



The tyre

Grip - tread pattern





The tyre

Grip

Société de Technologie Michelin
23, rue Breschet, 63000 Clermont-Ferrand

© Société de Technologie Michelin, 2001

Produced by Artice / Japa - Photographs from Michelin picture library
Made in France

Reproduction, representation, adaptation or translation of any part
of this work without the permission of the copyright owner is unlawful.

Requests for permission or further information should be addressed to:
Manufacture Française des Pneumatiques Michelin
Service Groupe Communication / Technique
Place des Carmes Déchaux, 63040 Clermont-Ferrand Cedex 09

Grip on road surfaces

4 Introduction

5 Foreword: grip and its double paradox



7 I Rubber and grip

8 I.1 RUBBER: A VISCO-ELASTIC MATERIAL

8 ■ What is a visco-elastic material?

8 *A little more information on...* the behaviour of elastic materials

9 *A little more information on...* the behaviour of viscous materials

10 *A little more information on...* the behaviour of visco-elastic materials

11 ■ Where does the visco-elasticity of tyre rubber come from?

12 ■ The modulus of rubber

13 I.2 INFLUENCE OF STRESS FREQUENCY AND TEMPERATURE ON THE BEHAVIOUR OF RUBBER

13 ■ Influence of stress frequency

14 ■ Influence of temperature

15 ■ Frequency - temperature equivalence

16 *A little more information on...* the WLF equation

17 I.3 THE MECHANISMS INVOLVED IN THE RUBBER-ROAD INTERFACE FRICTION

17 ■ Road roughness effects

18 ■ Molecular adhesion

19 Rubber and grip: don't forget the basics!

21



II How road roughness affects grip

22 II.1 CHARACTERISATION OF ROAD SURFACES

23 ■ Measurement of macroroughness

23 ■ Measurement of microroughness

24 ● [Concepts regarding road surfaces](#)

25 ■ Measurement of the load bearing surface

26 ■ Characterisation of the friction coefficient of a rubber-road interface

27 II.2 INFLUENCE OF ROAD SURFACES ON THE COEFFICIENT OF FRICTION

28 ■ Variation in friction coefficient on a dry surface

29 ■ Variation in friction coefficient on damp or wet road surfaces

30 ■ Relative importance of the rubber factor and the road surface factor in grip

30 ■ What about snow?

30 ■ And what about ice?

31 [How road roughness affects grip: don't forget the basics!](#)

33



III Generation of grip forces in the contact patch

III.1 FRICTION MECHANISMS OF A RUBBER BLOCK

- 34 ■ Shear (or pseudo-slippage)
- 35 ■ Slippage

III.2 LONGITUDINAL GRIP IN BRAKING

- 36 ■ Source of slippage
A little more information on... slippage and braking
- 37 ■ Longitudinal friction force
- 38 ■ Longitudinal friction coefficient μ
A little more information on... the coefficient of longitudinal friction
- 39 ■ The longitudinal friction law $\mu(G)$
- 40 ■ Generation of braking forces in the contact patch
A little more information on... the maximum shear value of the tread block and the beginning of slippage
- 42 ■ Examples of slippage and shear as a function of the coefficient of grip and the slippage rate
A little more information on... maximum length of shear and slippage
- 43 ■ Analysis of the $\mu(G)$ curve

45 Longitudinal grip in braking: don't forget the basics!

III.3 TRANSVERSAL GRIP IN CORNERING

- 46 ■ Centrifugal force
- 46 ■ Slip angle

48

- Transversal friction force

48

- Coefficient of transversal friction τ

48

A little more information on... the coefficient of transversal friction

49

- Effect of the bend radius on the maximum cornering speed

49

A little more information on... maximum cornering speed

50

- Law of transversal friction $Y(\delta)$

50

A little more information on... the transversal grip coefficient

51

- Generation of transversal forces in the contact patch

52

- Analysis of the $Y(\delta)$ law

52

A little more information on... the maximum length of shear and slippage

54

Transversal grip in cornering: don't forget the basics!

55

III.4 SHARING THE GRIP POTENTIAL ON THE ROAD

55

- Combined grip

55

- A potential to be shared

57

- ABS

57

A little more information on... how the ABS works

59



IV Grip on wet surfaces

61

IV.1 THE HYDRODYNAMIC ZONE: DISPERSAL AND DRAINAGE

61

A little more information on... the speed at which aquaplaning occurs

62

- A rounded footprint to reduce the pressure exerted by the bank of water on the tyre

62

A little more information on... the rounded contact patch which increases aquaplaning speed

- 63 ● Wide tyres and water dispersal
- 64 ■ Angled tread grooves to drain away water to the side

65 **IV.2 THE VISCODYNAMIC ZONE: STORING WATER IN THE TREAD GROOVES**

- 65 ■ Compression of the water by the tread blocks
- 65 *A little more information on...* the time for water transfer to the storage zones
- 67 ● Sipes and grip on wet surfaces

69 **IV.3 DAMP TO DRY ZONE: RESTORING DRY CONTACT**

- 69 ■ Edges to break through the film of water

70 *Grip on wet surfaces: don't forget the basics!*



71 **V Grip and vehicle handling**

72 **VI LOAD TRANSFER**

- 72 ■ Longitudinal load transfer
- 72 *A little more information on...* how load transfer affects braking efficiency
- 73 ■ Lateral load transfer
- 73 *A little more information on...* how load transfer affects cornering

74 **V.2 UNDERSTEER AND OVERSTEER**

77



VI Testing tyre grip

79

VI.1 ANALYTICAL TESTS

79

- Road simulators

80

- Laboratory vehicles

81

VI.2 VEHICLE TRACK TESTS

82

- Testing longitudinal grip

83

A little more information on... calculating the coefficient of grip μ

84

- Transversal grip tests

87



VII Grip and rolling resistance

88

- Where does rolling resistance come from?

88

- Maximise grip and minimise rolling resistance: a challenge in physical science

90

- Two different frequency ranges

A, B, C...

91



Index

Grip on road surfaces

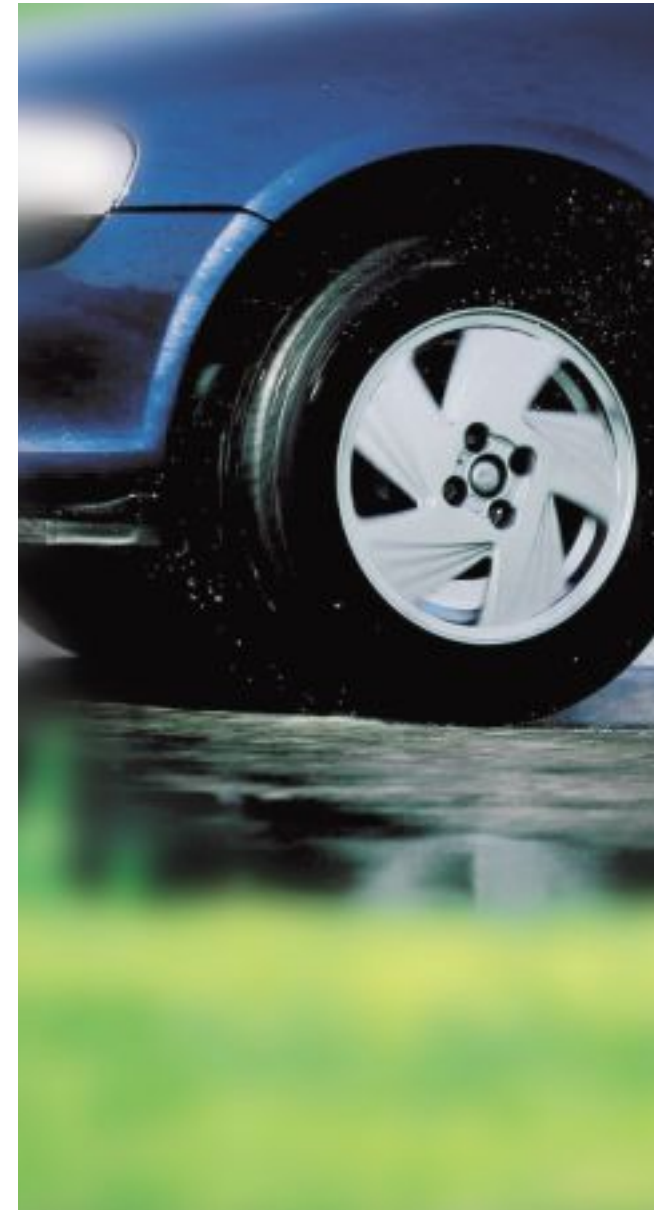


If there were no such thing as grip, cars just would not be able to move at all. The wheels would spin and the driver would not be able to budge the vehicle. Even on a straight road and at steady speed, there is no alternative to grip. This is because a moving vehicle has to deal with natural forces, such as the banking, the slope or the unevenness of the road, or rolling resistance, which are constantly trying to slow the vehicle down or push it off its path.

However it is only during cornering or braking that a driver or passenger is really aware of grip, because the vehicle has to be steered or speed has to be reduced without skidding, even on a wet road. In all circumstances, grip and safety go together. As the only contact point between the vehicle and the road, the tyre ensures two fundamental functions. It gives the vehicle its directional stability, which the driver needs to steer it. The tyre acts as a transmission component for brake and drive torque.

The tyre as a vital link in the grip system

Pneumatic tyres for automobiles began to be manufactured away back in 1895. They very quickly replaced the solid tyre, which inflicted increasingly severe punishment on vehicle mechanics and was a source of discomfort for passengers as the drive power and speeds became greater. Greater comfort however was not the only improvement, since the grip ensured by pneumatic tyres also proved to be vastly superior to that of solid tyres. Part of the kinetic energy developed by a vehicle has to be absorbed by the suspension system, the brakes and the tyres during cornering and braking. Where the car meets the road, there are only the vehicle's tyres to ensure the ultimate contact patch. The mechanics of grip are to be explained by the astonishing visco-elastic properties of the tyre's rubber which within the contact patch produce a host of physical phenomena that strive to counteract any untimely skidding over the road surface.



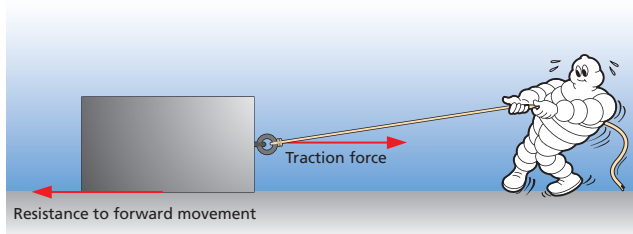
Grip and its double paradox

Two paradoxes are contained in the ability of the tyre to move and yet to grip at the same time.

Motionless yet moving!

The tyre contact patch of a vehicle travelling at constant speed does not move in relation to the road surface!

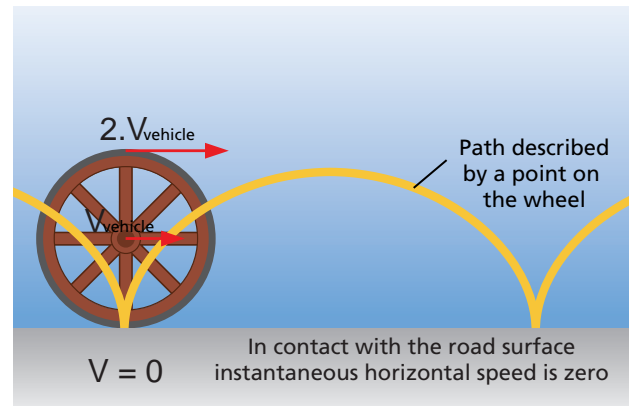
In order to fully apprehend this first paradox, it must be remembered that before the wheel was invented, men used sleighs and the load



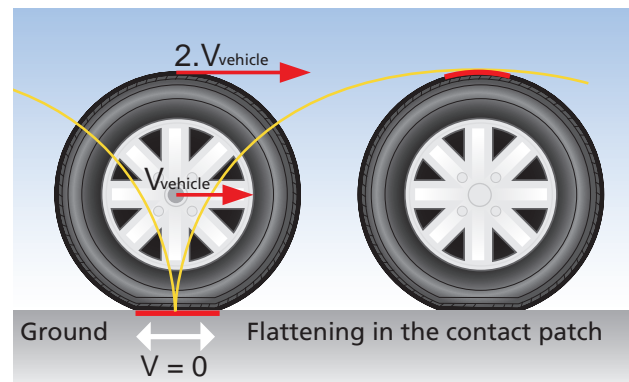
was dragged along the ground. There was a great deal of resistance to forward movement unless the sleigh was able to slide easily over snow, ice or wooden rollers. Friction was high because the movement over the ground was equal to the speed at which the mass travelled.

