The tyre

Rolling resistance and fuel savings

MICHELIN

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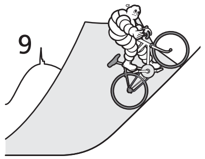

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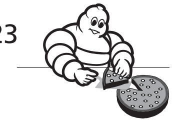

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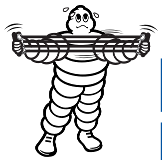

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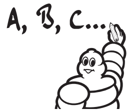

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Rolling resistance and fuel savings

Setting aside the much-dreamed-of concept of perpetual movement, all mobility on Earth requires the expenditure of energy. In the case of motor vehicles, this energy is supplied by fuel.

Energy makes the wheels go round, thus driving the vehicle forward. As the wheel goes round, the tyre is deformed to make contact with the road. All the forces required for acceleration, braking and cornering are transmitted through this contact patch. As it is deformed, the tyre also absorbs road surface asperities. It is the tyre's ability to be deformed which ensures grip and comfort.

Visco-elasticity: the source of rolling resistance

Tyre rubber compounds are visco-elastic. They therefore dissipate energy in the form of heat whenever they are being deformed. Visco-elasticity is the source of a tyre's grip but energy dissipation is also the source of rolling resistance.

Cost saving and preservation of the environment

Rolling resistance affects fuel consumption in the same way as natural phenomena like wind, slope and vehicle inertia, which must be overcome in order to move.

Reducing rolling resistance reduces costs and helps preserve the environment. Reducing a vehicle's fuel consumption means cutting down on fossil fuels and releasing fewer exhaust gases into the atmosphere while lowering the vehicle's operating cost per kilometre.

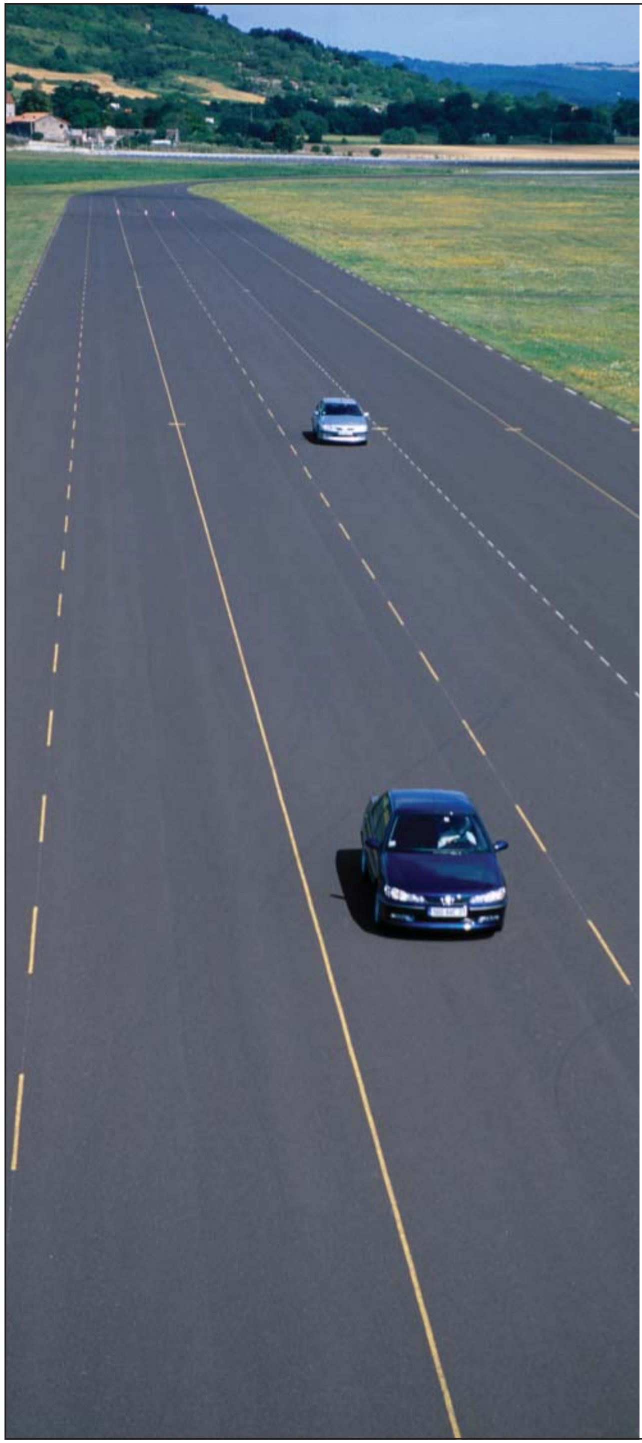
Rolling resistance has been reduced by a factor of three since the very first pneumatic tyres. In 1895, tyres had a rolling resistance coefficient of 25 kilograms per tonne, whereas Michelin's "green" tyre (Green X)—first produced in 1992—today offers a rolling resistance coefficient of 8 kilograms per tonne without compromising either grip or resistance to wear.

At the same time, considerable progress has been made on both vehicles (engine, aerodynamics) and roads (surfaces and profiles), enabling greater mobility for less energy. A new vehicle today uses fifteen percent less fuel and pollutes twenty times less than fifteen years ago.

Given the ecological constraints linked to the development of human activities in general and road transport in particular, further progress is crucial. Reducing rolling resistance will help improve the situation.

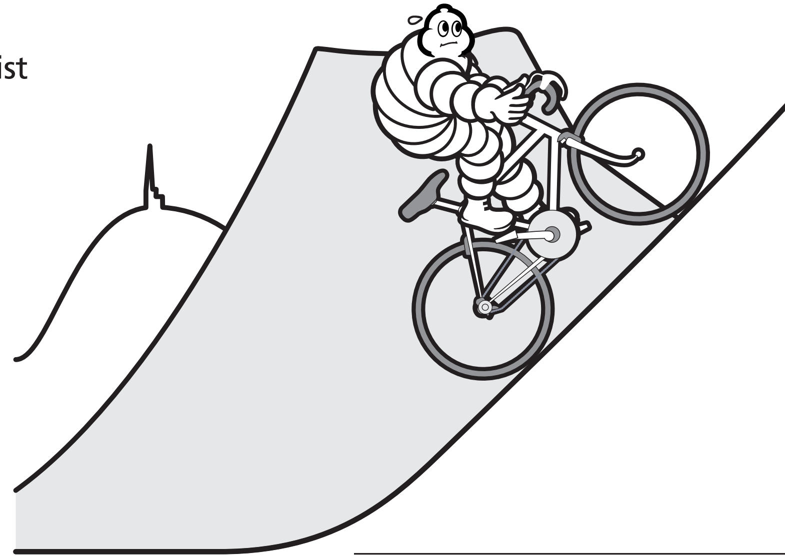
Understanding phenomena involved

In order to reduce rolling resistance by a factor of three, it was necessary to understand the mechanisms involved—tyre deformation when rolling, behaviour of rubber compounds—and to work out how to evaluate the proportion of fuel consumption directly due to a vehicle's tyres. This is what volume three of "The Tyre" encyclopaedia is all about.



I Rolling resistance and resistance to movement

A car driver cannot easily perceive
tyre rolling resistance.
Chapter one will therefore illustrate
this concept using a simple example.
We will also take a look
at all the forces that resist
a vehicle's movement.



Introduction to rolling resistance

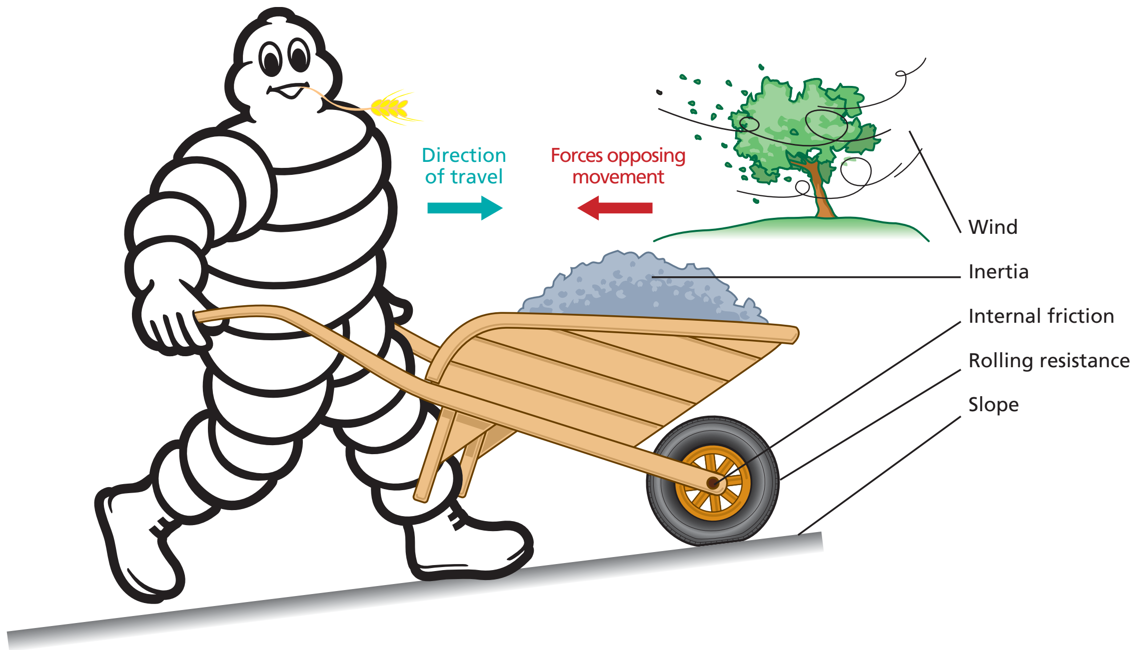
To move ourselves or an object, we have to apply force and thus expend energy. In a motor vehicle, energy expenditure dictates fuel consumption.

Let us take a simple example. To move a wheelbarrow forward you have to push it, in other words make an effort. The required effort increases if the load is heavier, if you are pushing it up a steep incline, against the wind or if the wheelbarrow hub has not been greased. We have already mentioned four forces which resist the movement of a vehicle:

- inertial forces, which depend on the vehicle's mass and variations in speed,
- gravitational forces, which depend on the slope and mass,
- aerodynamic forces, which depend on the wind, the speed of movement and the vehicle's shape,
- the internal friction of rotating parts.

Section I.2 will look at these forces in greater detail.

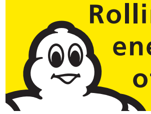
The effort to be made also depends on the ground and the wheelbarrow wheel. We all know that it is easier to push a wheelbarrow over hard ground than over soft ground. Similarly, a wheelbarrow with a metal-rimmed wheel or a properly inflated pneumatic tyre is easier to push than one with an under-inflated tyre. This is where the fifth resistive force comes in: **rolling resistance**.



WHERE DOES ROLLING RESISTANCE COME FROM?

Rolling resistance is mainly due to the visco-elastic properties of the rubber compounds used to make tyres. When being deformed, this type of material dissipates energy in the form of heat.

When rolling, a tyre is deformed by the load exerted on it, flattening out in the contact patch. This repeated deformation causes energy loss known as **rolling resistance**.



Rolling resistance is defined as the energy consumed by a tyre per unit of distance covered [1].

Rolling resistance can only be overcome by expending energy.

In the case of a motor vehicle, the energy is supplied by fuel. Rolling resistance thus has a direct effect on fuel consumption.

[1] As defined by the ISO 8767 standard on rolling resistance measurement methods.

THE MECHANICAL MANIFESTATION OF ROLLING RESISTANCE

Let us compare three different cases:

❶ A wheelbarrow with a metal-rimmed wheel being pushed along very hard ground. Both the wheel and the ground are considered perfectly non-deformable.

❷ A wheelbarrow with a metal-rimmed wheel (non-deformable) being pushed along soft ground (deformable).

❸ A wheelbarrow with a pneumatic tyre (deformable) being pushed along hard ground (non-deformable).

❶ Non-deformable wheel on hard ground

In the theoretical case of a perfectly non-deformable wheel and ground, it is very easy to push the wheelbarrow. No energy is lost through deformation and therefore there is no rolling resistance.

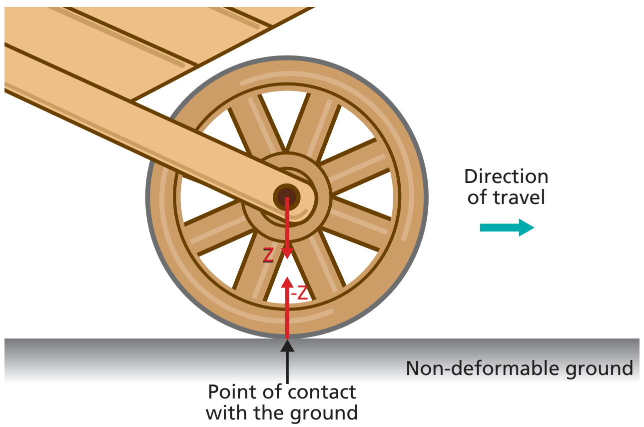
If we look at the vertical forces on the hub and where the wheel touches the ground, it can be seen that the weight (Z) on the wheel is perfectly balanced by the ground reaction force (-Z).

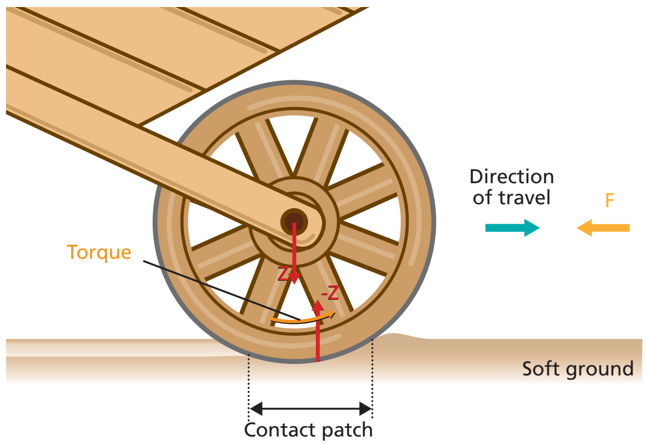
❷ Non-deformable wheel on soft ground

Pushing a wheelbarrow over soft ground is much more tiring. A lump of earth forms in front of the wheel as the soil is deformed under the weight of the wheelbarrow. Looking behind, you can see that the wheel has traced a rut in the earth. The ground has been deformed, absorbing energy.

If we look at the vertical forces on the hub and where the wheel touches the ground, it can be seen that the ground reaction force (-Z) is further forward in the contact patch than the Z force. The torque that results from this offsetting of the two forces opposes wheel rotation.
It is as if there were a force resisting the wheel's forward motion. This force (F) is the "mechanical" manifestation of the energy dissipated due to the soil's deformation.

Z: weight of the wheelbarrow on the wheel (i.e. load)
-Z: ground reaction force on the wheel





❸ Pneumatic tyre on hard ground

Unlike a non-deformable wheel, a pneumatic tyre is flexible: it hugs the ground for better grip and comfort.

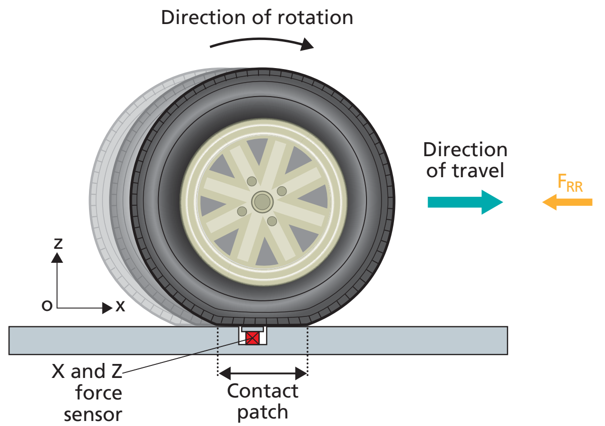
While a wheel is in contact with the hard ground at only one point around its circumference, a tyre has a whole patch in contact with the ground. The ground reaction force therefore applies throughout the contact patch.

When the ground's vertical reaction forces are measured as a tyre is rolled over it, they are seen to be on the whole greater in the front half of the contact patch than in the rear half. The sum of these forces (resultant force –Z) is therefore consistently towards the front of the contact patch.

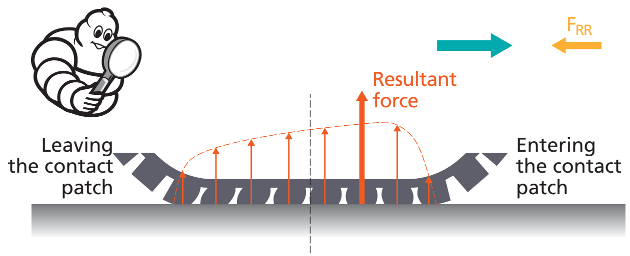
As in case ❷, this shifting of forces leads to a torque opposing wheel rotation. It is as if there were a force resisting the wheel's forward motion. This force is the "mechanical" manifestation of energy loss due to tyre deformation in the contact patch. It is known as the **"rolling resistance force"** (F_{RR}).

Note:
The rolling resistance force due to tyre deformation (case ❸) is 10 to 100 times less than the resistive force due to the deformation of soft ground (case ❷).

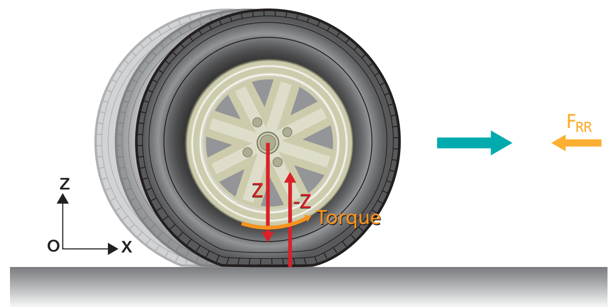
Measurement of vertical forces in a tyre's contact patch



The tyre is rolled at a stable speed over a surface incorporating a force sensor.



The measurement of vertical forces as the tyre is rolled over the sensor shows that the ground reaction forces on the tyre tread are greater near the front of the contact patch than near the rear. The sum of the forces (resultant force –Z) is therefore offset towards the front of the contact patch.



Because the ground reaction force is offset, a torque opposing tyre rotation is created. It is equivalent to a force (F_{RR}) that is known as the **rolling resistance force**.

EXPRESSION OF ROLLING RESISTANCE

Rolling resistance is defined as the energy consumed by a tyre per unit of distance covered.

Rolling resistance is therefore an energy expressed in newton-metres (N.m) divided by a distance in metres. It is thus equivalent to a force expressed in newtons (N).

The rolling resistance force acting on a moving vehicle depends on its tyres and its weight (i.e. load, Z).

Energy and force units

Energy can be expressed in joules (J)—which are equivalent to newton-metres—in calories (cal), or in watt-hours (Wh).

The energy lost per unit of distance can therefore be expressed in N.m/m.

Forces are expressed in newtons (N).
Obviously, 1 N.m/m = 1 N

The energy lost per unit of distance is therefore equivalent to a force.

Note:

$$1\text{ J} = 1\text{ N.m} = \frac{1}{3\,600}\text{ W.h} = 0.239\text{ cal}$$

ROLLING RESISTANCE COEFFICIENT

Tyre rolling resistance is characterized by a **rolling resistance coefficient** written as C_{RR} and equal to:

$$C_{RR} = \frac{F_{RR}}{Z}$$

By definition, a coefficient is a value without units. In our case, force F_{RR} and load Z are both expressed in newtons in compliance with standard international units. The rolling resistance coefficient C_{RR} is, as it should be, a value without units. It can also be expressed as a percentage or as "per mil".

Example:

$$C_{RR} = \frac{F_{RR}}{Z} = \frac{120\text{ N}}{10\,000\text{ N}} = 0.012 \text{ which is } 1.2\,\% \text{ or } 12\,‰$$

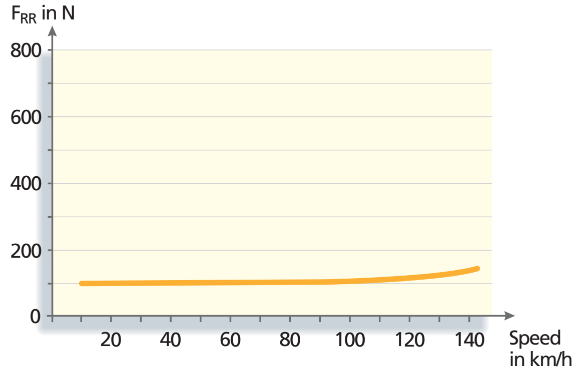
However, force F_{RR} is often expressed using the old unit of "kilogram-force" [1] and load using "tonne-force", in which case the coefficient is expressed in kg/tonne. A coefficient of 0.012 is therefore equivalent to a coefficient of 12 kg/t or 12 "per mil".

The expression "12 kg/t" means that if the tyre is supporting a load of one tonne, 12 kilograms-force (around 120 newtons) therefore need to be applied to avoid losing speed due to rolling resistance. To take another illustration, when a vehicle is being driven with tyres having a rolling resistance coefficient of 12 kg/t, it is using the same amount of energy as if it were climbing a slope of 1.2 %.

A tyre's rolling resistance coefficient is relatively constant up to 100 to 120 km/h, then it increases with speed. The values given by tyre manufacturers are measured on test drums, usually at 80 km/h in accordance with ISO measurement standards [2].

Tyre rolling resistance force versus speed

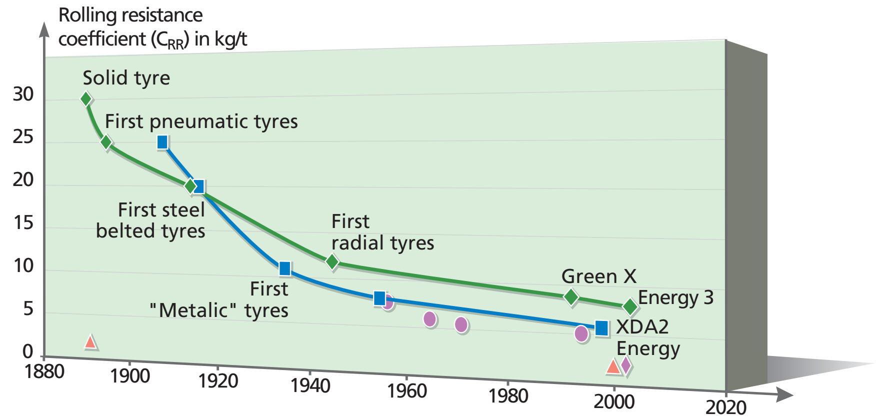
(values for a 1.2 tonne vehicle fitted with 4 tyres having a C_{RR} of 0.0085)



[1] A kilogram-force corresponds to the gravitational force acting on a mass of 1 kg. 1 kgf = 9.81 N.

[2] International Organization for Standardization: the ISO 8767 standard on passenger car tyres and ISO 9948 on truck tyres.

Milestones in the progression of rolling resistance since 1980



Typical values for 2002:

- Passenger car tyres: 8.5 to 13 kg/t for tyres currently available. 6 kg/t tyres specifically designed for electric vehicles (mainly urban usage) are already available on the market.
- Truck tyres: 4.5 to 10 kg/t.
- Bicycle road tyres: 2.5 to 5 kg/t

Passenger car tyres
Truck tyres
Railway wheels
Underground railway tyres
Shell Eco Marathon tyres

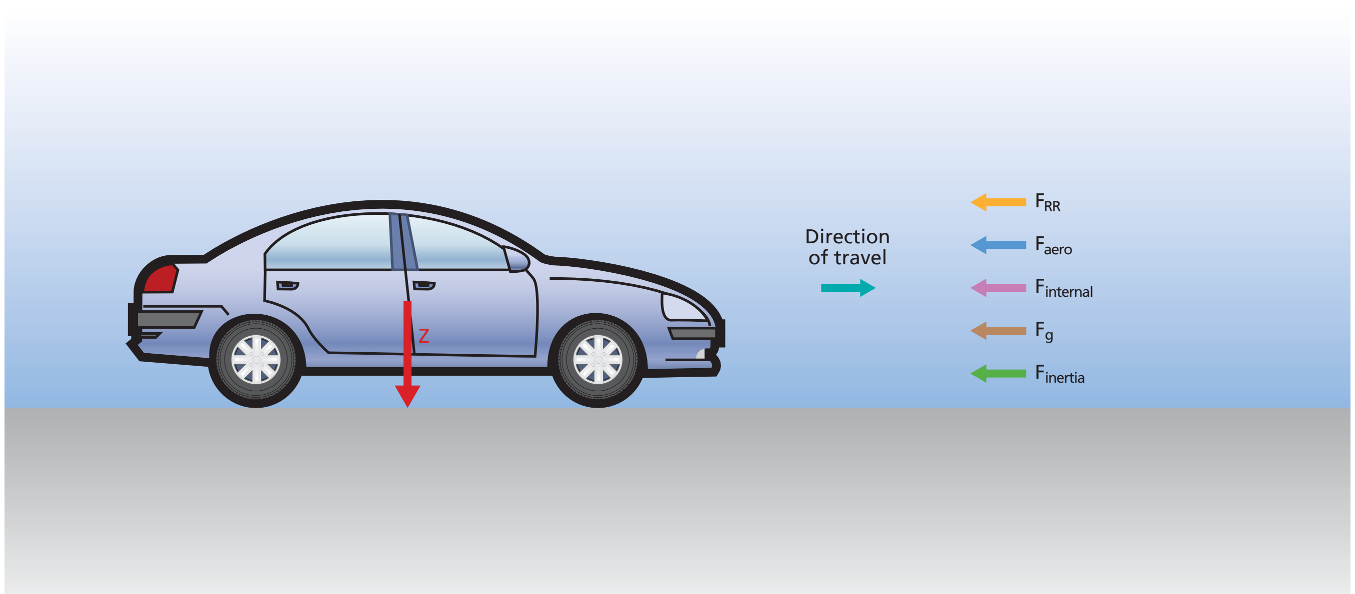
Shell Eco Marathon is an annual competition for ultra-low fuel consumption vehicles, some of which can cover 3,500 km on 1 litre of petrol.

I.2
Resistance to movement

Let us consider the case of a vehicle being driven at 90 km/h. In order to keep to the same speed, the driver must maintain a light pressure on the accelerator pedal. This means that the vehicle uses fuel, or in other words expends energy. If the driver takes his foot off the pedal and shifts into neutral, the vehicle will gradually come to a halt, even on a flat road. This is because of the resistive forces acting on the vehicle.

Resistance to movement is the sum of the resistive forces acting on a vehicle which must be overcome for the vehicle to move forward. The effort this requires is provided in the form of energy.

There are five main types of forces to overcome for a vehicle to move forward:
- rolling resistance forces, introduced in the previous section,
- aerodynamic forces,
- internal frictional forces,
- gravitational forces (when driving up a slope),
- inertial forces (when accelerating).



AERODYNAMIC FORCES

Aerodynamic forces result from a vehicle's movement through the air. They depend on the size and shape of the vehicle—or more specifically its frontal area and drag coefficient—and the speed at which it is travelling.

The **frontal area**, referred to as A, corresponds to a projection of the vehicle profile onto a vertical plane. It is the surface area seen when looking directly at the front of the vehicle from sufficiently far away. The frontal area of a passenger car is approximately 2 m² and that of a truck approximately 9 m².

Frontal area

Typical values:
passenger car: 2 m²
truck: 9 m²

The **aerodynamic drag coefficient**, referred to as C_D, relates to an object's resistance to movement through air for a given frontal area. The lower the coefficient, the more aerodynamic the object. Passenger cars currently on the market have a coefficient between 0.28 and 0.35. The coefficient of some aerodynamically efficient vehicle designs can be as low as 0.18. The drag coefficient for trucks lies between 0.5 and 1.5.

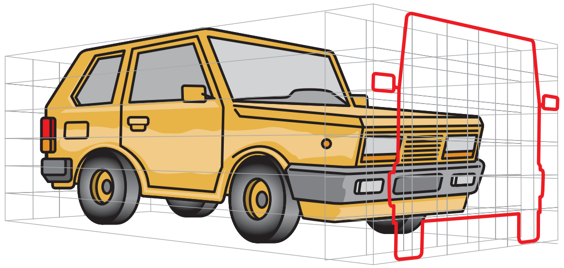
The aerodynamic drag force increases in proportion to the square of the **speed**. It is equal to:

$$F_{aero} = \frac{1}{2} \rho . A . C_D . V^2$$

where
F_{aero} is expressed in newtons
ρ is the air density ($\rho \approx 1.3$ kg/m³)
A is the vehicle's frontal area in m²
C_D is the drag coefficient
and V is velocity in m/s.

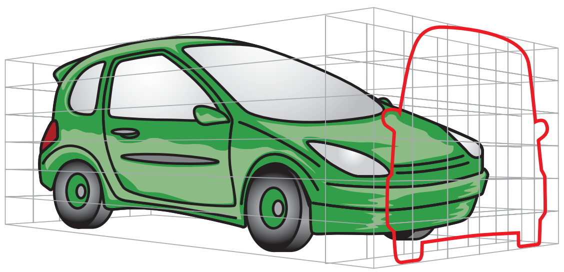
Aerodynamic drag coefficient and frontal area

Vehicle A



A = 3 m²
$C_D \approx 0.6$

Vehicle B



A = 3 m²
$C_D \approx 0.35$

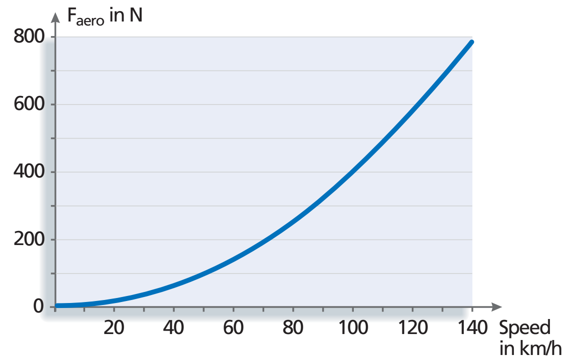
Vehicles of very different shapes can have the same frontal area, as illustrated. However, the drag coefficient of vehicle B is lower than that of vehicle A. At a given speed, the aerodynamic forces acting on vehicle B are weaker.

Typical values for 2002:

Average value for passenger cars currently on the market: $C_D = 0.32$
Low-consumption prototype: $C_D = 0.18$
Truck: $C_D = 0.5$ to 1.5
Bus: $C_D = 0.6$ to 0.7

Aerodynamic forces versus speed

(typical values for A = 2.5 m², $C_D = 0.32$, no wind)

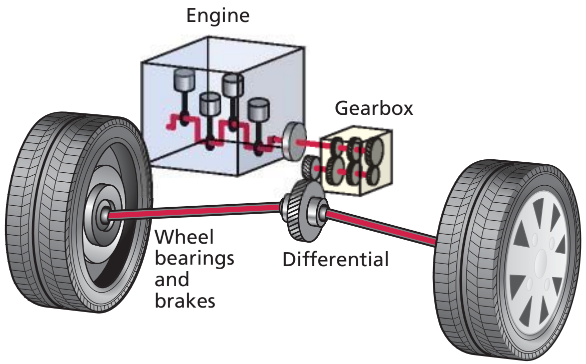


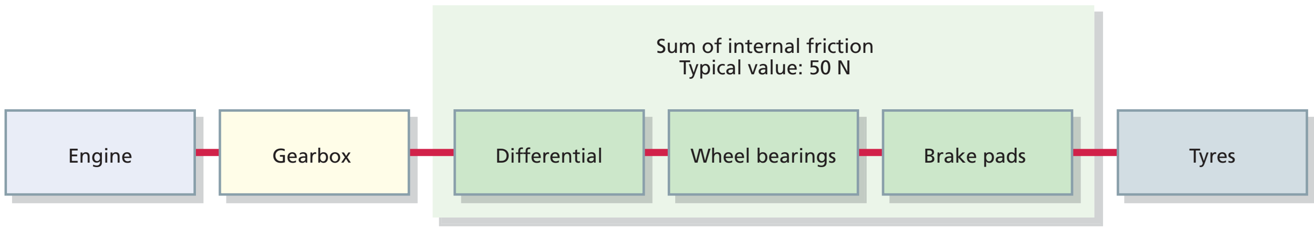
INTERNAL FRICTIONAL FORCES

Convention holds that the internal frictional forces of a vehicle correspond to friction in the drive train, i.e. in the differential and wheel bearings together with brake drag (friction between the rotors or drums and the brake pads when not being applied).

To simplify matters, we may consider that internal friction is independent of speed. It depends only on parameters intrinsic to the vehicle. For an average passenger car, we may consider that internal frictional forces add up to around 50 newtons.

Energy loss in the drive train





• The **drive train** goes from the engine crankshaft through to the tyres.

• Friction in the differential, wheel bearings and brake pads is nearly constant for a given vehicle, whatever the driving conditions.

However, friction in the engine and gearbox depends on factors such as the power the vehicle has to produce and the gear it is in. We will take engine and gearbox friction into account in our calculations by using efficiency expressed as a percentage rather than a constant force.

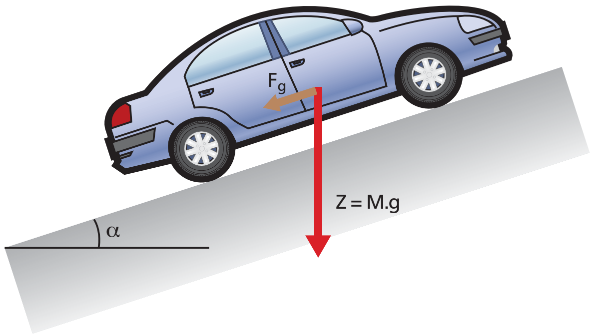
Vocabulary note:
Transmission is a synonym for gearbox.
The ratio between the engine speed and the speed of the wheels is known as the **gear ratio**.

GRAVITATIONAL FORCES

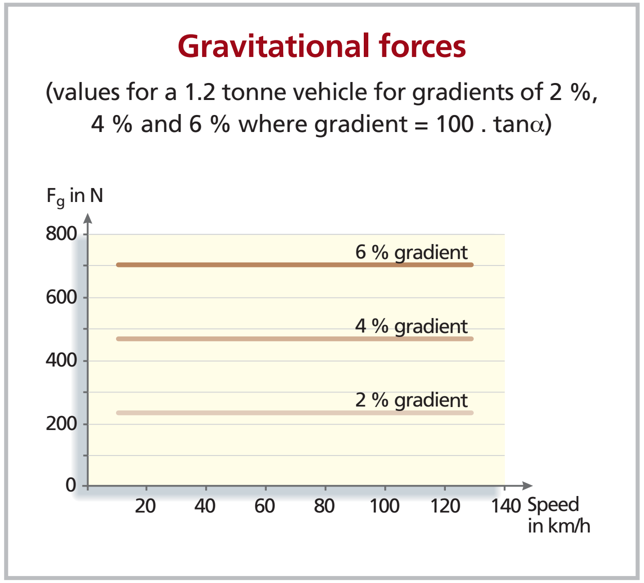
Gravitational forces, F_g, only apply when the road is inclined. The greater the gradient and vehicle mass, the greater the gravitational forces.

$$F_g = M \cdot g \cdot \sin\alpha$$

where
M is the mass of the vehicle in kg
g is the gravitational acceleration (9.81 m/s²)
α is the angle of the gradient.



Note:
Fuel consumption is measured according to regulatory cycles simulating driving without changes in elevation. In order to compare data in this document with these official measurements, we will assume below that all driving is on flat roads, so there are no gravitational forces.



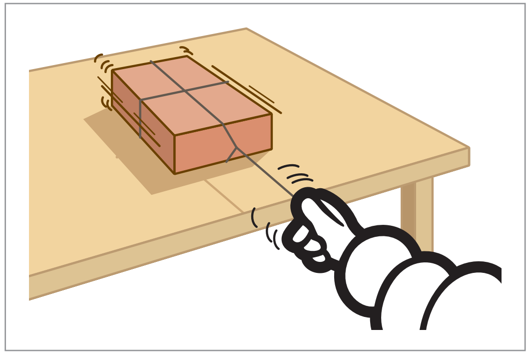
INERTIAL FORCES

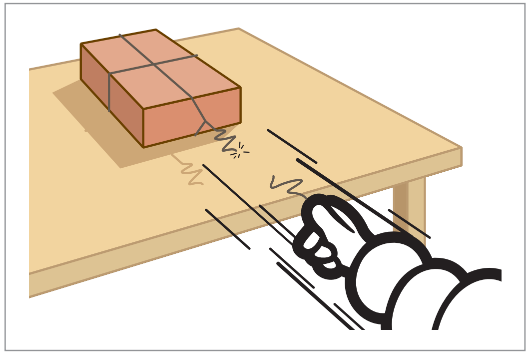
Let us take the example of a brick placed on a table. A string is attached to pull it across the table. If the string is pulled gently, the brick will move, but if it is pulled abruptly, it may break.

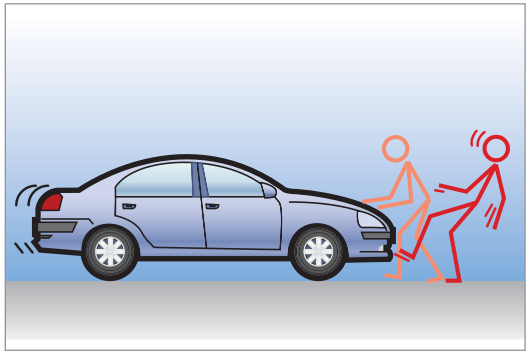
It is as if the brick will let itself be moved as long as it is not pulled too "abruptly". We might even consider the brick a little "lazy". In the language of physics, the brick is said to have **inertia**.

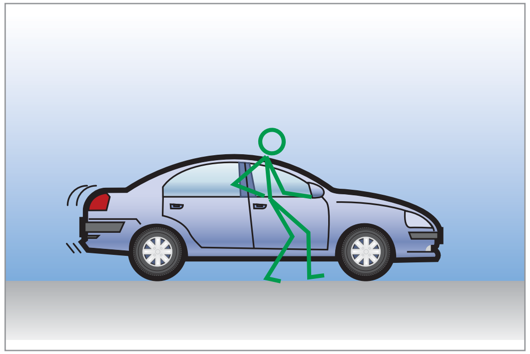
Inertia can also be seen when we want to slow down or stop a moving object. To take the example of a car, which is obviously bigger than a brick, let us assume that the car is coasting along at 3 or 4 km/h with the engine off. If I want to stop it suddenly by standing in front of it, I will get pushed over by the vehicle's momentum. However, if I stand on one side of the vehicle and gradually slow it down while moving along with the vehicle for a few steps, then I will manage to stop it. This is the other manifestation of inertia: a moving object seeks to continue along its path and resists efforts made to stop it.

In both illustrations, resistance is greater when we want to change the object's speed quickly.









To summarize, inertial forces are the forces which resist the acceleration or deceleration of a vehicle.

The greater the acceleration (or deceleration) we want to apply to the vehicle, the greater the inertial forces acting on the vehicle. At a constant speed, inertial forces are zero.

Inertial forces are directly proportional to the vehicle's mass. The heavier the vehicle, the greater its inertia.
An object does not only have inertia when braking or accelerating during translation. It also has inertia during rotation. We thus need to consider the rotational inertia of all the rotating parts in a vehicle (tyre-wheel assemblies, drive train elements, engine). The **rotational inertia** of a passenger car is estimated at 4 % of the vehicle's mass (three quarters of this amount being attributed to the tyre-wheel assemblies). Inertial forces are given by:

$$F_{inertia} = M_{eq} \cdot \dot{V}$$

where

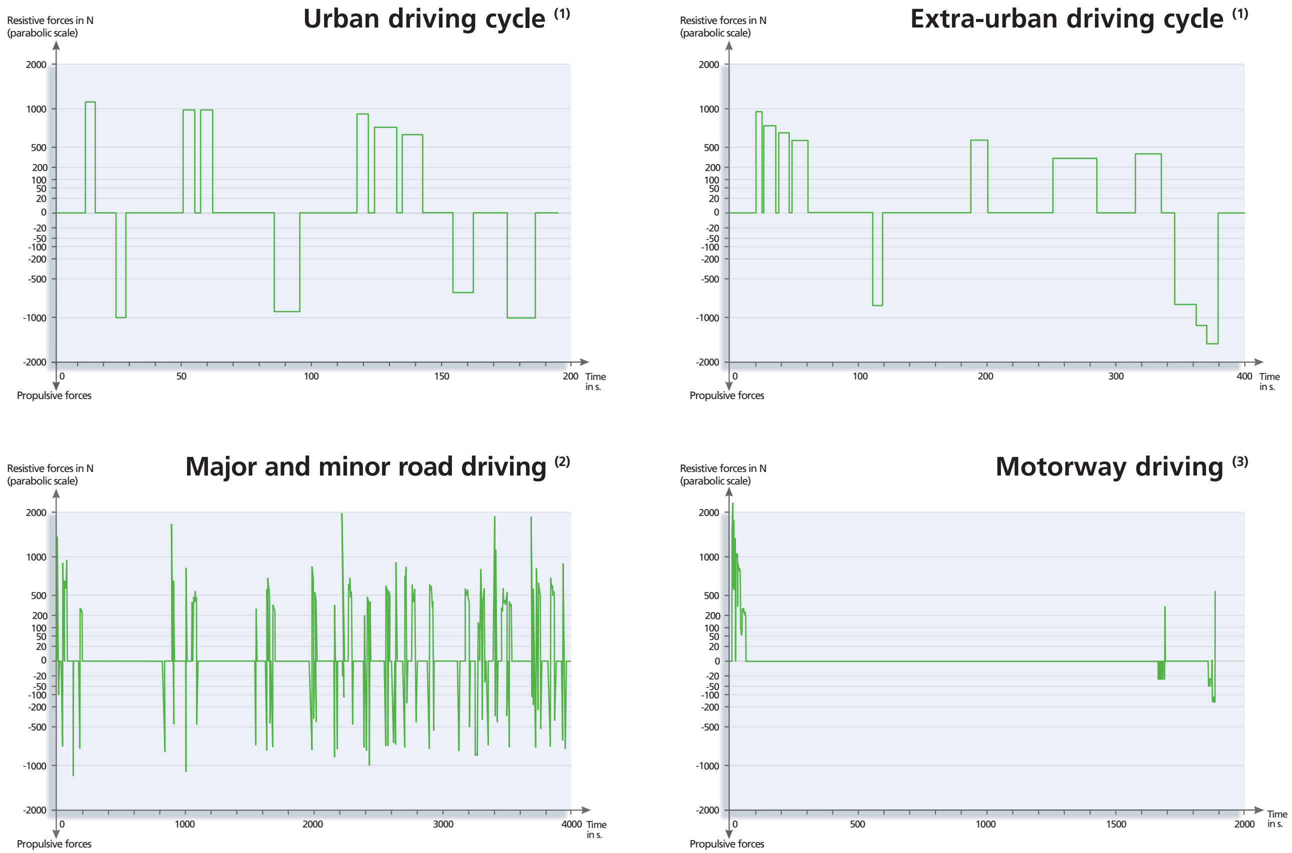
M_{eq} is the vehicle's **equivalent mass**, which is roughly the vehicle's mass plus an extra 4% expressed in kg

$\dot{V}$ is the acceleration or deceleration we want to apply to the vehicle in m/s^2

Inertial forces are very significant on trips involving many stops and starts such as at traffic lights, stop signs and road junctions.
Such stop-and-go trips are usually in towns, when crossing built-up areas or on winding roads. Speed is usually more constant on trips when a higher average speed can be maintained, such as peri-urban or motorway driving.

