ENGINE TORQUE AND TRACTION FORCE

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I. ENGINE TORQUE

What are the essential characteristics of a motor vehicle? Marketing departments know that it is the power and maximum speed which, at first, focused public attention, because it is the most rewarding data for the driver.

Both for the technician and for the discerning customer, it is the mass of the car, its engine torque and the engine rotation speed at which it is available which are essential data, because they determine the behavior of the vehicle in real situations, the service it can make and its cost price. Here are some explanations...

The origin of the movement

From point of view of physics, create movement comprises to accelerate a mass with a force. That is the traction force. It is acting on the drive wheels by contact with the ground.

But what makes the drive wheels turn? That is the engine torque!

The principle of the 4-stroke engine

All engines of gasoline or diesel land vehicles operate on the same principle, that of the four-stroke cycle:
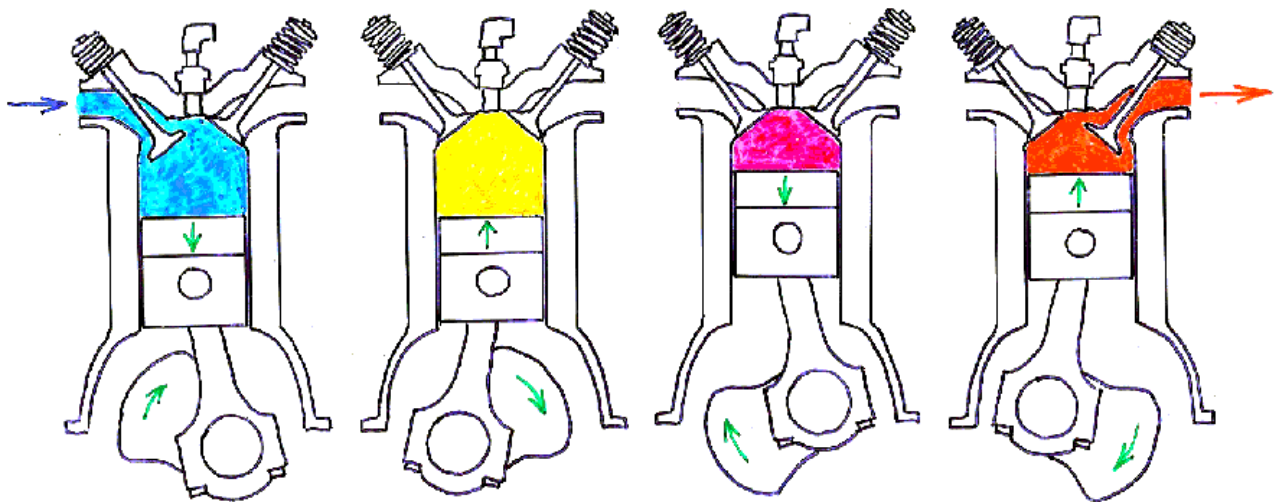
1. INTAKE   **2. COMPRESSION**   **3. COMBUSTION**   **4. EXHAUST**

The four-stroke cycle.

1. The first stroke is named *intake*: the intake valve is open while the exhaust valve is closed. The displacement of the piston creates a vacuum that allows the engine to suck a mixture of air and fuel (gasoline engine) or clean air, the fuel being injected directly into the combustion chamber (diesel engine).

2. The second stroke is called *compression*: the valves are closed, while the mixture is compressed by the rise of the piston.

3. The third stroke is called *combustion*: the two valves are closed, a spark ignites the air fuel mixture (gasoline engine) or it ignites spontaneously (diesel engine). The piston is then violently pushed down and makes the crankshaft to turn via the connecting rod, it is the only engine time of the cycle.

4. The fourth stroke is called *exhaust*; the intake valve remains closed while the exhaust valve is open. Raising the piston pushes the burned gases outwards, etc.

Torque Definition

The torque combines two sizes: a force and a lever arm.

In a car engine, this force is that which the piston exerts on the crankshaft by means of the connecting rod; the lever arm is the length of the crankshaft radius.