The wheel produced a technological revolution:

- Movement was no longer related to a load being dragged directly over the ground, but only to an axle hub.
- At any given time the contact point on the wheel was motionless with respect to the ground, since instantaneous horizontal speed was zero.



The above two features apply to any wheel, although the pneumatic tyre has transformed the old wooden wheel or the metal one, because it deflects and so flattens out on the road surface. There is no longer just a contact line across the width of the tyre since the tyre spreads out into a contact patch where the tread blocks are laid down and lifted off like caterpillar tracks.



Furthermore, even though the flattening of the contact area constantly produces micro-movements between the tread blocks and the road surface, the contact area does not move – it changes, as one contact area continuously replaces the previous one.

It is only when the vehicle brakes, accelerates or corners that the contact area and the road begins to move in relation to each other: this relative movement is known as slippage.

Slippage means no skidding!

Slippage in the contact patch is produced when braking, acceleration or cornering occurs.

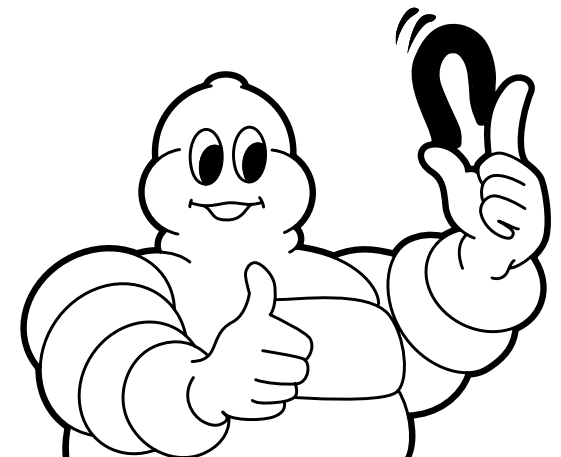
Here lies the second paradox, which is every bit as surprising as the first: a tyre slips in order not to skid!

Generating grip involves generating friction forces which counteract the vehicle's skidding off the road. However, it must be borne in mind that it is slippage which produces the friction forces of grip. In fact there are two forms of relative movement in the contact patch, micro-movement, commonly known as slippage, which counteracts macro-movement, commonly known as skidding.



I *Rubber & grip*

Tyres are made from rubber, that is elastomeric materials to which they owe a large part of their grip capacity. To begin with, we shall examine the special characteristics of these materials. Then, we shall take a detailed look at the phenomena involved in friction which generates grip.



I.1

Rubber: a visco-elastic material

■ WHAT IS A VISCO-ELASTIC MATERIAL?

A visco-elastic material is a deformable material with a behaviour which lies between that of a viscous liquid and an elastic solid.

When a perfectly elastic body, like a spring, for example, is subjected to a force, it distorts instantaneously in proportion to the force applied. Then, as soon as the force is no longer applied, it reverts to its initial shape. **Stress and deformation are simultaneous.**

A viscous fluid behaves differently. When we push a piston into a tube filled with oil or water, the piston's forward movement encounters resistance which increases when we try to push the piston in faster. Moreover, when we begin to press on the piston, a certain time elapses before we notice any movement. **Stress and deformation are out of phase:** this is called **hysteresis**.

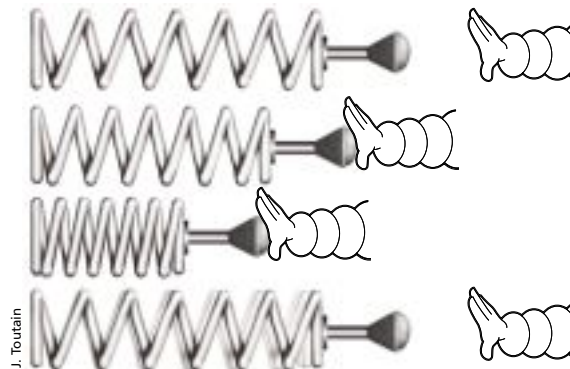
The viscosity of the fluid is due to the friction between its constituent molecules, which slows down its flow.



A little more information on... the behaviour of elastic materials



BEHAVIOUR OF A SPRING



- The harder we push on the spring, the more it is compressed: **there is proportionality** between force F and displacement X .
 $F = k \cdot X$, where k is the stiffness constant of the spring.

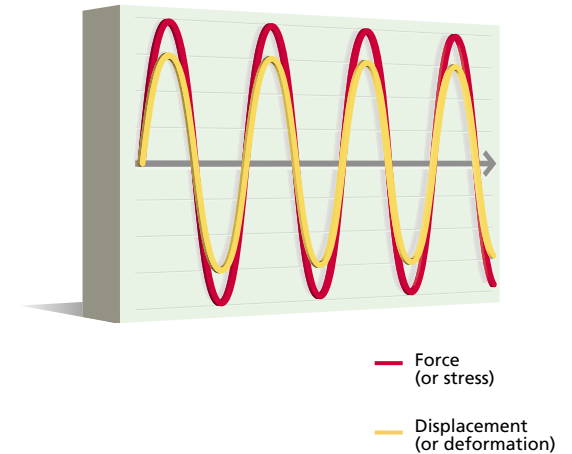
- As soon as we begin to push on the spring, it compresses, and as soon as we release it, it reverts to its initial length: force (F) and displacement (X) are **simultaneous**, as in stress (σ) and deformation (ϵ):

$$F(t) = k \cdot X(t) \text{ and } \sigma(t) = E \cdot \epsilon(t)$$

- Instantaneous return to the initial position shows that the spring restores all the energy supplied. **Energy losses are nil.**

ALTERNATE STRESSING OF A SPRING

If we apply a compression-extension type force, stress and deformation are proportional at each instant: the two signals are in phase.



Definitions and symbols:

Stress (symbol σ) = force per unit area.

Deformation (symbol ϵ) = elongation or compression as a ratio of the initial length.

E = intrinsic stiffness of the material, called the modulus of elasticity.

A little more information on... the behaviour of viscous materials



BEHAVIOUR OF VISCOUS MATERIALS

- The harder we push on the piston, the greater the resistance to movement. The force F to be applied to push the piston is not proportional to the travel, but **proportional to the speed** of the piston's forward movement (\dot{X}).

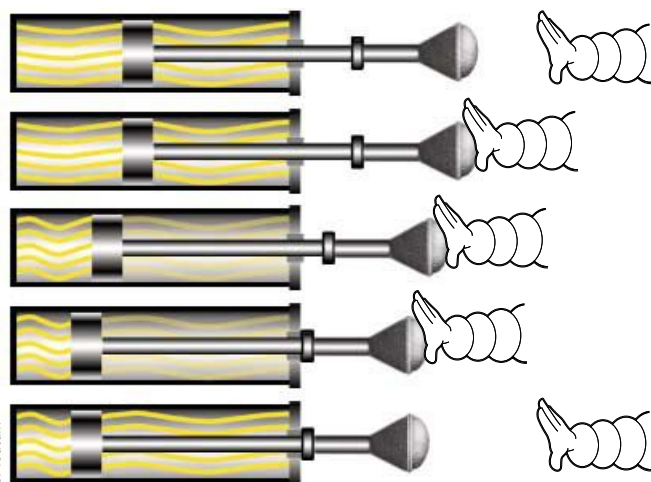
$F = \eta \cdot \dot{X}$, where η is the viscosity constant of the fluid.

- When we push sharply on the piston, it does not move immediately. We have to wait a few moments for the movement of the piston to become noticeable; piston movement **lags behind** the application of the force: this is **hysteresis**.

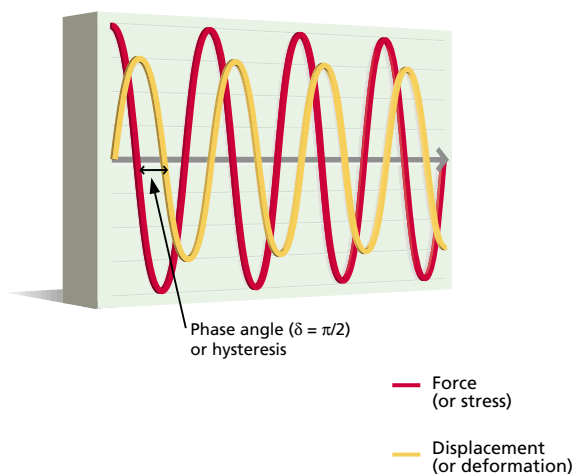
- When we release the piston, it does not return to its original position. **The energy supplied is not restored**, but dissipated in the fluid: there is **energy loss**.

ALTERNATE STRESSING OF A VISCOUS FLUID

If we apply a compression-extension type force, the appearance of deformation lags behind the stress. The two signals are in phase quadrature ($\delta = \pi/2$): when the force is maximum, deformation is minimum and vice-versa.



J. Toutain



A **visco-elastic material**, like chewing-gum, or an elastomer, exhibits behaviour which lies between that of the perfect spring and that of the perfect viscous fluid.

A visco-elastic material which has been deformed reverts to its initial shape, but only after a certain time (not always perceptible to the naked eye). This is called **hysteresis**.

This delay is accompanied by a dissipation of energy, in the form of heat. This is **energy loss**.



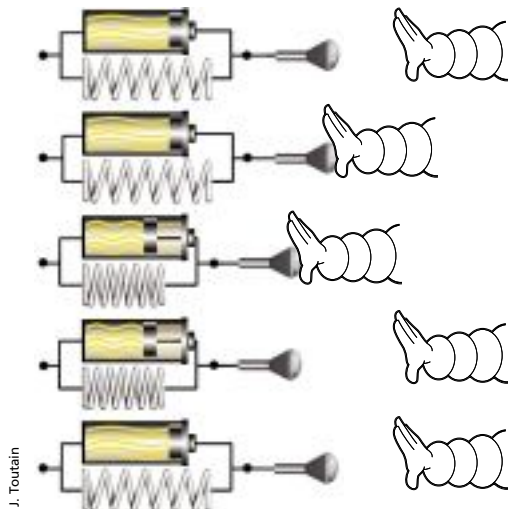
We shall see later that **hysteresis, directly related to the loss of energy, is at the origin of tyre grip mechanisms**.

A little more information on... the behaviour of visco-elastic materials



BEHAVIOUR OF VISCO-ELASTIC MATERIALS

- A visco-elastic material can be represented by a spring and piston assembly as shown below:

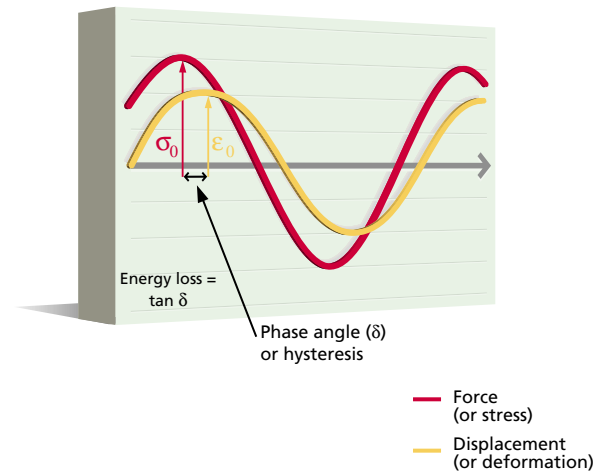


J. Toutain

- There is partial dissipation of the energy supplied. This is **energy loss**.
- Compression and return to the initial state take place with a phase lag in relation to the force applied; this is known as **hysteresis**.

ALTERNATE STRESSING OF A VISCO-ELASTIC SOLID

If we apply a stress of the compression-extension type, deformation lags behind the stress applied, but the phase angle (δ) is smaller than for a purely viscous material.



Symbols:

The phase angle symbol is δ ; it is directly linked to the phase shift overtime, i.e. hysteresis. The coefficient of energy loss, which translates the material's ability to dissipate energy, has the symbol $\tan \delta$.



The manufacturing of tyres requires a wide variety of natural and synthetic elastomers.

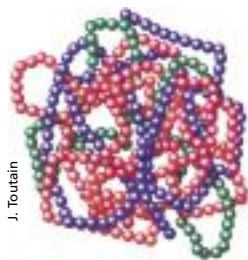


Numerous ingredients are required to produce rubber, which is why the different types of rubber in tyres are referred to as compounds. Above are pictures of elastomers, sulphur, antioxidants, zinc oxide and a vulcanisation accelerator. Reinforcing agents, such as carbon black and silica, are also used.