Inertial forces

when simulating four different types of trip (for a 1.1 tonne vehicle)



(1) As defined by Directive 98/69/EC

(2) Trip comprising 53 km of main roads and 40 km of minor roads going through 8 built-up areas

(3) Driving at a near-constant130 km/h

... inertial forces and equivalent mass

A little more information on...

Inertia of an object subject to translation

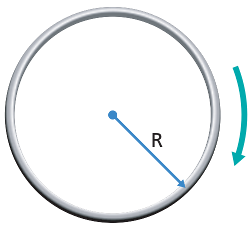
- Translational inertia = mass M
- Translational inertial force:

$F_{translation\text{-}inertia} = M \,.\, \dot{V}$ where F is in N, M is in kg, $\dot{V}$ is in m/s²

($\dot{V}$ is acceleration)

Inertia of an object subject to rotation

Let us take a ring:

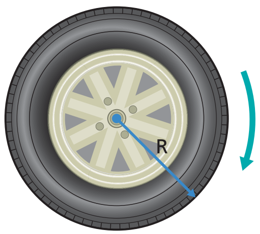


- Rotational inertia ("moment of inertia"): $I = M \,.\, R^2$
- Rotational inertial force:

$F_{rotation\text{-}inertia} = \dfrac{I \,.\, \dot{\omega}}{R}$ where F is in N, I is in kg.m², $\dot{\omega}$ is in rad/s², R is in m

($\dot{\omega}$ is angular acceleration)

Let us take a tyre-wheel assembly:

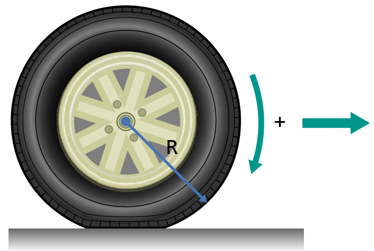


- Rotational inertia ("moment of inertia"): $I = \sum_{i=1}^{n} m_i \,.\, r_i^2$
- Rotational inertial force (in newtons):

$F_{rotation\text{-}inertia} = \dfrac{I \,.\, \dot{\omega}}{R}$ where R is the rolling radius

Inertia of a rolling tyre-wheel assembly,

subject to translation and rotation at the same time



Inertial force:

$$F_{inertia} = F_{translation\text{-}inertia} + F_{rotation\text{-}inertia} = M \,.\, \dot{V} + \frac{I \,.\, \dot{\omega}}{R}$$

By definition, $\dot{\omega} = \dfrac{\dot{V}}{R}$ (if there is no slippage)

therefore $F_{inertia} = M \,.\, \dot{V} + \dfrac{I}{R} \,.\, \dfrac{\dot{V}}{R} = M \,.\, \dot{V} + \dfrac{I}{R^2} \dot{V}$

$$F_{inertia} = \left(M + \frac{I}{R^2}\right) . \dot{V}$$

To calculate the inertia of an object subjected to both translation and rotation, we need to consider its equivalent mass M_{eq} rather than its actual mass M.

$$M_{eq} = M + \frac{I}{R^2}$$

Simple example:

For a wheel fitted with a 175/70/R13 MXT tyre

M_{wheel} = 6.1 kg; I_{wheel} = 0.125 kg.m²; M_{tyre} = 7 kg; I_{tyre} = 0.456 kg.m²
Rolling radius = 0.28m

therefore $\dfrac{I}{R^2}$ = 7.4 kg and $M_{eq\ tyre+wheel}$ = 20.5 kg

Typical values:

- Equivalent mass of a vehicle considering the rotational inertia of all rotating parts (tyre-wheel, drive train, engine): $M_{vehicle}$ + 4 %
- Equivalent mass of a tyre-wheel assembly: $M_{tyre+wheel}$ + 50 %

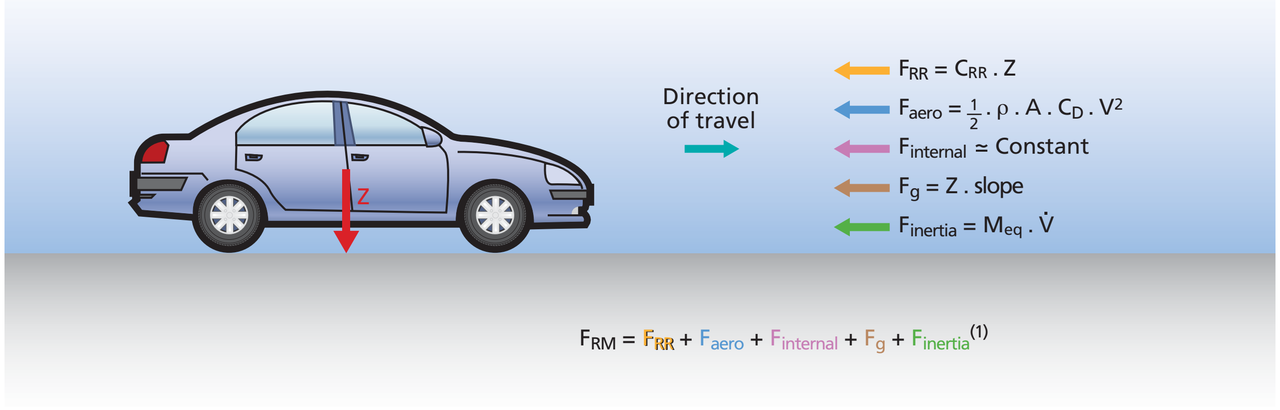
I Rolling resistance and resistance to movement

Resistance to movement is the set of resistive forces a vehicle has to overcome to be able to move. It requires energy to overcome these forces.

There are five forces a vehicle has to overcome in order to move:
- rolling resistance forces (F_{RR}),
- aerodynamic forces (F_{aero}),
- internal frictional forces ($F_{internal}$),
- gravitational forces when driving up a slope (F_g),
- inertial forces ($F_{inertia}$) when accelerating.

The sum of these resistive forces is defined as the resistance to movement (F_{RM}).

Resistance to movement

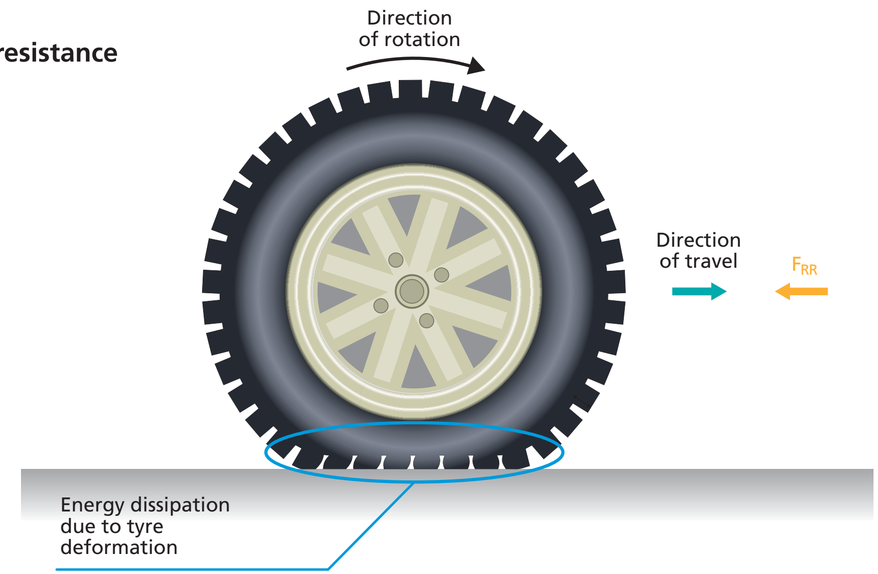


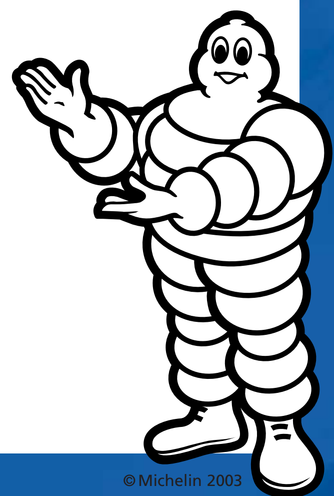
(1) The regulatory driving cycles used to measure fuel consumption simulate driving on flat roads (Fg = 0).

Rolling resistance is defined as the energy consumed by a tyre per unit of distance covered.

The main source of energy dissipation is the visco-elasticity of the materials of which tyres are made. Visco-elastic materials lose energy in the form of heat whenever they are being deformed. The energy thus lost results in a force which resists the tyre's rotation and consequently the vehicle's movement.

Rolling resistance

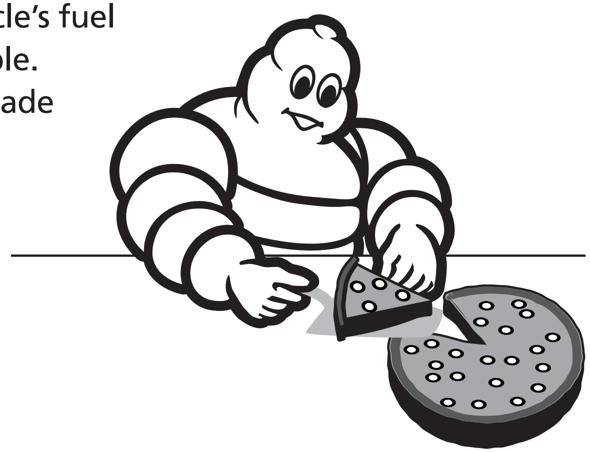




II The tyre's contribution to fuel consumption

We know that rolling resistance affects fuel consumption.
Now we need to specify its contribution.
This entails considering many parameters such as the type of trip, the type of driving, the vehicle's characteristics and engine efficiency.

The tyre's contribution to a vehicle's fuel consumption is far from negligible.
Significant fuel savings can be made by using tyres with low rolling resistance, which is important both for the economy and the environment.



II.1

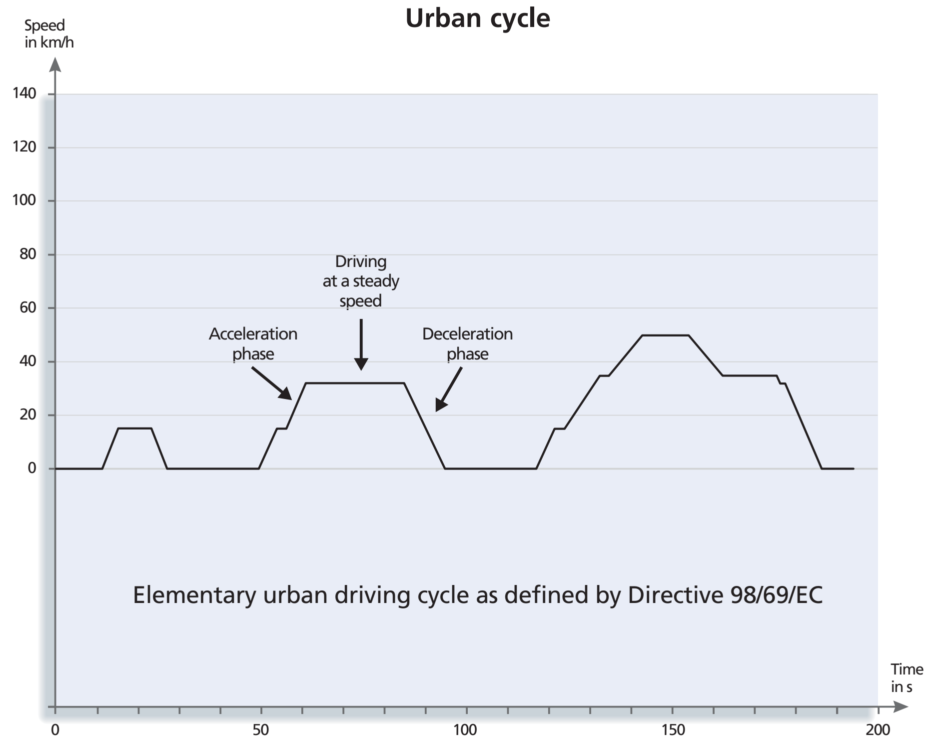
The tyre's contribution to resistance to movement

We saw in chapter I that on a flat road, resistance to movement (F_{RM}) results from the combination of four forces:
• inertia,
• aerodynamic drag,
• internal friction,
• rolling resistance.

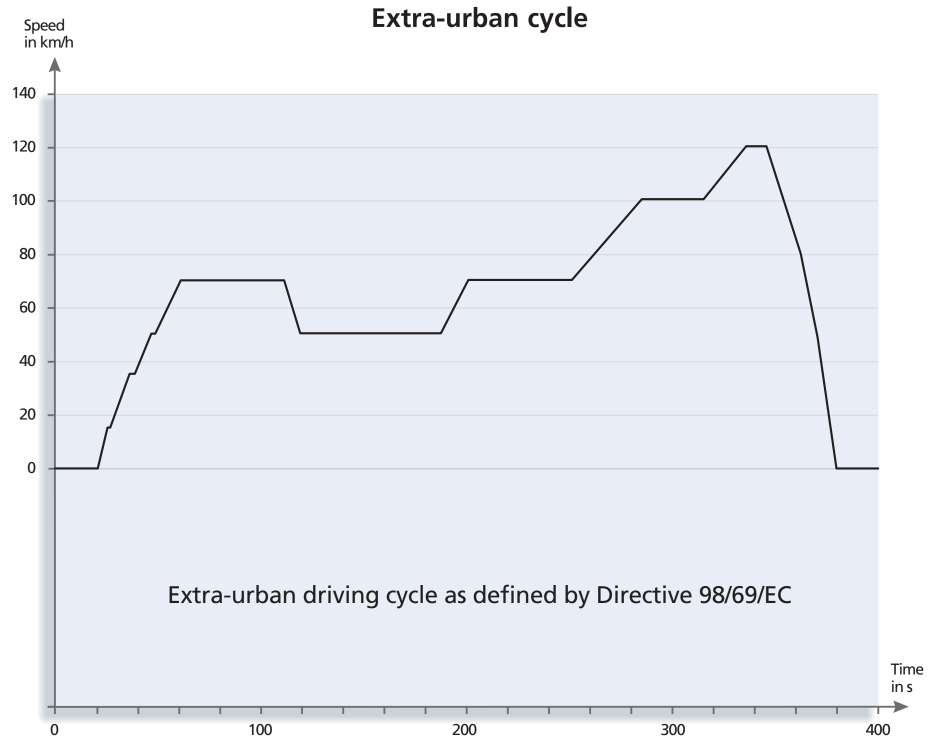
Internal friction [1] and rolling resistance forces are near-constant whatever the speed, acceleration and type of trip. Aerodynamic and inertial forces, however, are closely dependent on these factors.

To determine the tyre's contribution to fuel consumption, we will consider four types of trips:
• urban driving cycle,
• extra-urban driving cycle (such as on a by-pass),
• major and minor road driving,
• motorway driving.

Four typical trips

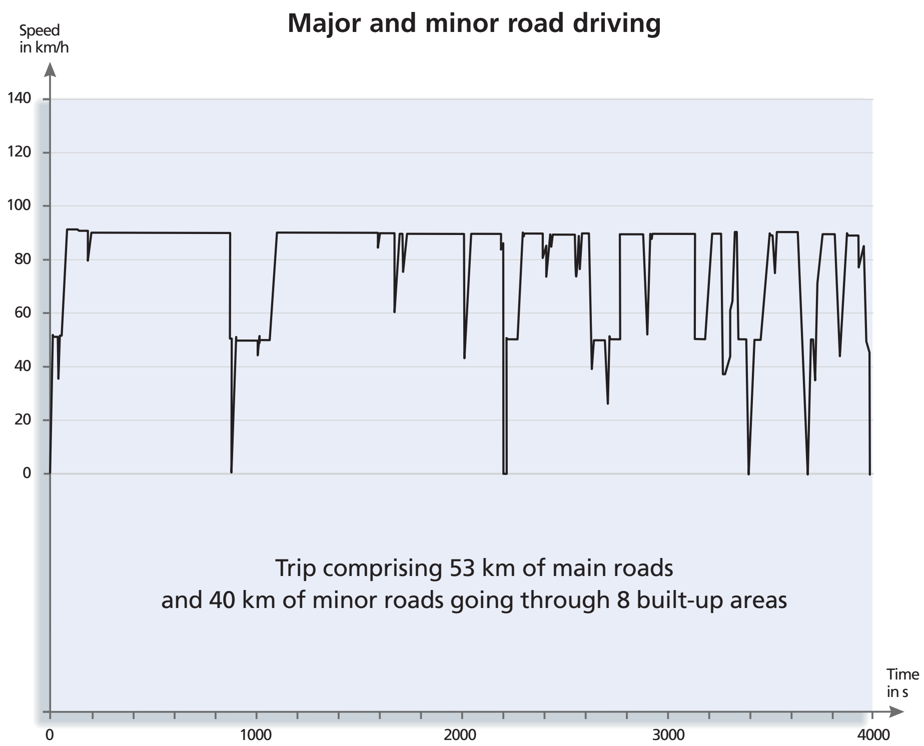


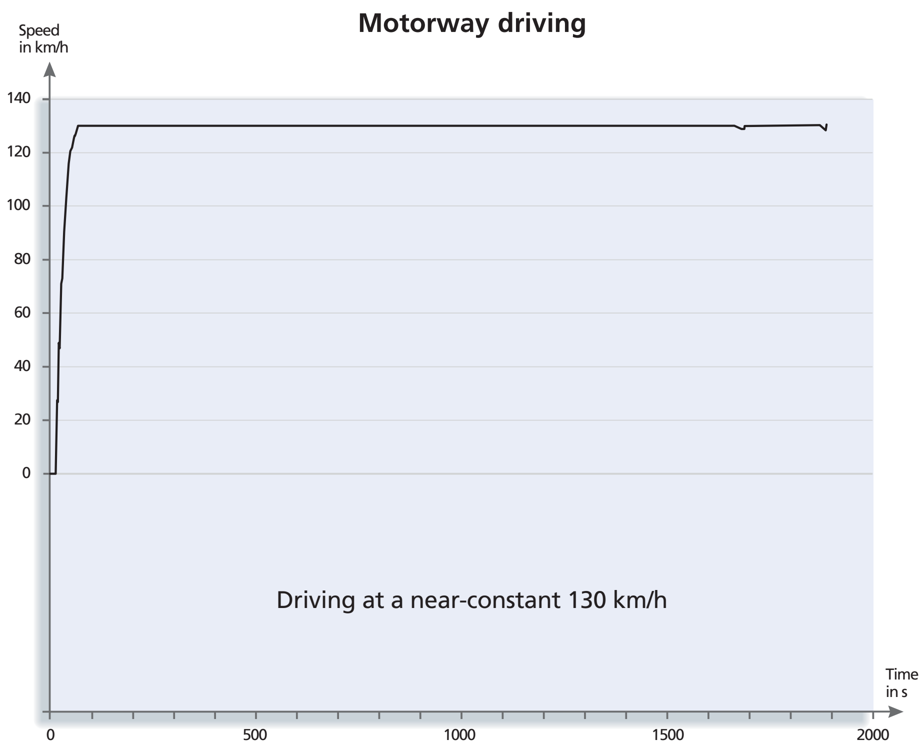
Elementary urban driving cycle as defined by Directive 98/69/EC



Extra-urban driving cycle as defined by Directive 98/69/EC

[(1)] Internal friction of wheel bearings, brakes and the differential. Our calculations will consider gearbox friction in terms of efficiency just as for engine efficiency.



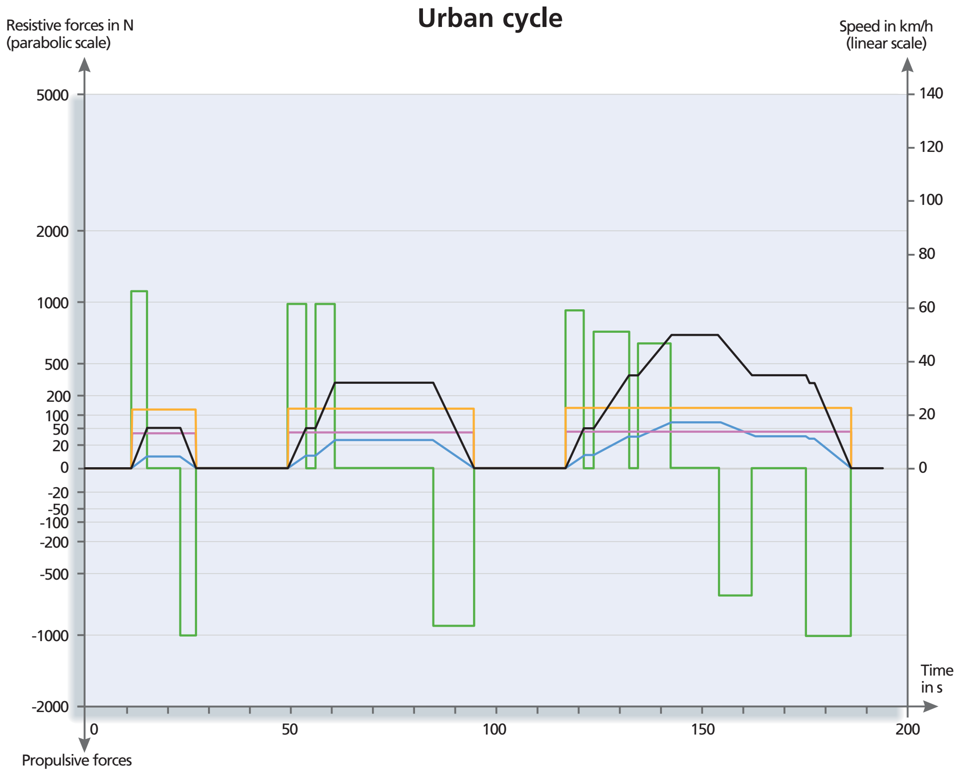


Inertial forces were calculated at each instant for each typical trip. **Inertial forces** (in green) exist only during acceleration and deceleration. They are zero at a constant speed.

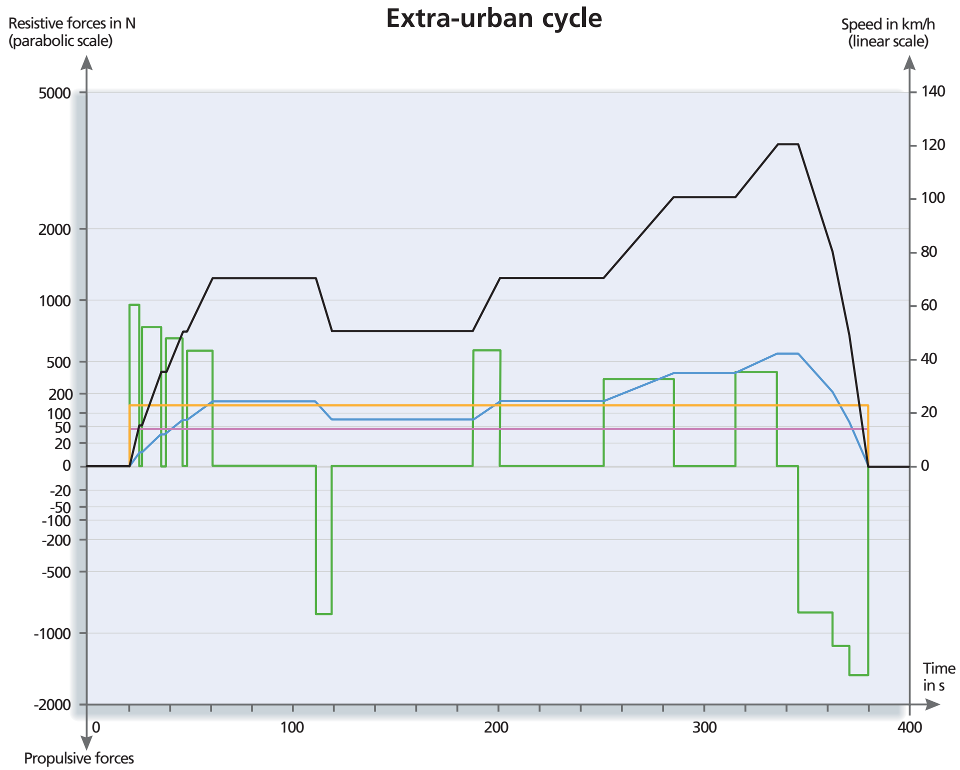
Aerodynamic forces (in blue) were calculated. They increase with speed.

Rolling resistance forces (in yellow) and **internal frictional forces** (in pink) are known for the tyre and vehicle in question. They are practically constant. Like the other forces, they only apply when the vehicle is moving.

Forces resisting movement



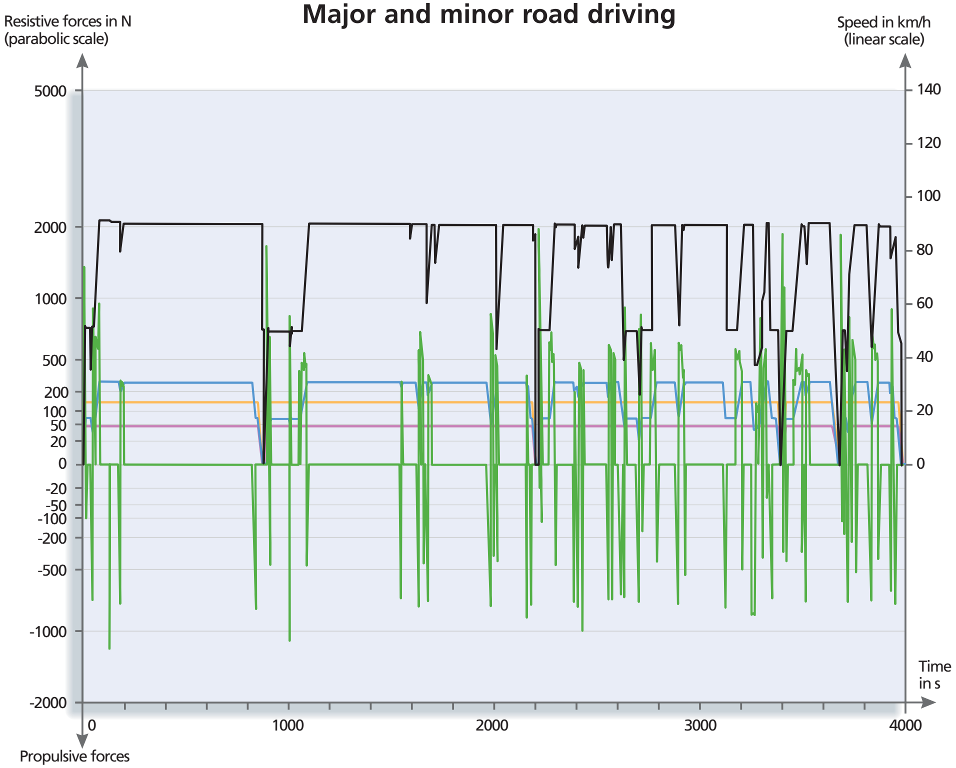
Elementary urban driving cycle as defined by Directive 98/69/EC



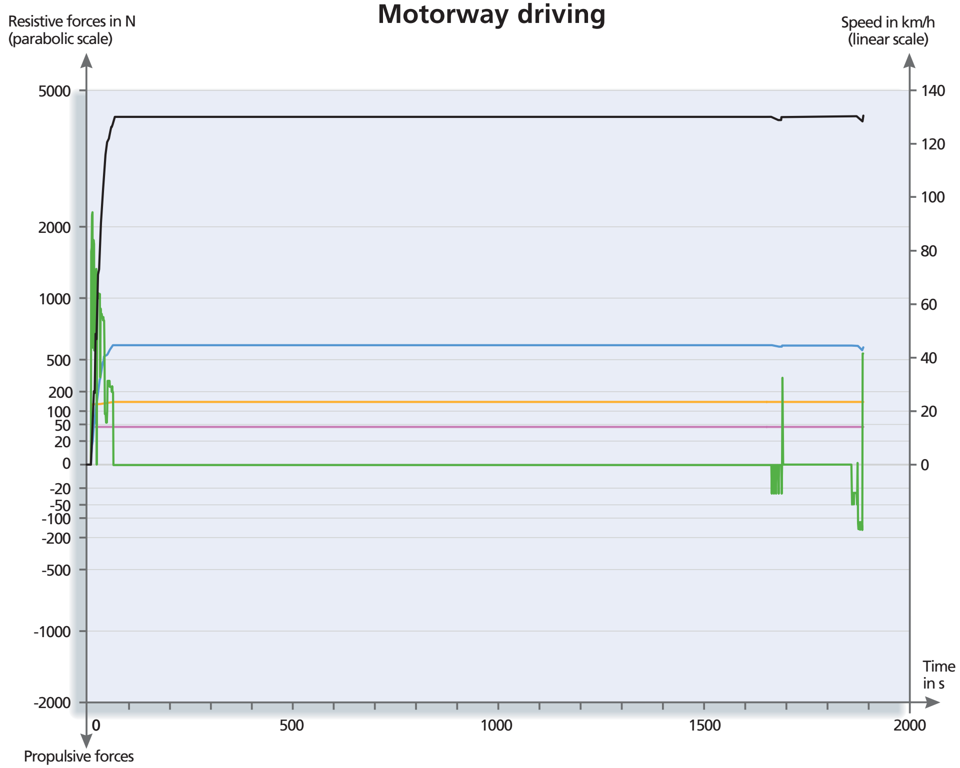
Extra-urban driving cycle as defined by Directive 98/69/EC

- $F_{inertia}$
- F_{aero}
- $F_{internal}$
- F_{RR}
- Driving pattern (speed versus time)

Hypotheses:
Vehicle mass: 1,100 kg
Aerodynamic drag (AC_D): 0.65 m²
Rolling resistance coefficient: 12 kg/t
Internal friction: 50 N
Engine: 51 kW



Trip comprising 53 km of main roads
and 40 km of minor roads going through 8 built-up areas



Driving at a near-constant 130 km/h

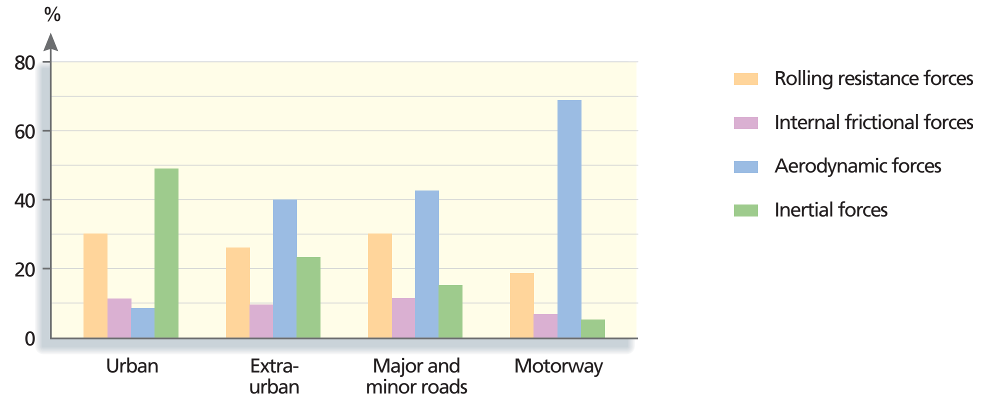
Detailed analysis of these graphs shows that the instantaneous percentage of total resistance to movement due to tyre rolling resistance for these typical trips continually varies between 10 and 70 %. The average is around 20 % for motorway driving, 25 % for the extra-urban cycle and 30 % for both the urban cycle and driving on major and minor roads.

Now we will work out the link between the rolling resistance of tyres and their contribution to fuel consumption. We can then assess the contribution of tyres with a low rolling resistance to fuel savings.

We need first to look at the concept of engine efficiency.

Rolling resistance as a percentage of resistive forces

(for four typical trips)



II.2

Fuel consumption and engine efficiency

A vehicle's fuel consumption depends on the resistive forces applying to it, i.e. inertia, drag, internal friction, rolling resistance and gravity. Multiplying these forces by the speed gives the **power required** [1], which is the power that the vehicle needs to provide at each instant in order to reach and maintain the speed desired by the driver.

Power is provided by the combustion of fuel. Petrol has an **energy value** of around 9.12 kilowatt-hours per litre.

Let us take the example of a vehicle driving along an expressway at a steady 100 km/h. In the absence of inertial forces (the speed being constant), the required force is around 500 N, which means a required power of 13.9 kW [2]. If all the fuel's energy value, without any loss, were used to meet this demand for power, the fuel consumed for 100 kilometres (one hour's driving) could be calculated as follows:

$$\frac{13.900 \text{ kWh/100 km}}{9.120 \text{ kWh/l}} \approx 1.5 \text{ l/100 km}$$

However, experience tells us that fuel consumption is much higher.

Energy value of petrol and diesel

	Petrol	Diesel
Mass NCV [1] in MJ/kg	43.5 [2]	42.5 [2]
Fuel density in kg/litre	0.755 [3]	0.845 [3]
Volume NCV [1] in MJ/litre in kWh/litre [4]	32.8 9.12	35.9 9.97

[1] The net calorific value (NCV) is the useful calorific power of a fuel, i.e. having subtracted energy lost by the formation of water vapour during combustion. The combustion process generates water which turns into steam due to the heat. Vaporization consumes energy which cannot be retrieved.

[2] *Source: Bosch, Mémento de Technologie Automobile, 2nd edition*

[3] *Source: Union Routière de France, Faits et Chiffres 2000*

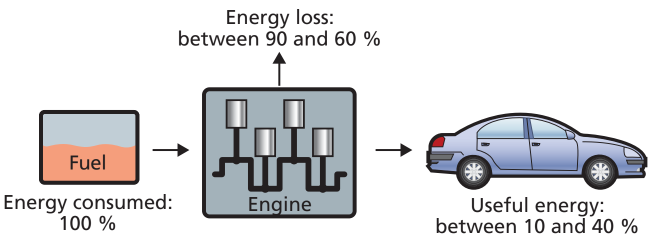
Note: The density of each fuel does not correspond to a universal value. It depends on the manufacturing process, ambient temperature and pressure. European standards EN 228 and EN 590 indicate that the density of petrol must lie between 0.720 and 0.775 kg/l and that of diesel between 0.820 and 0.845 kg/l at 15°C in a temperate climate.

[4] 1 kWh = 3.6 MJ

[1] The power required is also called "brake power output", i.e. the power actually provided to overcome the "braking forces" acting on the vehicle.

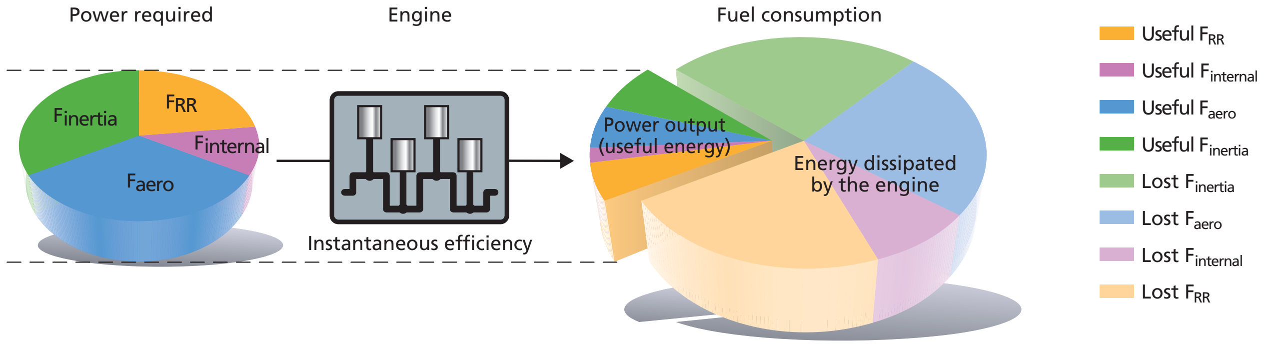
[2] See page 34 for details of calculations and vehicle characteristics.

The difference is because the engine dissipates a significant amount of energy in the form of heat for every litre of fuel consumed. In other words, **engine efficiency** is less than 100 %. Actually, the efficiency of an internal combustion engine continually varies between 10 and 40 %.



Fuel consumption does not only depend on the resistive forces exerted on the vehicle but also on engine efficiency.
To determine the quantity of fuel consumed by a vehicle due to rolling resistance, we need to know engine efficiency at each instant.

Energy dissipated by the engine



- The fuel consumption induced by each resistive force is composed of a useful part (energy actually transmitted to the wheel to meet the demand for power) and a lost part (energy dissipated by the engine as heat).
- The proportion dissipated by the engine depends on its efficiency at each instant.

Force, work and power

Force is the concept that describes the capacity to start an object moving (I push a shopping cart to start it rolling). **Work**, which is equivalent to **energy**, describes the capacity to produce an effort over time so as to cover a certain distance (I push the shopping cart 100 metres). **Power** describes the capacity to cover this distance faster or slower: if I push the trolley 100 metres in 15 seconds, the work is the same as if I push it 100 metres in 30 seconds but I have developed twice the amount of power. In terms of fuel consumption, force corresponds to consumption expressed as **litres/distance**, work to consumption expressed in **litres** and power to consumption in **litres/time**.

Force

Definition
Capacity to start an object moving, modify its movement (acceleration, braking, cornering) or deform it.

Notation and unit
Force is noted F and expressed in newtons (N).

Equation
The force needed to affect the movement of an object depends on the mass (M) of the object and the acceleration ($\dot{V}$) that we wish to impart. F equals:

$$F = M \cdot \dot{V}$$

where M is in kg
and $\dot{V}$ in m/s^2

Magnitude
A force of 1 newton is capable of imparting an acceleration of 1 m/s^2 to a mass of 1 kg (or an acceleration of 0.5 m/s^2 to a mass of 2 kg, or an acceleration of 2 m/s^2 to a mass of 0.5 kg).

Work

Definition
Energy needed to move a body a certain distance by applying a force.

Notation and unit
Work is noted W and expressed in joules (J). It may also be expressed in watt-hours (1 Wh = 3 600 J).

Equation
The work needed to move an object is equal to the product of the force needed to be applied (F) and the distance covered (d). Taking the simple case of a force applied parallel to the direction of travel, work equals:

$$W = F \cdot d$$

where F is parallel to the direction of travel, in N
and d in metres

Magnitude
1 joule corresponds to the work produced by a force of 1 newton applied for 1 metre.

Power

Definition
Energy or work provided per unit of time. In other words, the instantaneous capacity to provide energy.

Notation and unit
Power is noted P and expressed in watts (W).

Equation
Power is equal to work per unit of time, which equals the product of force and speed.

$$P = \frac{W}{t} = \frac{F \cdot d}{t} = F \cdot V$$

For an engine, the instantaneous power is the product of engine torque and speed of revolution (ω):

$$P = \text{torque} \cdot \omega$$

where torque is in N.m
and ω in rad/s

Magnitude
1 watt corresponds to a uniform transfer of 1 joule for 1 second.

ENGINE EFFICIENCY

The efficiency of an engine is defined as the ratio between the power required (brake power output) and the power consumed (fuel power consumption).

$$\text{Efficiency} = \frac{P_{\text{required}}}{P_{\text{consumed}}}$$

Engine efficiency does not have a constant value.

It varies at each instant depending on the power required, i.e. the resistive forces applying to the vehicle and the vehicle's speed. It also depends on the engine speed.

All the parameters determining the amount of fuel consumed as a result of each resistive force are therefore closely linked.

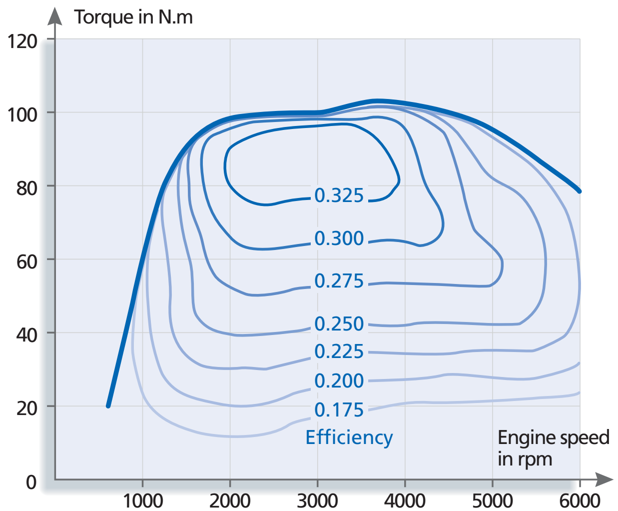
ENGINE MAPPING

Measurements recorded on test facilities can be used to plot a "map" of an engine's efficiency. These maps are very accurate but do not directly indicate engine consumption at each instant.

Engine map

(51 kW petrol engine)

Isoefficiency contours



Each "contour" links up all the engine operating points having the same efficiency. They are known as **isoefficiency contours**.