Since 1954, the international unit of torque is the newton-meter (Nm symbol), it is the product of a force expressed in newtons (N) and a lever arm expressed in meters (m): 1 Nm is the torque produced by a force of 1 N which is exerted on a lever arm of 1 m.
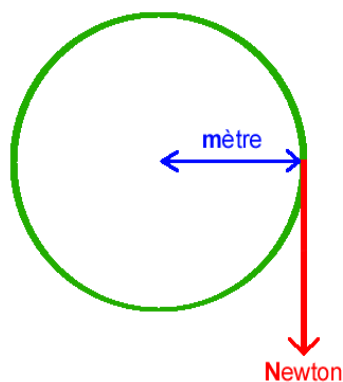
Torque is the product of two quantities: a force and a lever arm.

Measure the engine torque

How can we measure the torque of an engine?

It is used a 'dynamometer' which is a device equipped with a rev counter and a brake[*].

The operation is to run the engine full gas and then gradually apply the brake until the rotation speed is stabilized, while the throttle remains wide open: at this moment, the maximum engine torque is exactly equal to the braking force.

So just know the intensity of the braking force and the length of the radius on which it applies to deduce the value of the maximum engine torque[**].

The specific torque

The engine torque being used to accelerate a mass or climb a declivity, it is obvious that its value should be reported to the vehicle mass.

Hence the notion of 'specific torque' which is expressed in newton-meter per ton (symbol $Nm.t^{-1}$).

For example:

- a truck engine delivering a 2,000 Nm engine torque to a mass of 40 tons has a 50 $Nm.t^{-1}$ specific torque.

- a car engine delivering a 300 Nm engine torque for a mass of 1.5 tons has a 200 $Nm.t^{-1}$ specific torque.

Torque and power

These are the two essential characteristics of an engine. However, for the technician as to the driver, these two quantities do not have the same interest.

Indeed, power is a theoretical value obtained by combining the torque and engine rotation speed, so obviously dependent on high rotation speeds.

Besides the power claimed by the manufacturers is always a maximum value, available only at the specified rotation speed, and provided only if the throttle is wide open.

If one of these two conditions is not fulfilled or let alone both, the driver will have only just part of the announced power. But advertisers are careful not to specify this.

Unlike power, maximum torque is available only to intermediate rotation speeds (from 1,500 rpm to some recent diesel cars, sometimes as early as 1,000 rpm for some trucks), over a range of about 500 to 1,000 revolutions per minute only, but never to extreme rotation speed. Hence the usefulness of the rev counter.

This availability can obviously vary from one model to another, especially of one engine type to another, but follows the same rules, regardless of the brand or model.

The torque and engine rotation speed override power because they determine the actual performance when the car accelerates or comes to tow a load uphill.

That's the whole point of the diesel engines because of more generous torque available at lower rotation speeds and on a wider range than that of gasoline ones.

A numerical example

Take for example the Renault 2.0 DCI 150 engine whose characteristics are:

- maximum engine power 150 hp (150 ch, 110 kW) at 4,000 rpm (4,000 tr.min^{-1})

- maximum engine torque 340 Nm at 2,000 rpm (2,000 tr.min^{-1})
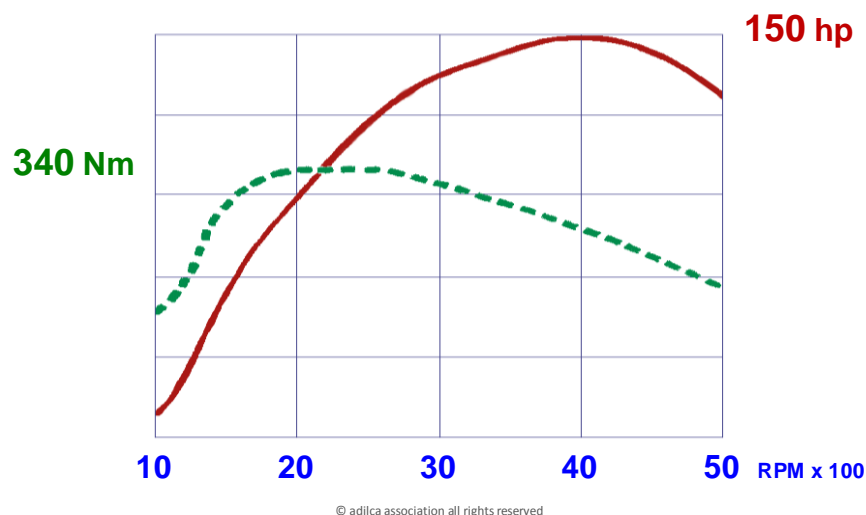
Torque (green) and power (red) of the 2.0 DCI 150 Renault engine (Renault document).

