

THE BRAKING FORCE

From the point of view of driving, emergency braking is probably the most difficult skill to perform. Yet it is an essential skill because, according to the Highway Code, only braking allows the driver to remain in control of one's car.

What does physics teach us about braking? What should be measured? What can be calculated? What about the braking force, this particular force without which nothing would be possible? What do we know about it? Here are some answers.

Braking tests

If you want to explore the secrets of braking, tests involving a driver, a modern car and a test track are necessary. The few measures will then be used for various calculations.

This kind of test is regularly organized by automotive testers, and the obtained results have much to teach us. But to guarantee reliable measures, how is it necessary to proceed? And what do we have to measure?

Choose the right track!

At first, what track to choose? It must obey the some characteristics: a flat road, a long straight line without slope or banking, stocked with uniform cover, an asphalt of last generation if you wish to measure maximal performance of braking.

The car must be recent, in good mechanical condition and entrusted to a driver able to brake efficiently (not so frequent it seems!). A passenger is required to balance the masses. Let's go!

A classic method: the decametre!

The more traditional method is to measure the initial speed of the car and the braking distance.

Indeed, from the point of view of Physics, two only values allow to calculate all other parameters of braking: deceleration, braking time, grip coefficient, etc.

Watch Out! To avoid approximations, it is necessary to calibrate the car's speedometer, so that the speed is accurately recorded.

The braking zone will then be approached in cruise control, set to a value that takes into account the uncertainty of the speedometer. No danger because the cruise control

switches off when the driver presses the brake pedal. In any case, the braking system is still able to stop a car even if the throttle is fully open.

Example: if you want to measure the braking distance with an initial speed of 65 mph (30 m.s^{-1}), and if the uncertainty of the speedometer is + 3 %, the braking zone must be addressed at 67 mph.

Then, just use an old good decametre for measuring braking distance!

Where begins this famous distance? There is no possible error if the car is fitted with a plaster gun headed toward the ground and electrically controlled by the illumination of the stop lamps.

In order to ensure the reliability of the results, it is best to calculate the average of at least three tests, braking performance may vary from one test to another according to the shape of the driver, the soil temperature or tyres and brake system.

A slacker's method: stopwatch!

Yes! A simple stopwatch can be sufficient!

Indeed, combining the braking time and the initial speed of the car, it is possible to calculate all other parameters such as deceleration, braking distance, etc. The decametre becomes useless and there is no need to get off the car, the slackers will appreciate!

Unfortunately, this method is less accurate than the previous one, except if the launching of the stopwatch is coupled to the illumination of the stop lamps. But in this case, what about the stopping of the stopwatch?

A modern method: the computer!

The preferred method of testers of the automotive press is also the most modern and the most practical.

It consists of using a braking computer, commonly called 'FREINOGRAPH' (trademark).

The device does it all: farewell plaster gun, tape measure or stopwatch! And need not to worry about the initial speed! Farewell sophisticated calculator!

What about this magical device?

It works in a very rudimentary way in reality, since it is provided as a deceleration sensor, a stopwatch and a basic calculator. The sensor measures the intensity of the

deceleration, the timer measures the duration. As its name suggests, the computer is then responsible for all subsequent calculations.

Neither mystery nor magic in all this: the laws of physics teach us that the intensity of the deceleration and braking time are enough to calculate all the other parameters such as the initial speed, the braking distance, etc. This is the role of the computer.

Only elementary precaution: the brake should lead to a full stop of the car, because this device cannot discern remaining speed.

Test results

The three methods described above give us different fundamental measures, given the performance of modern cars could be these:

- initial speed: 65 mph (30 m.s^{-1}),
- braking distance: 45 meters,
- braking time: 3 seconds.

What can you calculate next? A lot of values!

Deceleration

First simple calculation: deceleration, which is defined as the rate of change per unit time.

By combining the initial speed (30 m.s^{-1}) and the braking time (3 s), we easily calculate the intensity of the deceleration, here equal to 10 meters per second squared (acceleration or deceleration unit, symbol m.s^{-2}).