There is another less complex model known as **Willans lines**, which gives for a given engine a simple relationship between power consumed and power required. This is expressed:

$$P_{consumed} = a \,.\, P_{required} + b \,.\, N$$

where $P_{consumed}$ and $P_{required}$ are expressed in W
and N is the engine speed in rpm.

For internal combustion engines currently on the market, factor "a" is often around 2 and factor "b" lies between 5 and 7.

For example, studying a 51 kW [(1)] petrol engine gives us the relationship:

$$P_{consumed} = 2.23 \times P_{required} + 6.82\ N$$

In the theoretical case of the vehicle already described being driven at 100 km/h along the motorway, engine efficiency is 27 % for an engine speed of 3,000 revolutions per minute (in fifth gear) and fuel consumption stands at 5.64 l/100 km. At 4,000 revolutions per minute (in fourth gear), engine efficiency drops to 24 % and fuel consumption rises to 6.39 l/100 km [(2)].

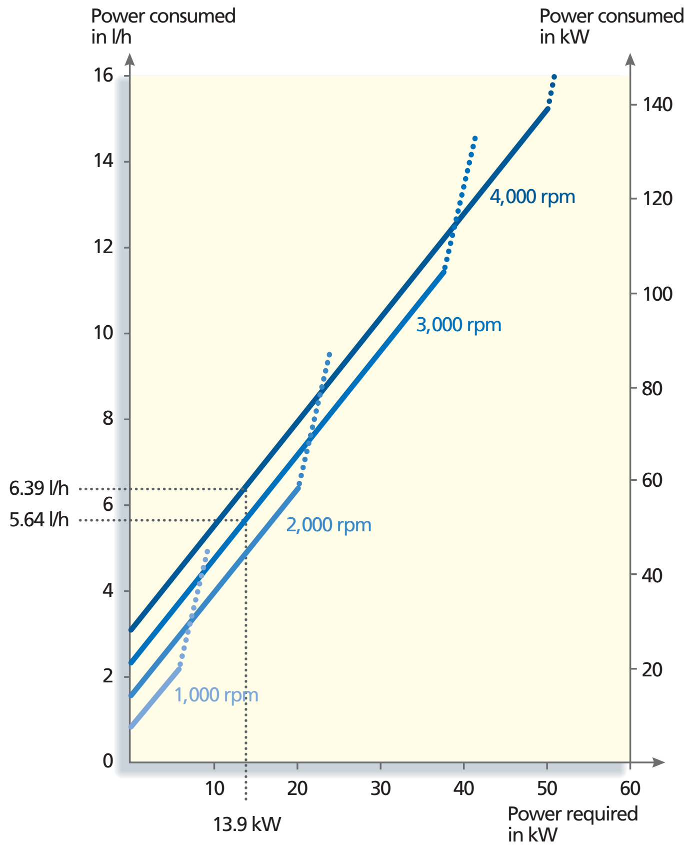
In the most complex, but most realistic, case where the vehicle is driven at varying speeds, we need to know the instantaneous efficiency of the engine and the power required at each instant in order to work out fuel consumption and, ultimately, the tyre's contribution to consumption.

[(1)] This figure indicates the maximum power the engine can supply.

[(2)] See page 34 for details of calculations.

Willans lines

(51 kW petrol engine)



• See Annex 1 for the explanation of how Willans lines are drawn up.

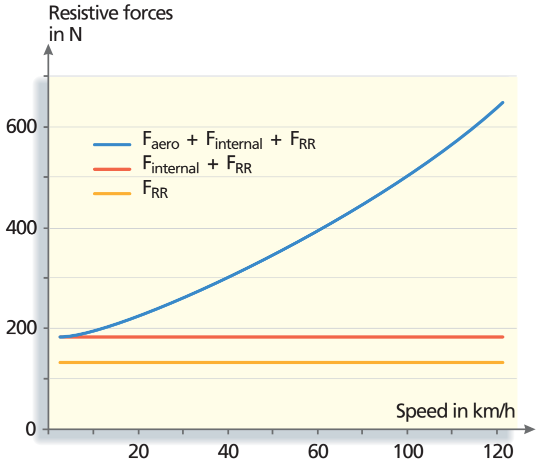
• Willans lines are valid only within the engine's usual operating range, shown opposite by a solid line. Within this range, the model's accuracy compared with the engine map is, for this 51 kW engine, around ± 2.5 %. The dashed lines correspond to a rapid deterioration in efficiency when the power required significantly increases (the driver pushes on the accelerator pedal) while the engine speed does not match the driving speed. A car is travelling at 70 km/h in fifth gear, for example, and the driver tries to accelerate without changing down a gear. Fuel consumption rises sharply but the car does not accelerate markedly.

• Equivalence between the graph's two vertical axes: for petrol, 1 l/h provides 9.12 kW.

...the fuel consumption of a vehicle travelling at 100 km/h

Let us consider a car travelling on an expressway at a constant 100 km/h, i.e. 27.8 m/s.

Vehicle characteristics:
- Mass: 1,100 kg
- Drag (AC_D): 0.65 m²
- Tyre rolling resistance coefficient: 12 kg/t
- Internal friction: 50 N
- Engine: 51 kW [(1)]



(1) This figure indicates the maximum power the engine can supply

There are about 500 N of **resistive forces** being exerted on the vehicle.
The **power required** therefore equals:

$$P_{required} = F \cdot V = 500 \times 27.8 = 13{,}900 \text{ W}$$

At 100 km/h, the vehicle therefore consumes 13,900 Wh in one hour.

The petrol's **energy value** is 9,120 Wh per litre.
Assuming 100 % engine efficiency, we would only need $\frac{13{,}900}{9{,}120}$ = 1.52 litres of fuel for 100 kilometres.

Realistically, for a 51 kW petrol engine, consumption is around 5 to 7 litres/100 km. The Willans relationship gives:

$$P_{consumed} = 2.23 \times P_{required} + 6.82 \times N_{rpm}$$

Assuming that at a constant 100 km/h the engine speed is 3,000 rpm (in fifth gear, for example), we have:

$$P_{consumed} = 2.23 \times 13{,}900 + 6.82 \times 3{,}000 = 51{,}457 \text{ W}$$

$$\text{Efficiency} = \frac{P_{required}}{P_{consumed}} = \frac{13{,}900}{51{,}457} = 0.27 \text{ i.e. } 27\,\%$$

$$\text{Fuel consumption} = \frac{51{,}457}{9{,}123} = 5.64 \text{ l/100 km}$$

If the engine speed increases to 4,000 rpm (in fourth gear, for example), we have:

$$P_{consumed} = 2.23 \times 13{,}900 + 6.82 \times 4{,}000 = 58{,}277 \text{ W}$$

$$\text{Efficiency} = \frac{P_{required}}{P_{consumed}} = \frac{13{,}900}{58{,}277} = 0.24 \text{ i.e. } 24\,\%$$

$$\text{Fuel consumption} = \frac{58{,}277}{9{,}123} = 6.39 \text{ l/100 km}$$

II.3
The tyre's contribution to fuel consumption

For a given vehicle, the percentage of fuel consumption accounted for by rolling resistance depends on:
- the speed and acceleration at each instant of the trip considered,
- the vehicle's characteristics (mass, streamlining, internal friction, gear ratio),
- the tyres' rolling resistance coefficient.

The fuel consumption due to rolling resistance (in litres per 100 km) also depends on the engine's efficiency at each instant of the trip considered.

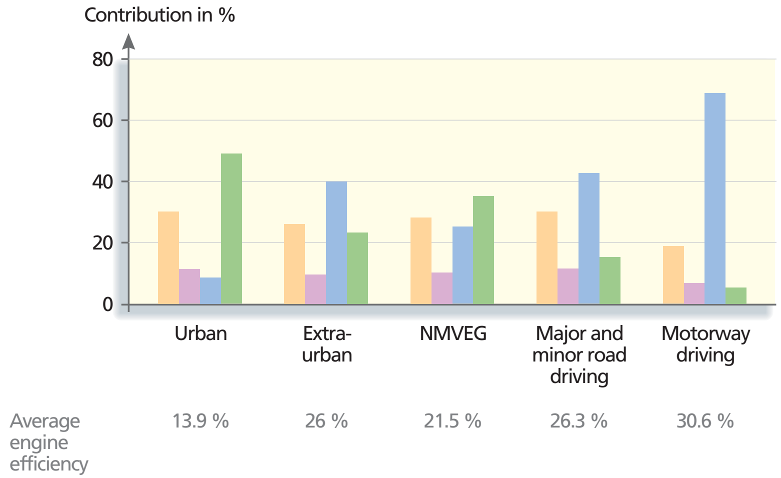
If all these parameters are known, the contribution of each resistive force to fuel consumption may be determined for the trip in question. This is what we did for the four typical trips and 51 kW engine previously described. The results are shown opposite. We have also included the result for a European NMVEG driving cycle (1).

From one type of trip to another, tyres with a rolling resistance coefficient of 12 kg/t account for between 20 % (motorway driving) and 30 % (urban cycle) of fuel consumption. Expressed as an absolute value, the tyre's contribution varies between 1.38 litres per 100 kilometres (motorway driving) and 2.57 litres per 100 kilometres (urban cycle).

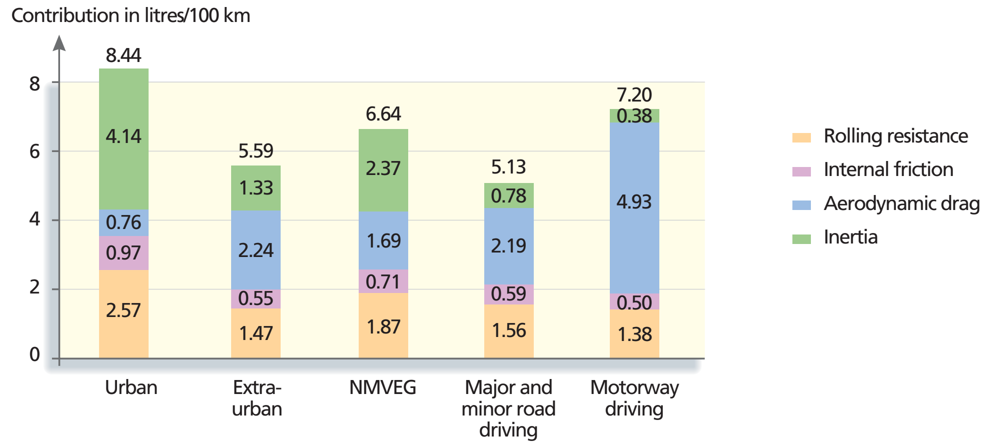
It may be seen that rolling resistance significantly affects fuel consumption. Let us now see how **"green" tyre** technology—tyres with a low rolling resistance—can reduce fuel consumption.

The contribution of rolling resistance to fuel consumption

(51 kW engine)



Hypotheses:
- Vehicle mass: 1,100 kg
- Aerodynamic drag (AC_D): 0.65 m²
- Rolling resistance coefficient: 12 kg/t
- Internal friction: 50 N
- Engine: 51 kW
- Calorific value of petrol: 32.8 MJ/l
- Average gearbox efficiency: 85 % for urban driving, 95 % for other trips
- Driving on flat roads



(1) NMVEG: New Motor Vehicle Emission Group. Driving cycle defined by Directive 98/69/EC with 4 elementary urban cycles and 1 extra-urban cycle.

...calculating the contribution of each resistive force to fuel consumption

1 For a given trip (regulatory driving cycle or driving an instrumented vehicle on the road), we calculated or measured the following parameters:

- instantaneous speed and acceleration (V_i et $\dot{V}_i$);
- engine speed at each instant (N_i).

2 Knowing the vehicle's characteristics and tyre rolling resistance coefficient, we can calculate the value of each resistive force and total resistive force (F_{RM}) for each speed at each instant.

$$F_{RR} = C_{RR} \, . \, Z$$

$$F_{aero} = \frac{1}{2} \rho \, . \, A \, . \, C_D \, . \, V^2$$

$$F_{internal} = \text{Constant}$$

$$F_g = Z \, . \, \sin\alpha \, ^{(1)}$$

$$F_{inertia} = M_{eq} \, . \, \dot{V}$$

$$F_{RM} = F_{RR} + F_{aero} + F_{internal} + F_g + F_{inertia}$$

(1) assuming flat roads, $F_g = 0$.

3 Knowing the engine characteristics, we can draw up Willans lines to give the power consumed for the power required (see page 33).

4 The Willans lines give us engine efficiency at each instant of the trip:

$$E_{instant} = \frac{P_{instant\ required}}{P_{instant\ consumed}}$$

5 Instantaneous fuel consumption equals:

$$Cons_{instant} = \frac{P_{instant\ consumed}}{NCV}$$

where $Cons_{instant}$ is in grams/second
$P_{instant\ consumed}$ is in joules/second
NCV (fuel Net Calorific Value) is in joules/gram

Total consumption for the trip considered equals:

$$Cons_{total} = \sum \left(Cons_{instant} \times \Delta t \right)$$

where $Cons_{total}$ is in grams
$Cons_{instant}$ is in grams/second
Δt is in seconds

6 Then we look at each resistive force in turn. For each, we calculate the power required and corresponding consumption at each instant ($Cons_{instant}$).

Let us consider the example of rolling resistance:

$$P_{instant\ consumed\ FRR} = \frac{P_{instant\ required\ FRR}}{E_{instant}}$$

$$Cons_{instant\ FRR} = \frac{P_{instant\ consumed\ FRR}}{NCV}$$

7 Fuel consumption due to rolling resistance therefore equals:

$$Cons_{FRR} = \sum \left(Cons_{instant\ FRR} \times \Delta t \right)$$

8 We calculate the amount of fuel consumption due to rolling resistance compared with total fuel consumption as follows:

$$Contribution_{FRR} = \frac{Cons_{FRR}}{Cons_{total}}$$

9 We then repeat steps 6 to 8 for each resistive force.

10 We can also calculate the average engine efficiency over the trip considered thus:

$$E = \frac{\sum (P_{instant\ required} \, . \, \Delta t)}{\sum (P_{instant\ consumed} \, . \, \Delta t)}$$

II.4

Fuel savings due to tyres with low rolling resistance

We have just seen that the tyre's contribution to a car's fuel consumption can vary widely, whether expressed as a percentage (20 to 30 %) or an absolute value (in which case it can double).

Paradoxically, we will see that the absolute savings made by using tyres with low rolling resistance are almost entirely independent of the type of trip.

Rolling resistance force "black" tyres - "green" tyres

$F_{RR} = C_{RR} \times Z = C_{RR} \times M \times g$

$F_{RR\ \text{"black" tyre}} = 0.012 \times 1{,}100 \times 9.81 = 129.5\ N$

$F_{RR\ \text{"green" tyres}} = 0.0085 \times 1{,}100 \times 9.81 = 91.7\ N$

C_{RR}: rolling resistance coefficient
Z: load in N
M: vehicle mass in kg
g: gravitational acceleration in m/s^2

FUEL SAVINGS MADE BY REPLACING "BLACK" TYRES WITH "GREEN" TYRES

"Black" tyres currently on the market have a rolling resistance coefficient of around 12 kg/t rather than the 8.5 or so kg/t of low rolling resistance tyres, often called **"green" tyres**.

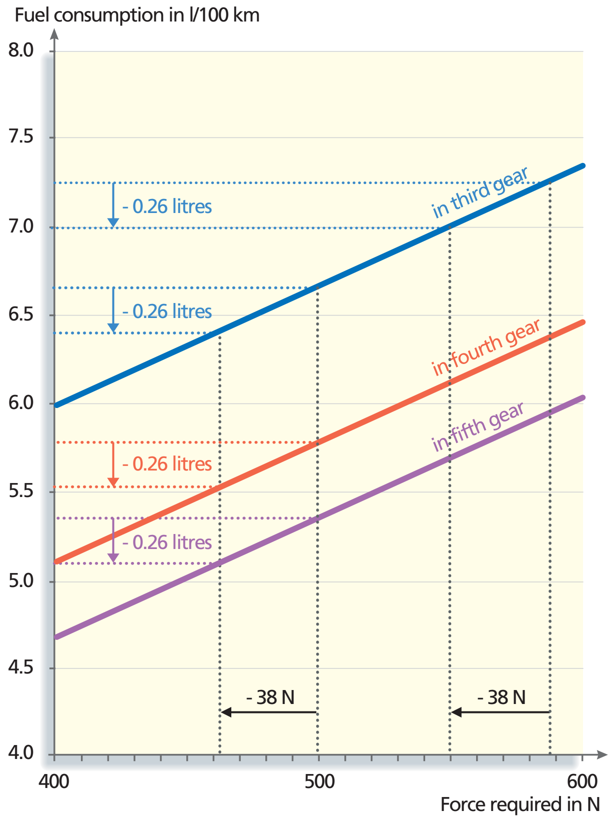
For a car of 1.1 tonnes, the rolling resistance force of a set of "black" tyres is therefore around 130 newtons, compared with 92 for a set of "green" tyres, which represents a difference of 38 newtons (see box on left).

The right-hand graph is derived from the Willans lines. It clearly shows that for a given vehicle, a reduction in force required always leads to the same savings in fuel consumption, whatever the engine speed, gear or force required. This means that **savings are near-constant** whatever the speed and type of trip. For the vehicle with a 51 kW engine previously described, fuel savings are around 0.26 litres per 100 km.

If we express the savings as a percentage, they represent between 3.2 % for the urban cycle and 5.1 % for driving on major and minor roads.

Fuel consumption versus force required

according to the Willans lines
for a 51 kW petrol engine



Annex 1 explains how this graph is drawn up. Like the Willans lines, this graph only applies within the engine's normal operating range.

If we consider a broad spectrum of cars currently on the market, we may say that lowering rolling resistance by 30 % leads to fuel savings of between 3 and 6 % without modifying vehicle design. However, these figures must be reconsidered for each vehicle and each type of trip.

For a 40-tonne truck designed to be driven mostly on motorways, a reduction of 20 % in rolling resistance can reduce fuel consumption by around 6 %.

Fuel savings due to the use of "green" tyres compared with "black" tyres

The table below shows the fuel savings made by a passenger car when "black" tyres (12 kg/t) are replaced by "green" tyres (8.5 kg/t). It may be seen that these savings are independent of the type of trip and the vehicle's original consumption. Whether the vehicle consumes 8 litres or 6 litres to start with, the savings remain stable at around 0.26 l/100 km.

		Typical trip	Urban	Extra-urban	NMVEG	Major & minor roads	Motorway
Consumption in l/100 km		**"Black" tyres** (12 kg/t)	8.44	5.59	6.64	5.13	7.2
		"Green" tyres (8.5 kg/t)	8.17	5.33	6.38	4.87	6.92
Savings compared with "black" tyres	in l/100km		0.27	0.26	0.26	0.26	0.28
	in %		3.2 %	4.7 %	3.9 %	5.1 %	3.9 %

Hypotheses:

Rolling resistance coefficient for "black" tyres: 12 kg/t
Rolling resistance coefficient for "green" tyres: 8.5 kg/t (29 % less)
Vehicle mass: 1,100 kg
Aerodynamic drag (AC_D): 0.65 m^2
Internal friction: 50 N
Engine: 51 kW
Average gearbox efficiency:
urban cycle = 85 %, others = 95 %

Note:

These calculations show slight differences in the savings made by "green" tyres from one type of trip to another when expressed as absolute values (from 0.26 to 0.28 l/100 km).

These differences are due to two factors:

- the use of the full engine map in calculations rather than the simplified Willans lines;
- during a trip, the difference in fuel consumption between "green" and "black" tyres is only seen when power is required—i.e. when the driver maintains pressure or pushes on the accelerator pedal—and not throughout the trip. If the ratio of "duration that power is required" over "duration of trip" were the same for all five typical trips, the savings would be exactly the same. This is not the case, however, and the savings in consumption over total distance covered differ slightly from one trip to another.

ADDITIONAL SAVINGS MADE BY OPTIMIZING THE GEAR RATIO

Replacing "black" tyres by "green" tyres on a given vehicle lowers the amount of power required at each instant because the wheels are easier to drive. This reduces consumption. However, it also reduces engine efficiency because the engine was optimized for a higher power requirement.

To maximize fuel savings, engine efficiency needs to be optimized taking the tyres' lower rolling resistance into account.
This is what automobile manufacturers do for new vehicles designed and certified to be fitted with "green" tyres. They optimize the gear ratio so that the engine revolves more slowly.

For the vehicle with a 51 kW engine already studied, when "black" tyres are replaced by "green" tyres, optimizing engine efficiency (slowing engine revolutions by around 5 %) will lead to fuel savings not of 0.26 litres per 100 kilometres but almost twice that—0.5 litres per 100 kilometres.

This shows how important it is to integrate the tyre in vehicle design considerations from the start so as to optimize the drive train and gear ratio.

Extra fuel savings made by optimizing the gear ratio

Calculations performed with SIMULCO software developed by INRETS [1]

Urban cycle

Reference fuel consumption with "black" tyres: 8.44 l/100 km

Consumption with "green" tyres (8.5 kg/t):		Without optimizing the gear ratio	After optimizing the gear ratio
Consumption in l/100 km		8.17	7.84
Savings compared to "black" tyres	in l/100 km	0.27	0.6
	in %	3.2	7.1

Extra-urban cycle

Reference fuel consumption with "black" tyres: 5.59 l/100 km

Consumption with "green" tyres (8.5 kg/t):		Without optimizing the gear ratio	After optimizing the gear ratio
Consumption in l/100 km		5.33	5.17
Savings compared to "black" tyres	in l/100 km	0.26	0.42
	in %	4.7	7.5

NMVEG cycle

Reference fuel consumption with "black" tyres: 6.64 l/100 km

Consumption with "green" tyres (8.5 kg/t):		Without optimizing the gear ratio	After optimizing the gear ratio
Consumption in l/100 km		6.38	6.15
Savings compared to "black" tyres	in l/100 km	0.26	0.49
	in %	3.9	7.4

Major and minor road driving

Reference fuel consumption with "black" tyres: 5.13 l/100 km

Consumption with "green" tyres (8.5 kg/t):		Without optimizing the gear ratio	After optimizing the gear ratio
Consumption in l/100 km		4.87	4.72
Savings compared to "black" tyres	in l/100 km	0.26	0.41
	in %	5.1	8.0

Hypotheses:

Rolling resistance coefficient for "black" tyres: 12 kg/t
Vehicle mass: 1,100 kg
Aerodynamic drag (AC_D): 0.65 m^2
Internal friction: 50 N
Engine: 51 kW
Average gearbox efficiency: urban cycle = 85 %, other cycles = 95 %
Calorific value of petrol: 32.8 MJ/l

Motorway driving

Reference fuel consumption with "black" tyres: 7.2 l/100 km

Consumption with "green" tyres (8.5 kg/t):		Without optimizing the gear ratio	After optimizing the gear ratio
Consumption in l/100 km		6.92	6.73
Savings compared to "black" tyres	in l/100 km	0.28	0.47
	in %	3.9	6.5

[1] Institut National de Recherche sur les Transports et leur Sécurité – French research institute on transport and safety.

A little more information on...

...optimizing the gear ratio

To understand the principle behind optimizing a vehicle's gear ratio, let us take the Willans lines again.

- We have seen that the relationship between power consumed and power required is expressed as follows:

$$P_{consumed} = a \cdot P_{required} + b \cdot N$$

where $P_{consumed}$ and $P_{required}$ are expressed in W and N is the engine speed in rpm.

We have also seen that efficiency is equal to:

$$E = \frac{P_{required}}{P_{consumed}} = \frac{1}{a + \left(\frac{b \cdot N}{P_{required}}\right)}$$

- If you remove the "black" tyres of a vehicle whose engine and gear ratio were optimized for that type of tyre and replace them by "green" tyres, the power required drops:

$$P_{required}\,(\text{"green" tyres}) < P_{required}\,(\text{"black" tyres})$$

$$\text{therefore} \quad E_{\text{"green" tyres}} < E_{\text{"black" tyres}}$$

- The manufacturer changes the gear ratio to alter engine speed and thus return to optimal efficiency.
He is seeking $N_{\text{"green" tyres}}$ such that:

$E_{\text{"green" tyres}} = E_{\text{"black" tyres}}$ i.e.:

$$\frac{1}{a + \left(\frac{b \cdot N_{\text{"green" tyres}}}{P_{\text{required "green" tyres}}}\right)} = \frac{1}{a + \left(\frac{b \cdot N_{\text{"black" tyres}}}{P_{\text{required "black" tyres}}}\right)}$$

which amounts to:

$$\frac{N_{\text{"green" tyres}}}{P_{\text{required "green" tyres}}} = \frac{N_{\text{"black" tyres}}}{P_{\text{required "black" tyres}}}$$

As $P_{\text{required "green" tyres}}$ is less than $P_{\text{required "black" tyres}}$, for $E_{\text{"green" tyres}}$ to be equal to $E_{\text{"black" tyres}}$, $N_{\text{"green" tyres}}$ must be lower than $N_{\text{"black" tyres}}$.

Example calculation:

- A vehicle is being driven at 100 km/h (27.8 m/s) in fifth gear at 3,000 rpm.
- Resistive forces: 500 newtons with "black" tyres
  462 newtons with "green" tyres

- As shown below, efficiency drops if the gear ratio is not changed:

Efficiency for "black" tyres:

$$\frac{1}{2.23 + \left(\frac{6.82 \times 3000}{500 \times 27.8}\right)} = 0.270 \quad \text{i.e. } 27\%$$

Efficiency for "green" tyres:

$$\frac{1}{2.23 + \left(\frac{6.82 \times 3000}{462 \times 27.8}\right)} = 0.262 \quad \text{i.e. } 26.2\%$$

- The engine speed must be lowered as follows to return to the optimal efficiency:

$$N_{\text{"green" tyres}} = \frac{N_{\text{"black" tyres}}}{P_{\text{required "black" tyres}}} \times P_{\text{required "green" tyres}}$$

$$= \frac{3000}{500 \times 27.8} \times 462 \times 27.8 = 2772$$

which is a drop of 228 rpm.

II.5

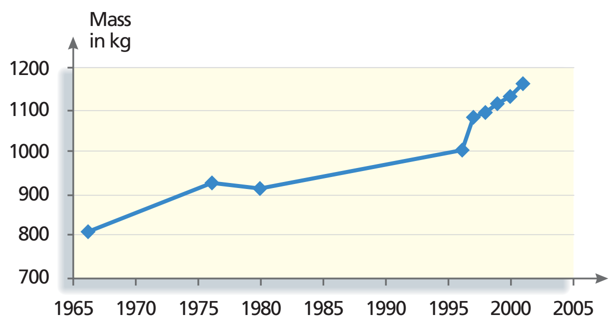
Fuel savings and reduction of exhaust gas emissions

FUEL AND CO_2: POTENTIAL REDUCTIONS WORLDWIDE

We have already seen that for the vehicle with a 51 kW engine previously described, it is possible to save 0.26 litres per 100 kilometres by using "green" tyres rather than "black" tyres without even changing the gear ratio. This means that, throughout its lifetime (about 40,000 km), the "green" tyre will save 104 litres of fuel for this vehicle compared to the "black" tyre. If all the world's passenger cars were to make the same savings, nearly 20 billion litres of petrol a year could be saved, which means an annual drop in CO_2 emissions of nearly 45 million tonnes.

To make such savings by modifying the vehicle design, we would need to reduce aerodynamic drag (AC_D) by over 20 % or its weight by over 100 kg, considering only urban and extra-urban driving cycles.

Weight of the average French car over time



Source: Argus de l'Automobile et des Locomotions

In our example of a vehicle with a 51 kW engine, replacing 12 kg/t tyres by 8.5 kg/t tyres leads to fuel savings of 0.26 litres per 100 kilometres. Assuming that each litre of petrol consumed produces 2.35 kg of CO_2, the following table shows the potential savings that this drop in rolling resistance would represent for all European cars and all the world's passenger cars.

Note:
The consumption of a litre of diesel produces about 2.66 kg of CO_2. The simulation below is based on the simplified hypothesis of petrol-driven cars only.

	Fuel consumption	CO_2 emissions for a petrol-driven passenger car
Savings per 100 km	**0.26 litres**	**0.611 kg**
Annual savings for a car (averaging 14,000 km a year)	**36.4 litres**	**85.54 kg**
Savings during tyre lifetime (40,000 km)	**104 litres**	**244 kg**
Annual savings for all European passenger cars (187 million vehicles)	**6,807 million litres**	**15,996 thousand tonnes**
Annual savings for all the world's passenger cars combined (525 million vehicles)	**19,110 million litres**	**44,908 thousand tonnes**

Source used to estimate the European and worldwide passenger car population (in 2002): DRI.WEFA

Michelin's Energy tyres, first marketed in 1992, have reduced rolling resistance due to a new manufacturing process using silica and silanes. Today's third-generation Energy tyres offer a rolling resistance coefficient as low as 0.008 (8 kg/t).

CO_2 emissions

Carbon dioxide (CO_2) may not be listed among the "pollutants" defined by regulations on "air pollution by emissions from motor vehicles", but it is still a greenhouse gas.

Overview of the greenhouse effect

Solar energy reaches Earth mostly in the form of visible light and ultraviolet light. The Earth in turn radiates part of this energy back as infrared rays, which are themselves partially intercepted by the atmosphere and reflected back to the ground. This natural phenomenon—called the **greenhouse effect** due to its similarities with the way a greenhouse works—helps keep Earth at the temperatures which can sustain life as we know it. The greenhouse effect is due to the presence in the atmosphere of greenhouse gases (including water vapour, carbon dioxide, methane and nitrous oxide). Carbon dioxide is the one greenhouse gas of particular relevance to the road transport sector.

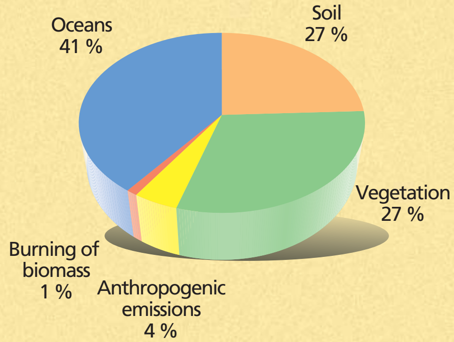
Carbon dioxide

Before the industrial era, natural emissions of CO_2 (from breathing, decomposition, oceans, volcanoes etc.) were balanced out by natural absorption (mainly due to photosynthesis and the oceans).
In the early XIXth century, a new source of CO_2 appeared: fossil fuel combustion for industrial, transport and domestic purposes (heating, for example). CO_2 emissions due to human activities are known as **anthropogenic emissions**. In 2000, they represented about 4 % of total CO_2 emissions. The Earth's biomass and oceans are able to absorb about 11 thousand million tonnes of these **anthropogenic emissions** per year. In 2000, this figure represented about 40 % of anthropogenic emissions; the rest gradually accumulates in the atmosphere.

Consequently, there is a man-made greenhouse effect which is leading to gradual global warming. There appears to be a well-documented increase in the atmosphere's average temperature over the past 150 years.

Applying the precautionary principle, the international community led by the UN is seeking to avoid the proliferation of man-made greenhouse gases, which include the carbon dioxide so relevant to the transport sector.

Distribution of natural and anthropogenic CO_2 emissions (world data)

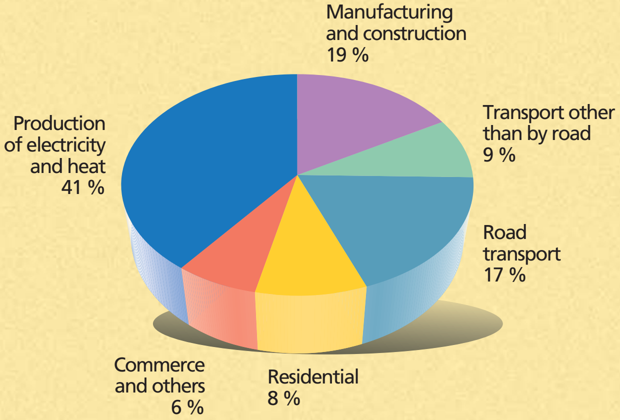


Sources: UNEP, "Industry as a partner for sustainable development", 2002

Sources: URF, "Faits et chiffres 2000"; J.M. Jancovici, "Le réchauffement climatique : réponse à quelques questions élémentaires", httpp://www.x-environnement.org/Jaune_Rouge/JROO/jancovici.html

The transport sector's contribution to anthropogenic CO_2 emissions from fossil fuel combustion

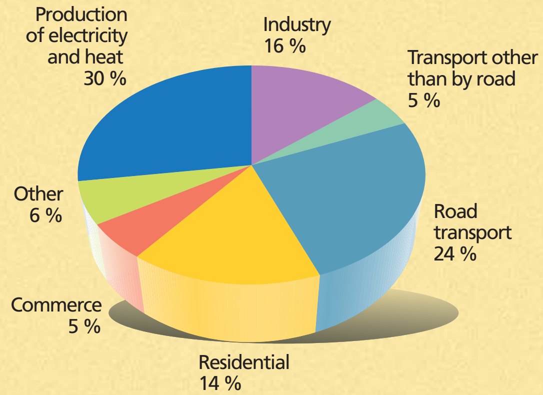
World, 1998



Total: 25.32 billion tonnes in 2000

Sources: World Business Council for Sustainable Development (WBCSD), "Mobility 2001", statistics provided by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) SRES emissions scenarios

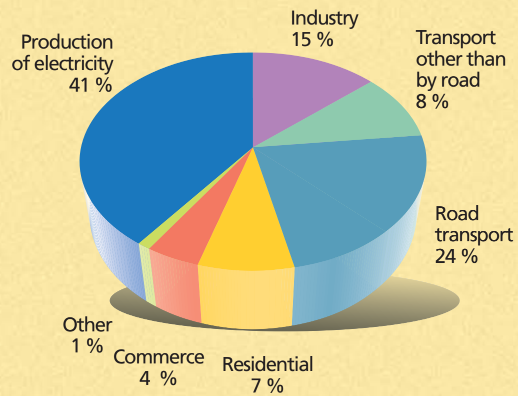
European Union (EU-15), 1999



Total: 3.1 billion tonnes in 1999

Sources: European Commission's green paper "Towards a European strategy for the security of energy supply", 29.11.2000; European Commission Directorate-General for Energy and Transport, "EU Energy and Transport in Figures 2001"

United States, 2000



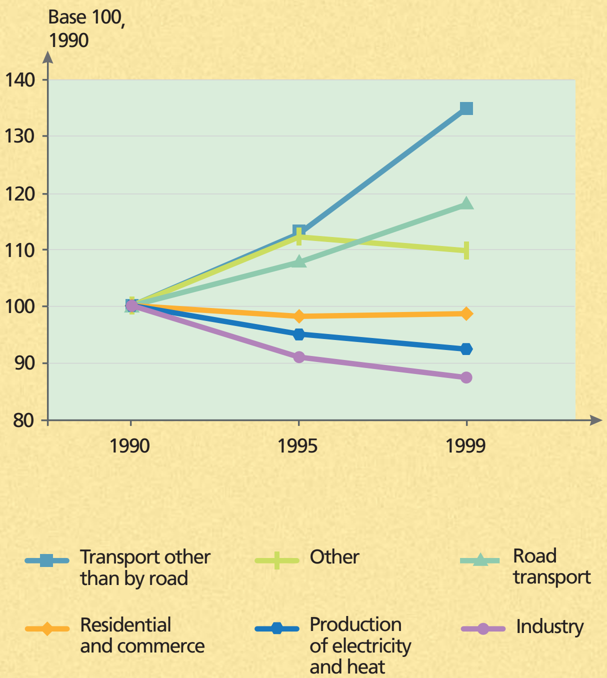
Total: 5.6 billion tonnes in 2000

Sources: Environmental Protection Agency (EPA), "Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2000"

CO_2 emissions (contd)

Evolution of European CO_2 emissions in all sectors (EU 15)

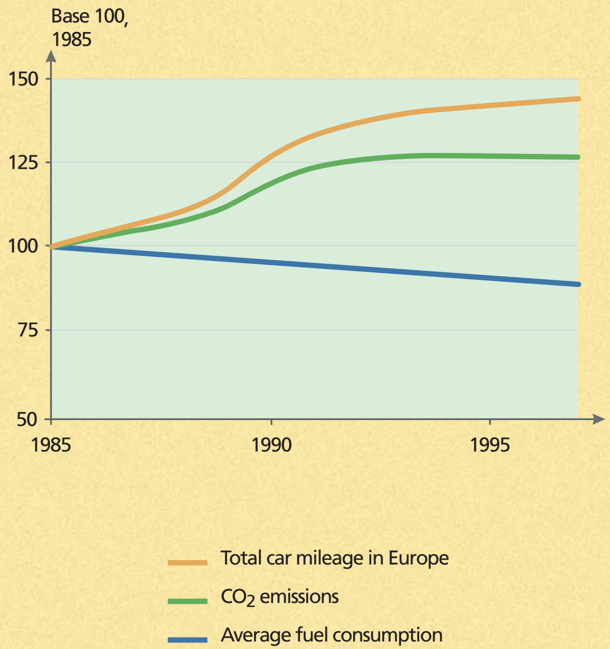
European Union statistics clearly show that CO_2 emissions by the road transport sector are increasing. As average fuel consumption of European vehicles is tending to fall, this increase must be due to greater road traffic.



Sources: European Commission, Directorate-General for Energy and Transport, "EU Energy and Transport in Figures 2001"

Evolution of car CO_2 emissions in Europe (EU 15)

Statistics provided by the European Automobile Manufacturers' Association (ACEA) show that over the past few years, cumulative passenger car CO_2 emissions have levelled out despite the rise in road traffic. This is because the average fuel consumption of cars has steadily decreased.



Source: http://www.acea.be/acea/publications.htm, "Addressing Climate Change"

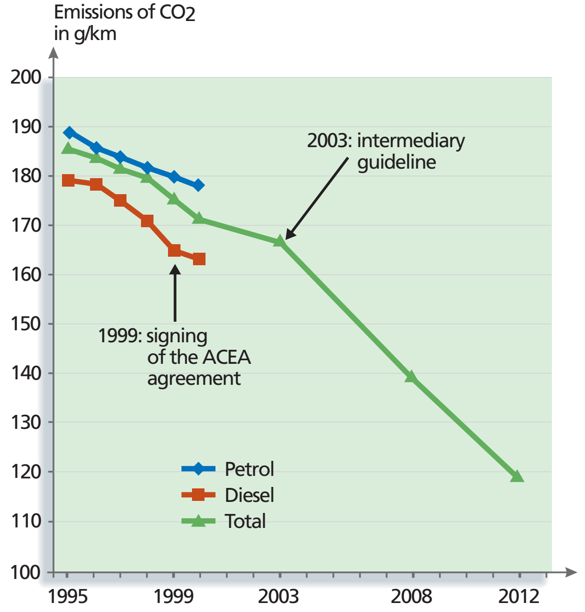
CAR MANUFACTURERS' COMMITMENT TO THE E.U.

In 1995, the European Commission proposed a European Union strategy to reduce the CO_2 emissions of passenger cars, and invited the automobile industry to sign an environmental agreement designed to reduce the average level of CO_2 emissions from new cars to 120 g/km by 2005 to 2010.

In 1999, the European Automobile Manufacturers' Association (ACEA) [(1)] signed a commitment to the European Union to reduce CO_2 emissions. In 2000, the Japan Automobile Manufacturers' Association (JAMA) [(2)] and the Korea Automobile Manufacturers' Association (KAMA) [(3)] also signed similar agreements.

Their commitment is to reduce the average level of emissions, by 2008 to 2009, to less than 140 g/km for new passenger cars sold in the European Union and to less than 120 g/km by 2012. An intermediary target of 165 to 170 g/km was set for 2003 to 2004.

Evolution of CO2 emissions from new passenger cars sold in the European Union



Equivalence between CO2 emissions and fuel consumption

	Equivalent consumption (in l/100 km)	
g of CO_2/km	Petrol	Diesel
165	7.0	6.2
140	6.0	5.3
120	5.1	4.5

The ACEA and JAMA agreements also plan to market vehicles emitting less than 120 grams of CO_2 per kilometre as of 2000. This represents fuel consumption of about 5 litres per 100 km for petrol-driven vehicles and 4.5 litres per 100 km for diesel-driven vehicles. In 2000, ACEA and JAMA manufacturers offered more than twenty models meeting these targets. KAMA manufacturers have agreed to market such vehicles as soon as possible.

If ACEA or JAMA manufacturers do not come within range of their intermediary target for 2003 (2004 for KAMA), or if the ACEA manufacturers do not achieve the 2008 objective for CO_2 emissions (2009 for JAMA and KAMA), the European Commission intends to draft new regulations on CO_2 emissions.

CC0, a Volkswagen prototype consuming 1 litre per 100 km. The vehicle is fitted with Michelin tyre-wheel assemblies with low rolling resistance prototype tyres and new-design wheels made of composite materials.

[(1)] ACEA members are BMW, Daimler Chrysler, Fiat, Ford Europe, GM Europe, Porsche, PSA, Renault, Volkswagen and Volvo.

[(2)] JAMA members are Daihatsu, Fuji Heavy Industries (Subaru), Honda, Isuzu, Mazda, Nissan, Mitsubishi, Suzuki and Toyota.

[(3)] KAMA members are Daewoo, Hyundai and Kia.