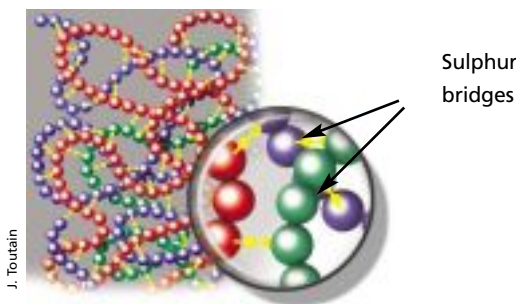
■ WHERE DOES THE VISCO-ELASTICITY OF TYRE RUBBER COME FROM?

The constituent rubbers of the tyre are **vulcanised elastomers**.

These elastomeric materials are made up of one or more **polymers**, long molecular chains which spontaneously take on the shape of a ball of wool and become entangled with each other.



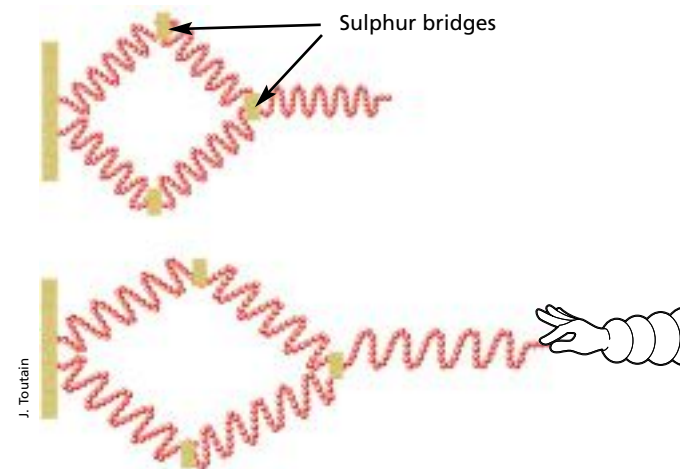
To make the tyre, these materials are **vulcanised**, i.e. cured after incorporation of sulphur. Curing causes the creation of **sulphur bridges** between the polymer chains.



As soon as an isolated polymer chain has fastened to a point, it behaves like a tiny spring.

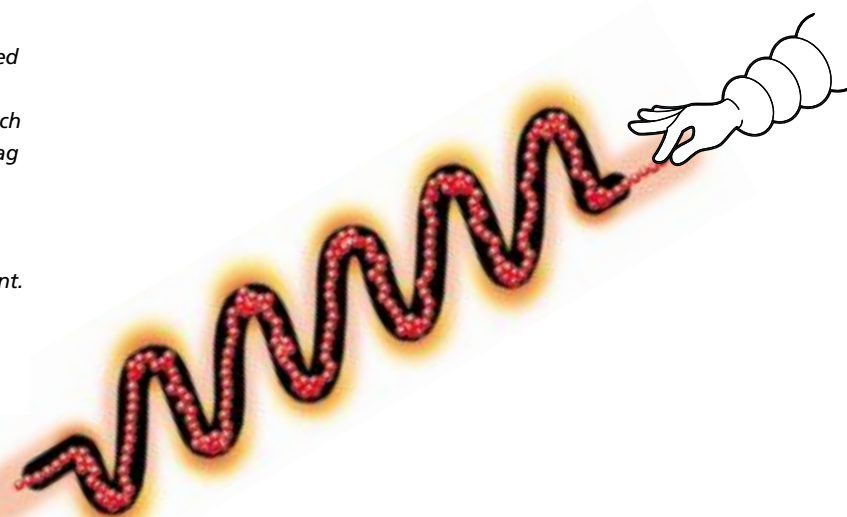


We might therefore think that the network of polymer chains resulting from vulcanisation constitutes a system of springs, with a perfectly elastic behaviour.



However, in moving, the segments of chains between the sulphur bridges rub against the other chains in their environment. It is this phenomenon which gives the material its viscous component.

Each molecular chain is confined by the other chains in its environment, in a "space" which may be represented by a zig-zag shaped tube. When we stretch the molecule, it rubs against the walls of this "tube", which slows down its movement.



Depending on their formulation, elastomer compounds behave differently.

The viscosity of the compound obtained varies according to the choice of polymers (polyisoprene, polybutadiene, butadiene-styrene, etc.). It also varies according to the number of sulphur bridges created by vulcanisation, and the nature and quantity of reinforcing agents.


Apart from **energy loss** and **hysteresis**, understanding the behaviour of rubber involves another variable: the **rigidity** of the material, characterised by its **modulus**.

■ THE MODULUS OF RUBBER

The modulus characterises the rigidity of a material: a low modulus is typical of a fairly soft material, whilst a hard material will have a high modulus.

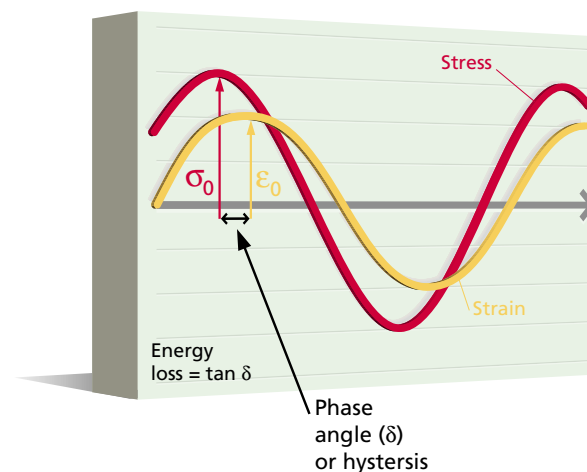


This modulus is defined as the ratio of the stress to strain (σ/ϵ).

 For grip purposes, the composition of the rubbers in tyre treads should be selected so that their modulus is moderate (flexible behaviour), and their hysteresis is maximum.

However, we are now going to see that energy loss, hysteresis and modulus vary not only from one compound to another, but also, for a given compound, depending upon the stress frequency and the temperature.

Alternate stressing of an elastomer



$$\text{Modulus} = \sigma_0/\epsilon_0$$




Measuring the rigidity of a material using a traction machine.

I.2

Influence of stress frequency and temperature on the behaviour of rubber

The modulus, energy loss and hysteresis of a visco-elastic material vary in response to two parameters: the frequency with which the force is applied and the temperature, which produce opposite effects on rubber.

■ INFLUENCE OF STRESS FREQUENCY

Let us go back to the example of the spring and piston assembly. 

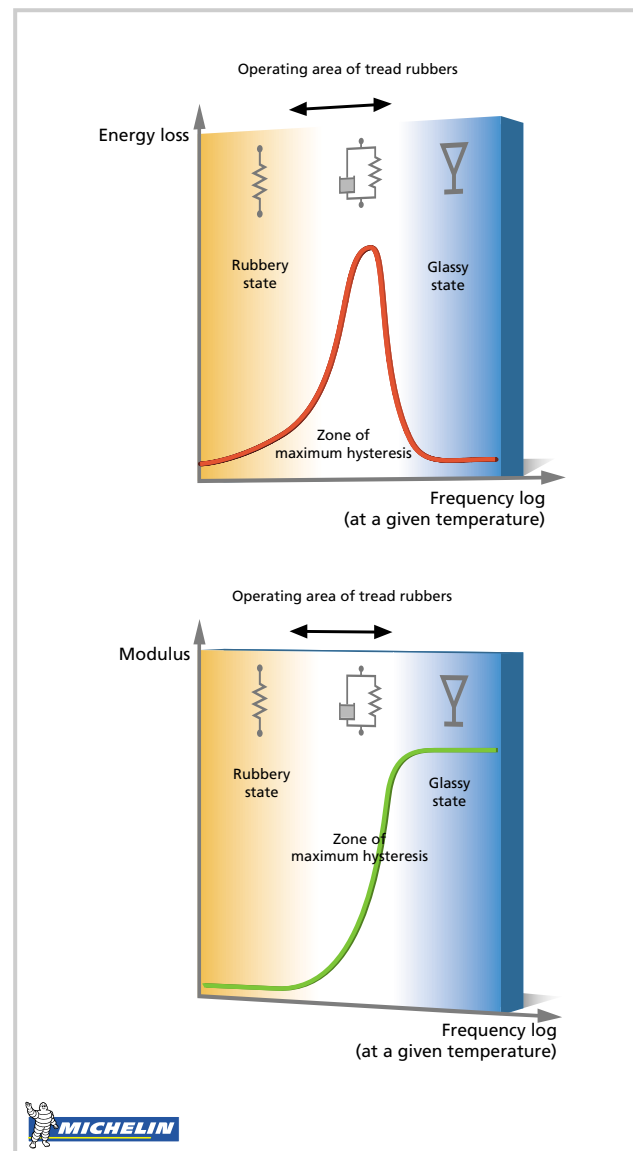
At **low frequency**, deformation occurs slowly. The force required to move the piston is slight. The piston offers little resistance. The spring side is dominant. **The material appears to be fairly elastic.** It is in a **rubbery state** and its **hysteresis is low**.

If the frequency increases, the force required to move the piston increases, and the piston's resistance increases. The piston side becomes dominant. **The material appears to be visco-elastic.** **This is the most favourable range for grip, because hysteresis is maximum.**

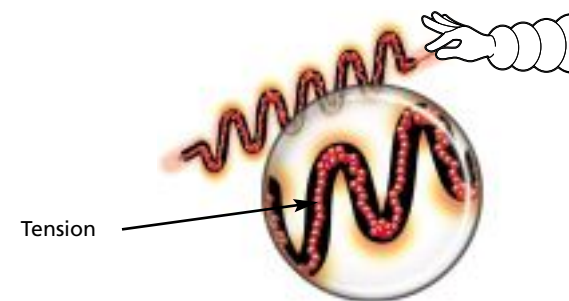
If the frequency increases still further, viscosity falls again.

What happens inside the material?

We have already seen that each molecular chain is confined within its environment composed of other chains.



When the molecular chain is subjected to tension, it subsequently moves inside its "confinement tube", being stretched in some sections, and compressed in others.



Each time the force is released, the chain reverts to equilibrium (**relaxation**). The speed with which the chain does this will depend upon its molecular mobility. If the frequency with which the forces are applied is greater than the material's **molecular mobility**, it will not revert to equilibrium.

- Consequently, at low frequency the chain is relatively mobile and appears to be flexible and elastic.

- If the frequency increases, the return to equilibrium is delayed. This is known as hysteresis.

- Then, if the frequency of force application continues to increase, the chains do not have the time to revert to equilibrium. Tension is permanent and the material becomes rigid and ceases to be viscous. **The rubber modulus quickly tends towards its maximum value and the rubber has glass-like mechanical properties; it becomes brittle.**

■ INFLUENCE OF TEMPERATURE

The frequency with which force is applied to rubber and the temperature of the material affect rubber in opposite ways.

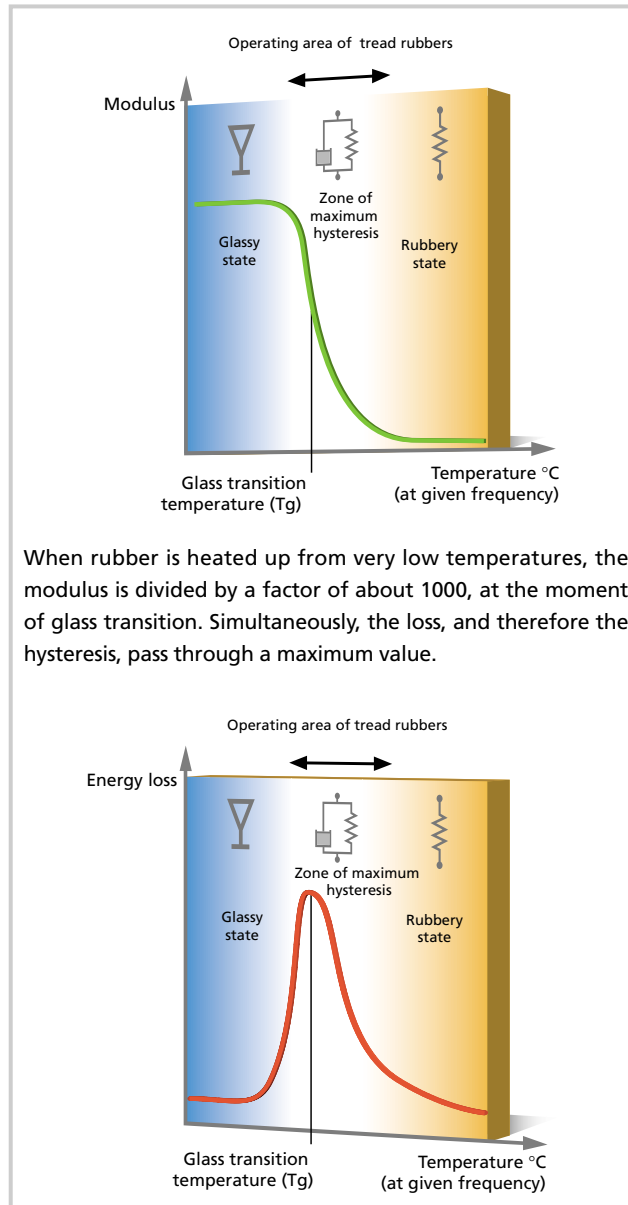
At very low temperature, the modulus of the rubber is high, i.e. **the material is rigid and brittle, a bit like glass**.