Grip coefficient

Second simple calculation: the grip coefficient, defined as the ratio between the deceleration and a reference's acceleration.

Deceleration equal to 10 m.s^{-2} compared to the reference's acceleration being that of the Earth's gravity (approximate value: ' g ' = 10 m.s^{-2}), the grip coefficient here is exactly 1 and this not surprising!

Indeed, the braking tests published regularly in the automotive press show that, contrary to popular belief, most modern cars (or rather: the tires they are fitted) are able to get a grip coefficient to 1 or greater.

Sliding tires

Suppose that during braking, the driver has activated the anti-lock system, and suppose that the system is configured to occur from 5 % slide, this means that during braking, the circumferential speed of the wheels was 5 % lower to car moving speed.

For example, at the precise moment when the car moving speed was 50 mph, the circumferential speed of the wheels was 47.5 mph.

Speed variation

Another simple calculation: the speed variation, which is defined as the speed acquired at each time interval.

The deceleration of the car is equal to 10 m.s^{-2} , this means that the speed decreases to 10 meters per second (speed variation unit, symbol m.s^{-1}) for each second elapsed.

Then, it is easy to calculate the speed acquired at each time interval:

- 20 m.s^{-1} at the end of one second of braking,
- 10 m.s^{-1} at the end of two seconds of braking,
- 0 at the end of three seconds of braking.

Braking distance

The braking distance is defined as the distance traveled during deceleration.

By combining the previous values, it is possible to calculate the distance to each time interval.

Thus, the car has traveled:

- 25 meters during the first second of braking,
- 15 meters during the second second of braking,
- 5 meters during the third second of braking.

Here is the complexity of the braking law, the distance is not the same during each time interval.

Braking force

The braking force is defined as the force that slows the car when the driver operates the brake pedal.

This famous force, that without which nothing would be possible, acts on tires in contact with the ground, so it is impossible to measure directly.

But it is still possible to calculate its intensity. For this, you just need to know the mass of the car, its deceleration and combine the two quantities.

Suppose a mass of 3,300 lb (1,500 kilogrammes, mass unit, symbol **kg**) moving on a flat road: a deceleration of 10 m.s^{-2} assumes a braking force of 15,000 newtons (force unit, symbol **N**).

Disregarding the air resistance and the rolling resistance and the engine brake, the braking force is the average force resulting from the interaction between the road surface and the four tires tread ⁽¹⁾.

Reciprocal action

According to the third principle of Newton (action - reaction), any force causes a reciprocal action of equal intensity but opposite direction.

Reciprocal action is created by the mass of the car, it consists of a horizontal thrust exerted on the Earth ⁽²⁾, but with no effect on its rotation, because of the mass ratio ⁽³⁾.

Pitch

The pitch is defined as the rotational movement of the mass of the car around its center of mass. This movement is due to the braking force, it is explained by the vertical distance from the ground to the center of mass.

The intensity of the pitch is proportional to the mass, deceleration and the ratio between the height of the center of mass and the length of the wheelbase.

Thus, if we consider a mass drive to 1,500 kg characterized by a center of mass of 0.5 meter tall and a wheelbase of 2.5 meters long, a 10 m.s^{-2} deceleration generates a 3 kN pitch.

Dynamic load

The pitch offloads the rear axle and increases the load on the front axle during braking, it is called dynamic load.

If we consider a car weighing 15 kN (approximate value: ' g ' = 10 m.s^{-2}) characterized by a center of mass of 0.5 m high, 2.5 m wheelbase, weight distribution of 900 kg on the front axle and 600 kg on the rear axle, a 3 kN pitch generates a 12 kN front wheels dynamic load (9 + 3) and 3 kN rear wheels dynamic load (6 - 3).

In other words, by offloading the rear axle (- 3 kN), pitch is added to the front axle load (+ 3 kN), the total weight of the car obviously remains the same.

Braking dispatch

The dynamic load conditions the braking dispatch, size we usually expressed as a percentage.