DEVELOPMENTS IN EUROPEAN POLLUTION LEVELS SINCE 1970

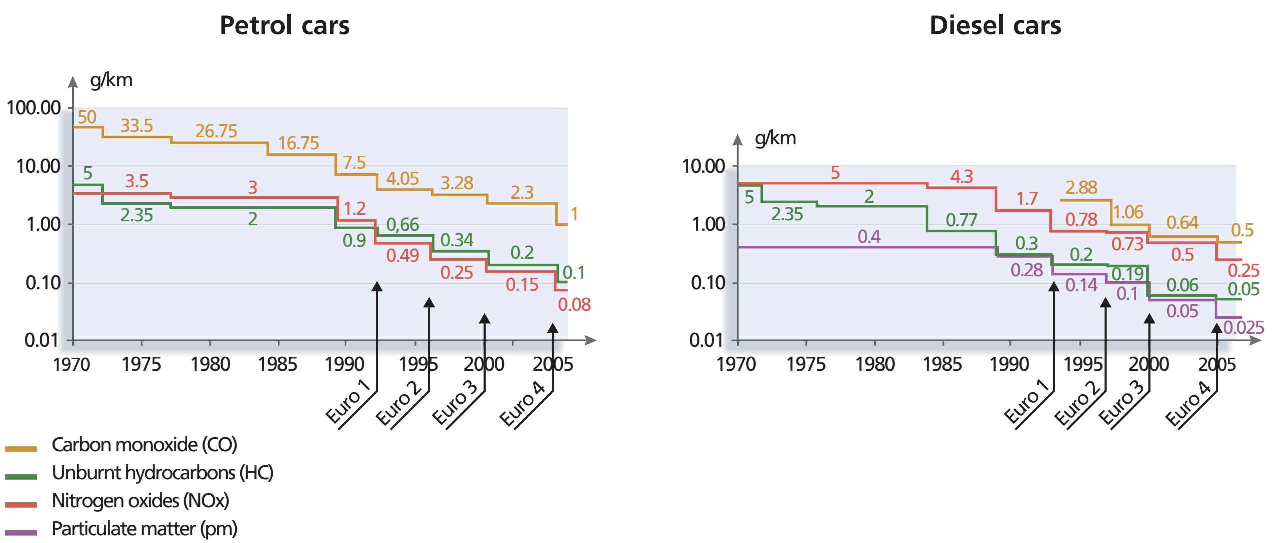
Decreasing fuel consumption helps decrease the emission of pollutants. There are four major types of pollutant in vehicle exhaust gases:

- nitrogen oxides,
- carbon monoxide,
- unburnt hydrocarbons,
- particulate matter.

Regulations have already eliminated all but traces of lead and sulphur in fuel and should completely eradicate them by around 2005.

In Europe, the first regulations on the pollutant emissions of passenger cars and light-duty vehicles were published in 1970 (Directive 70/220/EEC). Since then, over 15 new Directives have updated measuring methods and set ever-stricter maximum levels. These include in particular Directives 91/441/EEC and 94/12/EC used to draft the Euro 1 and Euro 2 standards, and Directive 98/69/EC which brought in the Euro 3 standard currently in force and Euro 4 which will be gradually implemented from 2005 on.

Evolution of regulatory emission levels for new passenger cars in the E.U.



- The first regulations, in 1972, applied to carbon monoxide and unburnt hydrocarbons. Further regulations in 1978 extended measures to nitrogen oxides. Compared to the 1970 levels, the emissions of new petrol-driven cars have been divided by 20 to 25 depending on the chemicals and the emissions of new diesel-driven cars by 10 to 80. These values will be cut even further from 2005 on.

- Since 1993, the limits set by European Directives on air pollution by emissions from motor vehicles are also known as "standards". All the standards applicable at a given date come under the umbrella term of "Euro" followed by a number. For passenger cars, application dates are as follows: standard Euro 1 – 92/93; Euro 2 – 96/97; Euro 3 – 2000/2001 and Euro 4 –2005/2006.

Note:
Values before 2000 have been reworked to take into account the new measurement cycle implemented in 2000.

Source: Union Routière de France, Faits et Chiffres 2000

Downward trend for atmospheric pollutants

As seen below, in the United States and Europe the emissions of carbon monoxide and volatile organic compounds (**VOCs**) due to road transport are falling faster than anthropogenic emissions in general. The same applies to nitrogen oxides in Europe.

The regulatory emission levels for new vehicles are decreasing even faster.

The efforts made these past years are paying off, with a clear downward trend on both continents [(1)].

Evolution of atmospheric pollutant emissions in the European Union and United States between 1990 and 1996-7

	European Union (EU 15) - Evolution between 1990 and 1996			United States - Evolution between 1990 and 1997			
	All anthropogenic sources combined	Road transport (all EU vehicles)	Emissions for each new petrol-driven passenger car [(2)]	All anthropogenic sources combined	Road transport (all US vehicles)	Emissions for each new petrol-driven passenger car [(3)]	Comments by the WBCSD
Carbon monoxide (CO)	- 20 %	- 26 %	- 70 %	- 4 %	- 11 %	0 %	CO (poisonous to mankind but short-lived) is primarily an infrastructure design issue in the construction of tunnels, etc.
Nitrogen oxides (NO_X)	- 10 %	- 14 %	- 77 %	+ 3 %	+ 11 %	- 60 %	Concerns have abated to some degree with the development of advanced technologies
Volatile Organic Compounds (VOC or HC)	- 13 %	- 25 %	- 56 %	- 10 %	- 16 %	- 39 %	Their role in [local] ozone production is a serious concern

[(1)] World data unavailable.

[(2)] Comparison between regulatory levels in 1990 and 1996 -1997 (Euro 2).

[(3)] Comparison between regulatory levels in 1990 and Tier 1 levels gradually brought in from 1991 to 1997.

Sources: European Commission, Directorate-General for Energy and Transport, "EU Energy and Transport in Figures 2001", World Business Council for Sustainable Development, "Mobility 2001", statistics provided by the Environmental Protection Agency (EPA)

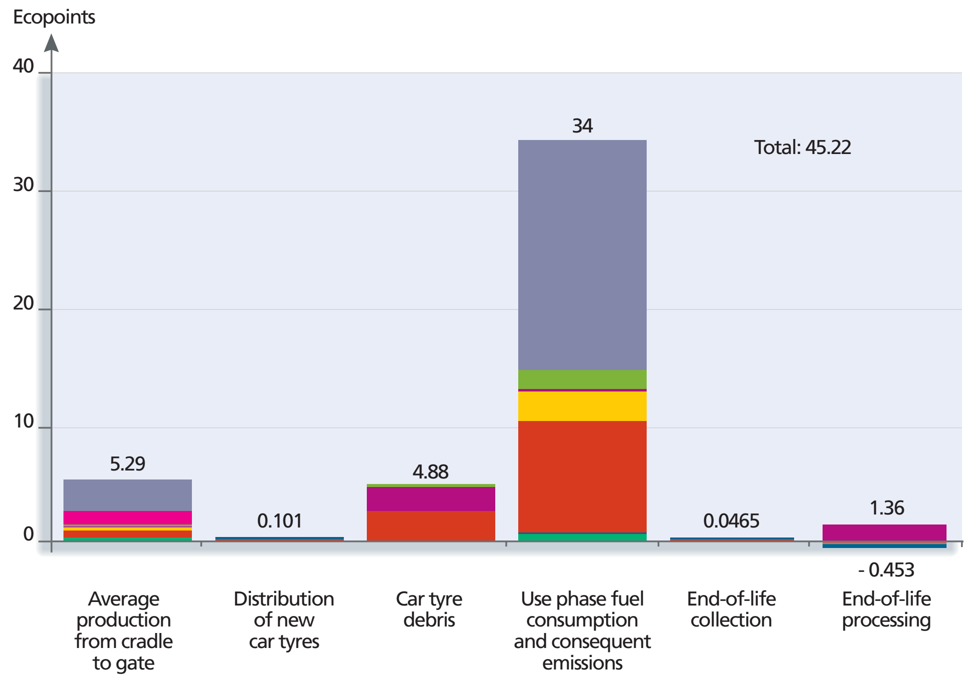
How the “green” tyre helps preserve the environment

Tyre manufacturers working within the BLIC [(1)] carried out a Life Cycle Assessment (**LCA**) in 2000/2001 for a standard size passenger car tyre (195/65 R15, speed index H, summer) representative of the European market. The tyre in question had two different tread compounds. One was reinforced with carbon black ("black" tyre) and the other with silica ("green" tyre). This study is now the European benchmark for passenger car tyres.

The tyre LCA clearly shows that the impact of tyres on the environment and human health is mostly due to fuel consumption, and thus to rolling resistance, and not to the tyre production phase or end-of-life collection and processing.

Fuel consumption represents 34 ecopoints [(2)] out of a total of 45 for the "black" tyre and 29 out of a total of 40 for the "green" tyre, i.e. 75 and 72 % respectively.

Impact on the environment and human health of a carbon black car tyre during its life cycle



Criteria applying to the assessment of ecopoints

- Damage to human health resulting from carcinogenic substances
- Damage to human health resulting from summer smog caused by emission of organic substances
- Damage to human health resulting from winter smog caused by emission of dust, sulphur and nitrogen oxides (emission of inorganic substances)
- Damage to human health resulting from an increase in diseases and death caused by climate change
- Damage to human health resulting from ionizing radiation
- Damage to human health resulting from increased UV radiation caused by the emission of ozone-depleting substances
- Damage to ecosystems caused by eco-toxic substances
- Damage to ecosystems caused by acidification and eutrophisation (combined)
- Damage to ecosystems by land use (change in species diversity)
- Depletion of resources resulting from usage of minerals (ores)
- Depletion of resources resulting from usage of fossil fuels

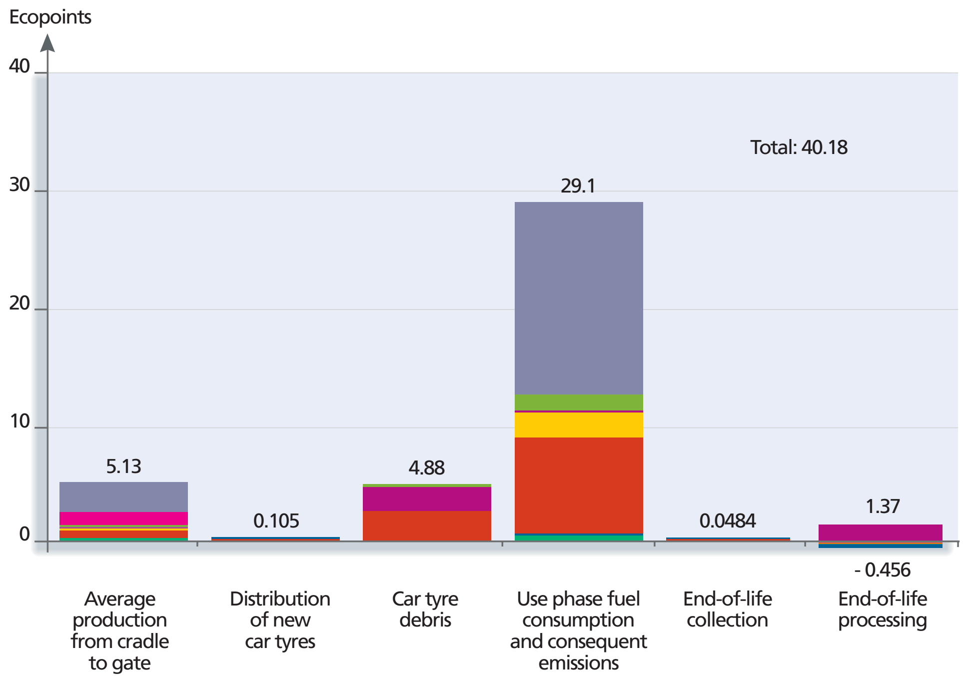
Source: BLIC

(1) BLIC: *Bureau de Liaison des Industries du Caoutchouc de l'Union Européenne* (European association for the rubber industry). Members are Bridgestone-Firestone, Continental, Cooper-Avon, Goodyear-Dunlop, Michelin, Nokian, Pirelli, Trelleborg and Vredestein.

(2) Eco-Indicator 99 method – PRé Consultants B.V.

Life cycle assessment (LCA)

Impact on the environment and human health of a silica car tyre during its life cycle



Source: BLIC

Compared with the "black" tyre, the average European "green" tyre reduces the impact on health and the environment by about 5 ecopoints (11 %) out of a total of 45 points.

Compared with a "black" tyre, in 40,000 km of driving, the average European "green" car tyre can reduce the impact on human health and the environment by the same amount (5 ecopoints) as the impact caused by its production and production of the raw materials of which it is made.

Life cycle assessment is a decision-making tool widely used by industry and law-makers. Automobile, electronics and other industrial firms apply it in the product design process, while law-makers use it for drafting regulations.

LCA is based on an iterative approach assessing the potential impact of a product system [(1)] on human health and the environment during its life cycle. The ISO 14040 standards define how to undertake an LCA. LCAs can be used as decision-making tools to design healthier, more environmentally-friendly products.

The main advantage of LCA is its comprehensive approach. It covers the whole life cycle from the extraction of raw materials to end-of-life collection and processing or disposal. In a tyre LCA, for example, the "use phase fuel consumption and consequent emissions" stage also takes into account the impact of fuel production and its delivery to the pump. Similarly, the "production" stage takes into account the impact of the production of raw and semi-finished materials.

LCA makes it possible to avoid making decisions which would only shift the impact from one life cycle stage to another, instead of actually reducing the impact on human health and the environment.

[(1)] A product system is defined as "*a set of elementary processes, related to each other in terms of energy and fulfilling one or more functions*". For tyres, the function is defined as the driving of a European-made passenger car over an average distance of 40,000 km.

II The tyre's contribution to fuel consumption

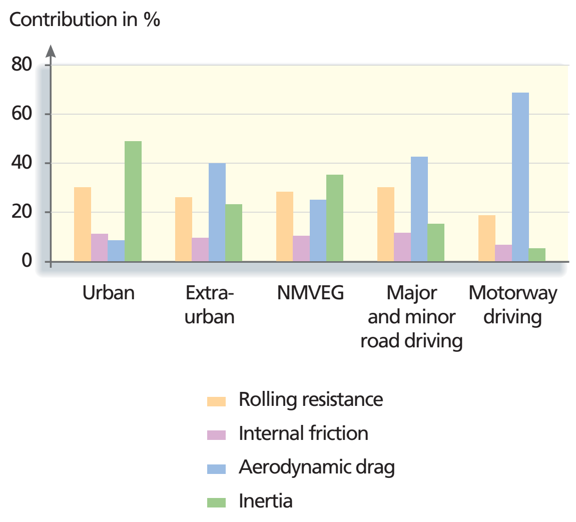
FUEL CONSUMPTION

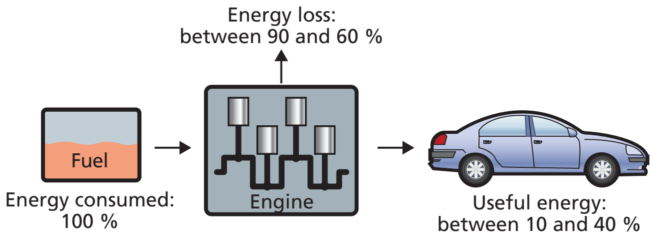
When on the road, the proportion of the vehicle's resistance to movement due to tyre rolling resistance continually varies between 10 and 70 %. The average is around 20 % for motorway driving, 25 % for extra-urban cycles and 30 % for urban cycles and major and minor road driving.

To overcome rolling resistance and other forces resisting movement, the vehicle consumes energy in the form of fuel.
However, the engine dissipates a considerable amount of energy in the form of heat. An internal combustion engine is only between 10 and 40 % efficient when running.

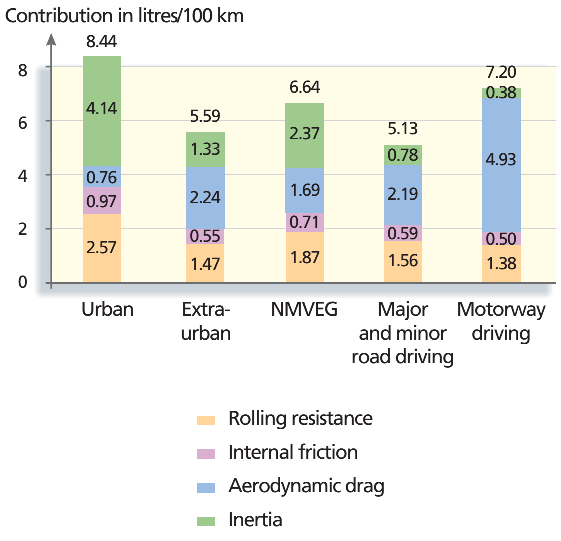
The fuel consumption due to tyre rolling resistance therefore depends not only on the type of trip, the type of driving, vehicle and tyre characteristics but also on the engine efficiency at any moment in time.

Percentage of total resistance to movement due to rolling resistance for five typical trips
(51 kW engine, 12 kg/t tyres)





Proportion of total resistance to movement due to rolling resistance for five typical trips
(51 kW engine, 12 kg/t tyres)



II The tyre’s contribution to fuel consumption

SAVINGS DUE TO "GREEN" TYRES

Even though the tyre’s contribution to fuel consumption varies according to the type of trip, the fuel savings obtained by replacing "black" tyres with "green" tyres is near-constant whatever the trip. For the car studied in this chapter, the savings made by replacing 12 kg/t tyres with 8.5 kg/t tyres (i.e. a 30 % reduction in rolling resistance) are around 0.26 litres/100 km without even changing the gear ratio.

If the tyre is considered from the first vehicle design stages, the manufacturer can optimize the drive train and gear ratio. In our example, the fuel savings would practically double.

If we consider a broad spectrum of tyres for cars currently on the market, we may note that a 30 % reduction in rolling resistance saves between 3 and 6 % of fuel if the gear ratio is not changed or between 6 and 8 % if it is. However, these percentages must be reconsidered for each vehicle and each type of driving.

Compared with a "black" tyre, in 40,000 km of driving the average European "green" car tyre can reduce the impact on health and the environment by the same amount as the impact caused by its production and production of the raw materials of which it is made.

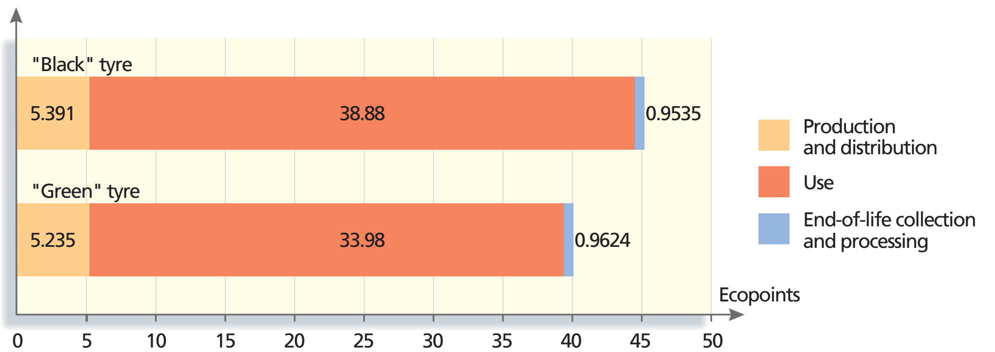
Fuel savings due to the use of "green" tyres with no changes to the gear ratio

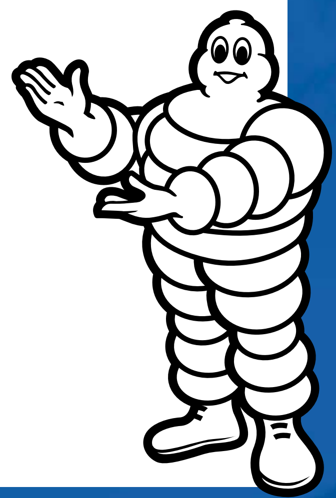
		Typical trip	Urban	Extra-urban	NMVEG	Major & minor roads	Motorway
Consumption in l/100km		"Black" tyres (12 kg/t)	8.44	5.59	6.64	5.13	7.2
		"Green" tyres (8.5 kg/t)	8.17	5.33	6.38	4.87	6.92
Savings compared with "black" tyres	in l/100km		0.27	0.26	0.26	0.26	0.28
	in %		3.2 %	4.7 %	3.9 %	5.1 %	3.9 %

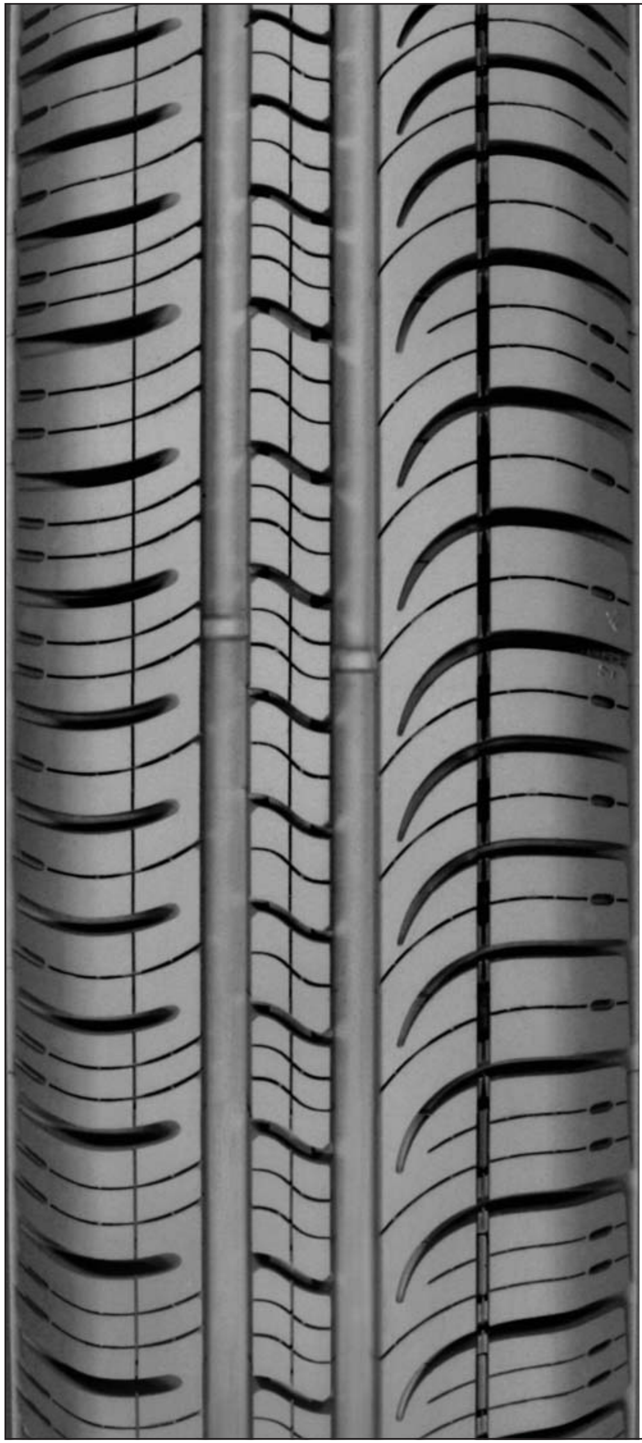
Fuel savings due to the use of "green" tyres after changing the gear ratio

		Typical trip	Urban	Extra-urban	NMVEG	Major & minor roads	Motorway
Consumption in l/100km		"Black" tyres (12 kg/t)	8.44	5.59	6.64	5.13	7.2
		"Green" tyres (8.5 kg/t)	7.84	5.17	6.15	4.72	6.73
Savings compared with "black" tyres	in l/100km		0.6	0.42	0.49	0.41	0.47
	in %		7.1 %	7.5 %	7.4 %	8.0 %	6.5 %

Life cycle assessment of an average European passenger car tyre

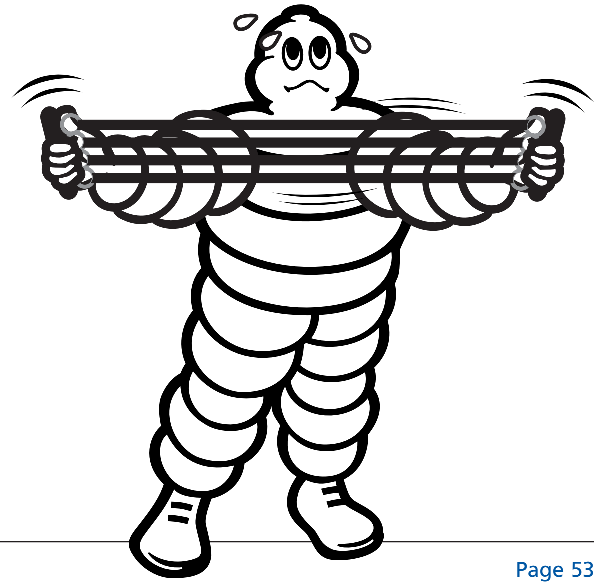






III Visco-elastic materials and energy dissipation

The rubber compounds used in tyres are visco-elastic, which means that they dissipate energy in the form of heat when being deformed. Deformation-induced energy dissipation is the cause of 90 % of rolling resistance.



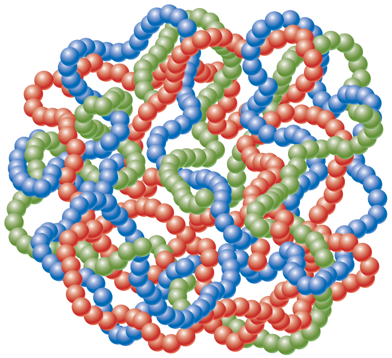
Rubber compounds used in tyres

Over 200 different raw materials are used to make tyres. To investigate the behaviour of rubber compounds in tyres, we will simplify matters by focusing on only three constituents: polymers, reinforcing fillers and sulphur.

The rubber compounds used in tyres are **reinforced, vulcanized elastomers**. They are made up of polymers which are combined with reinforcing fillers and sulphur before being cured [(1)].

POLYMERS

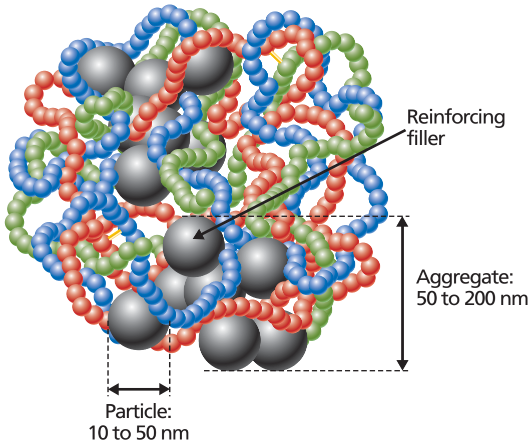
Polymers are long chains of molecules which spontaneously wind themselves around like balls of wool, becoming entangled with each other.



Polymers are **hysteretic** materials, which means that they dissipate energy when being deformed. This property makes the tyres **grip** the road.

REINFORCING FILLERS

To make the rubber compounds, reinforcing fillers are added to the polymers. They are then known as "reinforced materials".



The reinforcing filler used is either carbon black or silica.

***Carbon black** is a fine powder obtained by the incomplete combustion of petroleum oils.*

*The **amorphous silica** (SiO_2) used in tyres is obtained by the fusion of sand and sodium carbonate (Na_2CO_3) at a very high temperature. The sodium silicate thus obtained is placed in water, forming an aqueous solution which is then subjected to precipitation using sulphuric acid.*

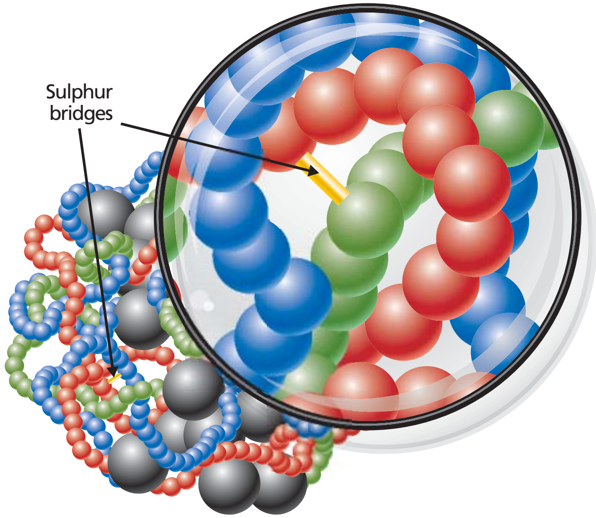
[(1)] The way that materials are cured using sulphur is known as **vulcanization** after Vulcan, the Roman god of fire, forges and volcanoes (where sulphur was extracted).

The reinforcing fillers help tyres better **resist wear** (abrasions, tears) and make them more rigid (thus improving **handling**). Without reinforcing fillers, tyres could only cover a few hundred kilometres in their lifetime.

Resistance to wear and rigidity are optimal for a reinforcement volume percentage of 20 to 25 % and reinforcing filler aggregates between 50 and 200 nm [(2)] (the exact values of the optimal percentage of reinforcing fillers and their aggregate size vary depending on the part of the tyre—e.g. the tread or sidewall—considered).

■ SULPHUR

Tyre compounds also contain sulphur. When the tyre is vulcanized, the high temperature leads to the creation of **sulphur bridges** between the polymer chains. These sulphur bridges give the material cohesiveness and **elasticity**.



Polymers, reinforcing fillers and sulphur bridges account for the rubber compounds' visco-elasticity, which itself depends on the quantity of each constituent.

[(2)] nm stands for nanometre: 10^{-9} metres i.e. one thousand millionth of a metre.

III.2 The origin of energy dissipation: visco-elasticity and deformation

A visco-elastic material can be deformed. Its behaviour lies somewhere between that of a viscous fluid and an elastic solid.

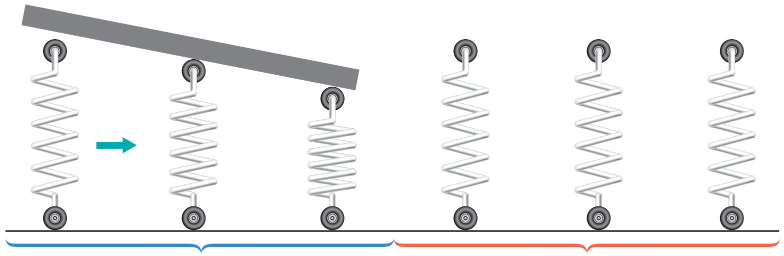
ELASTIC MATERIALS

When an elastic body such as a spring is subjected to a force, it is immediately deformed in proportion to the force applied. As soon as the force is released, it returns to its initial shape. For a theoretical, perfectly elastic body, the **deformation and stress are simultaneous and no energy is dissipated**.

VISCOUS MATERIALS

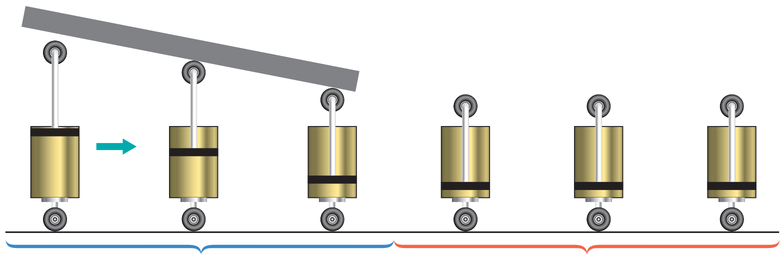
A viscous fluid such as oil does not behave in the same way. If a piston is pushed down an oil-filled tube, it encounters resistance. The quicker it is pushed, the more resistance is encountered. When there is no more pressure on the piston, it does not return to its initial position: all the **energy has been dissipated**.

Viscosity is due to friction between the molecules making up the fluid. Friction resists their movement.



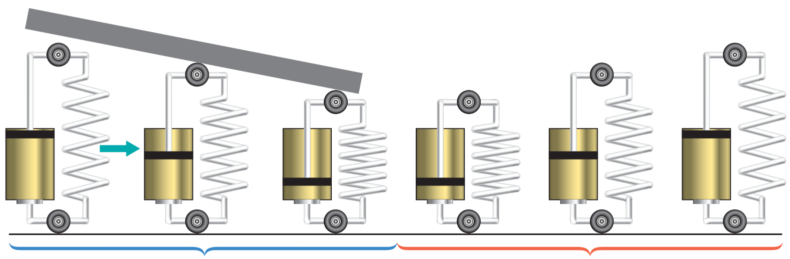
• Consider the behaviour of a spring with a castor on each end. The spring is rolled from left to right under an inclined bar.

The spring is compressed as it rolls forward under the bar. Once free of the bar, it immediately reverts to its initial height. The spring is capable of restoring all the deformation energy.



• Let us now replace the spring by a piston in an oil-filled cylinder.

The piston is depressed as it moves from left to right under the bar. Once free of the bar, it does not revert to its initial height. The piston has dissipated all the deformation energy.



• Let us now repeat the experiment with a spring + piston assembly.

The spring + piston assembly is compressed as it moves under the bar. Once free of the bar, it does not immediately revert to its initial height. The assembly has dissipated part of the deformation energy but can restore the other part.

VISCO-ELASTIC MATERIALS

The behaviour of **visco-elastic materials** such as chewing-gum or an elastomer, lies somewhere between that of a perfect spring and a viscous fluid. It can be represented by a spring + piston assembly.

When a visco-elastic material has been deformed, it reverts to its initial shape only after a certain time, not always perceptible to an observer. This phenomenon is known as **hysteresis**. The time lapse is associated with **energy loss** in the form of heat, i.e. **dissipation**.

The energy dissipation caused by repeated deformation is what causes rolling resistance.

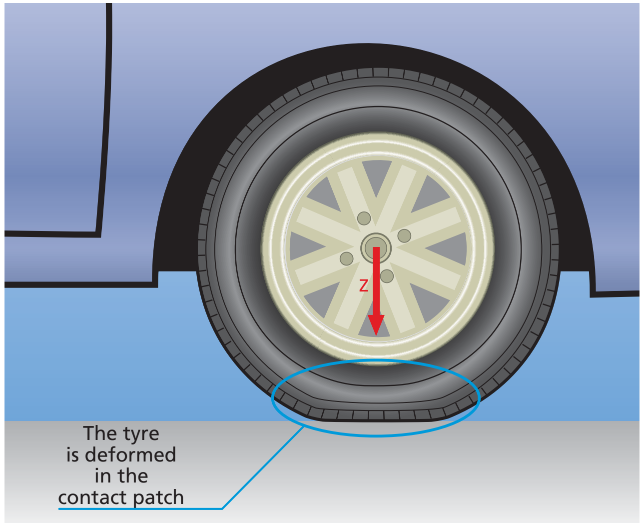
A rubber compound's propensity to dissipate part and restore part of the deformation energy depends on its **compounding**, i.e. the type and proportion of raw materials used in its manufacture—particularly polymers, sulphur and reinforcing fillers.

Note:
For more detailed information on the behaviour of elastic, viscous and visco-elastic materials, see the volume on *Grip* (pp. 8 – 10) in this collection.

TYRE DEFORMATION WHEN ROLLING

When a car is driven along, its tyres are subjected to repeated deformation leading to energy dissipation. Each point of a loaded tyre is deformed as the tyre completes a revolution. Such repeated deformation occurs across the tyre's whole width and thickness so that it hugs the road surface. The tyre's flexibility allows it to absorb surface unevenness and—unlike a wheel—develop a contact patch. To summarize, the tyre's ability to be deformed allows it to ensure comfort and grip.

However, repeated structural deformation also leads to **energy dissipation** which causes rolling resistance. We will look at the mechanics of deformation in chapter IV.



Factors affecting energy dissipation

MODULUS AND ENERGY DISSIPATION

Rigidity is expressed by a magnitude known as modulus. Flexible materials have a low modulus and rigid materials a high one.

The modulus, noted E, is defined as the ratio between stress (σ) and relative deformation, hereafter referred to as the strain (ε).

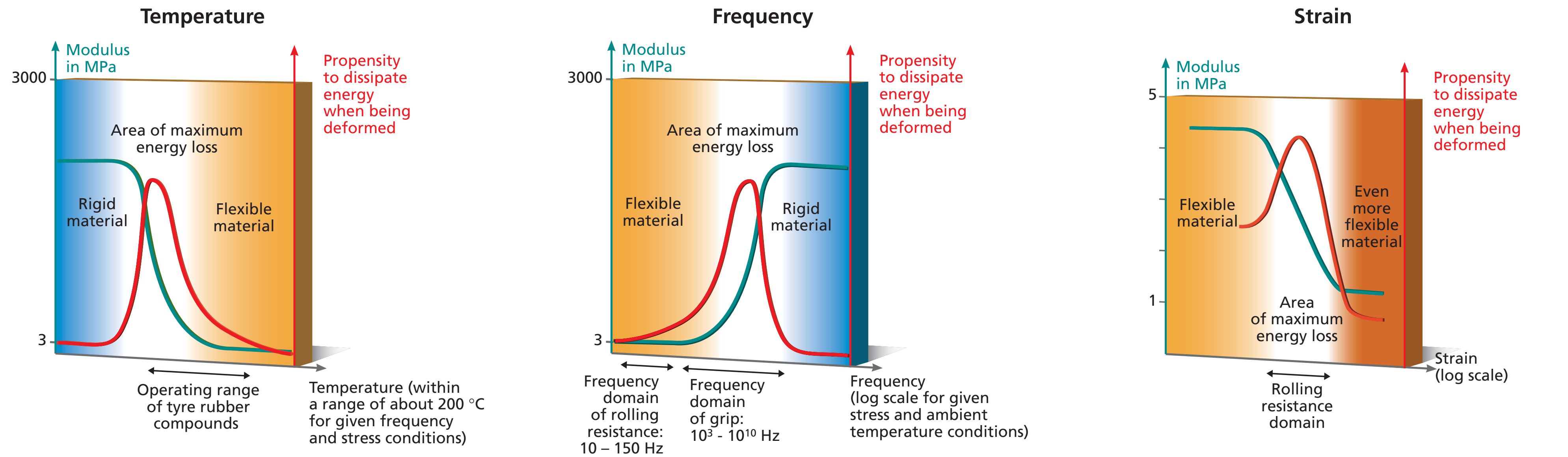
The rigidity, or modulus, of a tyre rubber compound subjected to alternating deformation depends on three factors:
- temperature,
- deformation frequency,
- strain level.

To simplify, we can say that:
- the higher the temperature, the more flexible the compound;
- the higher the frequency, the more rigid the compound;
- the greater the deformation, the more flexible the compound.

Actually, rubber compound rigidity is not linearly dependent on temperature, frequency or deformation. It is stable near minimum and maximum values but varies greatly within an intermediate range.

The areas of marked variations in rigidity are also areas of high viscosity, where the rubber compound has a propensity to dissipate more energy when being deformed. A drop in modulus is always accompanied by a peak in energy dissipation.

Effect of temperature, frequency and strain on a rubber compound's propensity to dissipate energy when being deformed



DEFORMATION FREQUENCIES

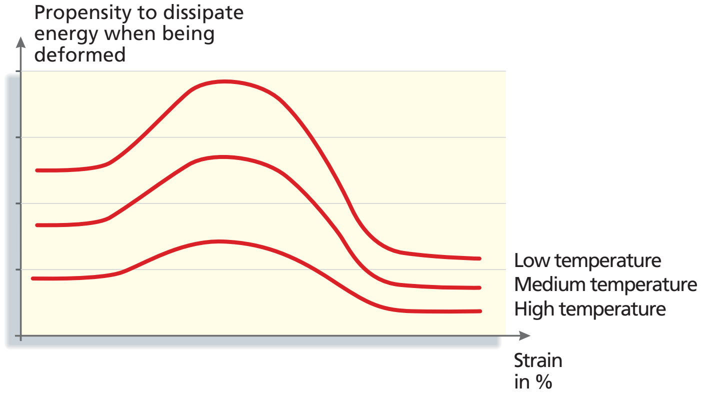
The **surface deformation** responsible for grip occurs at frequencies between 10^3 and 10^{10} Hz. The **structural deformation** responsible for rolling resistance occurs every time the wheel completes a full revolution, i.e. around 15 times a second for a car travelling at 100 km/h. This deformation occurs throughout the 10-150 Hz frequency range.

OPERATING TEMPERATURES

We have seen that a rubber compound's propensity to dissipate energy decreases as temperature increases. This is why the rolling resistance of a tyre is higher when it starts rolling than after a while. Car tyres usually take about 30 minutes' rolling to warm up. Their internal temperature then reaches a plateau, generally between 20 and 60 °C (in average driving conditions).

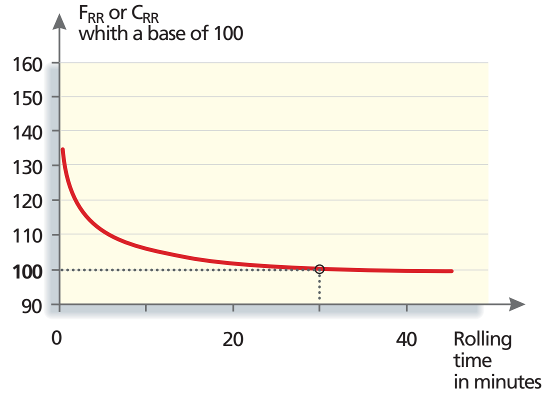
Note:
When braking, i.e. when grip is required, the surface temperature of the tyre tread is around 70 °C with ABS, but can exceed 150 °C when the wheels lock.

Effect of temperature on the propensity of rubber compounds to dissipate energy when being deformed



As temperature increases, the tyre rubber compounds' propensity to dissipate energy decreases.

Effect of rolling time on rolling resistance
(passenger car tyres)



Base 100: measurement taken after 30 minutes' rolling as per the ISO 8767 standard [1]

[1] See page 97 for measurement conditions.

STRAIN LEVELS

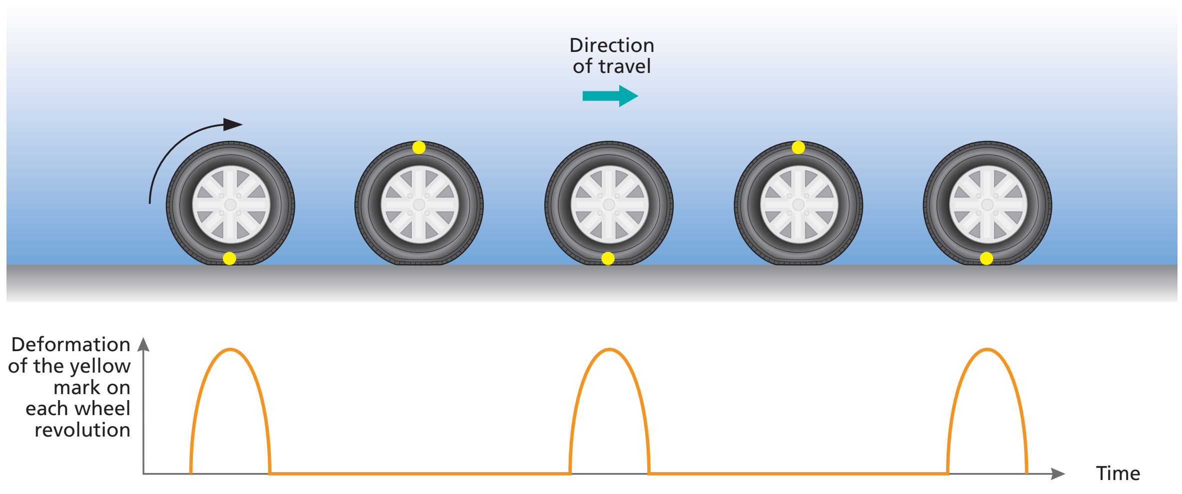
As a loaded tyre completes a revolution, it is deformed across its whole width and thickness so that the tyre hugs the road surface in the contact patch. Whenever this happens, the strain of the tyre rubber compounds varies within a 0 - 15 % range (typical value for cars and trucks).