A quick calculation shows that at maximum torque speed (2,000 rpm), the available power is only 97 hp (71 kW)! But available as long as the driver keeps the throttle fully open! If this is not the case, less than 97 hp are working.

Another equally rapid calculation shows that at maximum rotation speed (4,000 rpm), the engine torque available is only 260 Nm! It is clear that between the power and torque, it's necessary to choose!

Why to privilege the torque?

The value of the torque depends on the ability of an engine to be introduced into the

cylinders a perfectly homogeneous air-fuel mixture, and especially its ability to get the most energy during combustion.

The motor torque is still relatively small at low rotation speed, it reaches its maximum value at intermediate speed, then decreases inexorably as speed increases, as if the engine ended up suffocating.

As the engine operates in its maximum torque speed range, fuel consumption, environmental pollution and therefore the cost of the kilometer remain at the lowest values which the vehicle is capable.

For all these reasons, it is preferred that the maximum torque is delivered to a rotation speed not too high.

Focus on torque rather than power!
And the rotation speed at which it is issued (here: 275 Nm at 1,800 rpm)!

(*) *The expression 'brake horsepower' is often used. There are many brake systems, friction, hydraulic resistance, electrical or electromagnetic, but all they work on the same principle: the motor is coupled to a disk on which exerts a braking force. Despite their names, these devices do not measure the power but only the torque and the way it evolves according to the engine rotation speed. The power results from a subsequent calculation that combines two variables: the torque and rotation speed (see ADILCA folder 'engine power').*

(**) *Therefore, the technical data always refer to a 'maximum torque' and the corresponding engine rotation speed, which means that the throttle is wide open. If this is not the case, only a part of the torque indicated is available.*

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II. TRACTION FORCE

The role of transmission

The transmission refers to all the mechanisms that come between the engine and the drive wheels. Its principle comes down to that of a series of pinions whose function is to multiply the engine torque while reducing the speed of rotation.

Indeed, if the motor directly drove the driving wheels, these would turn too quickly while delivering insufficient torque, hence the role of the pinions and the necessary distinction between the driving torque (which is exerted on the axis of the crankshaft), and the traction torque (which is exerted on the axis of the driving wheels).

The torque multiplication and its corollary, the speed reduction, is a function of the number of sprockets and the quotient of their respective radii or number of teeth. The value thus obtained is a dimensionless quantity which takes the form of a decimal number, or of a fraction called the transmission ratio.
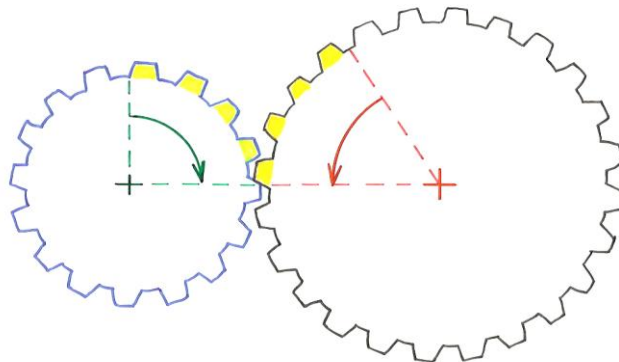
Principle of the gear-box[(*)]
A 16 tooth gear wheel (green arrow) drives a 24 tooth gear wheel (red arrow).
Here, the transmission ratio is 24/16 = 1.5.
So, the engine torque is multiplied by 1.5 while the rotation speed is divided by 1.5.

Here is an example of gear ratios values corresponding to a mid-range car with a 5-speed gearbox:

gear	1ère	2ème	3ème	4ème	5ème
transmission ratio	16	8,5	6	4,6	3,6
traction torque (Nm)	3 200	1 700	1 200	920	720

How to interpret this chart? Number 16 is the transmission ratio in 1st gear. The traction torque is then 16 times greater than the engine torque, while the rotational speed of the driving wheels is 16 times less than that of the crankshaft, etc. The counterpart of this multiplication is an equivalent reduction of the rotation speed. In other words, by reducing the rotation speed of the wheels, the transmission increases the traction torque, and *vice versa*.