At high temperature, the modulus is low, **and the material is flexible and elastic (rubbery state)**.

It is in the **intermediate temperature range**, situated around the temperature called the **glass transition temperature***, that the material is the most viscous. The polymer chains are sufficiently deformable for the segments of chains between the sulphur bridges to be able to move. In moving, they rub against their environment (other chains), which slows down their movement (hysteresis). **The material is in a visco-elastic state.**

We shall soon see how important hysteresis is in grip.

**The glass transition temperature is the temperature below which rubber tends towards an increasingly vitreous state and above which the material tends towards an increasingly rubbery state. Its symbol is T_g : T for temperature, g for "glass".*



When rubber is heated up from very low temperatures, the modulus is divided by a factor of about 1000, at the moment of glass transition. Simultaneously, the loss, and therefore the hysteresis, pass through a maximum value.

What happens inside the material?

Any rise in temperature increases **molecular mobility** and so facilitates movement.

In order to have a better grasp of this phenomenon, take cooking oil. When the oil is poured into the pan, it flows slowly. However, as the pan heats up, the fluidity of the oil increases and it flows more easily.

When the temperature increases, molecular chains revert more quickly to their state of equilibrium and can withstand more frequent force applications without becoming stiff. The material remains flexible and elastic.

In addition, the "confinement tube", which is composed of other surrounding chains, becomes more flexible, as if it had expanded, and gives the molecule greater space to move about in.



Bale of natural rubber.

FREQUENCY-TEMPERATURE EQUIVALENCE

There is consequently an inversely proportional relation between an increase in the temperature of a rubber and a reduction in the frequency of the stress to which it is subjected.

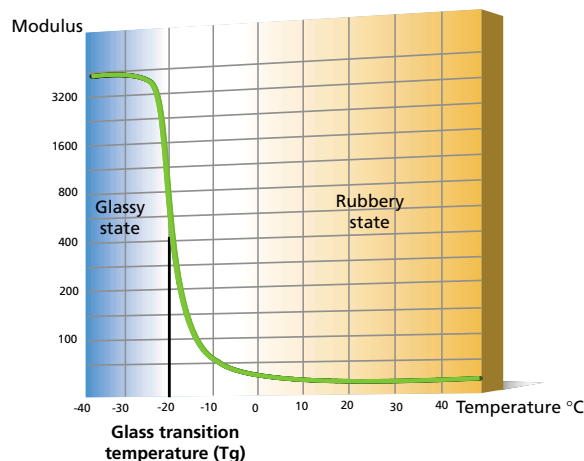
Whenever the stress frequency is increased at a given temperature, the material becomes rigid. Whenever the material heats up at a given stress frequency, it becomes softer.



It all comes down to a balance **between molecular velocity** - which increases with the temperature - **and speed of deformation**. If the speed of deformation is greater than the speed at which the molecule is capable of moving in its environment, the material appears rigid (glassy). If the speed of deformation is less, the material appears flexible (rubbery).

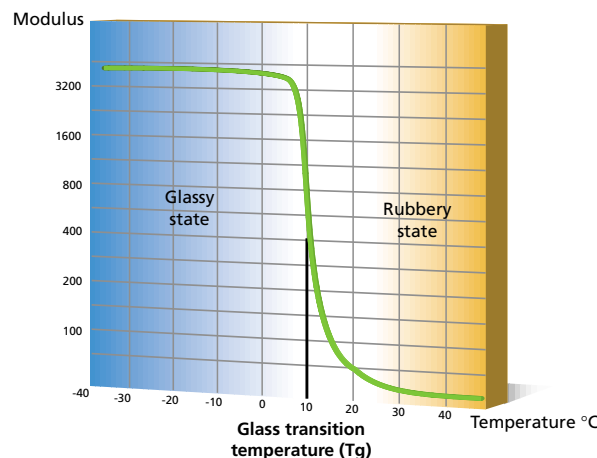
There is a law for determining frequency-temperature equivalence (which holds true for a given range). It is called the **WLF equation** (William Landel Ferry). To have an approximate idea, it can be considered that, in low frequencies (from 10 to 10^5 Hz), an increase in frequency by a factor of 10 has the same effect on the behaviour of the rubber as a 7 to 8°C drop in temperature.

For example, an elastomer with a **glass transition temperature** of -20°C at 10 Hz will have a glass transition temperature of about +10°C at 10^5 Hz.



for a stress frequency of 10 Hz

The above graph is plotted for a frequency of 10 Hz. Using the WLF equation, the graph can be calculated for other stress frequencies (see below).



for a stress frequency of 100 000 Hz

The rubber formula engineer is capable of obtaining compounds with a glass transition temperature of -60°C to 0°C at 10 Hz.



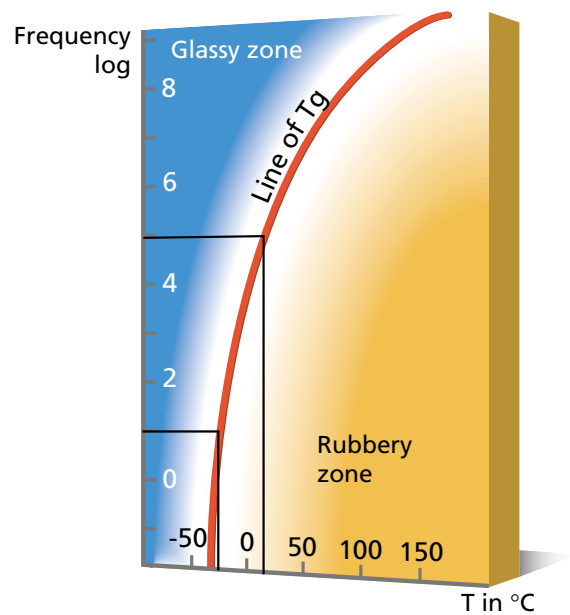
The composition of the rubbers used in tyre treads is chosen so that their modulus is fairly moderate (flexible behaviour), and their hysteresis is fairly high in the range of stress frequencies and temperatures encountered on the road. We shall see that deformability and viscosity are the two key factors in the mechanisms of grip.

A little more
information on...



the WLF equation

For any given rubber, the glass transition temperature increases with the stress frequency, which moves the vitreous state towards higher temperatures. This relation is given by the WLF equation.



I.3

The mechanisms involved in the rubber-road interface friction

Two stress mechanisms are involved in the relative slippage between the elastomer and the road surface.

- The first mechanism is the frequency excitation of the material by the road texture. The rubber is distorted when it slips over the rough spots on the road, the size of which varies from 1 centimetre (macrotexture range) to 1 micron (microtexture range). This mechanism is known as the **road roughness effect**. It is also described using the word **indentation**, which emphasises the penetration of road roughness into the rubber of the tyre tread.
- The second mechanism is **molecular adhesion**, which comes into play at a scale of one hundredth of micron, and is amplified by slippage.

In both cases, the visco-elastic properties of the rubber, and particularly its hysteresis, play an important role.

ROAD ROUGHNESS EFFECTS

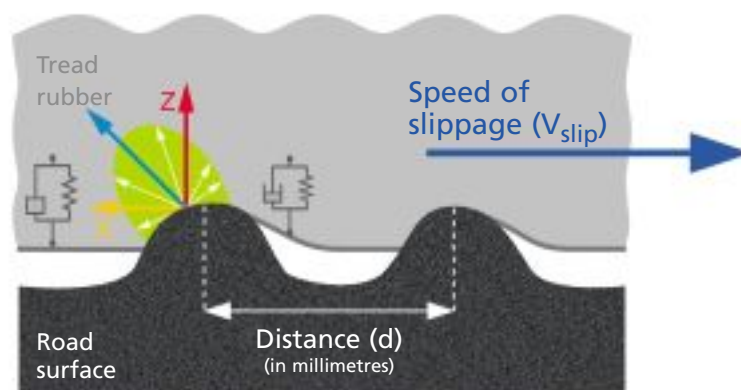
The flexibility of the rubber enables it to adapt to the shape of rough points on the road surface. Because rubber is viscous, the deformation of a tread block, as it moves over the road surface, can be compared to flow. The block strikes the rough spot and distorts, but, because of hysteresis, does not immediately return to its initial height on the other side of the rough spot.



The asymmetrical movement of the rubber over the rough spot generates reaction forces that counteract slippage.

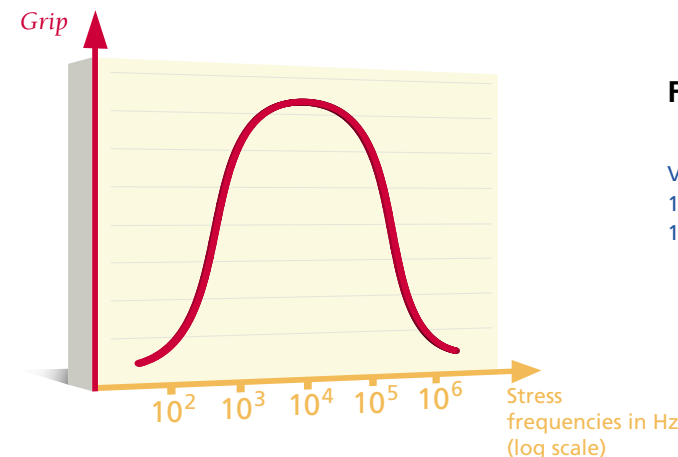


The road roughness effects on the tyre come from the small bumps on the road that measure a few microns to a few millimetres. Even in the presence of water, the phenomenon functions efficiently. The effect of the road roughness occurs within a range of stress frequencies between 10^2 and 10^6 Hz.



We can model the indentation by using a spring-damper assembly which undergoes a compression-relaxation cycle for a given deformation value. This generates hysteresis (and therefore an energy loss) in the damper at each cycle. The asymmetrical deformation of the rubber block around the rough spot generates a force field, in which the tangential force X opposes slippage.

Range of road roughness effects



$$\text{Frequency} = \frac{V_{\text{slip}}}{d}$$

Values:


$$1 \text{ m/s} < V_{\text{slip}} < 5 \text{ m/s}$$

$$10^{-6} \text{ m} < d < 10^{-2} \text{ m}$$

■ MOLECULAR ADHESION

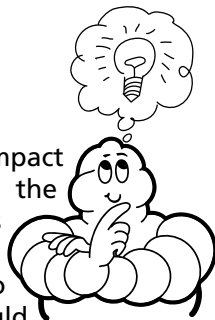
Adhesion results from molecular interactions occurring at the rubber/ground interface (Van der Waals* bonding). Bonds form, stretch and then break, to form again farther on.

The rubber's molecular chains therefore follow a cycle of stretching and breaking which generates visco-elastic work (friction between molecular chains in a certain volume of material). This work multiplies the bonding energy by a factor which can vary from 100 to 1000 depending on the temperature and the speed of slippage of the rubber over the road surface.

 **The essential condition for adhesion to be operative is for the rubber to be in direct contact with the road surface (distance between rubber and ground less than 10^{-6} mm), i.e. the road is clean and dry.**
Molecular adhesion occurs in a range of stress frequencies between 10^6 and 10^9 Hz.

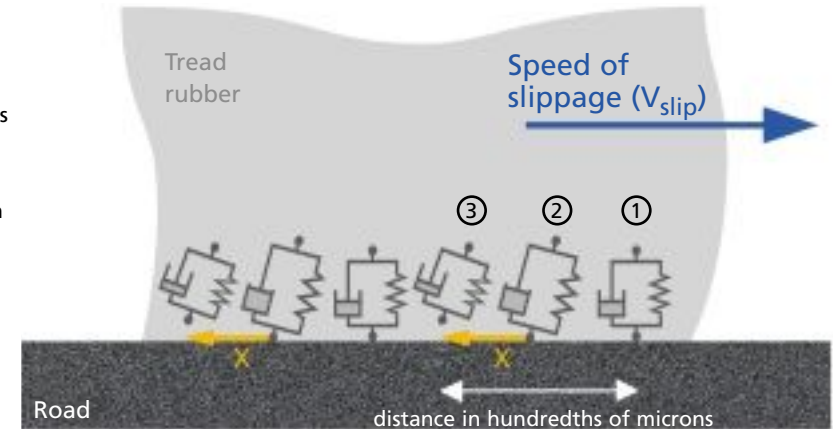
IN ORDER NOT TO SKID, THERE MUST BE MICRO-SLIPPAGE!