The rubber compounds' propensity to dissipate energy when being deformed is at its peak within this range (see red line on the graph opposite).

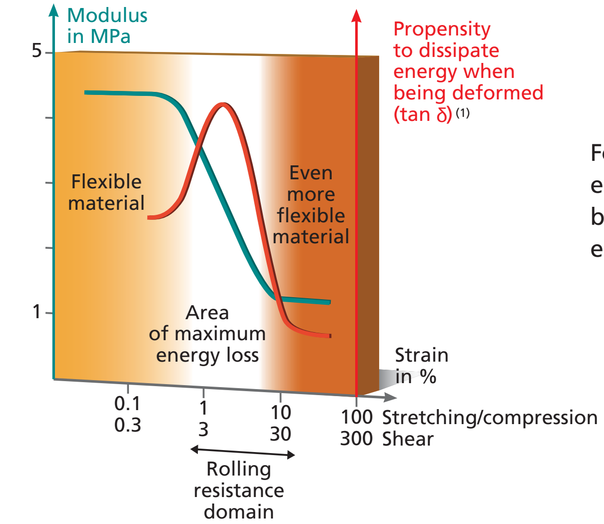
To reduce rolling resistance, it is necessary to reduce this propensity to dissipate energy. Therefore the material's drop in rigidity when the strain varies (green line) must be minimized. This sudden drop in rigidity as a function of deformation is referred to as a **non-linearity**.

The origin of this non-linearity is very complex and remains the focus of active research. Current knowledge allows us to give a simplified explanation. Although incomplete, this explanation will help us understand the reasoning behind the use of different materials to reduce rolling resistance.

Tyre deformation on each wheel revolution



Non-linearity



For alternating stretching and compression, the greatest energy loss by rubber compounds occurs for strains between 0.5 and 15 %. For alternating shear, the greatest energy loss is for strains between 1 and 50 %.

(1) For more information on tan δ, see the volume on *Grip* in the same collection.

DESORPTION

The surface of carbon black is able to physically interact with the polymer chains with which it is in contact, a phenomenon known as **adsorption**.

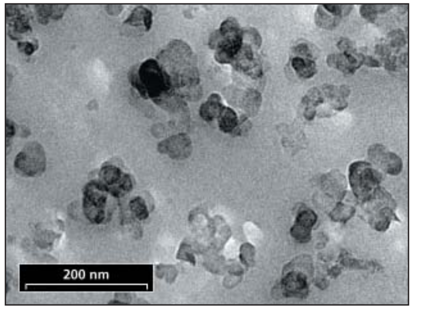
When the rubber compound undergoes alternating deformation, the non-deformable carbon black aggregates move alternately closer then further away from each other. As a result, the polymer chains may break away from the carbon black, a process known as **desorption**. The polymer chains then return to their equilibrium state (relaxed), which reduces compound rigidity and induces energy dissipation. The greater the deformation, the greater the probability of desorption.

Since all the segments of polymer chains between two adsorption sites are of various lengths, and the adsorption sites are of different kinds, the chains may break away at different strains. The drop in modulus occurs progressively between 0.5 and 15 % for alternating stretching and compression, and between 1 and 50 % for alternating shear.

EFFECT OF INTER-AGGREGATE DISTANCE ON ENERGY DISSIPATION

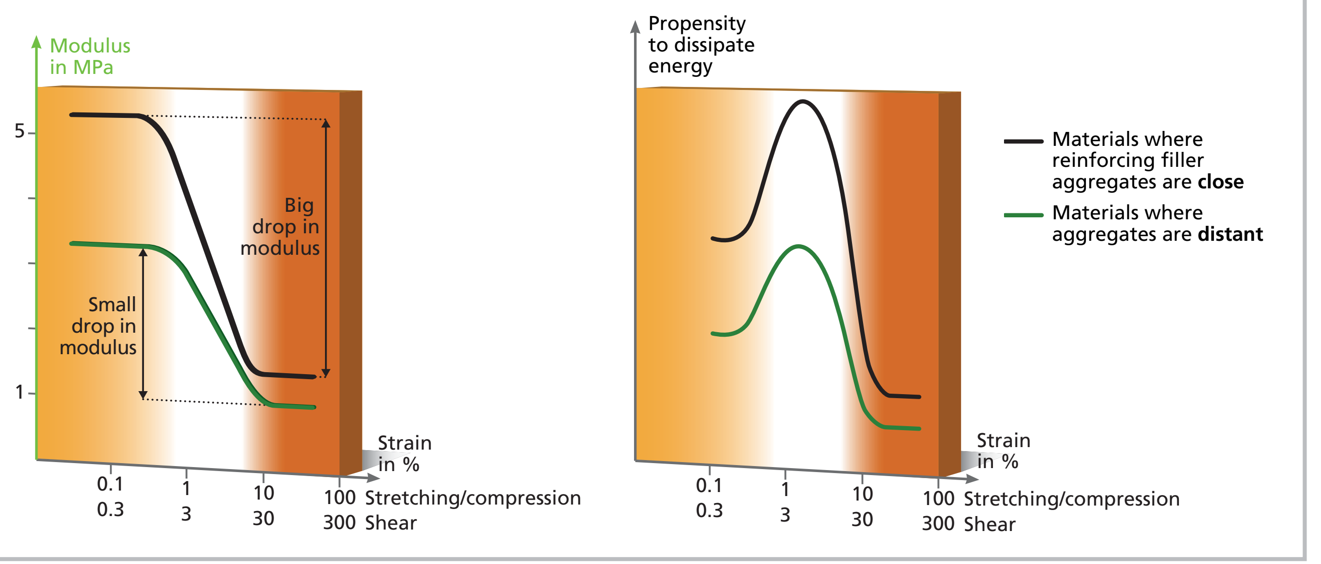
The closer the reinforcing filler aggregates are to each other, the greater the probability of desorption. This is borne out by experiments, which show that the drop in modulus is bigger when the carbon black aggregates are closer together.

Therefore, the further apart the reinforcing filler aggregates, the lower the propensity of rubber compounds to dissipate energy when subjected to alternating deformation.



Electron microscope view of a compound reinforced with carbon black. Enlarged 80,000 times.

Effect of filler aggregate spacing on non-linearity



III.4

Reducing energy dissipation

The energy loss due to the alternating deformation of rubber compounds is due only to the polymers they contain. The other raw materials (mainly reinforcing fillers, sulphur and oils) only reveal, amplify… or limit dissipation. This is especially true of reinforcing fillers, which amplify energy dissipation in any case but which amplify it more when the aggregates are close to each other. To reduce a tyre's energy dissipation, we can either:

- select less hysteretic polymers, or
- increase the distance between reinforcing filler aggregates.

However, we will see how difficult it is to implement these solutions without compromising tyre performance, especially tread grip and resistance to wear.

SELECTING LOW-HYSTERESIS POLYMERS

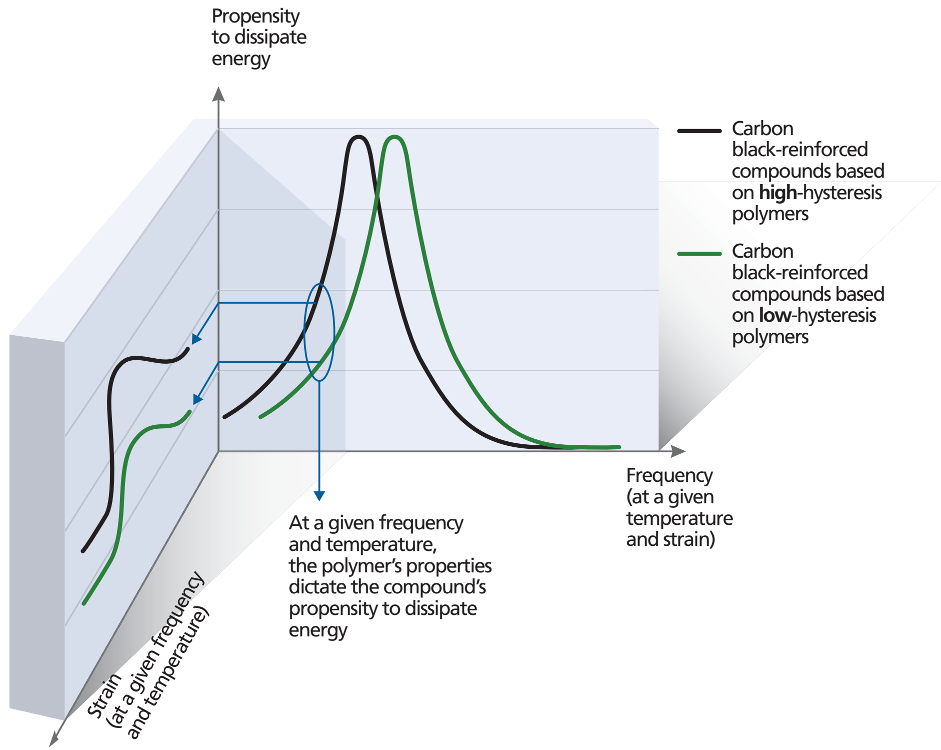
To simplify matters, we may say that certain polymers are only slightly hysteretic (dissipative). Their grip qualities are therefore limited, but they offer low rolling resistance. Others are more hysteretic, offering better grip but also higher rolling resistance [1].

[1] The hysteretic properties of a polymer actually depend on temperature and stress frequency. When we say that one polymer is less hysteretic than another, we mean that it offers lower hysteresis at the tyre's operating temperature and frequencies. Hysteresis depends on the temperature (or frequency) of the polymer's glass transition. For more information on glass transition temperature (Tg), see the volume on *Grip* in the same collection.

Prior to the early 1990s, the conventional way of reducing rolling resistance without compromising resistance to wear, i.e. without interfering with the reinforcing fillers, was to use less dissipative polymers. However, this meant that whenever rolling resistance was reduced, so was grip - a situation that tyre designers could not allow.

New solutions involve changing the distribution of reinforcing fillers within the compound.

Effect of the polymers used in a rubber compound on its propensity to dissipate energy



INCREASING DISTANCE BETWEEN REINFORCING FILLER AGGREGATES

As we have seen, the drop in modulus is bigger when the distances between reinforcing filler aggregates are smaller.

To reduce energy dissipation, we can therefore **increase the distances between reinforcing filler aggregates**.

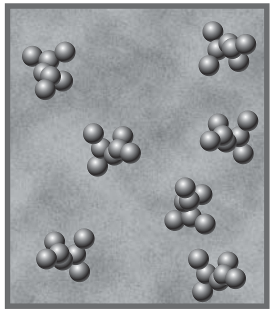
To increase the distances, we can either:
- reduce the percentage of reinforcing filler used in the compound, or
- increase the size of filler aggregates.

However, we have already said that these reinforcing fillers are responsible for the tyre's resistance to wear (abrasion strength and tear resistance) and the rigidity needed for good road handling. Wear resistance and rigidity are optimal when the compound includes a volume fraction of 20 – 25 % of reinforcing fillers and when the filler aggregates are between 50 and 200 nm. We cannot therefore greatly reduce the percentage of filler used nor increase the size of the filler aggregates without compromising overall tyre performance. Neither method leaves much room for optimization.

Method 1
Reducing the volume fraction of reinforcing filler

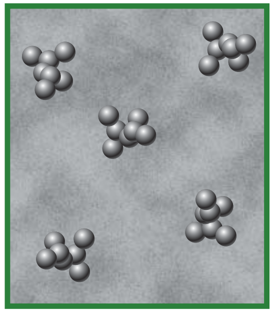
(while keeping aggregate size unchanged)

Rubber compound 1



Material with a large percentage of filler: carbon black aggregates are close to each other.

Rubber compound 2

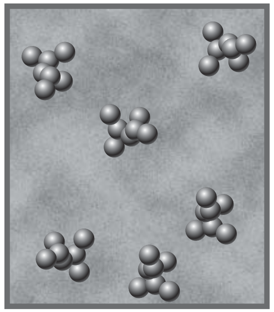


Less filler: the aggregates are further apart.

Method 2
Increasing the size of filler aggregates

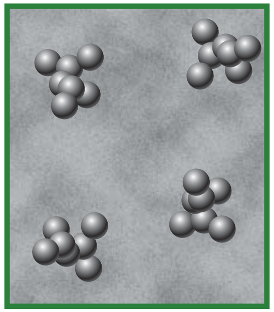
(while keeping the filler volume fraction unchanged)

Rubber compound 1



Material reinforced with small carbon black aggregates: filler aggregates are close to each other.

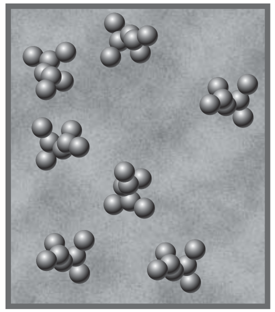
Rubber compound 2



Material reinforced with larger carbon black aggregates: filler aggregates are further apart on average.

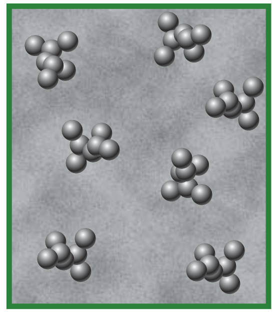
Method 3
Homogenizing the distribution of reinforcing filler

Rubber compound 1



Uneven distribution of filler: aggregates may be close to each other.

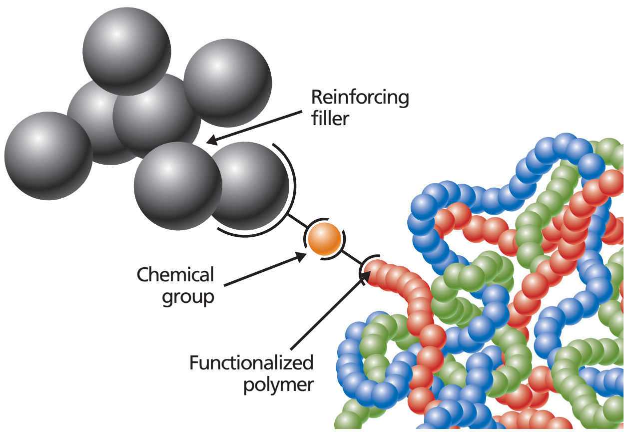
Rubber compound 2



Even distribution of filler: aggregates are further apart on the whole.

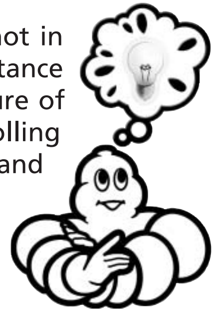
To increase the distance between reinforcing filler aggregates without changing either their volume fraction or size, it is possible to improve their distribution. This may be achieved in two ways.

The first is to **increase the filler/elastomer mixing time**. The second is to graft **chemical groups** (also known as functional groups) onto the end of the polymer chains. These groups bond to the filler aggregates, preventing them from getting too close to each other. The polymers bearing these chemical groups are known as **functionalized polymers**. The functional group used with carbon black is an amine. Silanols ($Si(CH_3)_2$ OH) are commonly used with silica.

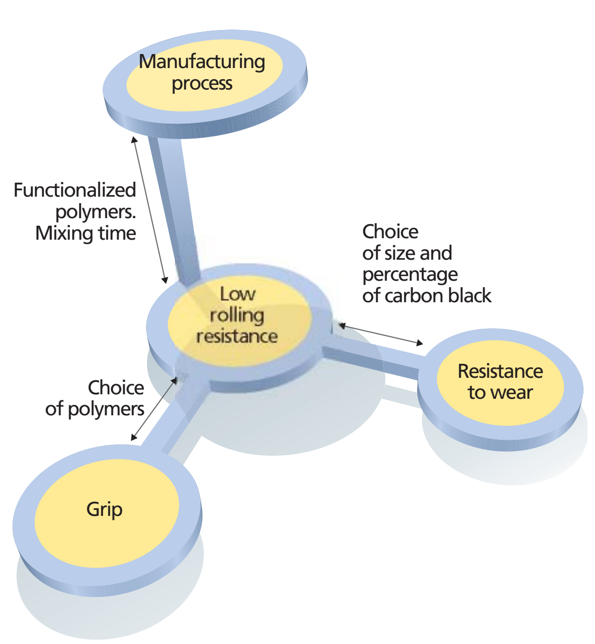


The difficulty with both solutions is the manufacturing process involved. It is difficult to use functionalized polymers because the compound becomes more viscous and harder to work with. It is also costly to increase the mixing time.

To summarize, the difficulty lies not in the design of low rolling resistance compounds, but in the manufacture of rubber compounds with low rolling resistance, high wear resistance and good grip. This is known as **performance trade-off**.



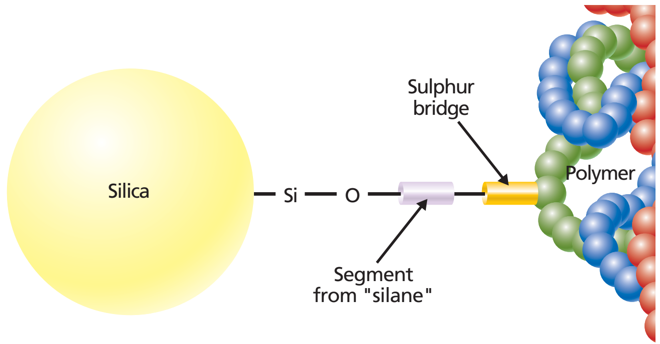
Performance trade-off



SILICA'S SPECIAL FEATURES

Unlike carbon black, silica does not naturally develop strong links with polymer chains, and tends to clump together. Due to the short distances and strong interactions between the filler aggregates, the resulting material is very dissipative in the rolling resistance domain. Simply replacing carbon black with silica would result in compounds with poor rolling resistance performance.

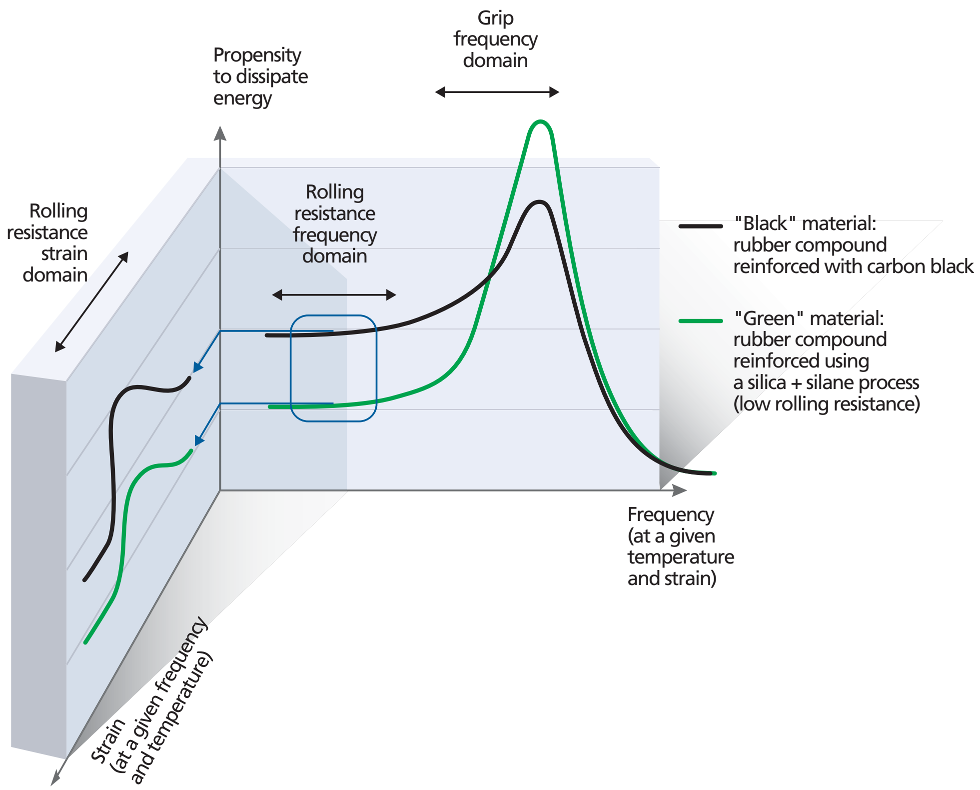
However, it is possible to create reactions between silica and polymers by using a **coupling agent** from the **silane** family. One end of this compound has a chemical group capable of spontaneously bonding with silica during mixing. The other end includes sulphur and attaches itself to any part of the polymer chain, a reaction which takes place primarily during curing.



This process results in an **excellent distribution of silica reinforcing fillers**. Energy loss due to tyre deformation is limited, thus lowering rolling resistance. In this case, there is no need to reduce the percentage of reinforcing filler, and the conflict between wear resistance and low rolling resistance disappears.

There is no need either to use low-hysteresis polymers, because the polymer + silica compound is very dissipative at high frequencies (grip domain) and much less dissipative at low frequencies (rolling resistance domain).

"Black" and "green" compounds



The materials have two energy dissipation peaks: one in the grip domain, the other in the rolling resistance domain. The propensity of the "green" compound to dissipate energy is high in the grip domain but weak in the rolling resistance domain. The same is true but less marked for the "black" compound, resulting in lower overall tyre performance.

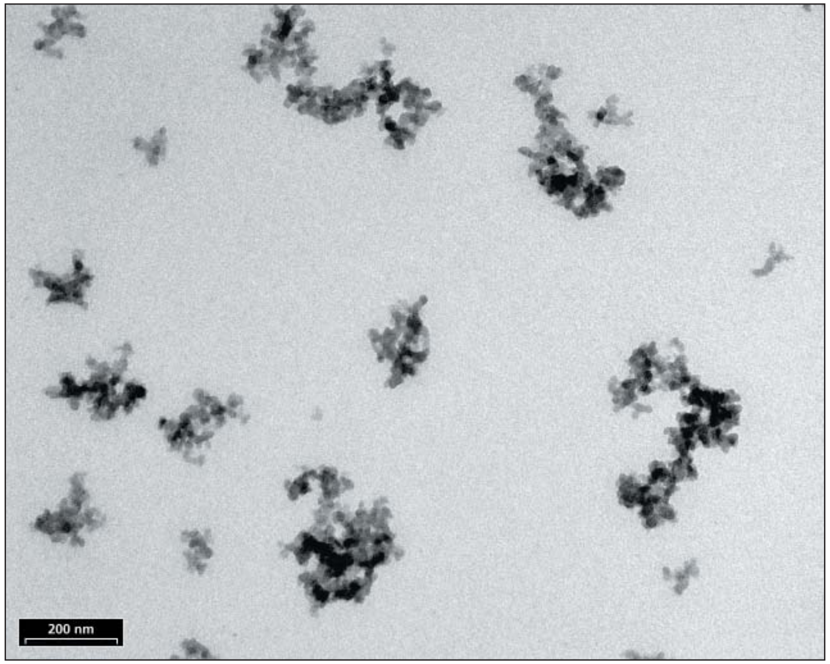
Note:
Laboratory apparatus cannot be used to plot these graphs as a function of frequency because it is impossible to achieve frequencies over several hundred hertz. However, we know that a fall in temperature has the same effect on the rubber compound as an increase in frequency. The energy dissipation versus frequency graphs shown here have been deduced from graphs of energy dissipation versus temperature previously plotted following experimentation.

The silica/silane combination therefore offers an excellent balance between lower rolling resistance, better grip, good handling and better resistance to wear.

However, using silica and silane requires modifying the mixing process so as to control the compound temperature throughout mixing operations [1]. The temperature must be high enough to allow the silica and silane to bond, but not so high as to induce an early reaction between the sulphur and polymer chains.

Obtaining a tyre with low rolling resistance requires not only the specific compounding of rubber mixes, but also a specific mixing process.

Today, while satisfactory results for certain applications are commonly achieved using carbon black, the best solution for passenger car tyre treads is the silica/silane compound.



Electron microscope view of silica aggregates. Enlarged 62,000 times.

[1] As explained in Michelin's U.S. patent number 5227425.

III Visco-elastic materials and energy dissipation

Tyre rubber compounds are visco-elastic: they dissipate energy in the form of heat during deformation. The energy dissipation thus induced accounts for 90 % of rolling resistance.

At a given temperature and stress frequency, energy dissipation in tyre rubber compounds is highest for a strain between 1 and 50 %.

A rolling tyre is subjected to strains precisely within this range (currently up to 15 %).

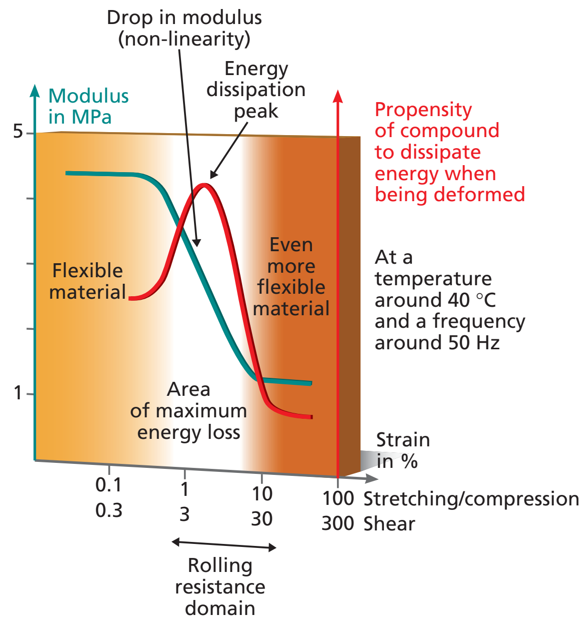
The propensity of rubber compounds to dissipate energy is linked to the drop in rigidity caused by deformation. Rigidity is known as **modulus**. The drop in modulus is known as a **non-linearity**.

The drop in modulus is directly related to interactions between polymers and reinforcing fillers.

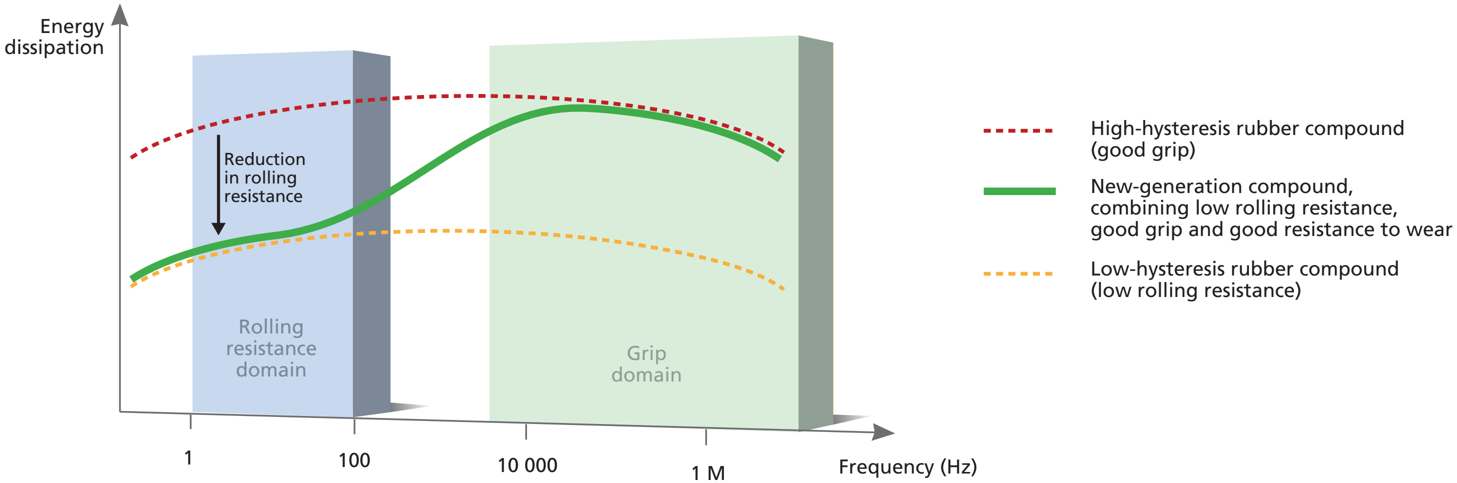
To reduce tyre rolling resistance without compromising either grip or wear resistance, the reinforcing filler aggregates must be distributed evenly throughout the compound.

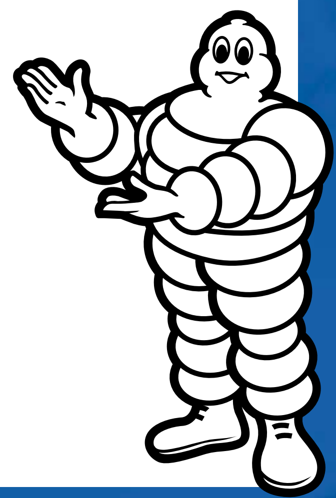
A combination of **silica** and a coupling agent known as **silane** currently offers an excellent trade-off, especially for car tyres.

Non-linearity and energy dissipation



Trade-off between grip and rolling resistance





IV The *mechanics* of rolling resistance

There are three physical causes of rolling resistance:

- the deformation of a tyre when it flattens out in the contact patch,
- aerodynamic drag of the rotating tyre,
- microslippage between the tread and the road surface or between the tyre and the wheel rim.

The first mechanism alone accounts for 80 to 95 % of rolling resistance. We will therefore take a brief look at the other two then focus on tyre deformation in the contact patch.

IV.1 Two secondary mechanisms: microslippage and aerodynamic drag of the rotating tyre

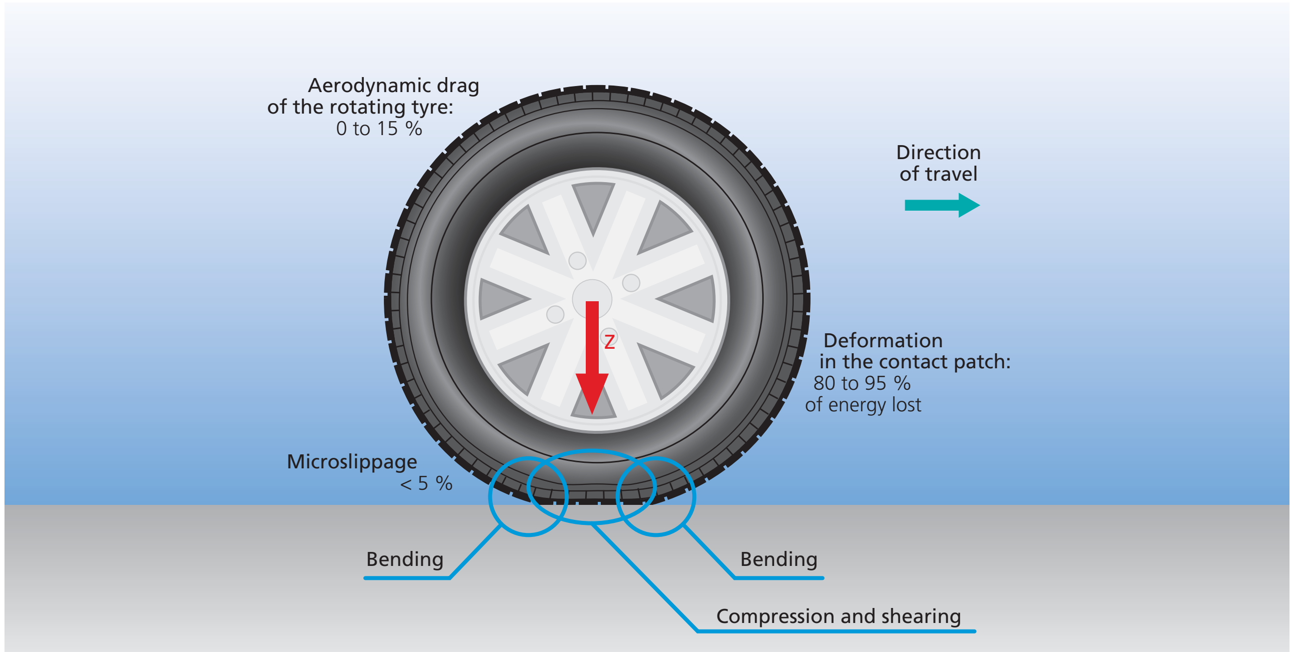
MICROSLIPPAGE

As a tyre rotates, the contact patch is constantly subject to microslippage which occurs between the tread blocks and the road surface. Microslippage also occurs between the tyre and the wheel rim. Both sources of microslippage lead to energy dissipation which contributes to rolling resistance. However, when a car is driven in a straight line without braking or accelerating, microslippage accounts for less than 5 % of total rolling resistance.

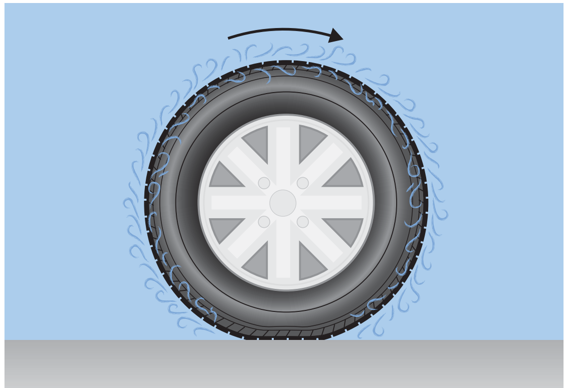
AERODYNAMIC DRAG OF THE ROTATING TYRE

Rotating objects disturb the air around them. This movement of air—or drag—resists the object's rotation. The bigger the object (i.e. the greater the surface area in contact with the air), the greater the resistance. Resistance also increases with the square of the speed of rotation (just as a vehicle's aerodynamic drag increases with the square of its speed). The aerodynamic drag of a rotating tyre accounts for between 0 and 15 % of rolling resistance.

The main three physical causes of rolling resistance

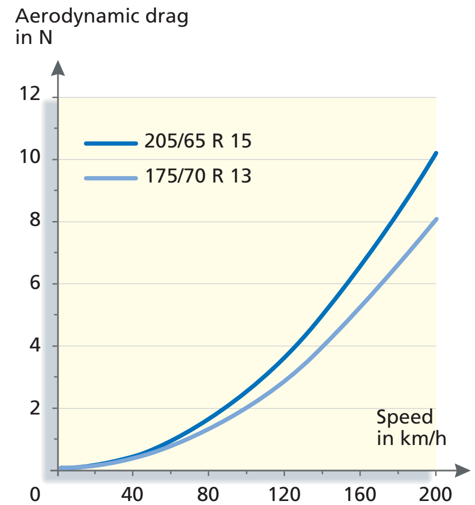


Aerodynamic drag of the rotating tyre



Effect of tyre size and speed on the aerodynamic drag of a rotating tyre

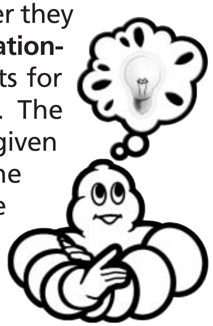
(values for a single tyre)



IV.2 Main mechanisms: repeated tyre deformation in the contact patch

The tyre is a complex composite made of elastomers with metal and fabric reinforcing materials. It is flexible enough to flatten out when in contact with the road surface and absorb surface irregularities. Its remarkable ability to be deformed is the key to a tyre's grip and comfort.

However, the elastomers of which the tyre is made are **visco-elastic materials**. They therefore dissipate energy in the form of heat whenever they are being **deformed. Such deformation-induced energy dissipation** accounts for about 90 % of rolling resistance. The amount of energy dissipated by a given rubber compound depends on the range of strains to which the tyre is subjected whenever the wheel completes a full revolution.



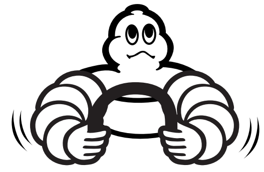
To understand the mechanics of rolling resistance, we therefore need to understand how the tyre is deformed on each wheel revolution.

BENDING, COMPRESSION AND SHEARING

Tyre flattening in the contact patch causes three main kinds of deformation:

- **bending** of the crown, the sidewalls and the bead area;
- **compression** of the tread;
- **shearing** of the tread and sidewalls.

Bending

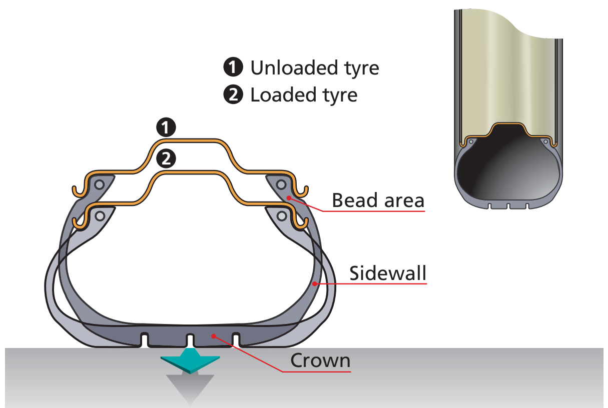


Compression

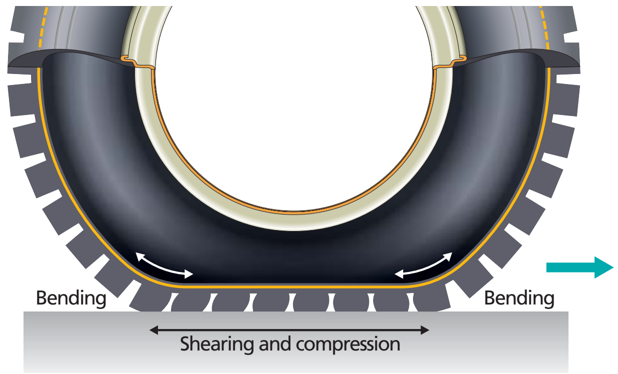
Shearing

Examples of tyre deformation when rolling

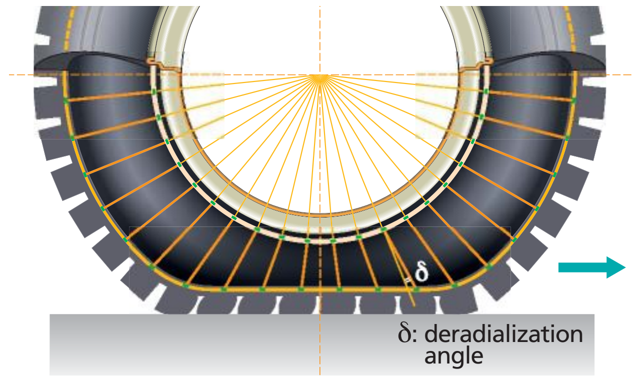
Transversal bending



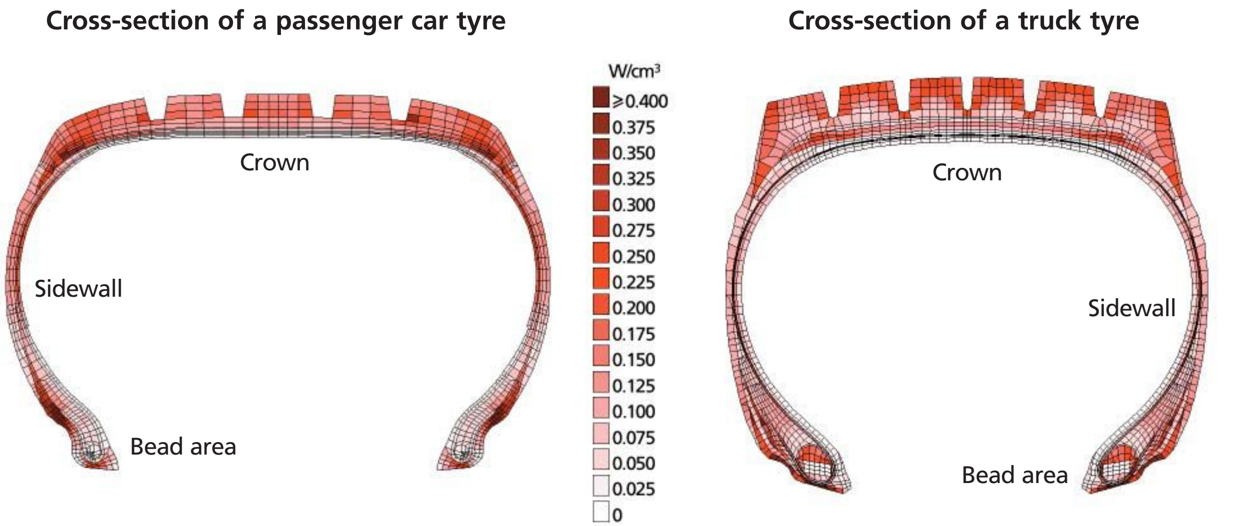
Longitudinal deformation of the crown



Shearing of sidewalls by deradialization



Energy dissipation maps



These maps were computed using the finite element method.

Energy dissipation is distributed as follows (typical values):
- crown: 70 %,
- sidewalls: 15 %,
- bead area: 15 %.

As crown deformation is the main source of energy loss, we will simplify matters by not going into details on sidewall or bead area deformation. We will instead focus on the tread.

PARAMETERS AFFECTING STRAIN LEVELS

We saw in chapter III that energy dissipation caused by deformation was at its greatest for strains between 0.5 and 15 % for compression and 1 and 50 % for shearing. We will now estimate strains in the crown of a rolling tyre.

Whether bending, compression or shearing, the tread strain depends on the following parameters:
- rigidity of the rubber compounds (modulus M),
- tread thickness (h) and void ratio (Void) [1],
- tyre inflation pressure,
- load (Z).