The traction force

The traction force means the force acting on the tyres of the drive wheels by contact with the ground to create or maintain the movement of the car[**].
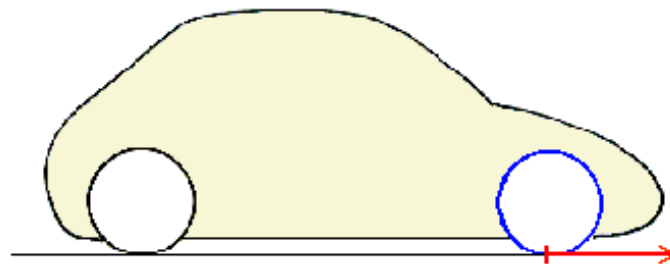
Traction force (front wheel drive).

The intensity of this force is a function of the engine torque, the transmission ratio and the radius of the drive wheels.

If we consider a mid-range car with engine torque 200 Nm, 5-speed gearbox, 0.3 m wheels radius, the maximum traction force acting by contact with the ground[***] is:

gear	1ère	2ème	3ème	4ème	5ème
traction torque (Nm)	3 200	1 700	1 200	920	720
traction force (N)	10 600	5 660	4 000	3 060	2 400

Motion and speed

The traction force is used:

- to create motion and speed; the following table shows the acceleration values that the previously calculated traction force can exert on a mass of 3,300 lb (1,500 kilograms, disregarding rolling resistance and air resistance:

gear	1st	2nd	3rd	4th	5th
acceleration (m.s^{-2})	7	3.8	2.7	2	1.6

- to balance the natural resistances (rolling resistance and air resistance) once the speed is stabilized; the following table gives the order of magnitude of the natural resistance that is exerted on a mid-range car and that the traction force must compensate to maintain a constant speed on a flat road:

speed (mph)	35	45	55	65	75
resistances (N)	310	470	680	890	1,150

- to balance the weight on the climbs (see ADILCA file '*sloping roads*'); the following table mentions the traction force needed to compensate for the gravitational force of a car weighing 3,300 lb (1,500 kilograms, g = 10 m.s^{-2}), this force being added to that required to compensate for natural resistances:

gradient	2 %	4 %	6 %	8 %	10 %
traction force (N)	300	600	900	1,200	1,500

(*) *A principle easy to display: at the contact point of the two wheels, the force received by the 24 tooth gear wheel is exactly equal to the force transmitted by the 16 tooth gear wheel, such is the Newton's action-reaction principle. The torque being the product of a force by a radius, and circumference being related to the radius by a constant (2 π), we deduce that the available torque on the axis of the 24 tooth gear wheel is 24/16th (3/2) of the initial torque (24/16 = 3/2). Moreover, when the 16 tooth gear wheel makes one revolution, the 24 tooth gear wheel makes only 16/24th (2/3) of a turn (16/24 = 2/3). Therefore, the rotation speed is reduced in the same ratio as the torque increase, and vice versa*

(**) *It is important to emphasize this point and to rectify two common mistakes:*
- the traction force is not acting on the center of gravity of the car, but on the tyres by contact with the ground, like the other forces that allow motion control of the car (see ADILCA files). Remember that no force, except the weight, can be exerted on the center of gravity of any mass.
- the action reaction principle states that any force exerted on a mass causes a reaction of equal intensity but of opposite direction. This reaction is often confused with the inertial force for which this principle can not be applied: there is no interaction in the case of an imaginary force (see ADILCA file 'inertial force'). But this principle perfectly applies in the case of the traction or engine brake force: when the car accelerates or decelerates, it exerts a thrust on the Earth, without affecting its rotational movement, because of the ratio of the masses (car : 15 x 10^2 kg; Earth: 6 x 10^{24} kg, a ratio of 1 to 4 x 10^{21}).

(***) *These are values calculated from the maximum torque delivered by the engine and measured at the end of the crankshaft. In other words, these values are purely theoretical: first, they assume that the engine is running at the appropriate rotation speed with the throttle wide open, secondly, disregarding the rotation resistance of the transmission (gearbox, drive shaft, differential, axle shafts). This resistance absorbs about 10 % of the initial energy*

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III. COUNTER TORQUE

How to evoke the engine torque not to mention the counter-torque, usually unrecognized characteristic of a car engine but whose value is yet another essential feature for driving.

The counter-torque is the technical term for what drivers commonly call the 'engine brake'. Indeed, any engine rotating inevitably delivers an opposing torque that occurs as soon as you remove the fuel supply.

Where the counter-torque comes from?