Of all the forces generated upon the impact of the rubber with the road, only the tangential resultant force opposes skidding. If the rubber did not slip over the ground, the forces of reaction to strain and of molecular bonding would not be tangential, but only vertical. Only the onset of slippage can generate forces which oppose skidding.

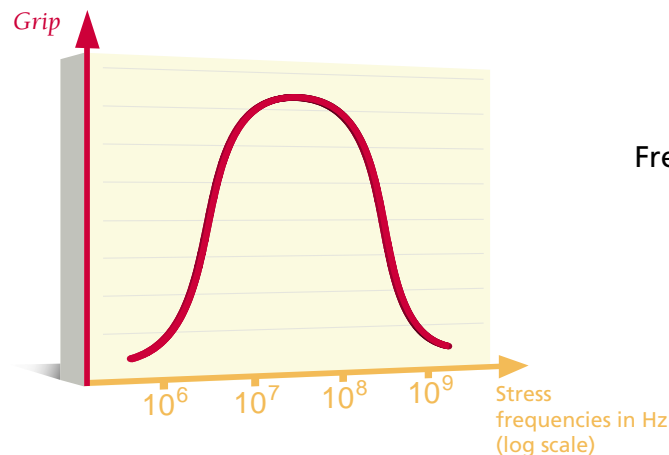


Stress cycle:

- 1 • The bond is created.
- 2 • The molecular chain is stretched: its viscous properties, represented by the piston, resist deformation, generating a friction force X which opposes skidding.
- 3 • The bond breaks and forms again farther on.



Adhesion frequency range



Frequency = number of cycles per second

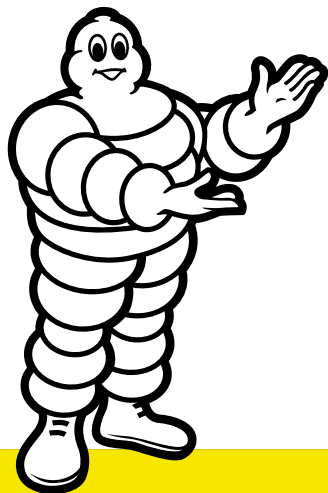
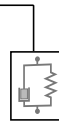
* Dutch physicist, winner of the Nobel prize, 1910.

I Rubber & grip

Rubber belongs to the family of **visco-elastic materials**, the behaviour of which can be symbolised by a

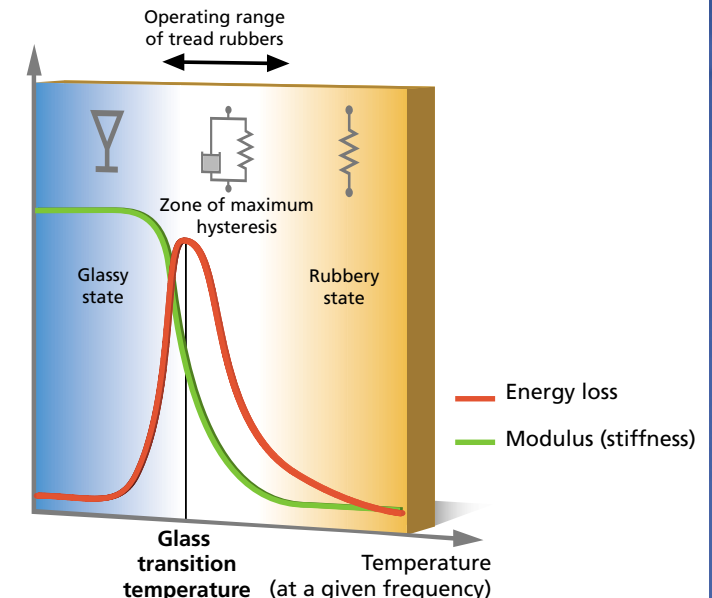
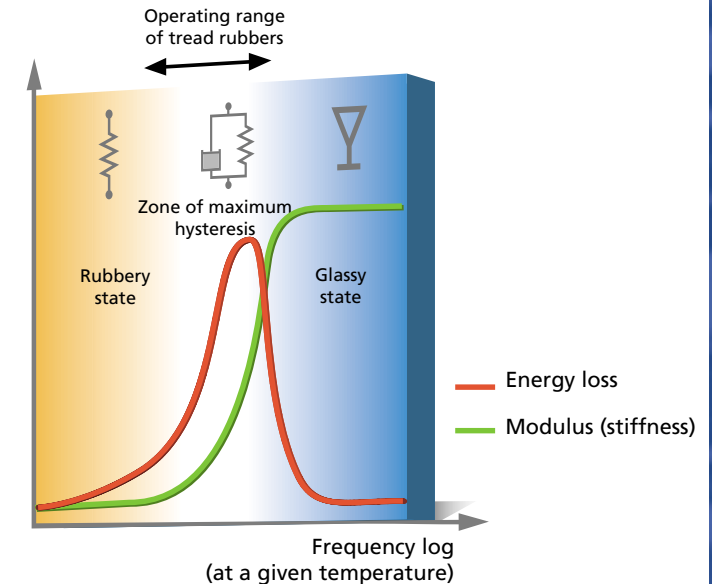
spring + piston assembly.

Visco-elastic materials revert to their original shape after being distorted. To recover their initial shape, a certain time is required. There is a delay between stress and strain. This is called **hysteresis** and the phase lag is accompanied by a **loss of energy**.



A rubber's flexibility, hysteresis and loss of energy vary according to the temperature and stress frequency:

- When the stress frequency increases, the rubber changes from a rubbery state to a vitreous state (hard and brittle).
- When the temperature increases, the rubber changes from a vitreous state to a rubbery state.
- It can be considered that, in the range of low frequencies (from 10 to 10^5 Hz), progression by a factor 10 in frequency has the same effect on the rubber's state as a 7 to 8° C drop in temperature.
- Rubber exhibits maximum hysteresis and suitable flexibility when it is close to its glass transition temperature (which increases with stress frequency). Consequently, tread rubber is designed so that it is in this state when the tyre is in service. Both the flexibility and hysteresis are conducive to friction which produces grip.

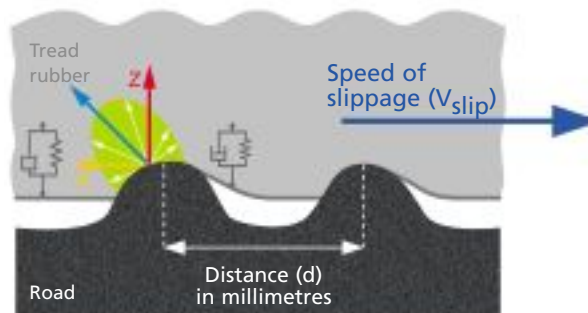


I Rubber & grip

Tyre grip results from the frequency excitation of rubber under the effect of slippage over the road.

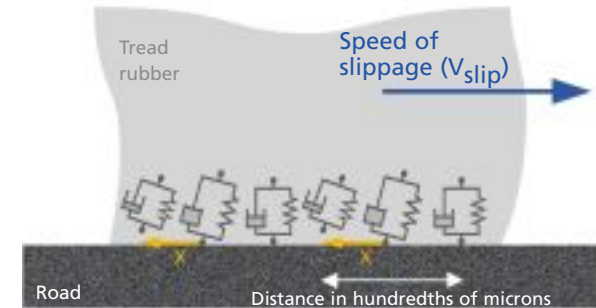
Two friction mechanisms come into play.

ROAD ROUGHNESS EFFECTS (INDENTATION)



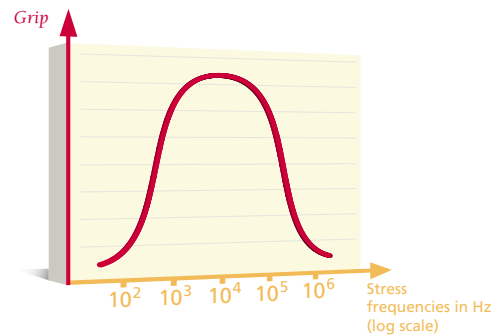
The tread block strikes against the rough spot and deforms, but, by a hysteresis effect, it does not immediately revert to its initial shape on the other side of the rough spot. This asymmetrical deformation generates a force field, the tangential resultant force of which (X) opposes skidding.

MOLECULAR ADHESION



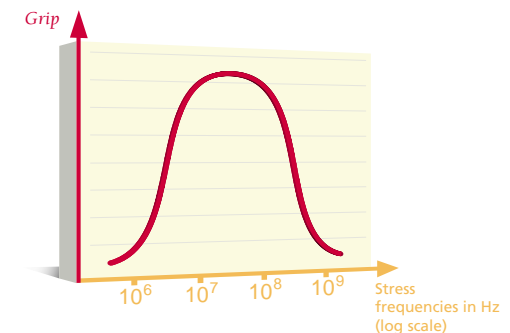
The molecular chain is stretched: its viscous properties, represented by the piston, resist deformation, generating a friction force X which opposes skidding.

FREQUENCY RANGE OF ROAD ROUGHNESS EFFECTS

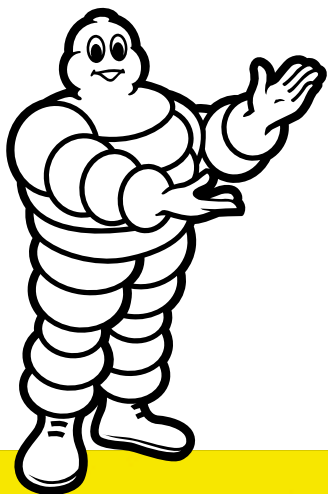


Road roughness continues to generate grip even when the road surface is wet.

MOLECULAR ADHESION FREQUENCY RANGE



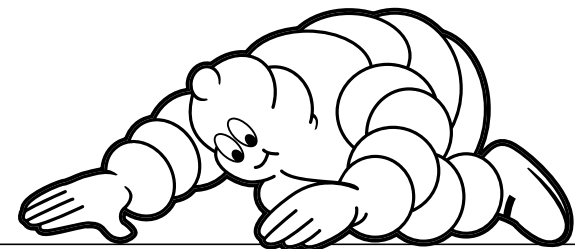
Surface wetness inhibits adhesion.





II *How road roughness affects grip*

Grip implies contact between two surfaces. In road grip, one is the tyre surface and the other is the road surface. Grip depends on the type of road surface and its state of repair, not to mention its roughness and whether it is wet or not.



II.1

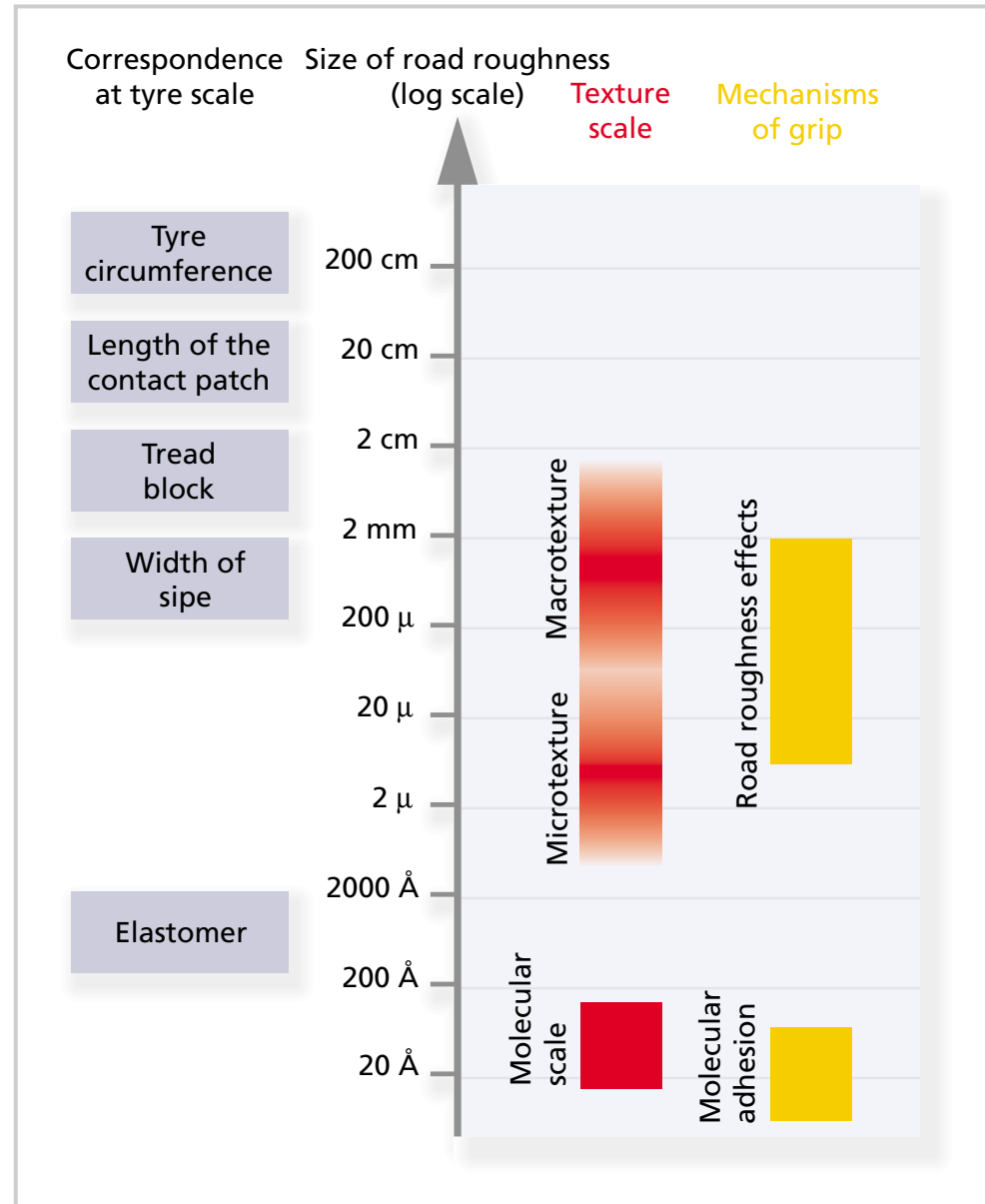
Characterisation of road surfaces

There must be contact between the tyre and the road for grip to be produced. Grip comes from road roughness effects and molecular adhesion.