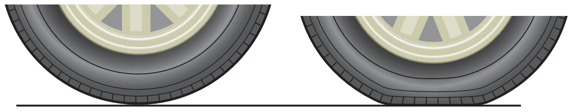
If we know these parameters, we can assess tyre strains using a simple model known as the **Koutny model**.

[1] The fraction of the contact patch area occupied by grooves.

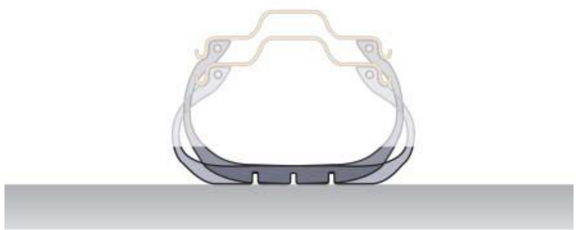
IV.2.1
Bending of the crown in the contact patch

When a car is being driven, the tyre crown hugs the road surface, developing a flat contact patch. The tyre flattens throughout the length and width of the tread. This is known as **longitudinal bending and transversal bending**.

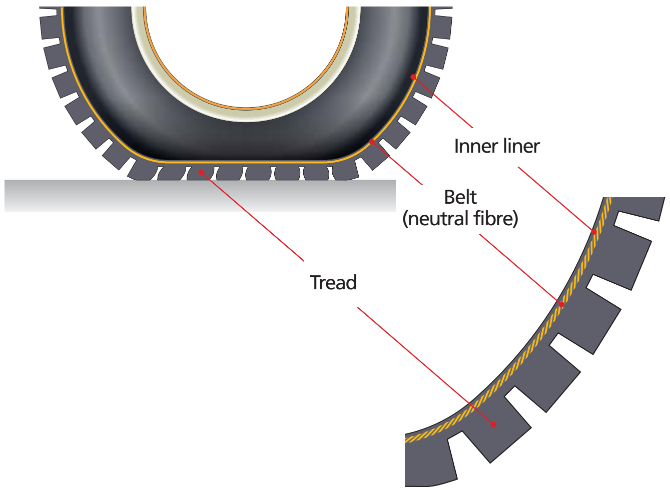
Longitudinal bending
of the crown in the contact patch



Transversal bending
of the crown in the contact patch



Whether the bending is longitudinal or transversal, the tyre **crown** can be likened to a composite structure with three superimposed layers:
• a central layer of metal—the belt—which is both unstretchable and incompressible;
• two layers of visco-elastic material on either side of the central layer (belt), one of which is the tyre's inner liner and the other the tread.



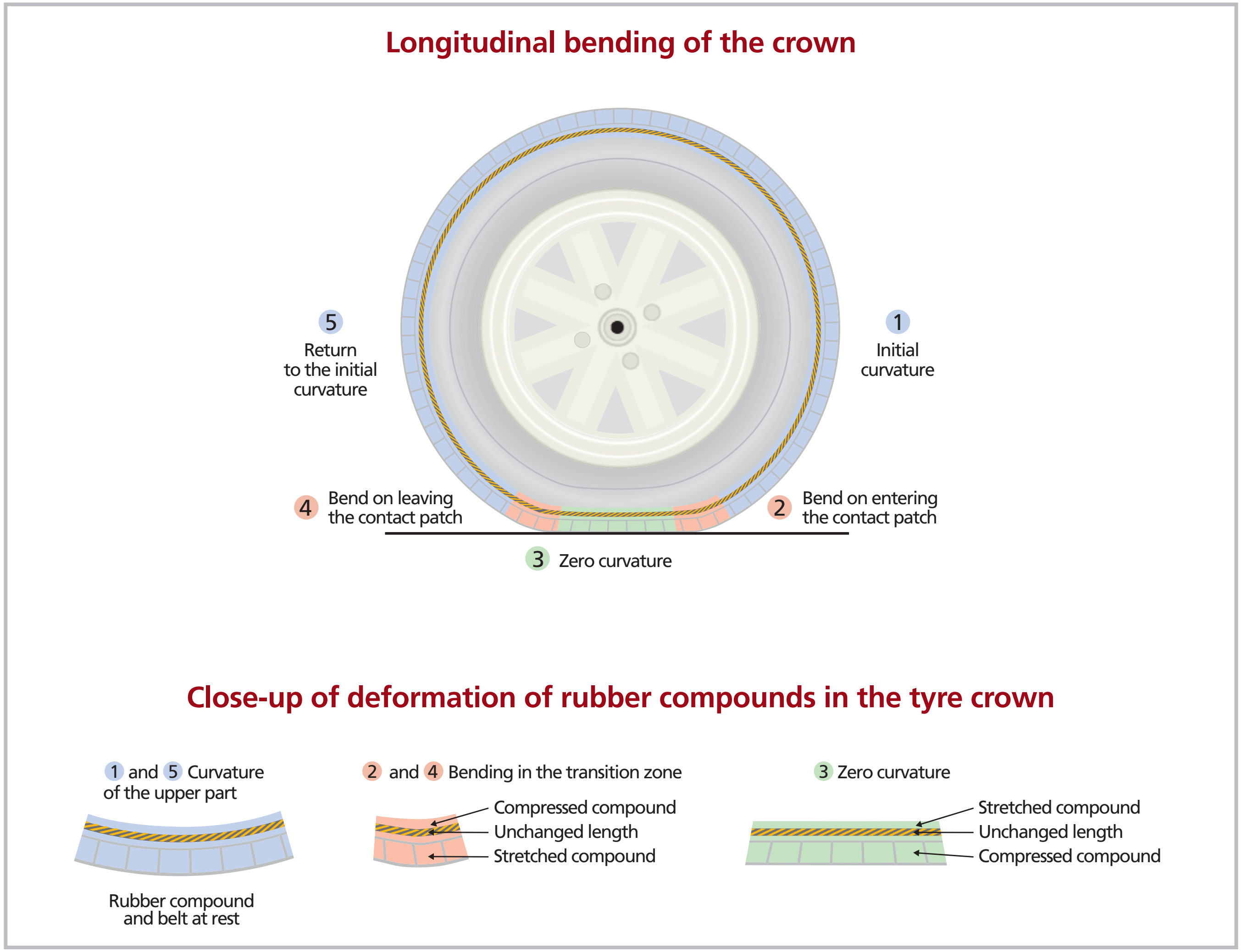
Now let us see how this composite structure is deformed during each full wheel revolution.

When the crown reaches the contact patch, its circumferential curvature is modified. The crown first bends, then flattens, finally returning to its initial shape on leaving the contact patch. When the crown bends, the outside layer is **stretched** and the inside layer **compressed**. Conversely, when it flattens out, the outside layer is compressed and the inside layer stretched.

Similar compression/stretching phenomena occur across the width of the crown.
Such repeated deformation leads to energy dissipation which in turn contributes to rolling resistance.

BENDING STRAIN LEVELS

The strain is the ratio between an object's deformation and its initial dimensions. If we pull on a 10-cm-long elastic band, stretching it a further one centimetre, its strain is $\frac{1}{10}$, i.e. 10 %.



In the case of bending, the strain depends on the ratio between the radius of the object's initial curvature and the radius of the curvature when the object is being deformed.

To calculate the tyre's longitudinal bending strain, we need to know the three successive curvature radii: radius of **curvature in the upper part** of the tyre (R_{upp}), radius in the **transition zones** ($R_{transition}$) and radius in the **contact patch**. In the contact patch, the radius is by definition infinite because the tyre is flat. The other two radii need to be calculated.

We can represent variations in belt curvature using a **simple geometric model** known as the **Koutny model**.

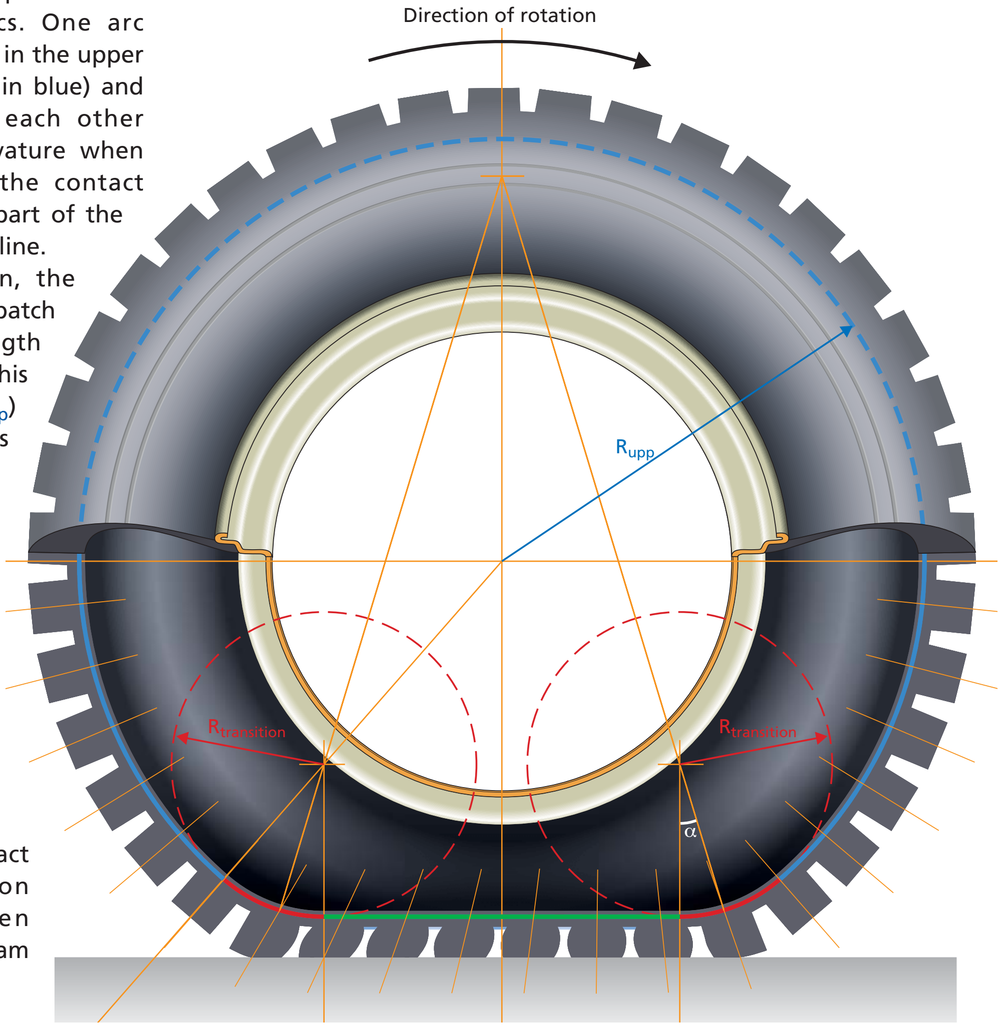
Although tyre designers today use finite element calculations, which require powerful computers, this simple model describes the mechanics of belt flattening accurately enough to determine the radius in the upper part of the tyre (R_{upp}) and the radius in the transition zone ($R_{transition}$).

Having determined these two radii, we can calculate the longitudinal strains of the tyre crown when rolling.

The longitudinal bending strain in the crown is about 3 % for passenger car tyres and 4 % for truck tyres.

Koutny model with three tangential circular arcs

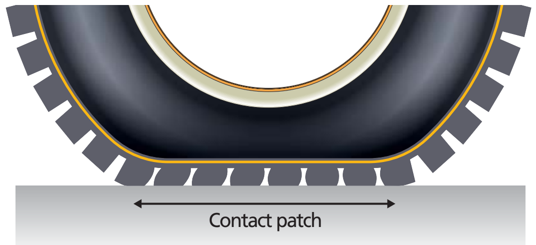
The Koutny model comprises three tangential circular arcs. One arc corresponds to curvature in the upper part of the tyre (shown in blue) and two arcs identical to each other correspond to tyre curvature when entering and leaving the contact patch (in red). The flat part of the belt is shown by a green line.
Knowing the deflection, the length of the contact patch and the invariable length of the belt, we can use this model to calculate (R_{upp}) and ($R_{transition}$) (calculations not shown).



Note:
The length of the contact patch and deformation magnitude have been exaggerated in this diagram for the sake of clarity.

IV.2.2
Tread compression in the contact patch

The tread blocks in the contact patch are compressed under the vehicle's load.



■ COMPRESSION STRAIN LEVELS

The calculations opposite show that the compression strain is about 5 % for passenger car tyres. It is about 14 % for trucks.

A little more information on...

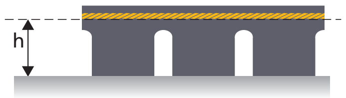
... the tread's longitudinal bending strain

The maximum strain (stretching or compression) of a tread block subjected to bending equals:

$$\varepsilon_{bending} = h \cdot \left(\frac{1}{R_f} - \frac{1}{R_i}\right)$$

where:

- h is the tread thickness in metres
- R_i is the radius of the initial curvature in metres
- R_f is the radius of the final curvature (during deformation) in metres



Note:

- When the object is flat, its curvature radius is infinite and $\frac{1}{R}$ equals 0.
- The bending strain to which each point of the tread block is subjected ("local" bending rate) is proportional to its distance from the belt.

Example calculation for a passenger car tyre (195/60 R15)

Hypotheses:

- Tread thickness: h = 9 mm, i.e. 0.009 metres
- Radius of upper part of tyre: R_{upp} = 0.3 metres
- Radius in transition zone: $R_{transition}$ = 0.145 metres

Calculation

of the longitudinal strain when the tyre bends in the **transition** zone:

$$\varepsilon_{bending} = h \cdot \left(\frac{1}{R_f} - \frac{1}{R_i}\right) = 0.009 \times \left(\frac{1}{0.145} - \frac{1}{0.3}\right) = 0.032$$

i.e. 3.2%

Calculation

of the longitudinal strain in the contact patch (**flattening**):

$$\varepsilon_{bending} = h \cdot \left(\frac{1}{R_f} - \frac{1}{R_i}\right) = 0.009 \times \left(\frac{1}{\infty} - \frac{1}{0.3}\right)$$

$$= 0.009 \times (0 - 3.33) = -0.03$$

i.e. 3%

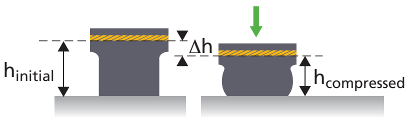
A little more information on...

... parameters affecting the compression strain of tread blocks

1 Compression strain

The compression strain ($\varepsilon_{compression}$) of an object is defined as the ratio between its deformation (Δh) and the initial height ($h_{initial}$).

$$\varepsilon_{compression} = \frac{\Delta h}{h_{initial}}$$



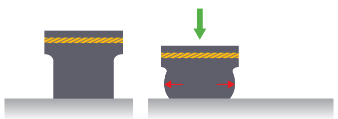
The compression strain depends on the pressure (σ) exerted on the object and the object's rigidity (modulus M).

$$\varepsilon_{compression} = \frac{\sigma}{M}$$

For a tread block, rigidity depends on the compression strain, thus:

$$\varepsilon_{compression} = \frac{\sigma}{M(\varepsilon)}$$

This is because the rubber compound of which tyres are made is incompressible. Therefore, when a tread block is vertically compressed, it expands sideways.



However, its dilation is not infinite. The more it is compressed, the more resistance it offers i.e. its rigidity increases.

The tread block's tendency to rigidify depends on its height to width ratio. A short, wide block rigidifies more than a tall, narrow block.

To take into account the tread block's variation in rigidity depending on its shape, the compression strain may be calculated using a formula such as follows:

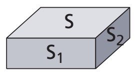
$$\varepsilon_{compression} = 0.33 \text{ x } \left(1 - e^{\left(\frac{\sigma}{M_{10} \,.\, F}\right)}\right)$$

where:

σ is the pressure exerted in MPa

M_{10} is the modulus measured at 10 % stretching in MPa, and

F is the aspect ratio equal to S/S' as defined below:



$$S' = 2\,(S_1 + S_2)$$

2 Determination of the pressure exerted

The pressure exerted on the tread blocks in the contact patch ($P_{contact}$) depends on the void ratio (Void) and tyre inflation pressure (P_{tyre}).

The average pressure in the contact patch is close to that of the tyre pressure i.e. around 2 bars for a passenger car tyre and 8 for a truck tyre.

However, the tread pattern includes grooves, i.e. voids which make up about 30 % of tyre tread. The other 70 % is in contact with the road surface. The average pressure exerted on tread blocks in contact with the road surface ($P_{contact}$) is about 45 % higher i.e. 3 bars for a passenger car tyre and 11 for a truck tyre.

$$P_{contact} = \frac{P_{tyre}}{1 - \text{Void}}$$

3 Example calculation for a passenger car tyre (195/60 R15)

Hypotheses:

- Initial dimensions of the tread block L x l x h = 20 x 20 x 10 mm
- Siping such that 25 % must be added to S'
- Aspect ratio = S/(S' + 25 %) = 0.4
- Modulus measured when stretched by 10 %: 50 bars i.e. 5 MPa
- Contact pressure: 3 bars, i.e. 0.3 MPa

Calculation of the compression strain:

$$\varepsilon_{compression} = 0.33 \text{ x } \left(1 - e^{\left(\frac{0.3}{5 \times 0.4}\right)}\right) = 0.05 \quad \text{i.e. } 5\%$$

Calculation of the deformation:

$$\Delta h = h_{initial} \cdot \varepsilon_{compression} = 0.01 \text{ x } 0.05 = 0.0005 \text{ m}$$

i.e. 0.5 mm

IV.2.3

Shearing of the tread in the contact patch

Tread blocks in the contact patch are subjected not only to compression but to **shearing**.

When a tread block enters the contact patch, because the tyre is round, the block does not make contact with the road surface vertically but at an angle (see righthand diagram). At this instant, it appears to lean backwards. As the tyre belt is unstretchable (because of its metallic content) but the tread block deformable, the tread block's progression is dictated by the belt. In the absence of slippage between the road surface and tread (good grip on a dry road), the angle of the tread block is determined by the relative position between its point of impact on the road surface (blue dot) and its point of attachment to the belt (green dot). To "keep up" with the belt as it gets closer to the middle of the contact patch, the tread block gradually becomes upright again. Finally, the shearing force exerted on it just before leaving the contact patch makes it appear to lean forwards.

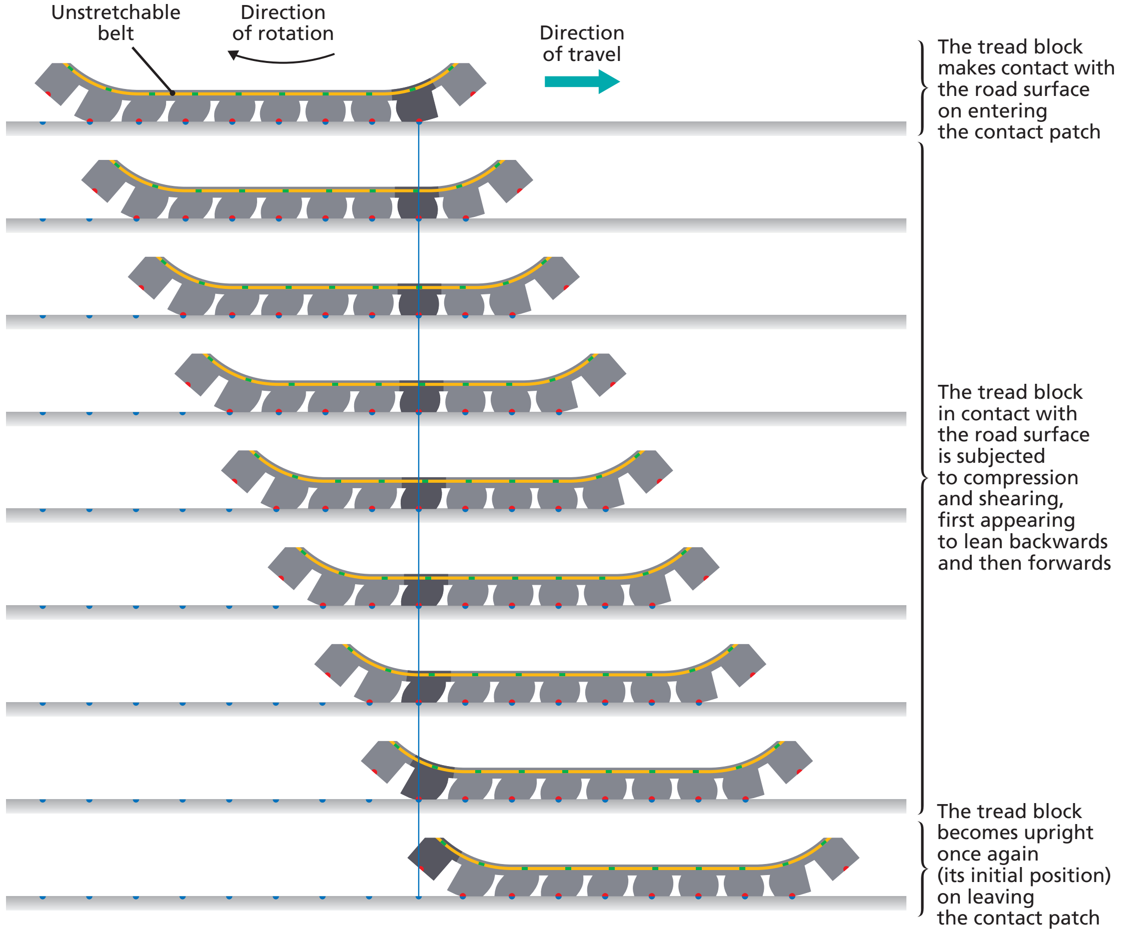
Reminder:

The length of the contact patch and deformation magnitude have been exaggerated in this diagram for the sake of clarity.

Movement of a tread block in the contact patch

Hypotheses:

Dry road (good grip). No cornering, braking or accelerating.



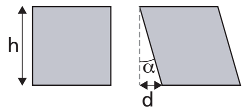
SHEARING STRAIN LEVELS

The calculations below show that the shear strain is around 8 % for passenger car tyres and around 15 % for truck tyres.

A little more information on...

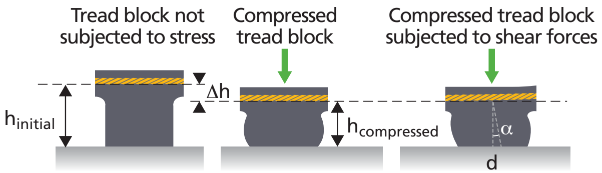
... the shear strain of tread blocks

The shearing of an object in the shape of a parallelepiped is defined by the $\frac{d}{h}$ ratio as shown below:



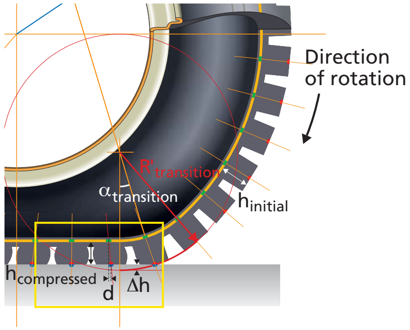
(d et h in metres)

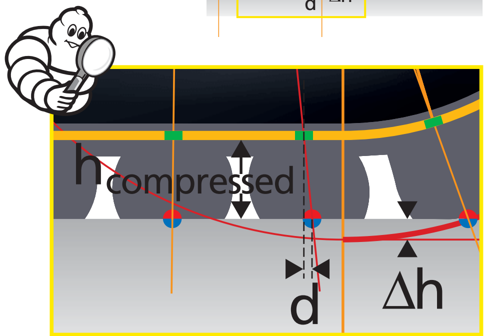
Tread blocks are subjected not only to shear forces but also to compression when in the contact patch. Compression (Δh) must also be taken into consideration.



$$\frac{d}{h} = \tan\alpha$$

Let us look at the Koutny model again to observe closely what happens when the blocks enter the contact patch:





We may prove geometrically that:

$$\frac{d}{h} \approx \tan\alpha_{transition} \approx \sqrt{2 \cdot \frac{\Delta h}{R'_{transition}}}$$

Example calculation
for a passenger car tyre (195/60 R15)

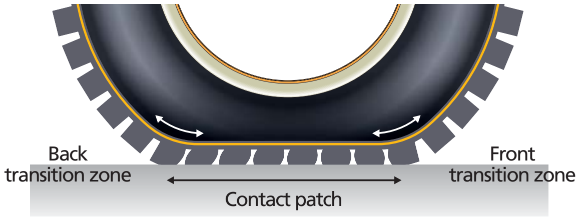
Hypotheses:

- Initial thickness of the tread block: h = 10 mm
- Deformation: Δh = 0.5 mm
- Radius in the transition zone (including tread block thickness): $R'_{transition}$ = 0.155 m

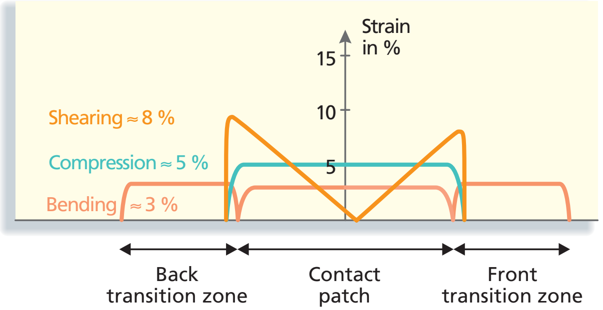
Calculation
of the shear strain:

$$\frac{d}{h} = \sqrt{2 \times \frac{\Delta h}{R'_{transition}}} = \sqrt{2 \times \frac{0.0005}{0.155}} = 0.080 \quad \text{i.e. } 8.0\%$$

Summary of crown strains in the contact patch



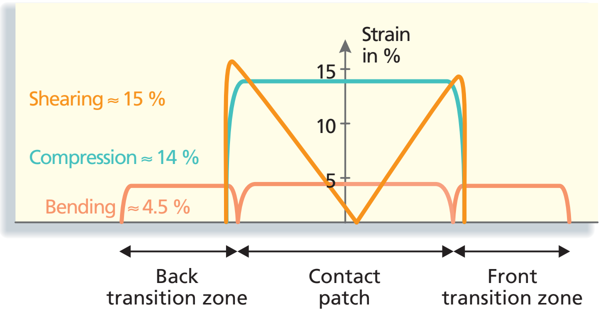
Passenger car tyres:



Hypotheses

(for a 195/60 R 15):
- Unloaded radius of the tyre: 300 mm
- Tread thickness: 10 mm
- Deflection: 20 mm
- Apparent modulus: 5 MPa
- Longitudinal void ratio: 10 %
- Tyre pressure: 2 bars
- Length of the contact patch + 2 transition zones = 307 mm, i.e. 1/6 of the tyre circumference

Truck tyres:



Hypotheses

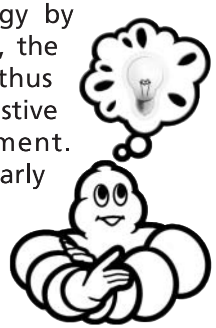
(for a 315/80 R 22.5):
- Unloaded radius of the tyre: 540 mm
- Tread thickness: 25 mm
- Deflection: 30 mm
- Apparent modulus: 6.5 MPa
- Longitudinal void ratio: 5 %
- Tyre pressure: 8.5 bars
- Length of the contact patch + 2 transition zones = 529 mm, i.e. 1/6 of the tyre circumference

IV.3 Manifestation of rolling resistance forces in the contact patch

We saw in chapter III that energy dissipation due to the alternating deformation of rubber compounds was greatest for strains between 0.5 and 15 % for compression and bending, and between 1 and 50 % for shearing.

The crown is subjected to just these strains when the tyre is rolling.

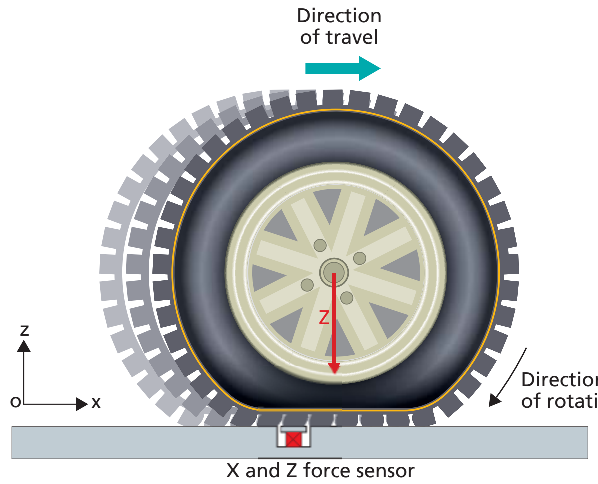
The energy thus lost makes the tyre resist the vehicle's forward movement. This is clearly perceptible when coasting very slowly (with negligible aerodynamic forces). As the driver is not providing the system with energy by pushing on the accelerator pedal, the vehicle gradually slows down, thus indicating the existence of a resistive force opposing vehicle movement. While this resistive force is particularly obvious in the situation just mentioned, it actually applies the whole time the vehicle is moving.



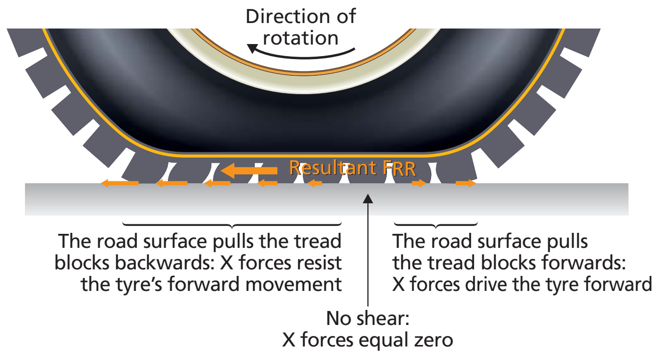
A simple experiment will help us see how forces are distributed in the contact patch when the resistive force is not balanced out by the wheel's acceleration torque (e.g. when freewheeling or, in the case of a non-driving wheel, when driving at a steady speed).

MEASUREMENT OF FORCES IN THE CONTACT PATCH

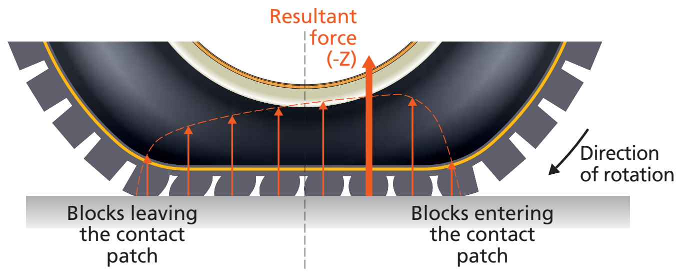
The loaded tyre (load = Z) is rolled over a surface integrating a force sensor.



The recording of **horizontal forces** shows that the ground reaction forces on the tread are greater at the back of the contact patch than at the front. This is why the tread block shear is not symmetrical but greater at the back of the contact patch. The resultant of these forces is directed backwards, thus opposing the tyre's forward movement. This horizontal resultant is the rolling resistance force, F_{RR}.

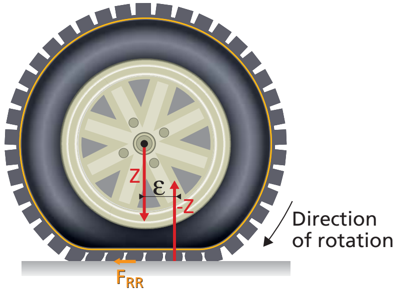


The recording of **vertical forces** shows that the ground reaction forces on the rubber compound are greater at the front of the contact patch than at the back. The resultant of these forces (–Z) is offset towards the front of the contact patch.



BALANCE OF FORCES ACTING ON THE TYRE

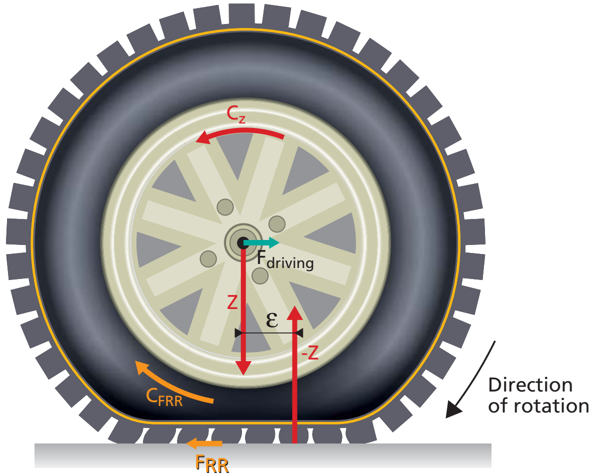
Let us consider a rolling tyre.



We have seen that a tyre is subjected to various forces:

- Z, the load, which is exerted vertically on the wheel bearings;
- -Z, the vertical ground reaction force which is equal in value and is exerted in the opposite direction to Z but further forward in the contact patch (distance ε);
- F_{RR}, the horizontal ground reaction force which corresponds to the rolling resistance force.

For this system to roll at a steady speed, the sum of the torques and the sum of the forces must both be equal to zero.



Balance of forces:

Horizontally: $F_{RR} + F_{driving} = 0$

Vertically: $Z + (-Z) = 0$

Balance of torques:

$C_Z = \varepsilon \times (-Z)$

$C_{FRR} = F_{RR} \times R$ (where R is the loaded radius)

$C_Z + C_{FRR} = 0$

The resultant of forces –Z and F_{RR} goes through the wheel centre.

We thus have: $F_{RR} = \dfrac{Z \times \varepsilon}{R}$

Reminder:

The length of the contact patch and deformation magnitude have been exaggerated in these diagrams for the sake of clarity.

This can only be true if a driving force is exerted at the wheel centre. This force ($F_{driving}$ shown in green) must be equal to F_{RR} in magnitude and be exerted in the opposite direction.

In a motor vehicle, this force is provided by the engine, which consumes energy in the form of fuel.

IV.4

Effect of external parameters on rolling resistance

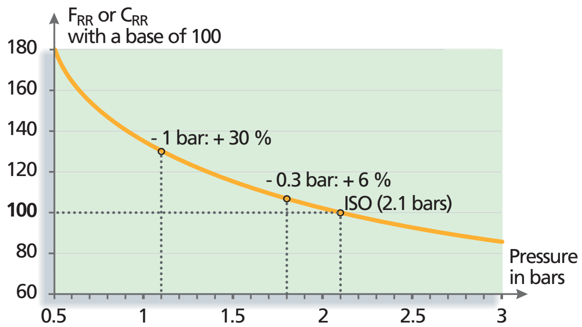
EFFECT OF TYRE INFLATION PRESSURE

Rolling resistance increases rapidly as tyre pressure decreases. While a lower tyre pressure reduces the compression of tread blocks in the contact patch, it also exacerbates tread bending and shearing. The end result is an increase in rolling resistance.

Field studies carried out on French roads [3] revealed that the tyres of more than half the cars were under-inflated by at least 0.3 bars. This results in a considerable increase in rolling resistance: +6 % when 0.3 bars below the recommended pressure and +30 % when 1.0 bar below. A 30 % increase in rolling resistance increases fuel consumption by between 3 and 5 %. Under-inflated tyres are also prone to irreversible damage.

Effect of tyre pressure on rolling resistance

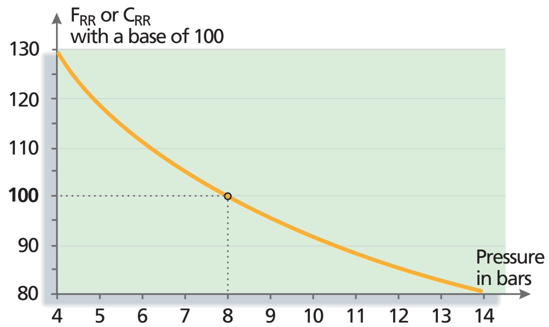
Passenger car tyres



Base 100: rolling resistance measured at 2.1 bars as per the ISO 8767 standard [1]

[1] Measurement conditions defined by the ISO 8767 standard: temperature = 25 °C, load = 80 % of the tyre's maximum capacity, speed = 80 km/h.

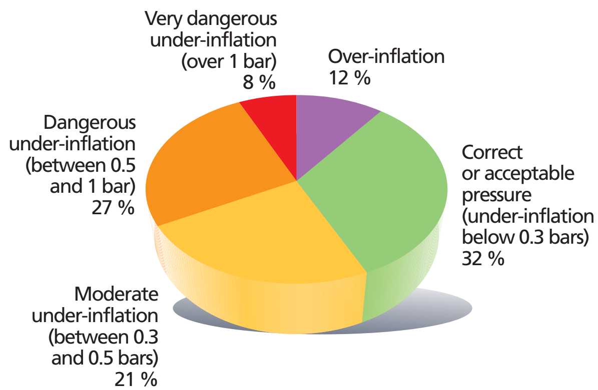
Truck tyres



Base 100: rolling resistance measured at 8 bars as per the ISO 9948 standard [2]

[2] Measurement conditions defined by the ISO 9948 standard: temperature = 25 °C, load = 85 % of the tyre's maximum capacity, speed = 80 km/h.

Distribution of passenger car tyre inflation (%)



Compared to passenger cars driven with properly inflated tyres, the tyre pressures measured on French roads indicate that an extra 2 % of fuel is consumed unnecessarily.

Note:
ISO measurement conditions are given in Chapter V.

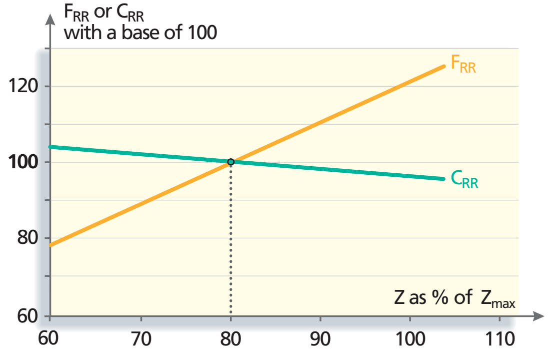
[3] Data collected on French motorways in 2000 during Michelin's "Fill up with air" campaign.

EFFECT OF LOAD

A tyre's rolling resistance coefficient decreases slightly as load increases because visco-elasticity decreases as temperature increases. However, the rolling resistance force (the result of load multiplied by the rolling resistance coefficient) increases with load. This is because a heavier load causes more bending and shearing.

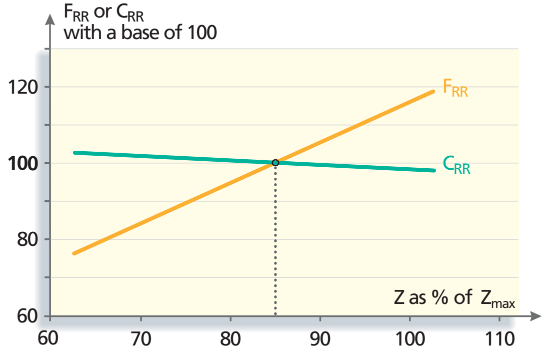
Effect of load on rolling resistance

Passenger car tyres



Base 100: rolling resistance measured at 80 % of the tyre's maximum load capacity as per the ISO 8767 standard [1]

Truck tyres



Base 100: rolling resistance measured at 85 % of the tyre's maximum load capacity as per the ISO 9948 standard [2]

Remember: $F_{RR} = C_{RR}(Z) \cdot Z$

[1] Measurement conditions defined by the ISO 8767 standard: temperature = 25 °C, tyre pressure = 2.1 bars, speed = 80 km/h.

[2] Measurement conditions defined by the ISO 9948 standard: temperature = 25 °C, tyre pressure = as specified for the tyre's maximum load, speed = 80 km/h.

A little more information on...

... the effect of tyre pressure and load on rolling resistance

A tyre's rolling resistance can be described by the following equation:

$$F_{RR} = k \cdot P^{\alpha} \cdot Z^{\beta}$$

where k = constant for a given tyre, and
for an average passenger car tyre: $\alpha \approx -0.4$
$\beta \approx 0.85$
for a truck tyre designed for motorway use:
$\alpha \approx -0.2$
$\beta \approx 0.9$

The effect of changes in tyre pressure and load on rolling resistance is such that:

$$F_{RR} = F_{RR\text{-}ISO} \cdot \left(\frac{P}{P_{ISO}}\right)^{\alpha} \cdot \left(\frac{Z}{Z_{ISO}}\right)^{\beta}$$

Example calculation

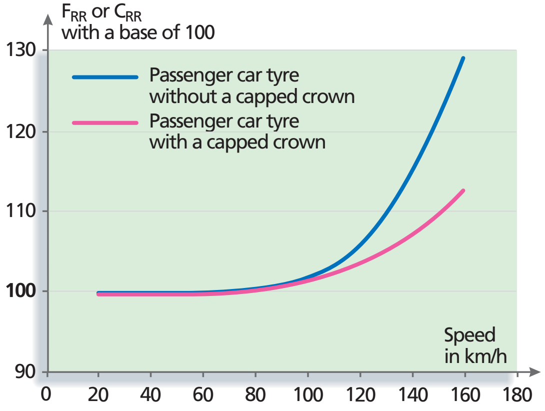
for a passenger car tyre 1 bar under the recommended tyre pressure (constant load):

$$F_{RR} = 100 \times \left(\frac{1.1}{2.1}\right)^{-0.4} = 129.5$$

i.e. an increase of 29.5% in rolling resistance.

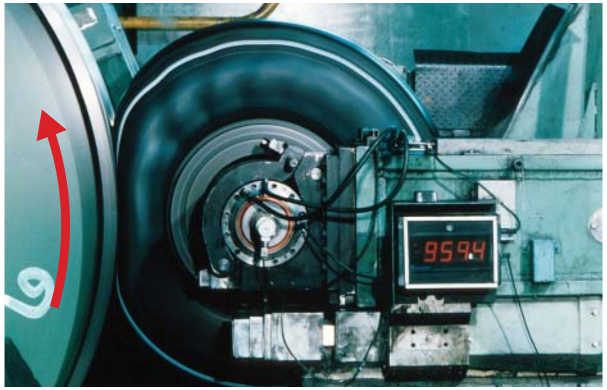
EFFECT OF HIGH SPEED

The rolling resistance of a passenger car tyre changes little with speed up to between 100 and 120 km/h, then increases significantly. This increase is due to the increase in aerodynamic drag of the rotating tyre (this force increases in proportion to the square of the speed) and the development of strong vibrations at high speeds. The tyre becomes severely deformed, leading to greater energy dissipation.