The so-called 'thermal' car and trucks engines all operate according to the principle cycle four stroke one of whose features is a fairly low yield of 25-45 % depending on the conditions.

These small values are due to many resistors accompanying the progress of a cycle: inertia of the gas admission, pistons motion, compression of the air (or air-fuel mixture) in the combustion chamber, friction inside the cylinders, friction of the rotating shafts, rotation of peripheral parts (distribution, oil pump, water pump, alternator) and comfort accessories (power steering, air conditioning).

Therefore, if one ceases to power the motor, these resistors create ample counter torque to slow the car, although it will never equal that of the brakes.

The availability of the counter torque does not obey the same laws as the engine torque. In fact, the counter-torque is always proportional to the rotational speed of the engine, which means that the highest value is obtained at the maximum speed set by the manufacturer. Hence again, the usefulness of the rev counter.

The engine brake force

As the engine torque, counter-torque is relayed and therefore multiplied by the transmission. So must be distinguished counter-torque and engine brake force.

The engine brake force means the force acting on the tyres of the drive wheels by contact with the ground when the accelerator is released.

If we consider a mid-range car with counter-torque 50 Nm, 5-speed gearbox, 0.30 m wheels radius, the engine brake force delivered by contact with the ground is:

Gear	5th	4th	3rd	2nd	1st
engine brake force (N)	600	760	1,000	1,410	1,600

Measure the counter-torque

The manufacturers give no indication as the value of the counter-torque and that's a shame, but it is nevertheless always possible to indirectly calculate its value, with a very easy to achieve experience.

Imagine stabilize the car speed downhill through the sole action of engine brake force: this would mean that the component of the weight that drives the car (see ADILCA file '*sloping roads*') is strictly equal to the sum of the three forces that brake the car (rolling resistance, air resistance, engine brake force).

It would suffice to know the gradient of the road, the mass of the car, its speed, its technical characteristics (transmission ratio, aerodynamic characteristics) to calculate all other movement parameters (component of the weight, air resistance, rolling resistance, engine brake force). Once these known parameters, it could be possible to isolate the value of the counter-torque[(*)].

The results of the experiment

Such an experience, completely new, was held May 25, 2001 on the slope of the Puy de Dôme (volcano eponymous in Auvergne state, France), site chosen because of its strong and steady slope (12 % over 4.1 km).

Puy de Dôme slope.
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The results of this experiment showed that the value of the counter-torque of a diesel engine car is 25 Nm per engine liter when the engine running at the maximum rotation speed permitted by the manufacturer.

Other experiments have shown that at equal displacement, the value of the counter-torque is substantially proportional to the mass of the pistons, the compression ratio and the engine rotational speed.

Finally, and contrary to popular belief, this value varies little from one engine type to another, gasoline engine offsetting the lower mass of pistons and a smaller compression by a higher rotation speed.

What is the use of engine brake force?

Where and how to use the engine brake force, what it can serve and why is it such an important value?

The engine brake force occurs as soon as you cut power to the motor, it is sufficient for the driver to release the accelerator to benefit!

The engine brake force serves to stabilize the car speed downhill, as we have said about the experience mentioned above. That's great, but not enough!

The proper use of engine brake force is the key to what is commonly called rational driving or eco-driving. Indeed and provided early enough to go, the engine brake force is sufficient most of the time to slow the car in almost all non-emergency driving situations!

The first advantage of this maneuver is to save fuel during slowdown, since all modern vehicles have, thanks to the electronic injection, a complete reduction of the fuel supply during the deceleration.

The second advantage of this way of doing is to avoid the brake wearing and the issue of micro-particles in the atmosphere.

These savings are probably negligible on a single slowdown but if they are multiplied by the number of situations encountered, they quickly become substantial, particularly in town.

Modern engines ...

Note that the technical development of modern engines to increase the torque at low rotation speed (supercharging, light alloy materials, downsizing[**]), the unfortunate effect was to significantly reduce the value of the counter-torque.

A few data to compare:

- in 1991, a Citroën ZX 1.9 D diesel equipped with a 2 liter standard engine delivered an engine torque of 120 Nm at 2,000 rpm and a counter-torque of 53 Nm at 4,600 rpm.

- in 2006, a Citroën C4 1.6 HDI 92 diesel equipped with a 1.6 liter supercharged engine delivered an engine torque of 215 Nm at 1,750 rpm, but a counter-torque of only 46 Nm at 4,800 rpm.