Thus, for example, the front axle must provide 80 % of the braking force (12/15), the rear axle only 20 % (3/15).

Kinetic energy

The kinetic energy is defined as the amount of energy gained by a mass movement. In other words, stop a mass means removing kinetic energy.

The kinetic energy acquired by a car is the chemical energy from the combustion of fuel, net of any losses due to the heating of the internal parts of the engine, to the drive peripheral accessories (oil pump, water pump, alternator, power steering, air conditioning) and those related to the rotation of the transmission (gearbox, differential).

Furthermore, a part of the energy produced by the engine is absorbed by the rolling resistance and the air resistance that is exerted on the car until the beginning of braking.

More simply, the kinetic energy is equal to half the product of the mass by the square of the speed. A quick calculation shows that the kinetic energy of the car at the start of braking is exactly equal to 675 kilojoules (energy unit, symbol **kJ**)⁽⁴⁾.

This amount of kinetic energy corresponds to the combustion of about 20 cm^3 of fuel (0.02 liter or 1 / 50th liter), that gives an idea of the energy efficiency of the fuel⁽⁵⁾ and the low efficiency of thermal engines (see ADILCA file '*fuel combustion*').

Braking force work

The work is defined as the energy consumed by the motion of a force.

This quantity is equal to the product of the force by the distance, it is easy to calculate the work done in the physical sense of the term, the braking force that is exerted on the car's tires: this work is here exactly equal to 675 kilojoules (work unit, symbol **kJ**).

The comparison with the initial kinetic energy of the car let us verify the accuracy of the James Joule theories (James Prescott Joule, English physicist, 1818-1889): work and energy are equivalent magnitudes, the concept of work being the link between the concepts of force, motion and energy.

The kinetic energy of the car (675 kJ) has been transformed by the work of the braking force (675 kJ), the two remaining variables always strictly equal!

Braking power

The power is defined as the energy consumed, produced or processed per unit of time.

Knowing the amount of kinetic energy (675 kJ) and braking time (3 seconds), it is easy to calculate the braking power equal to 225 kilowatts (power unity, symbol **kW**).

This is a great value, well above that delivered by most engines. To gain a better idea, simply put it in horsepower (power unit, symbol hp) unit still commonly used by automotives dealers. 225 kW corresponds to more than 300 hp!

This value confirms that the braking force is still largely able to stop any car, even if the throttle is fully open.

The seven forces acting on the car, the braking force is the first in order of size and importance.

And if one was referencing the car models from the power of their braking, and not in relation to the engine power?

Kinetic energy variation

Power being a power change per time interval, a power of 225 kW corresponding to a kinetic energy change of 225 kilojoules per second (energy variation unit, symbol **$\text{kJ}\cdot\text{s}^{-1}$**). However, this quantity is little expressive in the minds of the public.

By combining the previous values of speed and distance, we can then express this energy variation, not a function of time, but depending on the distance traveled during braking.

Thus, the car has lost:

- 375 kJ on a distance of 25 meters during the first second of braking,
- 225 kJ on a distance of 15 meters during the second second of braking,
- 75 kJ on a distance of 5 meters during the third second of braking.

This surprising result seemingly confirms that the kinetic energy is dissipated through the work of a force.

The rate of reduction of this energy is here 15 kilojoules per brake meter (energy change unit, symbol $\text{kJ}\cdot\text{m}^{-1}$), size only related to the test conditions (mass of the car, tires equipment and road surface), but also completely independent of the speed or distance traveled during braking.

Braking heat

What has become of this kinetic energy? The general principle of the conservation of energy and its equivalence in whatever form, the kinetic energy has been fully converted into an equal amount of thermal energy (675 kJ), so in heat level tires and brakes. This conversion was carried out at 80 % by the front wheels, to 20 % by the rear wheels.

Disregarding the tire tread heat exchanges with the road and the ambient air, we can calculate the temperature variation of the braking system, provided you know its mass and heat capacity of the material which it is made.