Base 100: rolling resistance measured at 80 km/h for both tyres as per the ISO 8767 standard [1]

High-speed vibrations



View of a severely deformed tyre rolling over its maximum speed on a test drum.
At high speed, the tyre's trailing edge (rear) is considerably deformed. This phenomenon is strictly limited and has no consequence on safety as long as the tyre pressure, maximum load and maximum speed prescribed for each tyre model are respected.
Such phenomena occur at even higher speeds for truck tyres.

Capped crown

In numerous tyre models, the outer layer is reinforced with cords laid parallel to the direction of travel, described as "reinforcement at 0 degree". This cap reinforces the tyre crown and increases its resistance to deformation at high speeds.

[1] Measurement conditions defined by the ISO 8767 standard: temperature = 25 °C, passenger car tyre pressure = 2.1 bars, load = 80 % of the tyre's maximum capacity.

EFFECT OF AMBIENT TEMPERATURE

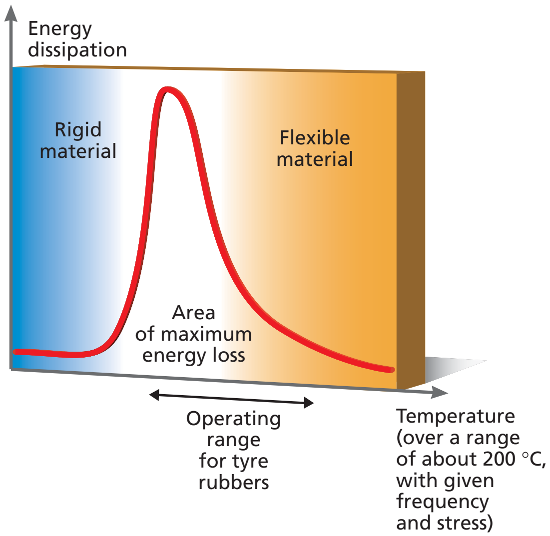
Leaving aside emergency braking, the internal temperature of a tyre fitted to a standard European passenger car in normal use usually lies between 20 and 60 °C when travelling, depending on the type of tyre, the way the car is driven and ambient temperature. Naturally, the higher the ambient temperature, the nearer to the upper limit the tyre's internal temperature is likely to be.

Within the tyre operating range, the amount of energy dissipated by elastomers when subjected to repeated deformation decreases as temperature increases. Rolling resistance is therefore lower when ambient temperature is high.

The variation in rolling resistance as a function of temperature is not linear. However, between 10 and 40 °C, a variation of 1 °C corresponds to a variation in rolling resistance of 0.6 %.

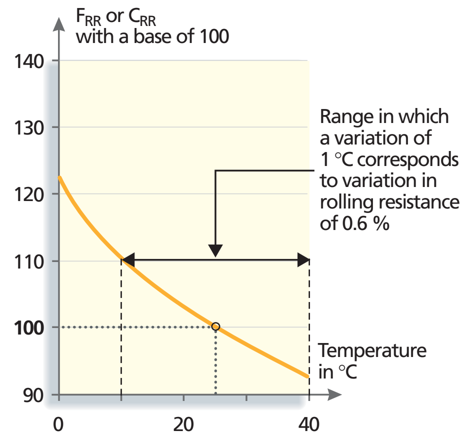
Effect of temperature on energy dissipation by elastomers

subjected to alternating deformation



Effect of ambient temperature on rolling resistance

(passenger car tyres)



Base 100: rolling resistance measured at 25 °C as per the ISO 8767 standard [1]

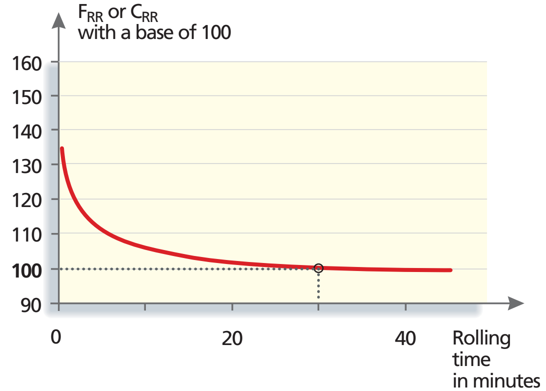
[1] Measurement conditions defined by the ISO 8767 standard: tyre pressure = 2.1 bars, load = 80 % of the tyre's maximum capacity, speed = 80 km/h.

EFFECT OF ROLLING TIME

Once a passenger car has started moving, its tyres take about 30 minutes to reach a steady operating temperature, between 20 and 60 °C. It actually takes much longer than that for a tyre to reach a completely stable temperature. However, the change in rolling resistance after the first 30 minutes is negligible.

Effect of rolling time on rolling resistance

(passenger car tyres)



Base 100: rolling resistance measured after 30 minutes of rolling as per the ISO 8767 standard [1]

[1] Measurement conditions defined by the ISO 8767 standard: temperature = 25 °C, tyre pressure = 2.1 bars, load = 80 % of tyre's maximum capacity, speed = 80 km/h.

This is why the ISO 8767 standard recommends a tyre rolling time of at least 30 minutes before taking the first measurement. If measurements are to be taken at different speeds, then the tyre should be run for at least 20 minutes at the new speed before any further measurements are taken.

It takes much longer for truck tyres to reach a steady operating temperature (about 3 hours for a completely stable temperature). The ISO 9948 standard recommends a warm-up period of at least 90 minutes before the first measurement, and thereafter at least 30 minutes between successive measurements.

EFFECT OF ROAD SURFACE ROUGHNESS

Measurements show that rolling resistance increases in proportion to the macroroughness of the road surface. This is because the macrorough asperities deform the tread block surface (indentation), causing local energy dissipation.

The macroroughness of a road surface plays a role in the tyre's grip by helping water to drain off during rainfall. However, the tyre's grip on wet roads is more dependent on the microroughness of the road surface. Certain surfaces are now capable of draining water directly through their internal structure.

Effect of road surface roughness on rolling resistance

Base 100: smooth road surface

Smooth steel	Smooth road surface	Macrorough road surface	Very macrorough road surface

Smooth steel	Smooth road surface	Macrorough road surface	Very macrorough road surface
97	**100**	120	140
	SH = 0.17 mm	SH = 0.98 mm	SH = 3.12 mm

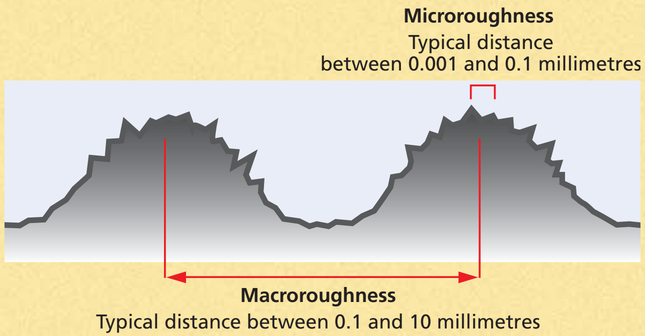
SH: average height of surface irregularity voids determined by the sand height method

Road surface roughness

Road surfaces are primarily formed by **aggregates** (crushed hard rocks) mixed with a binder (usually bitumen). The aggregates are of different sizes (6 to 14 mm) and are more or less smooth.

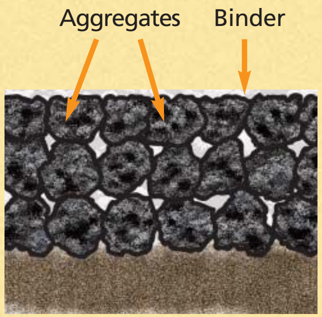
The larger the aggregates at the top of the road surface, the more **macrorough** it is considered to be (macrorough refers to roughness on the scale of millimetres). The smaller the aggregates, or the more worn the surface due to the repeated passage of vehicles, the less rough the surface. In this case it is considered to be **macrosmooth**.

The surface of the aggregates themselves may include micro-asperities between 1 and 100 microns in size. The road surface is in this case considered to be **microrough** (referring to roughness on the scale of microns or hundredths of a millimetre).
Microroughness plays a major role in grip.



Macroroughness can be measured using the **sand height** method. This consists of levelling out a given volume of normalised sand in a circular patch on the road surface. The circular surface area of the spread sand is measured and the mean depth of the voids can then be calculated.

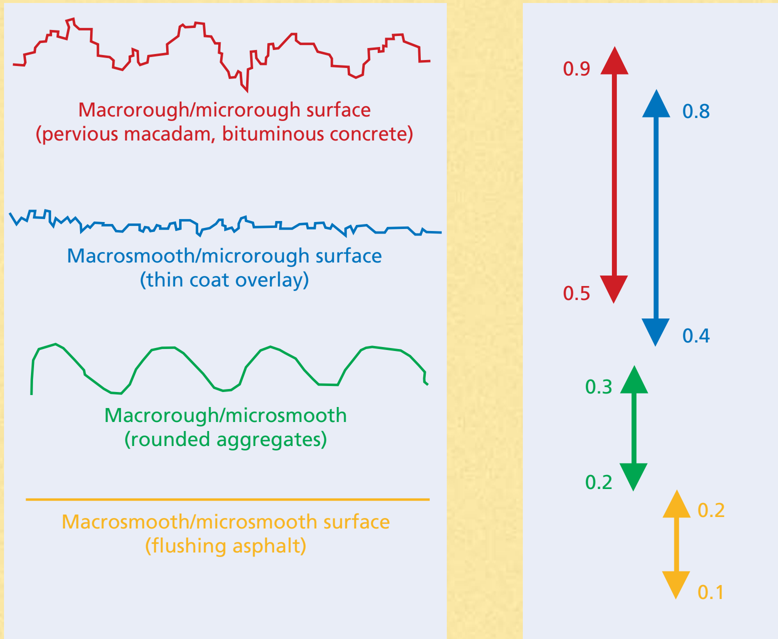
The internal structure of a **pervious macadam** allows rainwater to drain through it.



Pervious macadam: rainwater can run through the gaps between the aggregates.

Role of macro- and microroughness in grip

Type of road surface | **Grip coefficient in damp/wet conditions**



Note:
The grip coefficient of all dry road surfaces lies between 1 and 1.3.

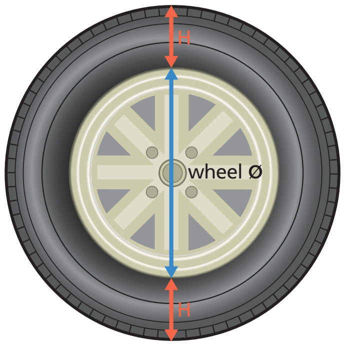
EFFECT OF TYRE DIMENSIONS

The rolling resistance coefficient of a tyre decreases as its outer diameter increases. This is because the bending of the tyre on entering and leaving the contact patch is less severe with a bigger diameter. Increasing the tyre diameter by 1 cm reduces rolling resistance by about 1 %.

For a given vehicle, tyre size can obviously only be increased within certain limits, including the space available (chassis and bodywork) for turning the wheels. Furthermore, for a given tyre pressure, the tyre's load capacity is dictated by its inner volume. To increase a tyre's outer diameter without increasing load capacity [(1)], the tendency is to increase the size of the wheel and decrease the width of the tyre and/or sidewall height. Modifying tyre size in this way has both positive and negative repercussions. Reducing tyre width decreases the vehicle's aerodynamic drag and thus lowers fuel consumption. However, it also shortens tyre life and makes fine-tuning vehicle handling performance more difficult. Reducing the sidewall height can improve road holding, but may also reduce comfort and resistance to shocks (against kerbs or when driving over potholes).

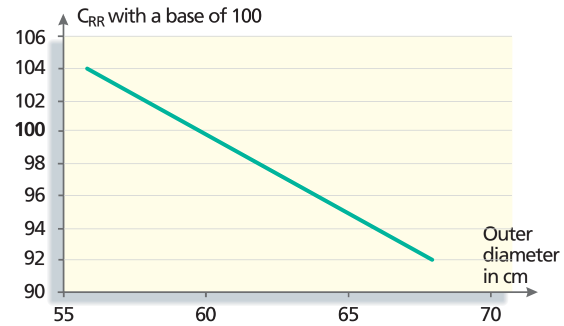
Tyre sizing is therefore a critical operation involving not only rolling resistance but vehicle performance as a whole. It is therefore necessary for tyre and car manufacturers to work closely together throughout the vehicle design phase to choose the best possible options.

Effect of the tyre's outer diameter on rolling resistance



A tyre's outer diameter depends on the:
- diameter of the wheel rim,
- height (H) of its sidewalls.

In both cases, an increase of one centimetre reduces rolling resistance by 1 %.

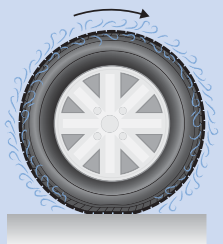
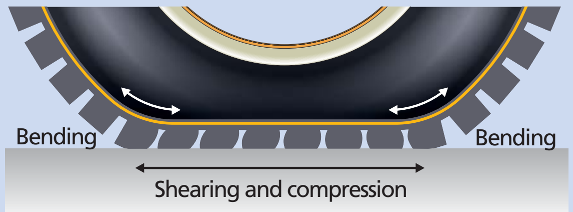
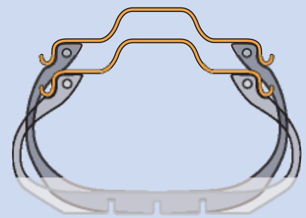


Base 100: rolling resistance of a 175/70 R14 tyre measured as per the ISO 8767 standard

(1) Unnecessary extra load capacity (tyre oversizing) would be disadvantageous since it would mean not only heavier tyres and higher production costs but also greater rolling resistance because of the tendency to prescribe a lower tyre pressure to make up for the consequent reduction in comfort.

(2) Reducing tyre width by 1 cm reduces $A.C_D$ by around 1.5 % (this figure varies according to the vehicle considered).

IV The mechanics of rolling resistance

What	Tyre surface and air	Tread				Sidewall and bead area	
How	Aerodynamic drag of the rotating tyre	Slippage on road surface	Repeated deformation leading to energy dissipation				
			Bending	Compression	Shearing	Bending	Shearing
							
Contribution to rolling resistance	< 15 %		60 - 70 %			20 - 30 %	

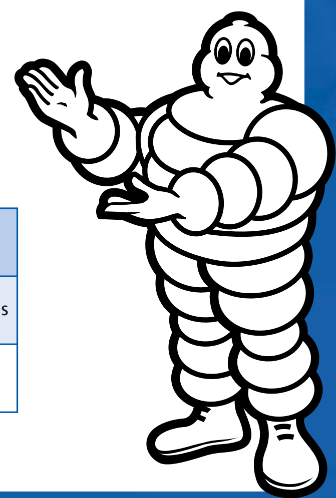
The elastomers used in tyres are visco-elastic materials. Therefore they dissipate energy in the form of heat whenever they are **being deformed**. Deformation-induced **energy dissipation** accounts for about 90 % of rolling resistance.

When rolling, the tyre is deformed in order to hug the road in the contact patch.
It is subjected to three major types of deformation: bending, compression and shearing.

The magnitude of deformation caused and hence the rolling resistance force depend on tyre pressure, load, rolling speed and road surface roughness.

Parameters affecting rolling resistance

Parameter	Tyre pressure ↘	Load ↗	Speed ↗↗	Road surface roughness ↗	Temperature ↘
Consequence	Magnitude of deformation ↗				Energy dissipation of tyre rubber compounds ↗
Effect on rolling resistance	↗	↗	↗	↗	↗



V Measurement and simulation

Regulatory measurements of fuel consumption and pollution are made on passenger cars and light-duty trucks in many countries. However, these tests do not determine rolling resistance even though the tyre's contribution to fuel consumption is included in the measurement results simply because the vehicle under test is fitted with tyres.
To determine rolling resistance, tyre manufacturers first subject the tyre to a series of laboratory measurements and computer simulations. They also measure heavy-duty truck fuel consumption on test circuits.

V.1

Measurement of tyre rolling resistance

V.1.1

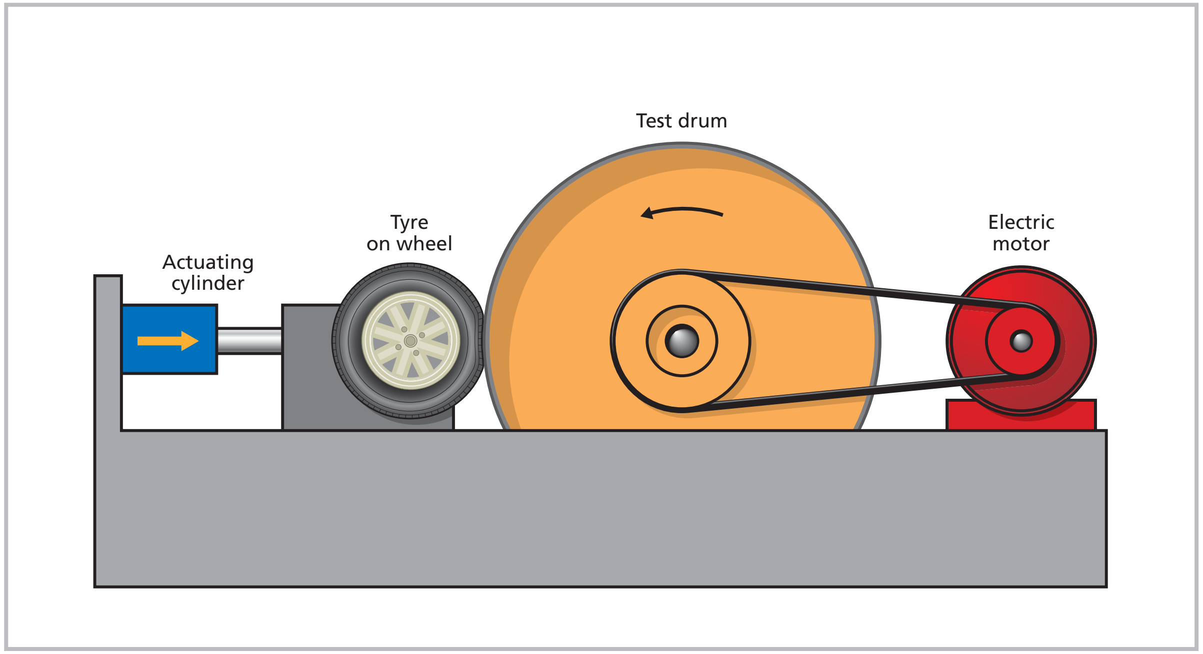
Measurements prescribed by the ISO 8767 and 9948 standards

Rolling resistance measurement methods and conditions are defined in several ISO [1] standards and in particular ISO 8767 for passenger car tyres and ISO 9948 for truck tyres. The prescribed measurement methods are identical in both standards - only the measurement conditions change (see page 97).

MEASUREMENT PRINCIPLES

The tyre is held against a large test drum by an actuating cylinder aligned with the centre of the drum. A motor coupled to the drum makes it rotate, thus making the tyre rotate. The tyre's rolling resistance has a braking effect on the drum's rotation which is then measured.

The standards prescribe four measurement options:
- measurement of deceleration
- three types of measurement at a constant speed:
  - measurement of the resistive force at the tyre spindle
  - measurement of the resistive torque on the drum hub
  - measurement of the electrical power absorbed by the motor to keep the drum rotating at a constant speed.



Note:
The methods presented here are a simplified overview of the ISO 8767 and 9948 standards (please see them for greater details and note that they are currently being updated – ISO working draft 18164).

MEASURING DECELERATION

The tyre and test drum system is accelerated to a speed slightly above 80 km/h. The motor is then uncoupled and the system allowed to slow down by itself. The method involves measuring the system's deceleration around 80 km/h in order to determine the tyre's rolling resistance.

Rolling resistance is just one of several factors that causes the system to slow down. Another is **friction** at the tyre spindle and test drum hub. Yet another is the **aerodynamic drag** of both the rotating tyre and test drum. It is therefore necessary to differentiate between rolling resistance, aerodynamic drag and friction.
The measurement therefore consists of three steps:

[1] International Organization for Standardization.

1 Determining the overall resistive force

The first task is to measure the deceleration of the test drum against which the tyre is being held ($\dot{\omega}_{drum}$). The tyre's deceleration can then be calculated ($\dot{\omega}_{tyre}$). The overall resistive force ($F_{overall}$) can be calculated from the radius (R) and inertia (I) of the tyre-wheel assembly (R_{tyre} and I_{tyre}) and of the test drum (R_{drum} and I_{drum}).

2 Determining frictional and aerodynamic drag forces

The tyre is then moved away from the test drum. The deceleration of the unloaded tyre ($\dot{\omega}_{unloaded\ tyre}$) due to tyre spindle friction and rotational aerodynamic drag is measured, as well as the deceleration of the unloaded test drum alone ($\dot{\omega}_{unloaded\ drum}$) due to its hub friction forces and aerodynamic drag forces.

It is thus possible to deduce the force resisting the unloaded tyre's rotation ($F_{unloaded\ tyre}$) and that resisting the unloaded test drum's rotation ($F_{unloaded\ drum}$).

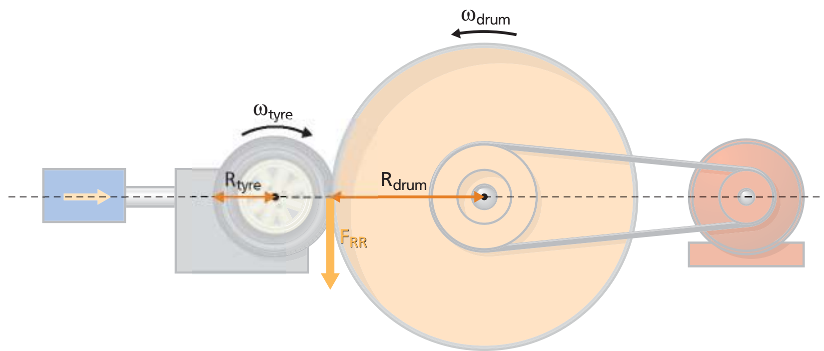
3 Determining the rolling resistance force

Force F_{RR} can be calculated thus:

$F_{RR} = F_{overall} - F_{unloaded\ tyre} - F_{unloaded\ drum}$

A little more information on...

... the deceleration measurements prescribed by ISO standards



Note:
ω is used for angular speed and $\dot{\omega}$ for angular acceleration or deceleration.

1 Calculation of the overall force

Known parameters: R and I

Measured parameters: $\dot{\omega}_{drum}$

$$\dot{\omega}_{tyre} = \dot{\omega}_{drum} \cdot \frac{R_{drum}}{R_{tyre}}$$

$$F_{overall} = \dot{\omega}_{drum} \cdot \frac{I_{drum}}{R_{drum}} + \dot{\omega}_{tyre} \cdot \frac{I_{tyre}}{R_{tyre}}$$

Therefore

$$F_{overall} = \dot{\omega}_{drum} \cdot \frac{I_{drum}}{R_{drum}} + \left(\dot{\omega}_{drum} \cdot \frac{R_{drum}}{R_{tyre}}\right) \cdot \frac{I_{tyre}}{R_{tyre}}$$

2 A. Calculation of the tyre spindle frictional force and the rotating tyre's aerodynamic drag force

$$F_{unloaded\ tyre} = \dot{\omega}_{unloaded\ tyre} \cdot \frac{I_{tyre}}{R_{tyre}}$$

B. Calculation of the test drum hub frictional force and the rotating drum's aerodynamic drag force

$$F_{unloaded\ drum} = \dot{\omega}_{unloaded\ drum} \cdot \frac{I_{drum}}{R_{drum}}$$

3 Calculation of rolling resistance force F_{RR}

$$F_{RR} = F_{overall} - F_{unloaded\ tyre} - F_{unloaded\ drum}$$

$$= \dot{\omega}_{drum} \cdot \frac{I_{drum}}{R_{drum}} + \dot{\omega}_{drum} \cdot \frac{I_{tyre} \cdot R_{drum}}{R^2_{tyre}} - \dot{\omega}_{unloaded\ tyre} \cdot \frac{I_{tyre}}{R_{tyre}} - \dot{\omega}_{unloaded\ drum} \cdot \frac{I_{drum}}{R_{drum}}$$

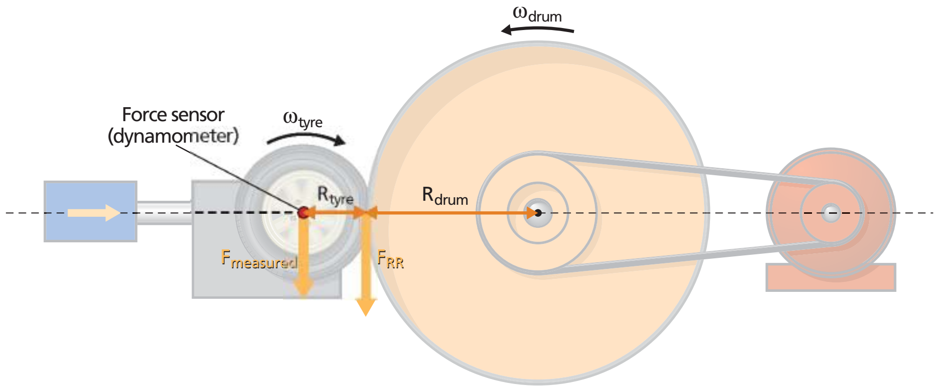
MEASURING THE RESISTIVE FORCE AT THE TYRE SPINDLE

The centre of the wheel is fitted with a vertical force sensor (dynamometer). Since the tyre tends to roll more slowly than the test drum, the drum tends to pull the tyre downwards (this concept becomes clearer if you consider the extreme case of the wheel being locked with no possibility of rotating. The drum drags the tyre abruptly downwards). This vertical traction force is measured at the wheel centre ($F_{measured}$). As the radius of both the tyre and the test drum are known, the rolling resistance force (F_{RR}) can then be calculated.

MEASURING THE TORQUE AT THE DRUM HUB

The centre of the test drum is fitted with a torque sensor (torquemeter).
The torque generated by the rolling resistance force (F_{RR}) is measured at the drum centre (O). As the radius of the test drum is known, F_{RR} can then be calculated.

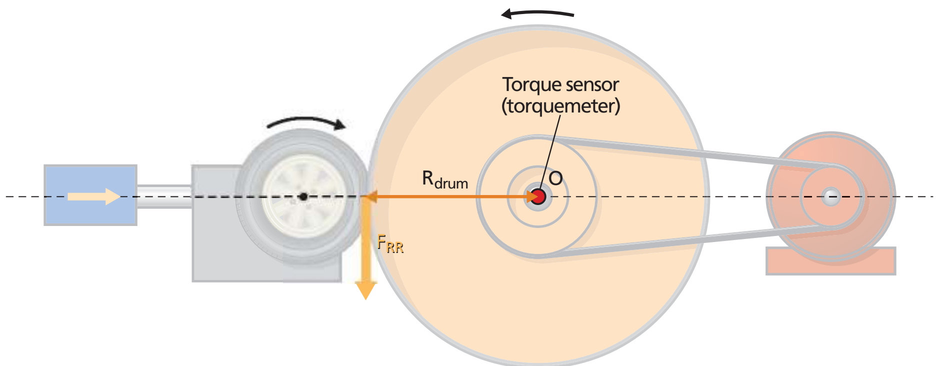
Measuring the resistive force as per ISO standards



$$F_{RR} = F_{measured} \cdot \left(\frac{R_{drum} + R_{tyre}}{R_{drum}} \right)$$

Note:
The tyre radius used is the loaded radius, i.e. the distance between the wheel centre and the surface of the drum.

Measuring the torque as per ISO standards

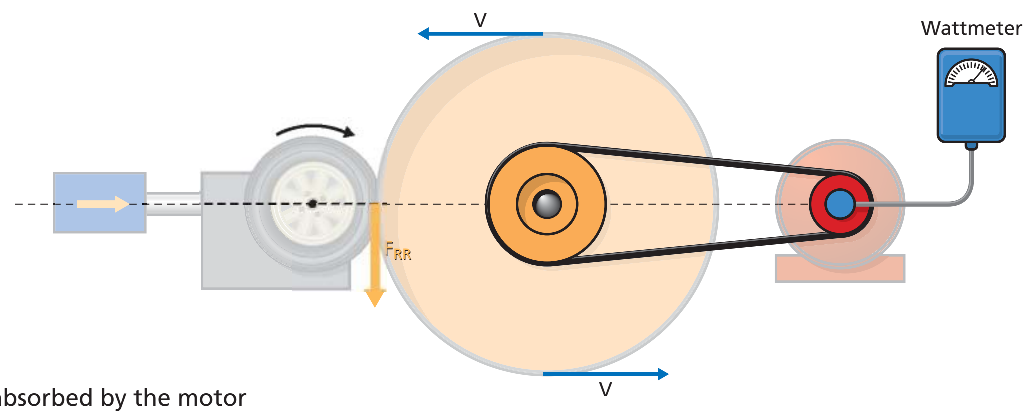


$$F_{RR} = \frac{Torque}{R_{drum}}$$

MEASURING THE ELECTRICAL POWER ABSORBED BY THE MOTOR

To keep the test drum running at a constant speed, the electric motor must provide as much power (P) as necessary to compensate for the power absorbed by the rolling resistance: F_{RR} x V. This power is measured with a wattmeter. Knowing the speed (V) at which the surface of the test drum is travelling, F_{RR} can be calculated.

Measuring electrical power as per ISO standards



P: power absorbed by the motor
V: travelling speed on the surface of the drum

$$F_{RR} = \frac{P}{V}$$

CORRECTING TEST DRUM CURVATURE

As we have seen, rolling resistance is caused by repeated tyre deformation when rolling, which leads to energy dissipation. A tyre is subjected to greater deformation by a test drum than if it were placed against a flat surface, because the curved surface "penetrates" the tyre to a greater extent. Consequently, the test drum's curvature has a significant effect on rolling resistance. The correction rule below makes it possible to calculate the approximate value of rolling resistance were the measurements taken on a flat surface.

$$F_{RR\ flat\ surface} = F_{RR\ measured} \cdot \sqrt{\frac{R_{drum}}{R_{drum} + R_{tyre}}}$$

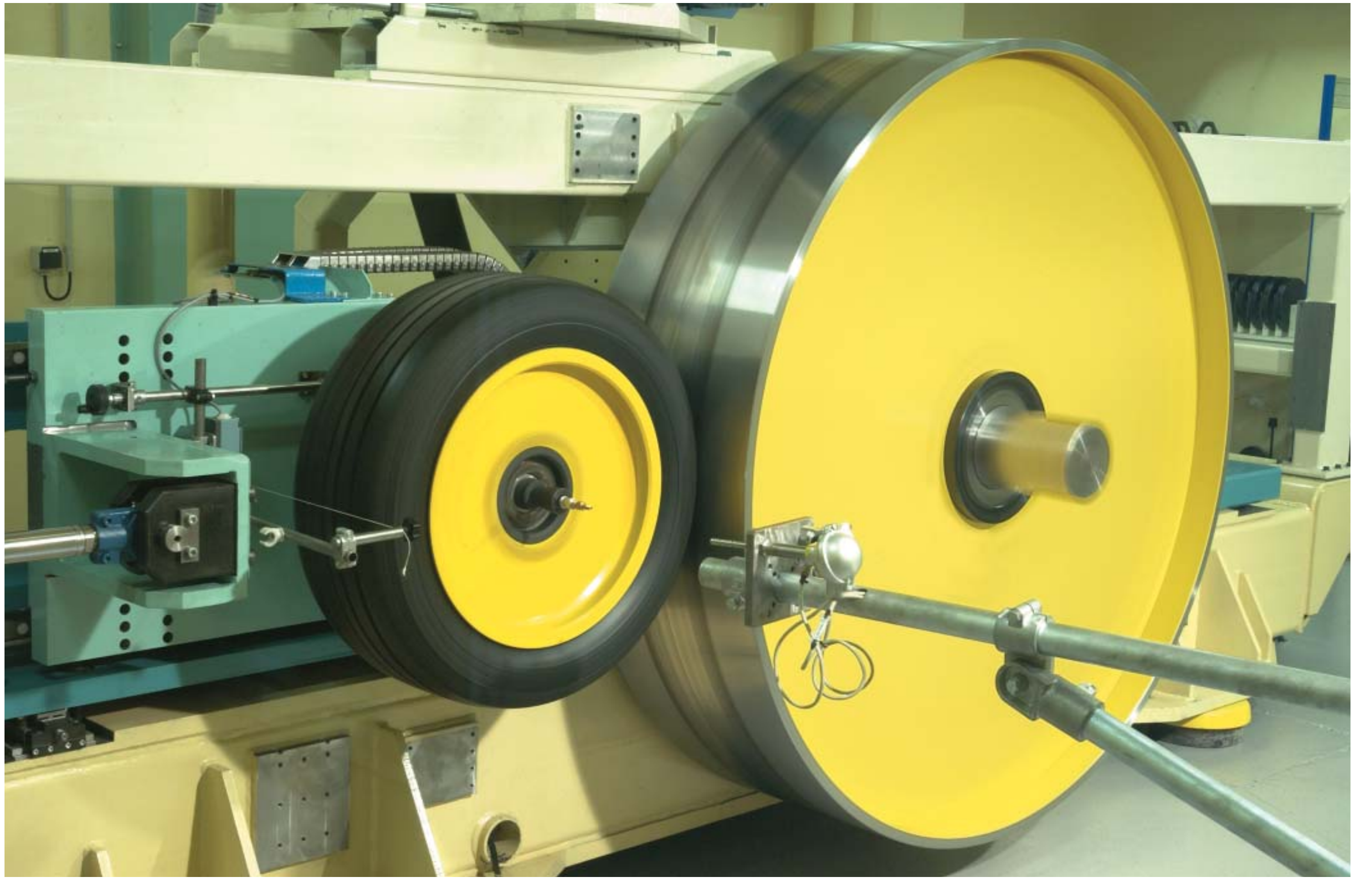
As an example, a 195/65 R15 passenger car tyre giving an ISO measurement of 10 kg/t against a drum 1.7 metres across actually has a rolling resistance coefficient of 8.5 kg/t on a flat surface.

Similarly, a 385/70 R22.5 truck tyre giving an ISO measurement of 5 kg/t against a drum 2.7 metres across actually has a rolling resistance coefficient of 4.2 kg/t on a flat surface.

CALCULATING THE ROLLING RESISTANCE COEFFICIENT

Knowing the load (Z) applied to the tyre and the rolling resistance force (F_{RR}), the following equation gives the rolling resistance coefficient against a test drum or a flat surface:

$$C_{RR\ drum} = \frac{F_{RR\ measured}}{Z} \qquad C_{RR\ flat\ surface} = \frac{F_{RR\ flat\ surface}}{Z}$$



Test stand used to measure rolling resistance

Thermal stabilization before measurements

Rolling resistance depends on tyre temperature. As tyres roll, they warm up and reach a stable temperature only after a certain while.
A passenger car tyre takes about 30 minutes to reach this temperature, which lies between 20 °C and 60 °C.

The ISO 8767 standard therefore recommends a warm-up time of at least 30 minutes to allow the tyre to reach a stable temperature before the first measurement is taken. If further measurements are to be taken at different speeds, the tyre must be rolled for at least 20 minutes at the new speed before the next measurement is taken.

Truck tyres take much longer to reach a stable temperature - around 3 hours for complete thermal stability. The ISO 9948 standard recommends a warm-up period of 90 minutes before the first measurement and at least 30 minutes before each successive measurement.

ISO 8767 method for passenger car tyres

Measurement conditions:

- **Tyre:**
  - broken in for 1 hour at at least 80 km/h then kept in the test location for 3 hours at 25 °C
  - warmed up to achieve thermal stability: 30 minutes at the test speed before the first measurement, then 20 minutes at each new speed for successive measurements
- **Test drum:**
  - diameter between 1.5 and 3 metres
  - smooth surface or textured to a roughness of 180 µm (80 grit).

Test parameters:

- **Temperature:** 25°C
- **Load:** 80 % of the tyre's maximum capacity
- **Tyre pressure:** capped. At the start it is 2.1 bars, which is 0.3 bars below the ISO-prescribed pressure
- **Speed:** 80 km/h only or, optionally 50, 90 and 120 km/h

Measured parameters:

- Test speed
- Load
- Initial and final tyre pressure
- Test rim (designation and material)

ISO 9948 method for trucks and buses

Measurement conditions:

- **Tyre:**
  - broken in then kept for 6 hours in the test location at 25 °C
  - warmed up to achieve thermal stability: 90 minutes at the test speed
- **Test drum:**
  - diameter between 1.7 and 3 metres
  - smooth surface or textured to a roughness of 180 µm (80 grit)

Test parameters:

- **Temperature :** 25 °C
- **Load:** 85 % of the tyre's maximum single load capacity
- **Tyre pressure:** capped. At the start it is the prescribed pressure for the tyre's maximum load capacity
- **Speed:**
  - for load indices of 122 and above and speed symbols K, L and M: 80 km/h
  - for load indices of 122 and above and speed symbols F, G, H, I and J: 60 km/h
  - for load indices below 122: 80 km/h and, if required, 120 km/h

Measured parameters:

- Test speed
- Load
- Initial and final tyre pressure
- Test rim (designation and material)

V.1.2

Measurements prescribed by SAE standards

European tyre manufactures today mainly apply ISO measurement methods, whereas US manufacturers comply with the two standards recommended by the Society of Automotive Engineers, Inc. (SAE):
- SAE J1269
- SAE J2452.

SAE STANDARD J1269

This standard applies to tyres for passenger cars, light trucks, highway trucks and buses. There is a choice of three recommended types of measurement, all taken at a constant speed:
- measurement of the resistive force at the tyre spindle,
- measurement of the resistive torque,
- measurement of the electrical power absorbed by the motor.

The measurement method is very similar to the constant speed measurements prescribed by the ISO standards and described in the previous section. However, the measurement conditions are different, particularly the:
- test drum diameter and surface texture,
- temperature,
- load conditions and tyre pressure.

SAE J1269 and J2452 methods

- **Temperature:** 24 ± 4°C
- **Test drum:**
  - diameter: at least 1.22 m, typically 1.7 m
  - surface texture: 80 grit

SAE J1269 method

- **Load:** different loads during the test, between 50 and 90 % of the maximum capacity for passenger car tyres, between 40 and 100 % for light trucks and between 25 and 100 % for highway trucks
- **Tyre pressure:** regulated at values prescribed in the standard according to load
- **Speed:** 80 km/h

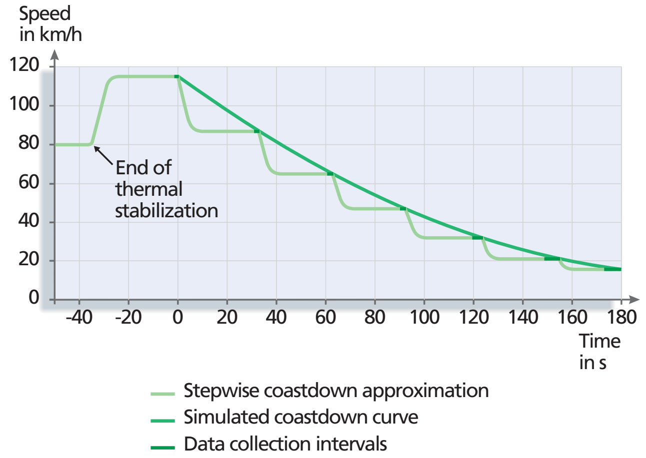
SAE J2452 method

- **Load:** different loads during the test, between 30 and 90 % of the maximum capacity for passenger car tyres, and between 20 and 100 % for light trucks
- **Tyre pressure:** regulated at values prescribed in the standard according to load
- **Speed:** 6 or 7 steps between 115 and 15 km/h

SAE STANDARD J2452

This standard applies to passenger car and light truck tyres. Rolling resistance is measured at different speeds between 115 and 15 km/h using a defined stepwise coastdown methodology over a 3-minute period. Rolling resistance may be determined by measuring either the resistive force at the tyre spindle or the resistive torque at the drum hub.

Stepwise coastdown



V.2 Laboratory measurements of light-duty vehicle pollution and fuel consumption

Many countries have regulations on the measurement of exhaust gas emissions of **passenger cars** and **light trucks**.

"Pollution" regulations define **measurement conditions** and the **limit values** for emissions of the following pollutants: carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NO_X), and particulate matter for diesel engines (compression-ignition engines).

"Fuel consumption" regulations define the **measurement conditions** for both consumption and carbon dioxide (CO_2) emissions for **passenger cars**.

These measurements are taken on chassis dynamometers that can simulate different **regulatory driving cycles**: urban and extra-urban cycles in most countries and also motorway cycles, especially in the United States (see pages 104 to 107).

Trucks, earth-moving vehicles and **farm vehicles** do not have to comply with any regulations on pollution or fuel consumption once fully assembled. Only their engines are subjected to laboratory pollution measurements with upper limits on the following emissions: CO, HC, NO_X, particulate matter and exhaust fumes.

As these engine measurements do not include tyre rolling resistance, we will not investigate them any further in this document. However, just as for passenger cars, progress in truck engine, vehicle and tyre design is helping lower pollution levels.

UTAC (Union Technique de l'Automobile, du motocycle et du Cycle) pollution and fuel consumption chassis dynamometer in Montlhéry, France

TEST PRINCIPLES [1]

The vehicle is set up on a chassis dynamometer which simulates the resistance to forward movement experienced when driving on roads.

During the test, the exhaust gases are collected then analysed to determine:

• for pollution measurements: the mass of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_X) and, for diesel engines, particulate matter. The results are given in g/km.

• for fuel consumption measurements: the mass of carbon monoxide (CO), total hydrocarbons (THC) and carbon dioxide (CO_2) in g/km. Fuel consumption is then calculated using the **"carbon balance method"**.

[1] As defined by "pollution" Directive 98/69/EC, modifying Directive 80/220/EEC and included in "fuel consumption" Directives.

Pollution and fuel consumption measurements

Measurement parameters:

- Speed (tolerance of ± 2 km/h with respect to the theoretical speed)
- Time (tolerance of ± 1s)
- Braking effort
- Temperature in the test chamber (between 20 and 30 °C)
- Air humidity
- Engine tuning: as per manufacturer’s specifications
- No heating, lighting or air-conditioning
- Fuel: reference fuel as defined by the Directive
- Vehicle: run in for at least 3,000 km and kept at between 20 and 30 °C for at least 6 hours before the test.