Road roughness effects, a.k.a. **indentation**, require road surface "indenters", i.e. small bumps which will dig into the surface of the rubber.

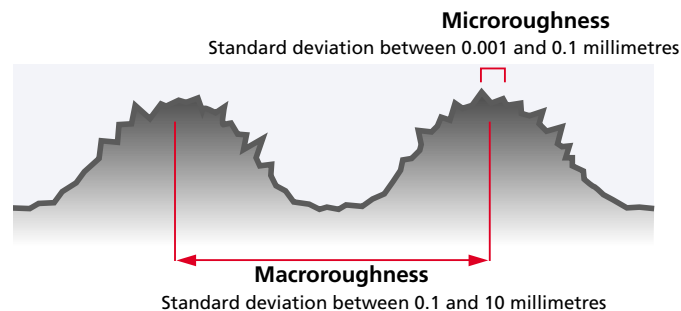
Molecular adhesion necessitates direct contact between the rubber and the road surface, i.e. the road must be dry. For water dispersal, the road surface offers two solutions:

- **drainage** of the water towards the sides of the road (camber, banking) or downwards (porosity);
- **storage** of the water in the pits of the surface so that the peaks of the bumps stand clear of it.



When considering tyre grip, several features of road surface geometry must be examined and assessed.

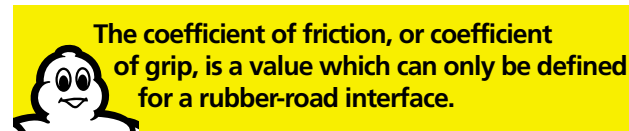
- **Macroroughness.** This is the name given to the road surface texture when the distance between two consecutive rough spots is between 100 microns and 10 millimetres. This degree of roughness contributes to indentation, and to the drainage and storage of water. Macroroughness is due to the size of the aggregates used in the composition of the road surface;



- **Microroughness.** This is the name given to the road surface texture when the distance between two consecutive rough spots is between 1 and 100 microns. It is this degree of roughness which is mainly responsible for tyre grip. Microroughness is related to the surface roughness of the aggregates and sands used in the composition of the road surface;

- The **load bearing surface**, which depends on road roughness, must also be considered since it determines local pressures in the contact patch.

The road surface can also be characterised by measuring its **coefficient of friction** with a reference rubber block or reference tyre.



Although engineers often speak of the friction coefficient of a road surface, a matching rubber or tyre, as well as specific surface conditions (dry, damp, wet, new, worn, etc.), are self-understood. The expression **friction coefficient** must consequently be used with caution.

■ MEASUREMENT OF MACROROUGHNESS

Macroroughness can be measured on the road surface, on a road core sample, or on a moulding made of the surface. Optical sensors are used to measure the "height" of surface irregularities. Another method consists in levelling out a determined volume of standardised sand over the surface of the road in a circular patch. The circular area of the spread sand is then measured to calculate the mean height of the asperity voids in the road surface*.

* This method requires several measurements in order to be representative and cannot be used for draining mixes.

■ MEASUREMENT OF MICROROUGHNESS

Microroughness is assessed by indirect methods. In particular, the size of **microroughness** can be evaluated by taking aggregate surface photos with an optical or electron microscope. These photos are then compared with a subjective scale, graduated from 1 (for an extra-smooth standard road surface) to 100 (for an extra-rough standard surface).

Concepts regarding road surfaces

Road surfaces are made of mineral **aggregates** obtained by crushing hard rocks of sandstone or granite, for example, as well as of **sand** and **finer**, that are all bound together by bitumen most of the time.

The size of the aggregates, which are the main components, ranges from 6 to 14 mm.

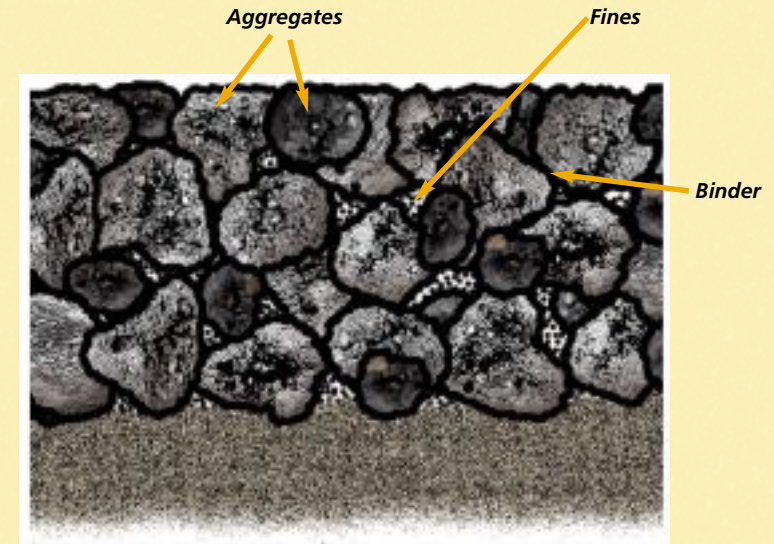
Road surfaces can be made by applying a coat of bitumen to the road, and then spreading the aggregates over it: these are called **surface coatings**.

Most often however the aggregates, sands and fines are hot-mixed with the **binder** to produce bituminous concrete which is then laid down on the road and compacted. These are known as **bituminous mixes**.

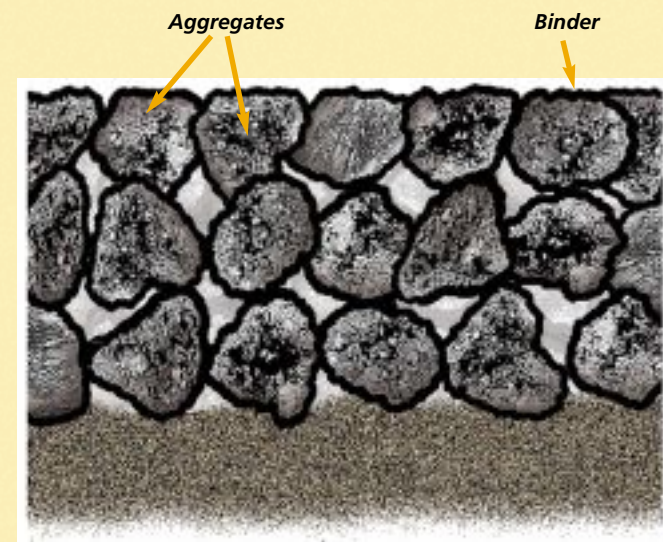
Standards define a wide variety of bituminous mixes, which are designed for different applications, such as support layers or surface layers.

For **bituminous concretes**, the various sizes of aggregates, sand and fines are distributed in such a way that the gaps between them is as small as possible, which gives the whole surface good mechanical cohesion and sealing.

In **draining mixes**, the size of the aggregates used leaves empty spaces to enable the water to permeate downwards.

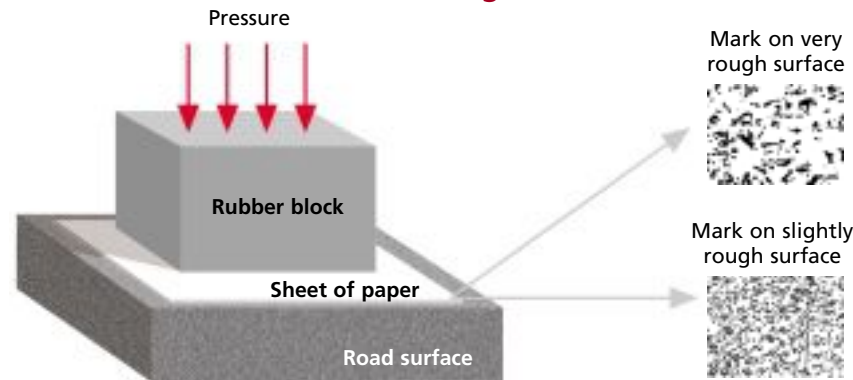


Standard road surface: bituminous concrete, in which the fines occupy the space left by the large aggregates, giving the whole surface good mechanical compactness.



Draining mix: rain water can flow into the spaces left between the aggregates. The binder ensures "bonding" at the points of contact between the aggregates.

Measurement of the load bearing surface



The marking on the sheet of paper indicates the amount of load bearing surface for a given rubber and the mean pressure on the rough spots.




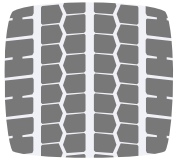




MEASUREMENT OF THE LOAD BEARING SURFACE


This measurement consists in determining what proportion of the area of a rubber block, compressed on a road surface at a given pressure, is actually in contact with the surface.

One method consists in taking an imprint of the contact between the block and the ground.

The results of this measurement show that, in general, only 5 to 10% of the block's surface bears on the irregularities in a new road surface.

Percentage of contact with the road and pressure in the contact patch

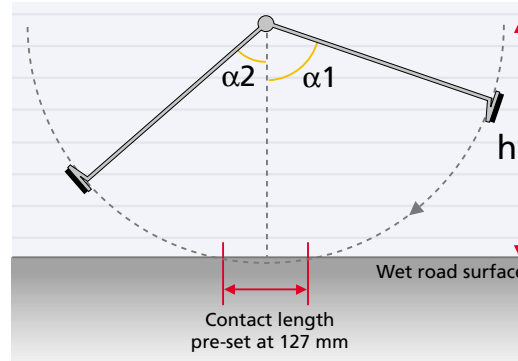
| |  2 bars  150 cm ² | |  8 bars  500 cm ² | |
|--|--|--|--|--|
| Inflation pressure | 2 bars | | 8 bars | |
| Rubber/void percentage | 30 % | | 30 % | |
| Mean pressure in the contact patch | 3 bars | | 11 bars | |
| Percentage of rubber in contact with the road (load bearing surface) | on very rough surfaces  7% | on slightly rough surfaces  60% | on very rough surfaces  7% | on slightly rough surfaces  60% |
| Local pressure on rough spots (mean value) | 43 bars | 5 bars | 157 bars | 18 bars |

 For a Car tyre, the load bearing area on a new road surface is 7 to 15 cm², and develops local pressures of 40 bars or more. For a Truck tyre, the load bearing area is 25 to 50 cm² and the local pressures reach 150 bars or more. On a worn road surface, microroughness is less and the local pressures decrease.

N.B. 1 bar = 10⁵ Pa = 15 p.s.i



Operation of the Skid Resistance Tester



The SRT pendulum is used to determine the characteristic coefficient of friction for a given rubber on a wet surface. The friction of the block on the surface is representative of a slippage speed of 3 m/s.



■ CHARACTERISATION OF THE FRICTION COEFFICIENT OF A RUBBER-ROAD INTERFACE

Measurement using a rubber block

This measurement is made using an instrument known as the SRT (Skid Resistance Tester).

On the end of the pendulum there is an elastic support to which a rubber block is attached. The block is dragged over a wet surface when the pendulum swings. The height of the pendulum is set so that the friction travel over the surface is calibrated. The initial energy of the system is calculated using the angle α_1 , the residual energy after friction on the surface is calculated using the rise angle α_2 . The difference between the two angles indicates the energy consumed by friction, which characterises the grip of the rubber-wet road interface.