For example, the heat capacity of the cast-iron, commonly used for car brake discs, is about 0.5 kJ per kilogram per kelvin (thermal capacity unit, symbol $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$).

This means that if the car is equipped with two ventilated disc brakes 14 kg mass acting on the front wheels and two full disc brakes 6 kg mass acting on the rear wheels, the braking system temperature rise of about 77 K (temperature unit, symbol **K**) in front, about 45 K in the back, values in addition to the initial temperature of the system.

Mass / contact surface ratio

The weight of the car and the contact surface of the tires on the ground allow the calculation of the mass / contact surface ratio.

Assuming a mass of 1,500 kg and a total area of ground contact of the four tires equal to 1,000 cm^2 (0.1 m^2), this ratio is here equal to 1.5 (dimensionless).

In practice this means that each centimeter square of the tire tread has to brake a mass of 1.5 kg. This ratio provides information on the work of the tire tread. Therefore it determines the composition of the gum and textures tires because the manufacturer must find a compromise between grip and endurance.

Braking surface

Finally, we can calculate what is called the braking surface, that is to say the total area of the road surface that participated in braking.

Assuming a 0.1 m^2 contact surface of the four tires and a 45 meters braking distance, the total area of the road surface participating in the braking is equal to 4.5 m^2 .

We can logically deduce that to reduce the braking distance, it would suffice to equip the car wider tires, filled with a softer compound.

Indeed, in this case, the increase in width would result in a reduction in length, so away, the braking surface remains unchanged.

Therefore, for the physicist, almost all braking mysteries have been solved!

(1) The various values calculated in these pages assume that the car is moving on a flat road. If not, the component of the weight parallel to the road (see ADILCA file 'slopes') is added to the braking force uphill, this force is hiding downhill.

(2) Reciprocal action makes coating work, which can be seen for example in automotive circuits in areas of heavy braking.

(3) If we compare a 2 tons car and Earth ($6 \times 10^{24} \text{ kg}$), the mass ratio is $2:6 \times 10^{21}$, 1 per 3,000 trillion.

(4) Disregarding the rotational kinetic energy of the wheels and of the non-disengaging part of the transmission.

(5) It can be inferred that, if the engine performance was perfect and in the absence of natural resistance forces (rolling resistance and air resistance), this volume of fuel would be sufficient to propel a stationary mass of 3,300 lb up to the speed of 65 mph.

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RELATIONSHIPS BETWEEN PHYSICAL QUANTITIES

Weight

$$P = M \cdot g$$

P: weight, expressed in **N**

M: mass, expressed in **kg**

g: gravitational acceleration of the Earth (approximate value: $g = 10 \text{ m.s}^{-2}$)

consistency of the units: $P = \text{kg} \cdot \text{m.s}^{-2} = \text{kg.m.s}^{-2} = \text{N}$

Example: calculate the weight of a 1,500 kg car mass:

$$P = 1,500 \times 10 = 15,000 \text{ N}$$

Deceleration

$$Y = V^2 / 2 D$$

Y: deceleration, expressed in **m.s⁻²**

V: initial speed, expressed in **m.s⁻¹**

D: braking distance, expressed in **m**

consistency of the units: $Y = (\text{m}^+ \cdot \text{s}^{-1})^2 \cdot \text{m}^{-1} = \text{m}^{+2} \cdot \text{s}^{-2} \cdot \text{m}^{-1} = \text{m.s}^{-2}$

Example: calculate the deceleration of a car under following conditions: initial speed car 30 m.s^{-1} , braking distance 45 m:

$$Y = 30^2 / (2 \times 45) = 900 / 90 = 10 \text{ m.s}^{-2}$$

Braking time

$$T = V / Y$$

T: braking time, expressed in **s**

V: initial speed, expressed in **m.s⁻¹**

Y: deceleration, expressed in **m.s⁻²**

consistency of the units: $T = \text{m}^+ \cdot \text{s}^{-1} \cdot \text{m}^{-1} \cdot \text{s}^{+2} = \text{s}$

