stating the useful (or useable) Power output from an engine. The total power generated by an engine does not get transferred to the wheels, as part of this Power is lost in the form of heat, vibration, friction, and other mechanical losses Etc. The remaining Power available to turn the wheels is termed BHP and for an internal combustion engine, BHP is about 30-40% of the total Power generated by engine: yes, they are very inefficient!

Horse Power cannot be measure directly, therefore it's fortunate we have a formula for converting Torque to Power. By measuring the useful Torque output from the engine I.E. the Torque available to turn the wheels, we can then convert it to Horse Power. The way in which this is achieved, is to measure the Torque generated when applying an external load to the engine; for example, when the engine is made to work and operate a 'Brake'.
The Torque measured is then converted to Horse Power, more correctly referred to as 'Brake Horse Power', because of the way in which the Torque was measured. The diagram above shows an engine on a test bed, but the diagram below explains what is happening in a more diagrammatic form:



The engine rotates at a fixed number of RPM.
The rotating drum on the output shaft turns against a belt, which has one end secured to a strong point on the ceiling and the other end attached to a Gauge, that reads the Force applied to the belt by the rotating Drum: that is, by the Engine.

The Belt is then tensioned like a Brake so that the Engine must do more Work to turn the Drum; the greater the tension in the Belt, the more Work the Engine must do and the greater is the measured value of Force on the Gauge.
When in a steady state, we can measure the RPM of the Engine and the Force on the Gauge. Knowing the radius of the Drum allows us to calculate the Torque delivered by the Engine. Using the 'Power = Torque x RPM x Constant' we can work out the Power in Watts and then convert that to Horse Power; more correctly referred to as Brake Horse Power: and that is it!

Conclusion

In this article I have explained the following terms; their units of measurement and where applicable, the relationship between them:

- Torque
- Vector and Scalar quantites
- Power
- Energy and Work Done
- Horse Power and Brake Horse Power

Torque applies to any system in which a Force exerts a turning motion; therefore, electric motors and bicycles also generate Torque, as well as internal combustion engines.

In fact, the reason why a car with an electric motor accelerates so well, is because certain electric motors give maximum Torque at zero revs; unlike an internal combustion engine, where Torque generally increases with revs up to a maximum value in any gear, before tailing off as more Work is Done internally combating friction, as the pistons move faster and faster in the cylinders. This in turn leaves less Power to do external Work, such as turning the road wheels: that's why speed is limited in each gear, the lower ones in particular, where the associated engine revs are high: this is not an issue for an electric motor!
I hope this little article has been of value and cleared up some of the mystery surrounding these various quantities and their units of measure.
Physics is fun!

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