Measurements on reference tyres

Measurements are made of the forces developed in the contact patch of a tyre, "dragged over" a wet road surface under given conditions of speed, load and inflation pressure.

There are two types of measurements:

- Either the wheel is prevented from turning ("locked wheel" situation) and the torque on the hub is measured, the **longitudinal grip coefficient** being then calculated using the torque value;
- Or the wheel is free to rotate, but with a given slip angle. This generates a self-aligning force which is subsequently measured so that a **coefficient of transversal friction** can be computed.

II.2

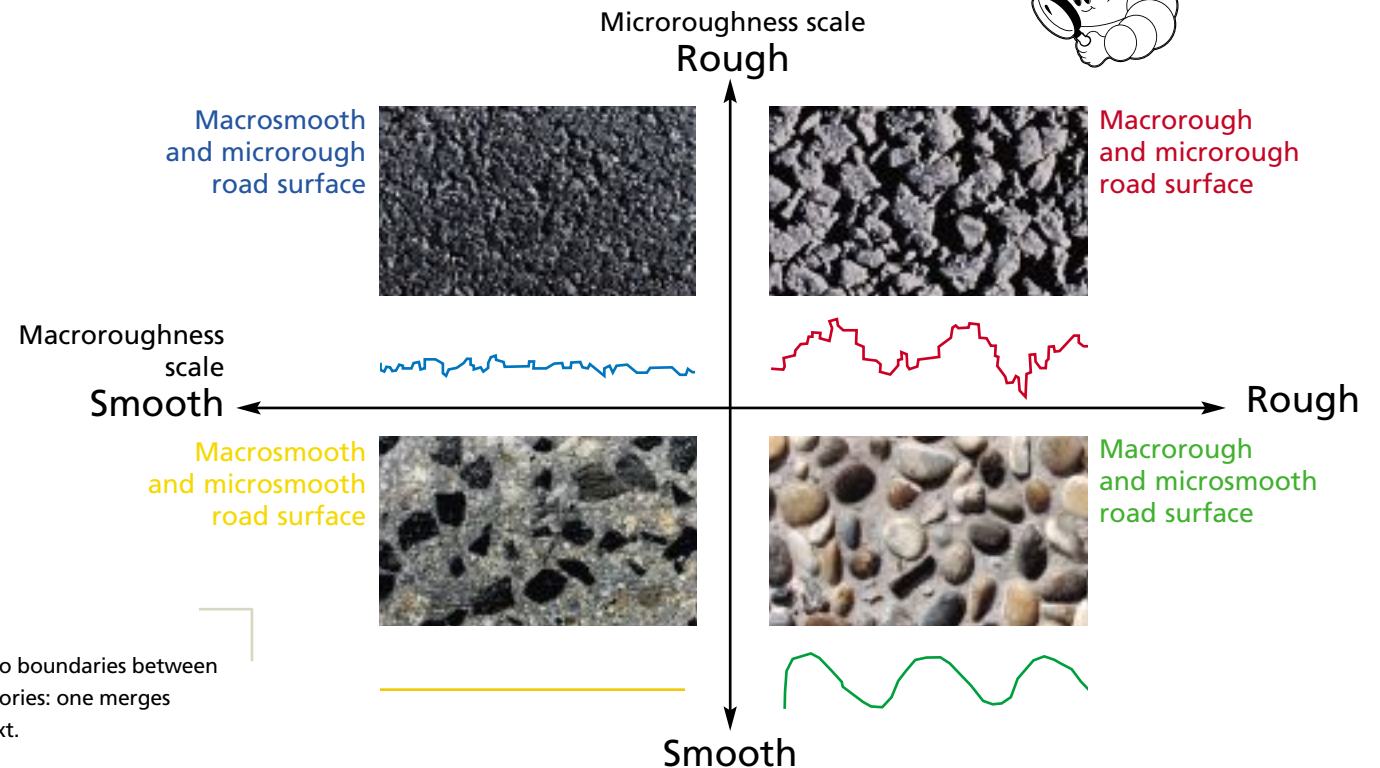
Influence of road surfaces on the coefficient of friction

As an initial approximation, road surfaces can be classified into four categories.

It has been observed that the value of the coefficient of friction - or coefficient of grip - μ on a dry road surface is always between 1 and 1.3*. However, on a wet surface, the coefficient of grip is always worse and varies enormously with the nature of the surface.



* Values for μ_{\max}



N.B.

There are no boundaries between these categories: one merges into the next.



■ VARIATION IN FRICTION COEFFICIENT ON A DRY SURFACE

Variations in the friction coefficient on dry surfaces are slight, and we might consider, at first glance, that on all dry surfaces the coefficient of grip is close to 1. However, we find slight variations (from 1 to 1.3) which are explained by the fact that the "efficiency" of the molecular adhesion and road roughness effects depend on the road surface texture.

Molecular adhesion

The molecular adhesion mechanism requires direct contact between the rubber and the road surface. It therefore depends on the load bearing surface in the contact patch, which, for a given tyre and inflation pressure, reduces when the roughness of the surface increases. However, surface roughness is part of one of the two grip mechanisms.

Roughness effects (indentation)

As soon as the rubber starts to slip over the road surface, the macroroughness and microroughness of the surface cause a frequential excitation of the rubber over a whole frequency range. This is also

described using the word **indentation**, which emphasizes the penetration of road roughness into the rubber of the tyre tread.

Examples of stress frequencies, in Hz

| Roughness | Frequencies for $V_{\text{slip}} = 1 \text{ m/s}$ | Roughness | Frequencies for $V_{\text{slip}} = 5 \text{ m/s}$ |
|--------------------------|---|-----------------------------------|---|
| macroroughness of 1 cm | 10^2 | microroughness of 0.1 mm | $5 \cdot 10^4$ |
| macroroughness of 0.2 mm | $5 \cdot 10^4$ | microroughness of 1 μm | $5 \cdot 10^6$ |

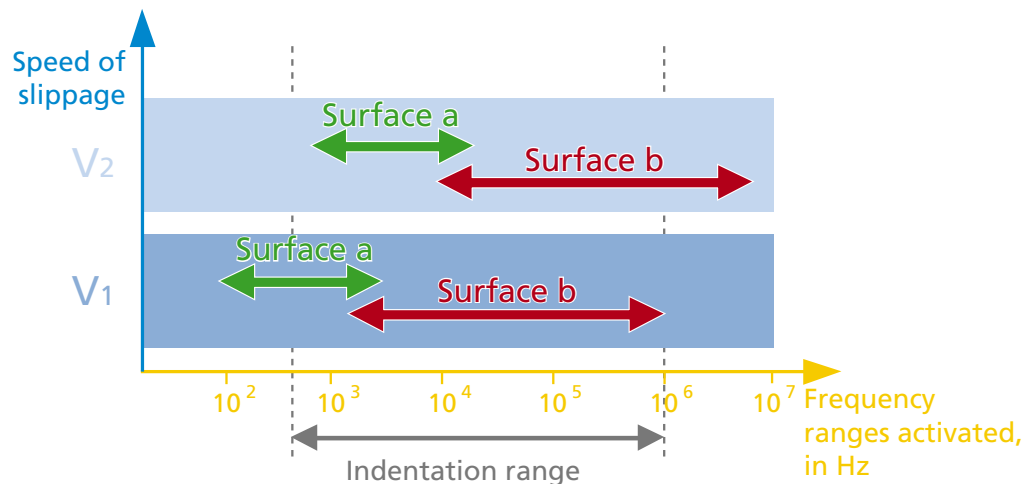
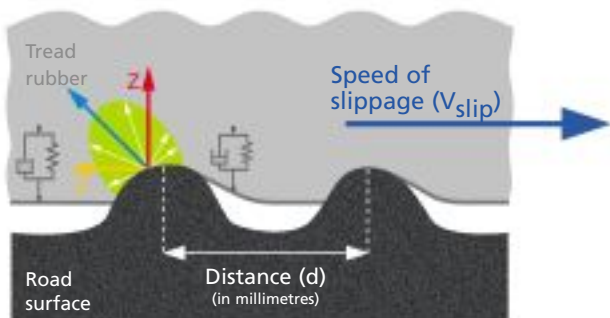
The excitation frequency band depends on the distance between surface irregularities and the speed of slippage (V_{slip}) of the rubber over the road surface.

In reality, a road surface contains macro-indenters and micro-indenters of different scales and excites the tread rubber over an entire frequency range. The frequency bands activated by indentation

therefore vary according to the combination of "type of surface and the speed of slippage".

The characteristics of tread rubber are such that, when tyre operating frequencies and temperatures greater than T_g are considered, hysteresis increases when stress frequency increases. Since hysteresis is the key parameter in the efficiency of the indentation mechanism, the grip caused by indentation at a given speed of slippage improves when the scale of the surface irregularities decreases. However, this equation is only true if the frequencies scanned remain between 10^2 and 10^6 Hz (frequency range of indentation), and provided that the rubber is not overheated by sharp braking.*

** When braking sharply, in the absence of an anti-locking brake system (ABS), the vehicle's wheels may lock, and the temperature in the contact patch may quickly reach 200°C. Temperatures such as these lead to tread rubber crumbling - we leave skidmarks on the road surface - and indentation efficacy decreases.*



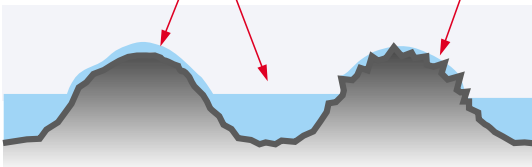
■ VARIATION IN FRICTION COEFFICIENT ON DAMP OR WET ROAD SURFACES

On a **damp surface**, the friction coefficient is always worse and varies enormously with the type of surface. This is because a film of water between the rubber and the road prevents the **molecular adhesion** mechanism from working, unless this film is broken. However, the **indentation** mechanism, which is vital to grip, is still operational.

On a damp surface, we find that microrough road surfaces give the best grip, macroroughness playing a secondary role.

Macroroughness drains and stores water but does not break through the residual film of water

Microroughness, by creating individual high-pressure points between the surface and the tyre, breaks through the film of water

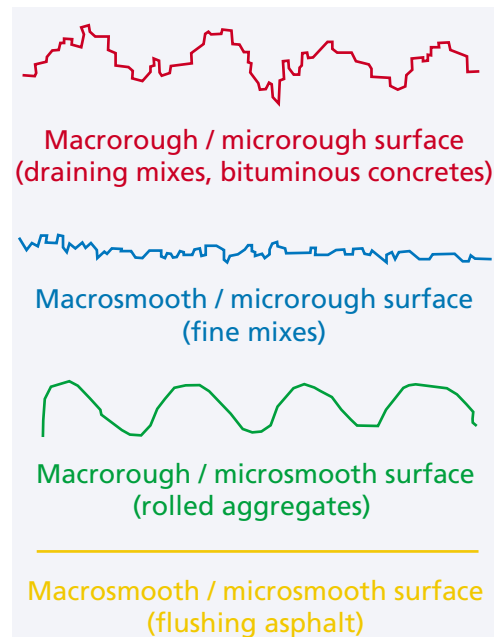


If the depth of water increases (**wet surface**), microroughness may become flooded. Macroroughness continues to indent, drain and store, but there is a risk of aquaplaning at high speed.

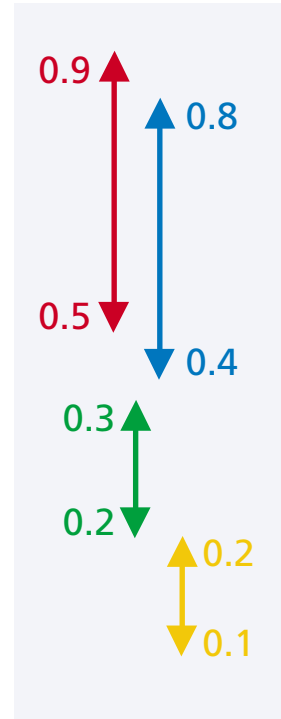
Water therefore interferes with grip and the tyres must be designed to disperse this water quickly and effectively by adjusting the shape of the contact patch, the tread pattern and the sipe arrangement.

How road surfaces affect grip

Types of road surface



Coefficient of friction in damp and wet conditions



Coefficient of friction on a dry road surface

On all dry road surfaces, the coefficient of grip is between 1 and 1.3.

■ RELATIVE IMPORTANCE OF THE RUBBER FACTOR AND THE ROAD SURFACE FACTOR IN GRIP

Changing from one type of road surface to another has more effect on the coefficient of grip than changing from one tread compound to another.



■ WHAT ABOUT SNOW?