Example: calculate the braking time under following conditions: initial speed car 30 m.s^{-1} , deceleration 10 m.s^{-2} :

$$T = 30 / 10 = 3 \text{ s}$$

Speed acquired as a function of the braking time

$$V_b = V_a - (Y \cdot T)$$

V_b: speed acquired, expressed in **m.s⁻¹**

V_a: initial speed, expressed in **m.s⁻¹**

Y: deceleration, expressed in **m.s⁻²**

T: braking time, expressed in **s**

consistency of the units: $V = m \cdot s^{-1} - (m \cdot s^{-2} \cdot s) = m \cdot s^{-1} - m \cdot s^{-1} = m \cdot s^{-1}$

Example: calculate the car speed acquired under following conditions: initial speed 30 m.s⁻¹, deceleration 10 m.s⁻², braking time 2 seconds:

$$V_b = 30 - (10 \times 2) = 30 - 20 = 10 \text{ m.s}^{-1}$$

Distance traveled during braking according to acquired speed

$$D = (V_a^2 - V_b^2) / (2 Y)$$

D: distance traveled, expressed in **m**

V_a: initial speed, expressed in **m.s⁻¹**

V_b: speed acquired, expressed in **m.s⁻¹**

Y: deceleration, expressed in **m.s⁻²**

consistency of the units: $D = (m \cdot s^{-1})^2 - (m \cdot s^{-1})^2 / (m \cdot s^{-2}) = m^{+2} \cdot s^{-2} \cdot m^{-1} \cdot s^{+2} = m$

Example: calculate the distance traveled by car from initial speed 30 m.s⁻¹ to acquired speed 10 m.s⁻¹, the deceleration being 10 m.s⁻²:

$$D = (30^2 - 10^2) / (2 \times 10) = (900 - 100) / 20 = 800 / 20 = 40 \text{ m}$$

Grip coefficient

$$\mu = Y / g$$

μ: grip coefficient, dimensionless;

Y: deceleration, expressed in **m.s⁻²**

g: gravitational accélération of the Earth (approximate value: **g = 10 m.s⁻²**)

consistency of the units: $\mu = (m^{+1} \cdot s^{-2}) \cdot (m^{-1} \cdot s^{+2}) = \text{dimensionless}$.

Example: calculate the grip coefficient which allows a 10 m.s⁻² deceleration:

$$\mu = 10 / 10 = 1$$

Slide coefficient

$$a = (V - v) / V$$

a: slide coefficient, dimensionless;

V: car speed, expressed in **m.s⁻¹**

v: wheels rotation speed, expressed in **m.s⁻¹**

consistency of the units: $(m^{+1}.s^{-1}) . (m^{-1}.s^{+1}) = \text{dimensionless}$.

Example: calculate the slide coefficient under following conditions: car speed 20 m.s⁻¹, wheels rotation speed 18 m.s⁻¹:

$$a = (20 - 18) / 20 = 2 / 20 = 0,1 = 10 \%$$

Braking force

$$F = M . Y$$

F: braking force, expressed in **N**

M: mass, expressed in **kg**

Y: deceleration, expressed in **m.s⁻²**

consistency of the units: $F = \text{kg} . \text{m.s}^{-2} = \text{N}$

Example: calculate the braking force under following conditions: a 1,500 kg car mass, a 10 m.s⁻² deceleration:

$$F = 1,500 \times 10 = 15,000 \text{ N}$$

Pitch

$$R = M . Y . H / L$$

R: pitch, expressed in **N**

M: mass, expressed in **kg**

Y: deceleration, expressed in **m.s⁻²**

H: height of the center of mass, expressed in **m**

L: wheelbase, expressed in **m**

consistency of the units: $R = \text{kg} . \text{m}^{+1}.s^{-2} . \text{m}^{+1} . \text{m}^{-1} = \text{kg.m.s}^{-2} = \text{N}$