To achieve such a result, technicians and engineers have produced a real tour de force: 20 % less displacement and 79 % more torque, available to a rotation speed 12.5 % lower.

Yes feat, but unfortunately at the expense of counter torque! Especially in the meantime, to meet the new comfort and safety standards, the mass of the empty car increased from 2,277 lb (1,035 kg) to 2,765 lb (1,257 kg): + 21.5 %!

All characteristics to consider for anyone who wants to practice eco-driving successfully!

Torques and driving

Note the plural! All the art of driving is to exploit torques, right time and right place. To achieve this, the driver may use:

- the throttle (the opening or closing conditions the quantity of fuel introduced into the cylinders, and thus the intensity of the engine torque or the counter-torque),

- the rev counter (to control if the motor works as often as possible in one of two favorable rotation speed range)

- the gearbox (the transmission ratio determines the traction force or the engine brake force corresponding to the requested work).

(*) *Unlike the engine torque is measured at the end of the crankshaft, the value of the counter-torque resulting from such an experiment is a global value that includes both the rolling resistance of the four wheels and that related to the rotation of the transmission (axle shafts, differential, drive shaft, gearbox).*

(**) *Downsizing: Technique that aims to reduce engine capacity and weight of the engine while getting more power and torque thanks to optimized cylinder charging.*

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IV. RELATIONSHIPS BETWEEN PHYSICAL QUANTITIES

Engine torque

$$Te = F \cdot D$$

Te: engine torque, expressed in **Nm**
F: engine force, expressed in **N**
D: length of the lever, expressed in **m**
consistency of the units: **Te** = N . m = **Nm**

Example: calculate the engine torque under the following conditions: engine force 4,000 N, crankshaft radius 0.05 meter:

$$Te = 4{,}000 \times 0.05 = 200 \text{ Nm}$$

Transmission ratio

$$X = (n4 / n3) \cdot (n2 / n1)$$

X: transmission ratio, dimensionless
n1: number of teeth of the primary countershaft gear
n2: number of teeth of the secondary countershaft gear
n3: number of teeth of the differential driving pinion
n4: number of teeth of the differential crown

Example: calculate the transmission ratio with the following combination (5th gear): primary countershaft 43, secondary countershaft 33, differential driving pinion 13, differential crown 61:

$$X = (61 / 13) \times (33 / 43) = 4.692 \times 0.767 = 3.6$$

Traction torque

$$Td = Te \cdot X$$

Td: traction torque, expressed in **Nm**
Te: engine torque, expressed in **Nm**
X: transmission ratio, dimensionless
consistency of the units: **Td** = **Nm**

Example: calculate the traction torque under the following conditions: engine torque 200 Nm, 3.6 transmission ratio (fifth gear):

$$Td = 200 \times 3.6 = 720 \text{ Nm}$$

Traction force

$$F = Td / R$$

F: traction force, expressed in **N**
Td: traction torque, expressed in **Nm**
R: radius of driving wheels, expressed in **m**
consistency of the units: $F = N.m \cdot m^{-1} = N$

Example: calculate the traction force on the tyres by contact with the ground under the following conditions: traction torque 720 Nm, drive wheel radius 0.3 meters:

$$F = 720 / 0.3 = 2,400 \ N$$

Engine brake force

$$F = Ta \cdot X / R$$

F: engine brake force, expressed in **N**
Ta: antagonist torque, expressed in **Nm**
X: transmission ratio, dimensionless
R: radius of driving wheels, expressed in **m**
consistency of the units : $F = N.m \cdot m^{-1} = N$

Example: calculate the engine brake force on the tyres by contact with the ground under the following conditions: counter-torque 50 Nm, drive wheels radius 0.3 m, 8.5 transmission ratio:

$$F = 50 \times 8.5 / 0.3 = 1,416 \ N$$

Accélération

$$Y = F / M$$

Y: accélération, expressed in $m.s^{-2}$
F: traction force, expressed in **N**
M: mass, expressed in **kg**
consistency of the units: $Y = N \cdot kg^{-1} = kg.m.s^{-2} \cdot kg^{-1} = m.s^{-2}$

Example: calculate the acceleration of a 3,300 lb (1,500 kg) car mass subjected to a 2,400 N traction force:

$$Y = 2,400 / 1,500 = 1.6 \ m.s^{-2}$$

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