Note:
Only a simplified overview of what the Directives require is given here. For more details, please refer to the Directives themselves.

Pollution measurements

Tyres:

- Size: the widest size specified as original equipment by the automobile manufacturer. If more than 3 sizes are certified, choose the second widest. The model is not indicated in the test report.
- Run in at the same time as the vehicle or with between 50 and 90 % of original tread depth.
- Tyre pressure specified by the manufacturer, as used for the preliminary road test to adjust the dynamometer. May be raised by up to 50 % if the measurements are recorded on a twin-roll dynamometer.

Measured parameters:

- Mass of CO, HC, NO_X, and, for diesel engines, particulate matter.

Fuel consumption measurements

Tyres:

- One of the tyres specified as original equipment by the automobile manufacturer. Tyre pressure as recommended for the load and speed, adjusted if necessary to test bed operation.

Measured parameters:

- Mass of CO, THC, CO_2.

Calculated parameters:

- Fuel consumption in l/100 km.

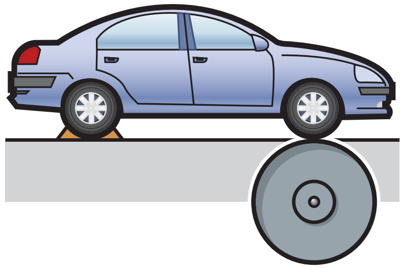
DYNAMOMETER ADJUSTMENT

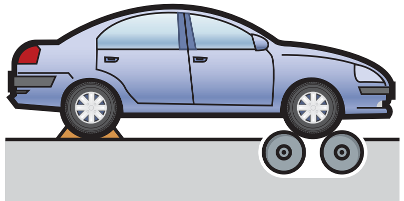
The dynamometer must be able to reproduce all the forces to which a running vehicle is subjected:
- rolling resistance forces,
- inertial forces,
- internal frictional forces,
- aerodynamic forces.

The dynamometer is calibrated either using data obtained from a road coastdown test or from calibration tables stipulated in the Directive.

Dynamometers

There are two types of dynamometer: single-roll and twin-roll.





Note:
Tyre deformation is greater on a single-roll dynamometer than on a road, and still greater on a twin-roll dynamometer. Dynamometer-generated rolling resistance is greater than road-generated rolling resistance. At a normal tyre pressure, the deformation inflicted by a twin-roll dynamometer could even damage the tyre. European Directives therefore allow the tyre to be inflated up to an extra 50 % for twin-roll dynamometer tests.

DETERMINING FUEL CONSUMPTION BY THE CARBON BALANCE METHOD

The **carbon balance method** may be used to calculate fuel consumption from the quantity of carbon found in the exhaust gases collected.
Even with the complex chemical transformations taking place in an internal combustion engine, the relationship between fuel consumption and carbon emissions can be stated relatively simply:

- The main four fuels currently used are made almost exclusively of saturated hydrocarbons (alkanes). Saturated hydrocarbons are composed of **carbon** (C) and hydrogen (H) only, in known proportions.
- When combustion takes place, all the carbon from the fuel is emitted in the exhaust gases, combined with oxygen from the air in the form of carbon dioxide (CO_2), carbon monoxide (CO) or as unburnt hydrocarbons (HC, also referred to as VOC – Volatile Organic Compounds).

We may consider that an engine produces as much carbon as it consumes in the form of fuel. The quantity of fuel used can therefore be determined by the amount of carbon collected in the exhaust gases.

The calculation formulae are given in the box below.

Fuel consumption calculation (1)

Petrol vehicles

$$C = \frac{0.1154}{\rho} \times \left[(0.866 \times THC) + (0.429 \times CO) + (0.273 \times CO_2) \right]$$

Diesel vehicles

$$C = \frac{0.1155}{\rho} \times \left[(0.866 \times THC) + (0.429 \times CO) + (0.273 \times CO_2) \right]$$

Liquefied petroleum gas (LPG) vehicles

$$C_{norm} = \frac{0.1212}{0.538} \times \left[(0.825 \times THC) + (0.429 \times CO) + (0.273 \times CO_2) \right]$$

Natural gas vehicles (NGV)

$$C_{norm} = \frac{0.1136}{0.654} \times \left[(0.749 \times THC) + (0.429 \times CO) + (0.273 \times CO_2) \right]$$

where :
C: fuel consumption in litres per 100 km (for petrol, LPG or diesel) or in cubic metres per 100 km for NGV
THC: total hydrocarbon emissions measured, in g/km
CO: carbon monoxide emissions measured, in g/km
CO_2: carbon dioxide emissions measured, in g/km
ρ: test fuel density measured at 15 °C. A reference fuel density is used for LPG and natural gas.

(1) As per Directive 1999/100/EC.

CARBON AND CO_2 EMISSIONS PER LITRE OF FUEL CONSUMED

Even if the exact amount of CO_2 produced by one litre of fuel depends on various factors such as temperature, ambient pressure and fuel quality, the following may be considered typical values:

- 1 litre of petrol used produces 2.35 kg of CO_2, i.e. 0.64 kg of carbon;
- 1 litre of diesel used produces 2.66 kg of CO_2, i.e. 0.72 kg of carbon.

Note:
The CO_2/C ratio equals 3.67. This is the ratio between the molecular mass of CO_2 (12 + (2 x 16) = 44) and the atomic mass of carbon (which is 12).

A little more information on...

... the carbon balance method

Let us break down the carbon balance equation used to calculate fuel consumption for petrol vehicles:

$$C = \underbrace{\frac{0.1154}{\rho}}_{\text{Term A}} \times \underbrace{\left[(0.866 \times THC) + (0.429 \times CO) + (0.273 \times CO_2)\right]}_{\text{Term B}}$$

1 Term B is used to calculate the **mass of carbon** emissions in g/km, knowing how much carbon there is in CO_2, CO and in the hydrocarbon (HC) used – petrol in this case:

Mass of HC, CO and CO_2 emissions in g/km

$$\text{Mass of carbon} = \left[(0.866 \times THC) + (0.429 \times CO) + (0.273 \times CO_2)\right]$$

Percentage of carbon in petrol: 86.6 %

Percentage of carbon in CO: 42.9 %

Percentage of carbon in CO_2: 27.3 %

2 Term A: petrol contains 86.6% of carbon. Therefore the **mass of petrol consumed** is given by: $\frac{\text{mass of carbon}}{0.866}$ i.e. 1.154 x mass of carbon.

Equation $C = 1.154 \times \left[(0.866 \times THC) + (0.429 \times CO) + (0.273 \times CO_2)\right]$ gives us the mass of fuel consumed in g/km. However, we want to express this in l/100 km.

To **convert grams to litres**, we must first divide by 1,000 to obtain a value in kilograms, and then divide by the fuel density, ρ, given in kg/l.
Thus:

$$C = \frac{1.154}{\rho \times 1000} \times \left[(0.866 \times THC) + (0.429 \times CO) + (0.273 \times CO_2)\right]$$

We must then multiply the result by 100 to get a **result in litres/100 km**.
Term A is therefore:

$$\frac{1.154 \times 100}{\rho \times 1000} = \frac{0.1154}{\rho}$$

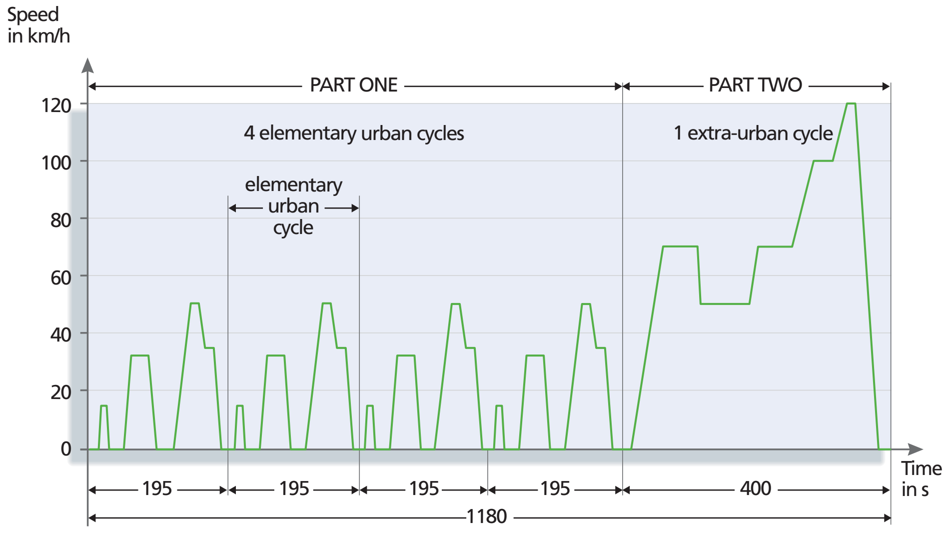
E.U. DRIVING CYCLE

The European regulatory driving cycle is the same for both fuel consumption and pollution measurements. Automobile manufacturers thus take both sets of measurements during a single test.

The cycle simulates 4.052 km of urban driving (part ONE) and 6.955 km of extra-urban driving (part TWO – driving on expressways and bypasses).

Regulatory driving cycle as defined by European Directive 98/69/EC

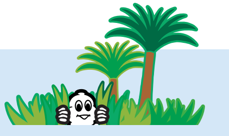
applicable to passenger cars and light-duty trucks (weighing ≤ 3.5 t)



Maximum speed: 120 km/h
Average speed for part one: 18.7 km/h
Average speed for part two: 62.6 km/h
Total simulated distance: 11.007 km
Total duration: 19 min 40 s

- Part ONE comprises four "elementary urban cycles", each made up of 15 successive phases (idling, acceleration, steady speed, deceleration, idling, etc.). The urban cycle was drawn up in 1958 after following a Renault Dauphine car in Paris. It therefore represents a very slow urban cycle.
- Part TWO comprises one extra-urban cycle made up of 13 phases.
- Exhaust gases are collected continuously throughout the cycle.

Survival kit for the maze of terms…



The full regulatory driving cycle is abbreviated **NMVEG** (for new MVEG). It is derived from the MVEG (the European Commission’s Motor Vehicle Emission Group) cycle but, for Euro 3 and later, minus 40 seconds of idling time prior to rolling.

Part ONE of the cycle is also known as the **ECE cycle** (Economic Commission for Europe), **MVEG-A cycle**, or even **UDC** (Urban Driving Cycle).
Part TWO is also known as the **EUDC** (Extra Urban Driving Cycle).

U.S. DRIVING CYCLES

There are three American regulatory driving cycles used in the certification of passenger cars and light-duty trucks with respect to **pollutant** emissions:
- **FTP 75**: cycle simulating urban driving from a cold start followed by a hot-start urban cycle;
- **SFTP-US06**: "aggressive" motorway driving;
- **SFTP SC03**: urban driving with air-conditioning on (not shown here).

Fuel consumption measurements are based on the **FTP 75** cycle and the normal motorway driving cycle **HWFET**.

Survival kit for the maze of terms...

FTP stands for Federal Test Procedure. **SFTP** stands for Supplemental FTP.

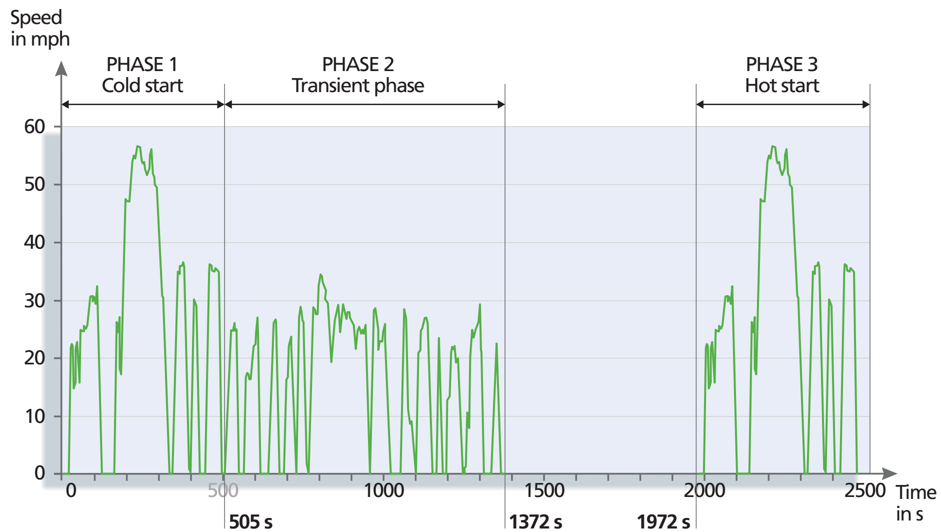
The first two phases of the **FTP 75** cycle correspond to the old **FTP 72** cycle, also referred to as:
- **UDDS** in the USA (UDDS stands for Urban Dynamometer Driving Schedule). Note that there is a UDDS truck cycle which must not be confused with FTP 72.
- **EPA II** in the USA (EPA stands for Environmental Protection Agency).
- **LA-4** in California (LA stands for Los Angeles).
- **A10** or **CVS** in Sweden (CVS stands for Constant Volume Sampler).
- **ADR 27** in Australia (ADR stands for Australian Design Rules).

The **FTP 75** cycle is also called **EPA III**.

HWFET stands for HighWay Fuel Economy Test.

Driving cycle FTP 75

(urban driving)



Average speed: 21.2 mph (34.1 km/h)
Maximum speed: 56.7 mph (91.2 km/h)
Total rolling time: 31 min 17 s (1,877 s)
Stopping time: 10 minutes
Distance travelled: 11.04 miles (17.8 km)
Weighting factors: PHASE 1 = 0.43
PHASE 2 = 1
PHASE 3 = 0.57

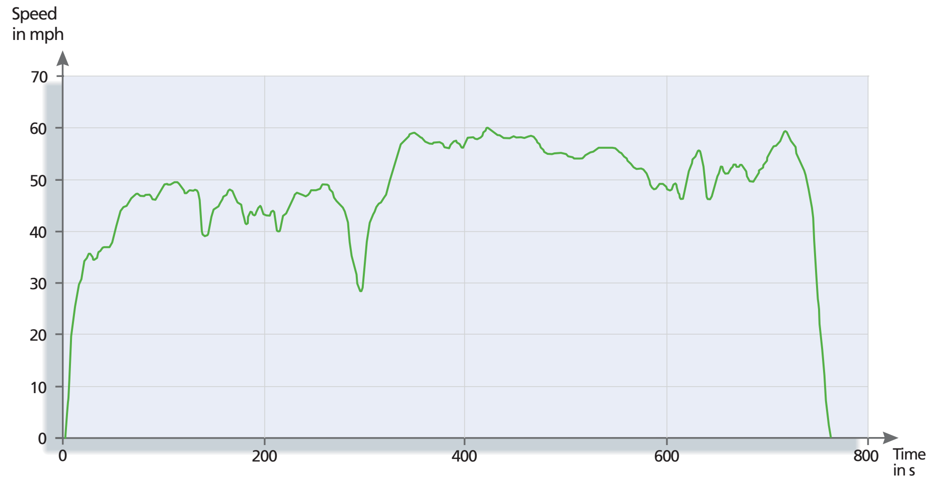
Driving cycle SFTP US06

("aggressive" motorway driving)

Average speed: 48.4 mph (77.9 km/h)
Maximum speed: 80.3 mph (129.2 km/h)
Total rolling time: 9 min 56 s (596 s)
Distance travelled: 8.01 miles (12.9 km)

Driving cycle HWFET

(normal motorway driving)



Average speed: 48.3 mph (77.7 km/h)
Maximum speed: 60 mph (96 km/h)
Total rolling time: 12 min 45 s (765 s)
Distance travelled: 10.26 miles (16.5 km)

JAPANESE DRIVING CYCLES

There are currently two Japanese regulatory driving cycles:

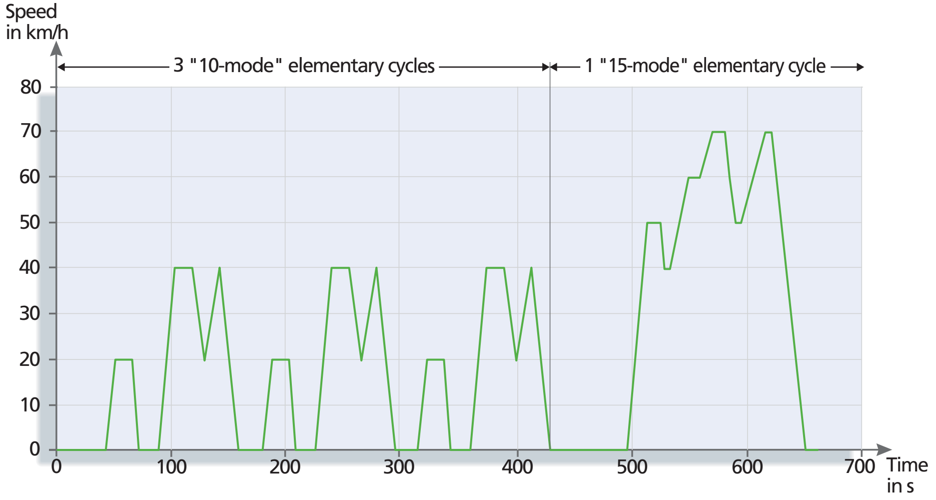
- One hot-start cycle known as 10-15 mode for measuring the pollution and fuel consumption of passenger cars and light trucks.
- One cold-start cycle known as 11 mode applied in addition to 10-15 mode for measuring the pollution of petrol-driven passenger cars and light-duty trucks.

10-15 mode simulates urban driving (three "10-mode" elementary cycles) followed by peri-urban driving (one "15-mode" elementary cycle). It is a hot-start cycle, with the measurements only beginning after 15 minutes of rolling at 60 km/h, a measurement during idling then a further 5 minutes' rolling at 60 km/h and finally a "15-mode" elementary cycle, which means a total warm-up time of more than 20 minutes. Measurement results are given in **g/km**.

11 mode simulates another urban trip, this time from a cold start. Measurement results are given in **g/test**.

10-15 mode

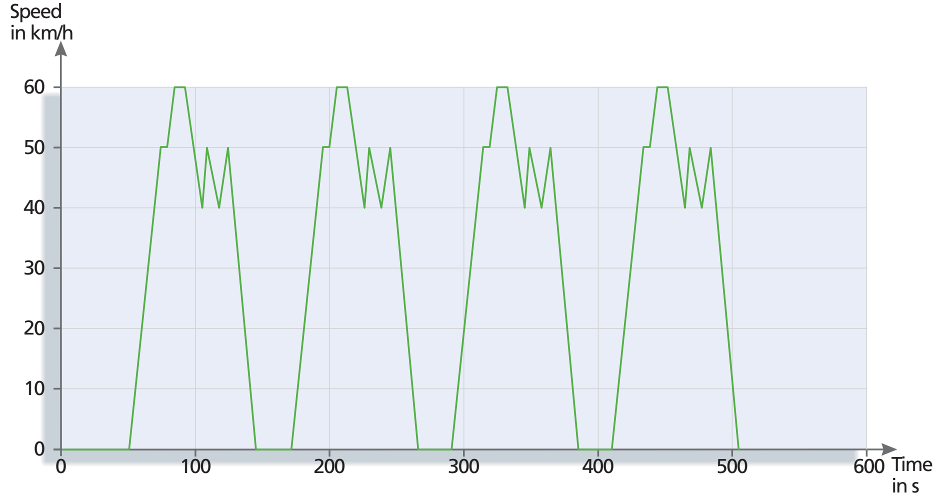
(hot-start urban driving cycle)



Average speed: 22.7 km/h
Maximum speed: 70 km/h
Total rolling time: 11 min (660 s)
Distance travelled: 4.16 km

11 mode

(cold-start urban driving cycle)



Average speed: 29.1 km/h
Maximum speed: 60 km/h
Total rolling time: 8 min 25 s (505 s)
Distance travelled: 4.084 km

V.3

Measurement of heavy-duty truck fuel savings

There are no regulations or standards for **heavy-duty truck** pollution or fuel consumption once the trucks are fully assembled. Only their engines are pollution-tested using an engine dynamometer.

To evaluate truck fuel savings due to the lower rolling resistance of a new truck tyre, tyre manufacturers use comparative measurements of fuel consumption during road tests.

TEST PRINCIPLES

Two identical trucks are first fitted with the same reference tyres. They are driven on the same circuit at the same speed at the same time in order to measure their exact fuel consumption per 100 km. This is to determine the slight but inevitable difference in fuel consumption between two vehicles which are theoretically identical in order to correct the results of subsequent comparative tests.

Secondly, one of the trucks is fitted with the new type of tyre to be tested. The trucks are driven around the circuit in the same conditions as before.

Fuel consumption is measured at the end of each test session by weighing the detachable fuel tank fitted on both trucks specifically for these tests. Fuel consumption corresponds to the difference in fuel tank weight before and after the test, divided by the kilometres covered and corrected taking the initial calibration test difference into consideration.

To obtain consistent measurement results, the tests should be completed at least three times over distances of at least 50 km.

Measurements can also be taken using a flowmeter, which gives a real-time readout of fuel consumption throughout the test. However, the vehicle's instrumentation and flowmeter calibration make this measurement method more complex to implement.

A third measurement option—used most often in the USA—is to calculate instantaneous fuel consumption from fuel injector signals.

Truck fitted with a flowmeter

A little more information on...

... calculating comparative fuel consumption

1 **Calibration measurement:**

Fuel consumption of vehicle 1 with reference tyres: $C_{\text{ref. tyre vehicle 1}}$

Fuel consumption of vehicle 2 with reference tyres: $C_{\text{ref. tyre vehicle 2}}$

Correction coefficient:

$$\text{Coef} = \frac{C_{\text{ref. tyre vehicle 1}}}{C_{\text{ref. tyre vehicle 2}}}$$

2 **Comparative measurement:**

Fuel consumption of vehicle 1 with reference tyres: $C'_{\text{ref. tyre vehicle 1}}$

Fuel consumption of vehicle 2 with new tyres ("B"): $C'_{\text{B tyre vehicle 2}}$

3 **Correction:**

Fuel consumption that vehicle 1 would have had if fitted with the "B" tyres:

$$C'_{\text{B tyre vehicle 1}} = \text{Coef} \times C'_{\text{B tyre vehicle 2}}$$

4 **Difference in fuel consumption between the reference tyres and the "B" tyres:**

$$\Delta = C'_{\text{B tyre vehicle 1}} - C'_{\text{ref. tyre vehicle 1}}$$

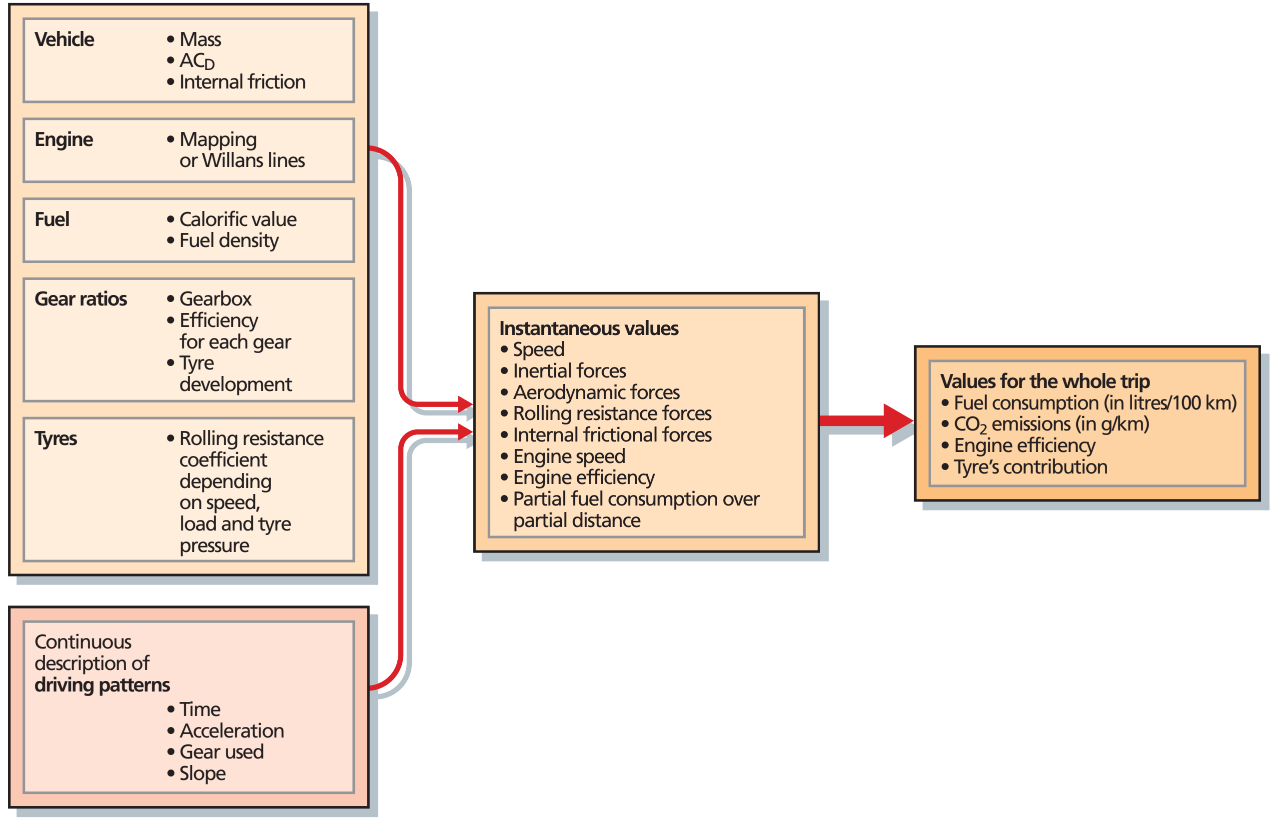
V.4 Modelling fuel savings due to low rolling resistance tyres

It is time-consuming and costly to take fuel consumption measurements with dynamometers or on roads. Computer modelling is a faster, cheaper way of designing better performing tyres.

Computer modelling is based on both data libraries containing various detailed driving patterns and on inpu data specifying the vehicle, fuel and tyres. Modelling also takes into account engine and gearbox operation, enabling the instantaneous fuel consumption to be calculated throughout the trip.

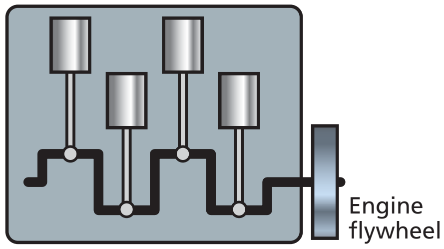
Computer simulations of this type can predict the tyre's contribution to fuel consumption and the fuel savings to be made by lowering rolling resistance.

Diagram showing how fuel consumption—including the tyre's contribution—may be modelled through computer simulations

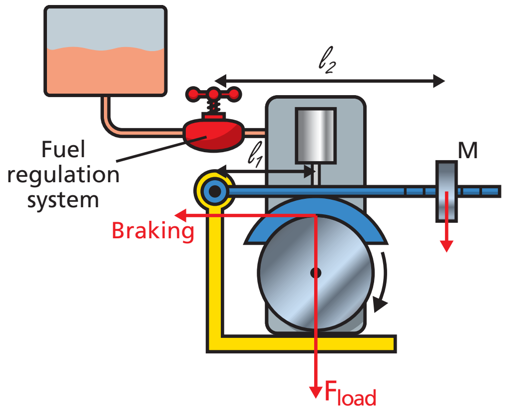


Engine mapping and Willans lines

Engine maps are plotted using measurements taken on engine dynamometers.
The measurement principle can be represented as shown on the simplified diagram opposite:



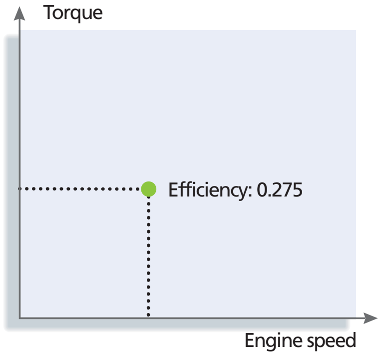
Engine
(with no gearbox)



Engine on the dynamometer

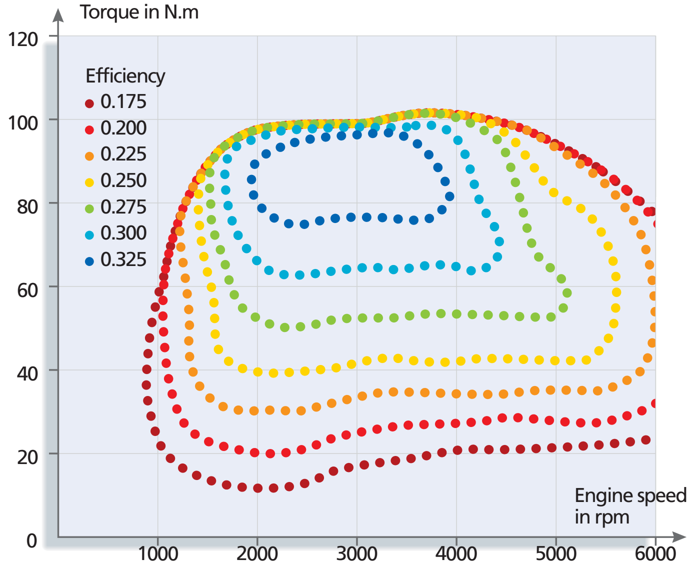
	Equations	Notations
A braking torque ($T_{braking}$) is applied to the engine using the lever and mass. The torque can be adjusted by sliding the mass along the lever.	$F_{load} = Mg \cdot \frac{\ell_2}{\ell_1}$ $F_{braking} = \mu \cdot F_{load}$ $T_{braking} = F_{braking} \times R_{flywheel}$	M: mass in kg g: acceleration of gravity equal to 9.81 m/s² μ: friction coefficient of the brake pad against the test drum
The engine speed (N) is adjusted by regulating the fuel flow rate. At a steady speed, the engine torque is equal to the braking torque. The engine's angular speed (ω) multiplied by the torque ($T_{braking}$) gives the engine power output (P_{output}).	$\omega = 2 \pi N \times 60$ $P_{output} = T_{engine} \times \omega$	N: engine speed in rpm ω: angular speed of the engine in radians/second ($\omega = 2 \pi N$) P: power in watts T_{engine}: in N.m
The fuel flow rate measured is used to calculate the power consumed by the engine. It is then possible to calculate engine efficiency.	$P_{consumed}$ = flow rate x NCV $\text{Efficiency} = \frac{P_{output}}{P_{consumed}}$	Flow rate: in l/s NCV: net calorific value of the fuel in megajoules per litre (MJ/l). The NCV of petrol is 32.8 MJ/l.

Engine efficiency can be mapped against engine speed (N) and torque as both values are known.



This operation is repeated as many times as needed until all useful torque and speed values have been covered. This results in a map as shown.

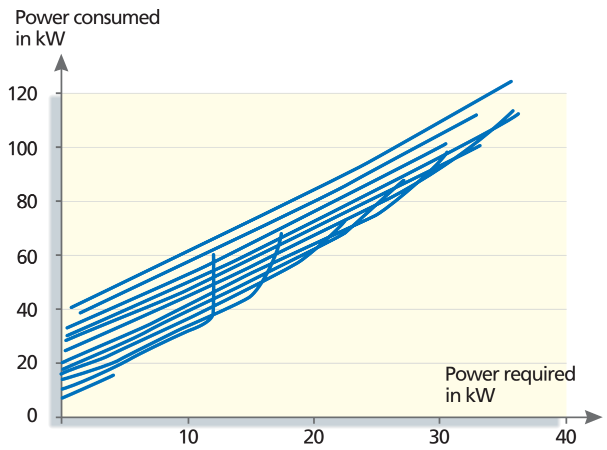
This three-dimensional map (torque, engine speed and efficiency) is accurate but do not directly indicate fuel consumption.



WILLANS LINES

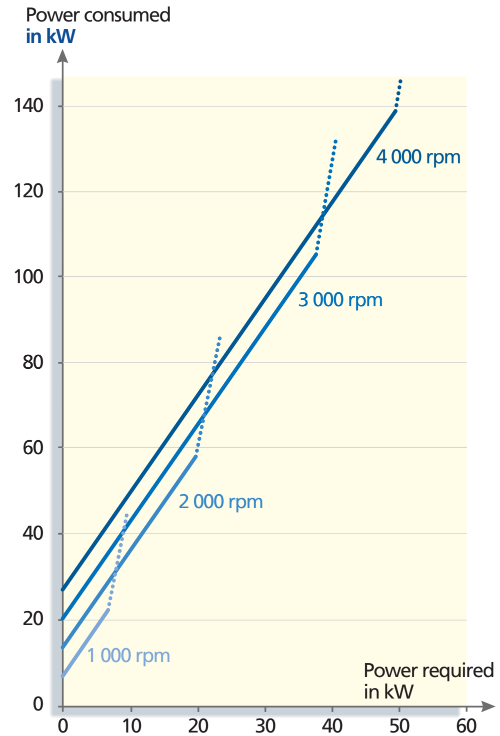
(example based on a 51 kW petrol engine)

Engine dynamometer results provide the power consumed (fuel power consumption) for power required (brake power output) at each engine speed.
When plotted, this gives a graph of power consumed versus power required for different engine speeds. For each engine speed, the plotted curve is almost straight.



These curves may be approximated to straight lines through linear regression, resulting in a simple relationship between power consumed and power required at each engine speed accurate to within ± 2,5 %. The straight lines describing this relationship are known as Willans lines. For the 51 kW engine used in the examples, the relationship is:

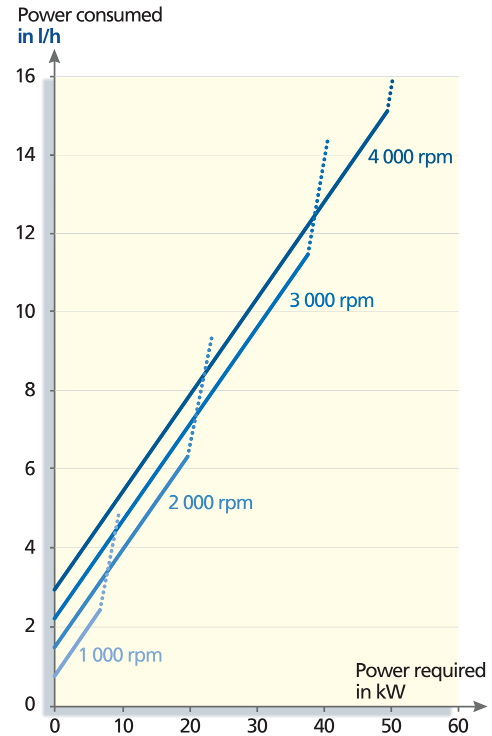
$$P_{consumed} = 2.23 \times P_{required} + 6.82 \times N$$



The power required can be converted to l/h.

$$P_{consumed} \text{ (in l/h)} = \frac{P_{consumed} \text{ (in kW)}}{\text{NCV (in kW.h/l)}}$$

NCV: net calorific value of the fuel.
The NCV of petrol is 32.8 MJ/l, i.e. 9.12 kWh per litre.



Note:
The dotted lines correspond to a rapid deterioration in efficiency when the power required significantly increases (the driver pushes on the accelerator pedal) while the engine speed does not match the driving speed. A car is travelling at 70 km/h in fifth gear, for example, and the driver tries to accelerate without down-shifting. Fuel consumption rises sharply but the car does not accelerate markedly.

Willans lines can also show the force consumed as a function of force required:

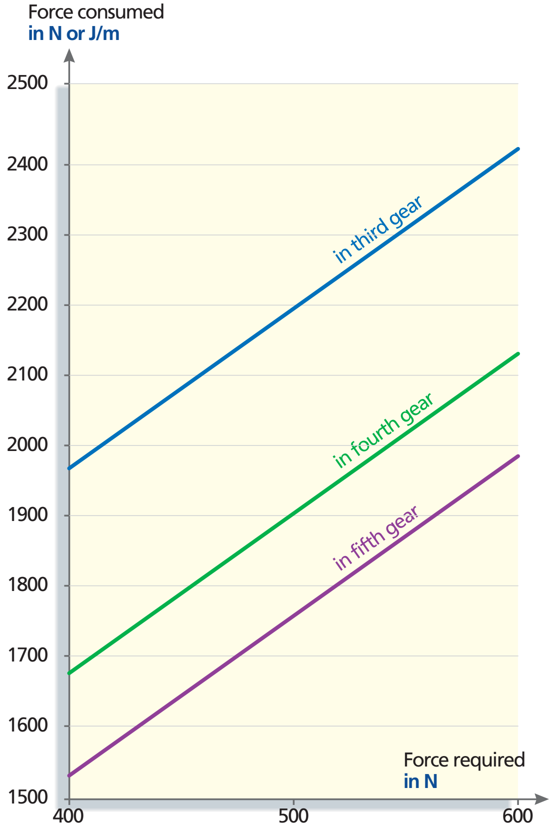
$$P_{consumed} = a \times P_{required} + b \times N \quad \text{and} \quad P = F \times V$$

$$\text{Therefore} \quad F_{consumed} = \frac{P_{consumed}}{V} = \frac{a \times P_{required}}{V} + \frac{b \times N}{V}$$

$$F_{consumed} = a \times F_{required} + \frac{b \times N}{V}$$

Where F is in N (equivalent to J/m)
P is in W (equivalent to J/s)
V is in m/s

Quotient $\frac{N}{V}$ —which is equal to the number of engine revolutions per metre travelled—gives the overall gear ratio, i.e. the demultiplication ratio between the engine speed and the vehicle's speed. For a given vehicle, it is characteristic of the gear the car is in. The Willans lines then look as follows.

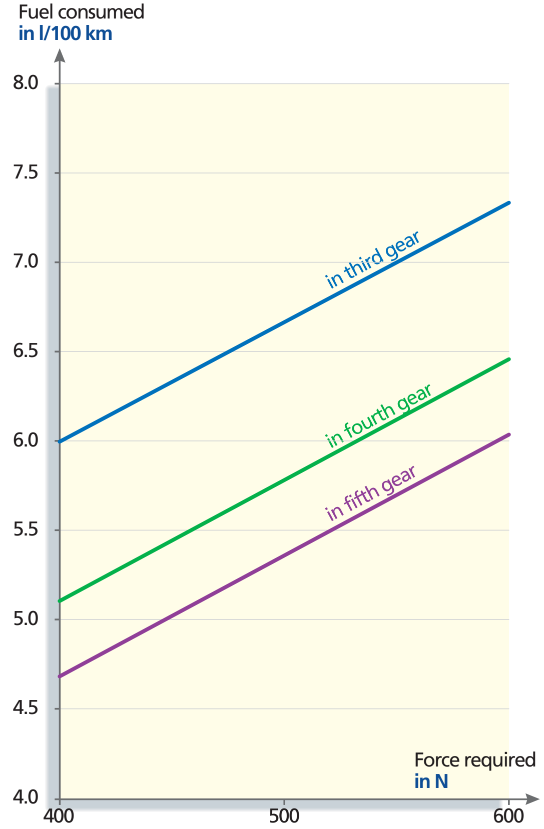


Knowing the NCV of the fuel used, the force consumed can be converted into fuel consumed (l/100 km).

$$Cons = \frac{F_{consumed}}{NCV} \times 10^5$$

where $F_{consumed}$ is in J/m
NCV in J/l

The calorific value of petrol is 32.8 MJ per litre.



Figures and conversions

Rolling resistance coefficient

A coefficient of 0.012 is equivalent to a coefficient of 12 kg/t and 12 per thousand.

Conversion of the main units of energy

1 joule (J) = 1 newton-metre (N.m)
1 watt-hour (Wh) = 3,600 joules
1 megajoule (MJ) = 0.278 kWh

Equivalence between fuel consumption, CO_2 emissions and C emissions for petrol and diesel vehicles

CO_2 emissions are expressed either in tonnes of carbon dioxide (CO_2) or in tonnes of carbon (C). The invariable ratio between them equals 3.67. This corresponds to the ratio between the molecular mass of CO_2 (12 + (2 x 16) = 44) and the atomic mass of carbon (12).

While the exact quantity of CO_2 emitted per litre of fuel depends on numerous factors such as temperature, ambient pressure and fuel quality, the following are typical values:

- 1 litre of petrol consumed produces 2.35 kg of CO_2, i.e. 0.64 kg of carbon;
- 1 litre of diesel consumed produces 2.66 kg of CO_2, i.e. 0.72 kg of carbon.

Consequently, a fuel consumption of 1 l/100 km results in CO_2 emissions of 2.35 g/km for petrol and 2.66 g/km for diesel.

Energy value of the main four fuels

	Mass NCV	Fuel density	Volume NCV	Equivalent of volume NCV in kWh [4]
Petrol	43.5 MJ/kg [1]	0.755 kg/litre [2]	32.8 MJ/l	9.12 kWh/l
Diesel	42.5 MJ/kg [1]	0.845 kg/litre [2]	35.9 MJ/l	9.97 kWh/l
LPG	46.1 MJ/kg [1]	0.54 kg/litre [3]	24.9 MJ/l	6.92 kWh/l
NGV	47.7 MJ/kg [1]	0.654 kg/m^3 [3]	31.2 MJ/m^3	8.66 kWh/m^3

The net calorific value (NCV) is the useful energy value of a fuel, i.e. having subtracted energy lost by the formation of water vapour during combustion. The combustion process generates water which turns into steam due to the heat. Vaporization consumes energy which cannot be retrieved.

(1) *Source: Bosch, Mémento de Technologie Automobile, 2nd edition*

(2) *Source: Union Routière de France, Faits et Chiffres 2000.*
Note: The density of each fuel does not correspond to a universal value. It depends on the manufacturing process, ambient temperature and pressure. European standards EN 228 and EN 590 indicate that the density of petrol must lie between 0.720 and 0.775 kg/l and that of diesel between 0.820 and 0.845 kg/l at 15 °C in a temperate climate.

(3) at 15 °C. *Source: European Directive 1999/100/EC.*

(4) 1 kWh = 3.6 MJ.

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