Example: calculate the pitch of a 1,500 kg car mass under following conditions: 0.5 m height of the center of mass, 2.5 m wheelbase, 10 m.s⁻² deceleration:

$$R = 1,500 \times 10 \times 0.5 / 2.5 = 7,500 / 2.5 = 3,000 \text{ N}$$

Braking force work

$$E = F \cdot D$$

E: work, expressed in **J**

F: braking force, expressed in **N**

D: braking distance, expressed in **m**

consistency of the units: $E = \text{kg} \cdot \text{m} \cdot \text{s}^{-2} \cdot \text{m} = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} = \text{J}$

Example: calculate the 15,000 N braking force work over 45 meters braking distance:

$$E = 15,000 \times 45 = 675,000 \text{ J}$$

Kinetic energy

$$E = \frac{1}{2} M \cdot V^2$$

E: kinetic energy, expressed in **J**

M: mass, expressed in **kg**

V: initial speed, expressed in **m.s⁻¹**

consistency of the units: $E = \text{kg} \cdot (\text{m}^+ \cdot \text{s}^{-1})^2 = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} = \text{J}$

Example: calculate kinetic energy of a 1,500 kg mass car moving at 30 m.s⁻¹:

$$E = \frac{1}{2} \times 1,500 \times 30^2 = 750 \times 900 = 675,000 \text{ J}$$

Kinetic energy variation

$$\Delta E = \frac{1}{2} M \cdot (V_a^2 - V_b^2)$$

ΔE: kinetic energy variation, expressed in **J**

M: mass, expressed in **kg**

V_a: initial speed, expressed in **m.s⁻¹**

V_b: speed acquired, expressed in **m.s⁻¹**

consistency of units: $E = \text{kg} \cdot [(\text{m} \cdot \text{s}^{-1})^2 - (\text{m} \cdot \text{s}^{-1})^2] = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} = \text{J}$

Example: let's calculate the kinetic energy variation of a 1,500 kg mass car from initial speed 30 m.s⁻¹ to acquired speed 15 m.s⁻¹:

$$\Delta E = \frac{1}{2} \times 1,500 \times (30^2 - 15^2) = 750 \times (900 - 225) = 750 \times 675 = 506,250 \text{ J}$$

Braking power

$$B = E / T$$

B: braking power, expressed in **W**

E: kinetic energy, expressed in **J**

T: braking time, expressed in **s**

consistency of the units: $P = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} \cdot \text{s}^{-1} = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-3} = \text{W}$

Example: calculate the braking power clearing a 675,000 J work in 3 seconds:

$$B = 675,000 / 3 = 225,000 \text{ W}$$

Heat variation

$$\Delta T = E / M / C$$

ΔT: heat variation, expressed in **K**

E: kinetic energy, expressed in **J**

M: mass of braking system, expressed in **kg**

C: heat capacity of the cast-iron, expressed in **J.kg⁻¹.K⁻¹**

consistency of the units: $\Delta T = \text{kg}^{+1} \cdot \text{m}^{+2} \cdot \text{s}^{-2} \cdot \text{kg}^{-1} \cdot \text{kg}^{-1} \cdot \text{m}^{-2} \cdot \text{s}^{+2} \cdot \text{kg}^{+1} \cdot \text{K}^{+1} = \text{K}$

Example: calculate the heat variation of a 20 kg cast-iron braking system ($C = 500 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$) clearing a 675,000 J kinetic energy:

$$\Delta T = 675,000 / 20 / 500 = 67,5 \text{ K}$$

Net energy produced by fuel combustion:

Diesel (density $845 \text{ kg} \cdot \text{m}^{-3}$): **41.7 MJ.kg⁻¹** (**35.2 MJ.l⁻¹**)

Gasoline (density $760 \text{ kg} \cdot \text{m}^{-3}$): **43.7 MJ.kg⁻¹** (**33.2 MJ.l⁻¹**)

LPG (density $550 \text{ kg} \cdot \text{m}^{-3}$): **45.1 MJ.kg⁻¹** (**24.8 MJ.l⁻¹**)

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