Depending on the temperature and the mechanical compaction work caused by the passage of vehicles, snow passes through different states which are similar to other types of surface:



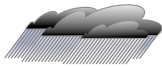
- melting snow is similar to water (dealt with later);
- fresh, deep snow is similar to a crumbly surface (not dealt with in this book);
- compact, cold snow is like dry ice.





■ AND WHAT ABOUT ICE?

At very low temperatures, ice is dry and is similar to a microrough surface (microroughness of 10^{-6} m) and produces micro-indentation and molecular adhesion. However, in microroughness, asperities are very small and easily become flooded.

At temperatures between -5 and 0°C , the pressure of the tyre on the road causes slight surface melting of the ice, which is in turn covered by a thin film of water. The ice is then like a flooded microsmooth surface.

Snow and ice are cold surfaces which require the use of tyre compounds that retain a moderate modulus at low temperatures*.

| Effect of road surface variations on grip (for a given tyre) | | |
|---|---------------------|---|
| | Coefficient of grip | |
| Any dry surface | 1 à 1.3 |  |
| Damp surfaces | |  |
| • Macro- and micro-rough surfaces | 0.7 | |
| Wet surfaces | |  |
| • Macro- and micro-rough surfaces | 0.6 | |
| • Macro- and micro-smooth surfaces | 0.2 | |
| Maximum coefficients of grip (μ_{\max}) measured for an MXV3A tyre on different surfaces: dry surface, damp draining mix, wet bituminous concrete with depth of water = 2 mm, wet polished concrete with depth of water = 2 mm. | | |

| Effect of the rubber compound on grip (for a given damp surface and a given tyre) | | |
|---|---------------------|---|
| | Coefficient of grip | |
| Competition compound | 0.8 |  |
| Car compound 1 | 0.7 |  |
| Car compound 2 | 0.6 |  |
| Truck compound | 0.55 |  |
| Maximum coefficients of grip (μ_{\max}) of an MXT 175/70 R 14 tyre on a damp draining mix, for different tread compounds. | | |

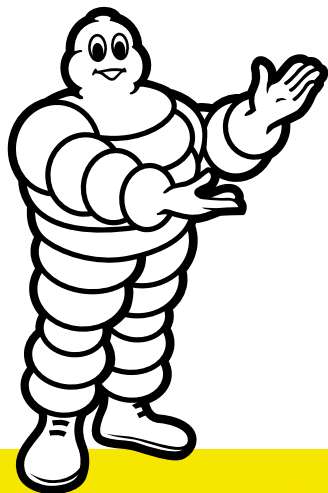


* See the chapter concerning the influence of temperature on the behaviour of rubber on page 14.

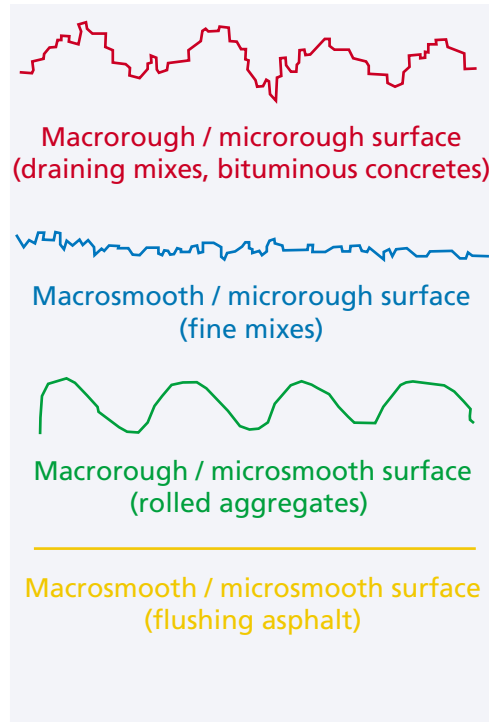
II How road roughness affects grip

- In order to grip, the tyre must be in contact with the road surface, which activates the grip mechanisms, i.e. indentation and molecular adhesion.
- The friction coefficient of a surface can be characterised for a given rubber.
- In DRY WEATHER, this friction coefficient depends very little on the type of surface. It is always close to 1*.
- In WET WEATHER, the coefficient depends very much on the type of surface.

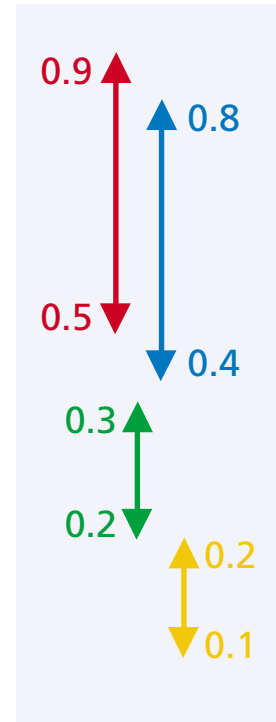
* Values for μ_{\max}



4 typical types of road surface



In damp or wet conditions, coefficients of friction differ greatly



Molecular adhesion is possible because the high-pressure points produce dry contact between the road surface and the tyre.

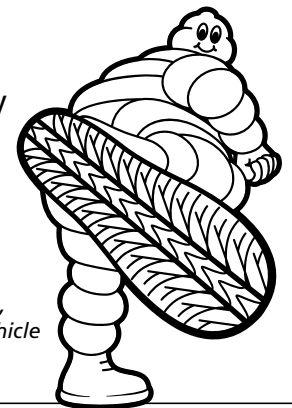
Molecular adhesion is impossible.

III Generation of grip forces *in the contact patch*

Grip is necessary to keep a vehicle on its course, even when it is straight and the speed is constant. The natural forces which constantly tend to push the vehicle off-course or slow it down must be counteracted. Examples of the origin of these forces are wind, road camber, gradients, surface irregularities and rolling resistance. When the vehicle is subjected to these forces, the contact patch naturally becomes the centre of micro-slippage which activates the mechanisms of molecular adhesion and indentation between the rubber and the road surface.

However, grip is involved mainly in two types of situation: when we alter the vehicle's speed (deceleration - acceleration)* and when we modify its direction (cornering). These two situations involve the two components of grip: longitudinal grip and transversal grip.

*As the mechanisms involved in braking and acceleration are comparable, we shall concern ourselves here mainly with braking, which is vital for vehicle safety.

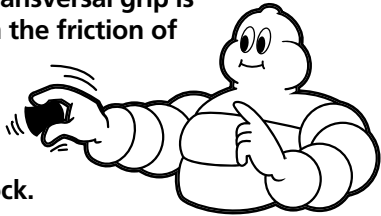


III.1

Friction mechanisms of a rubber block

Whether longitudinal or transversal grip is involved, grip results from the friction of the tyre tread blocks on the road surface.

We shall therefore look first of all at what happens to the rubber block.



We have seen that a tyre's contact patch is almost immobile in relation to the road surface. It moves along like a caterpillar track, with micro-slippage in relation to the road surface. Thus, at each wheel revolution, the tread blocks which come into contact with the road surface do not roll on the surface. They behave like friction pads. Let us look at what happens.

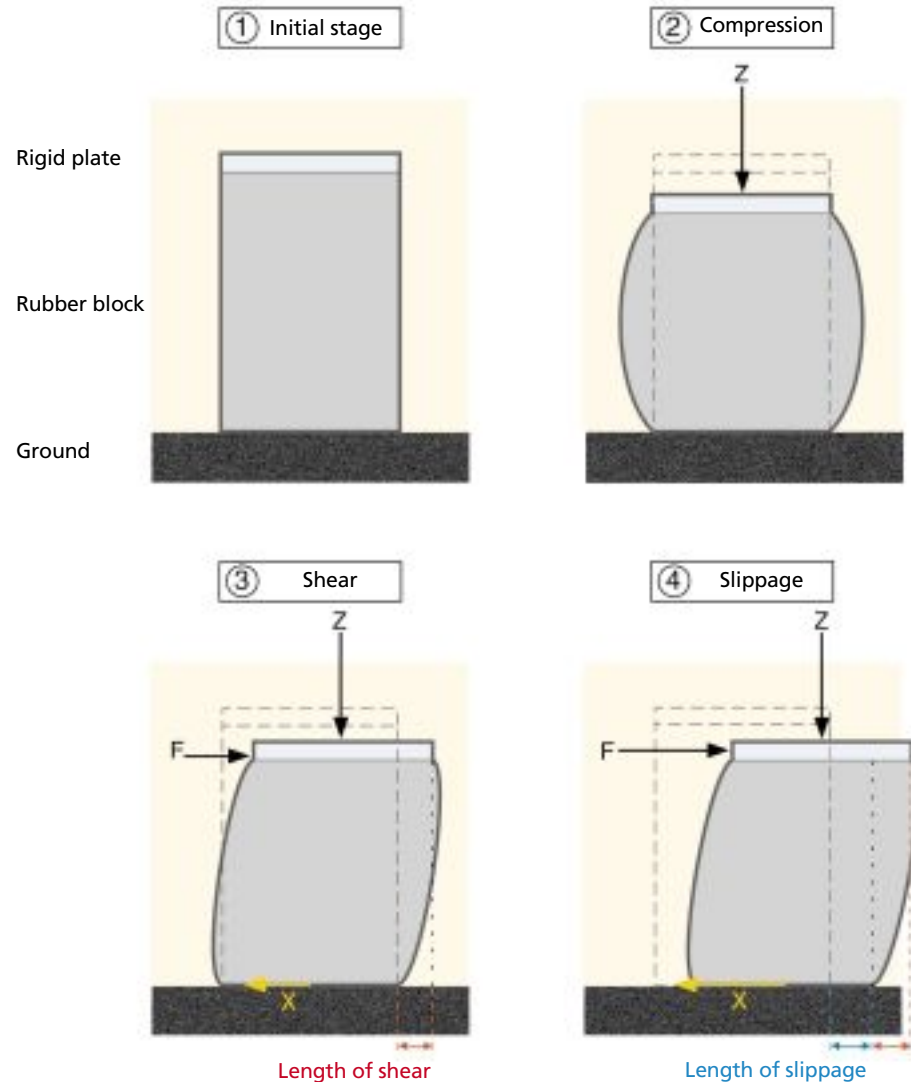


■ SHEAR (OR PSEUDO-SLIPPAGE)

Let us consider a block of rubber to which a rigid plate has been secured. The block is compressed on the ground by a force Z , perpendicular to the ground.

A force, F , is applied to the plate, parallel to the ground and its magnitude gradually increases. At the beginning, the rubber block deforms without slipping on the surface. This is **shear**. From this it can be deduced that rubber-surface contact produces a resistance force, equal in magnitude and opposite in direction to force F . This resistance force is called the **friction force**, X .

Shear and slippage of a rubber block



This phase is also called “**pseudo-slippage**”, as everything takes place as if the plate had slid in relation to the road surface. In fact, slippage is already occurring at molecular level, but with an amplitude far too small for the interface to move perceptibly in relation to the surface. The rubber’s deformation capacity will determine the extent of this pseudo-slippage.

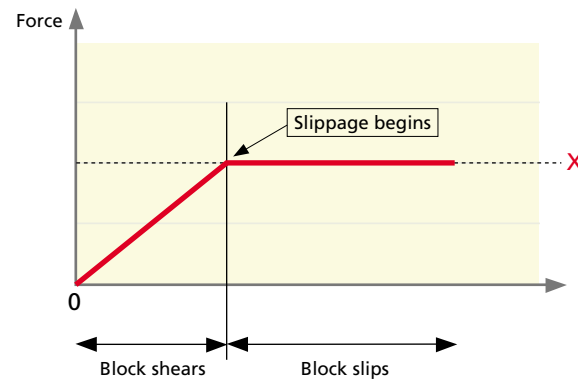
■ SLIPPAGE

If force, F , continues to increase, the rubber block will start to slip over the surface, whilst retaining its maximum shear. We obtain “true” slippage at the rubber-ground interface.

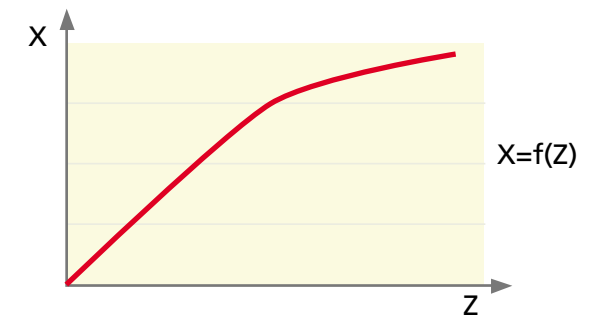
In fact, there is a value of force, F , beyond which the rubber-ground interface can no longer resist. The block rubs on the ground generating a friction force X , which has reached its maximum level.

This maximum friction force is called **Coulomb’s Friction Force**.

Beginning of slippage



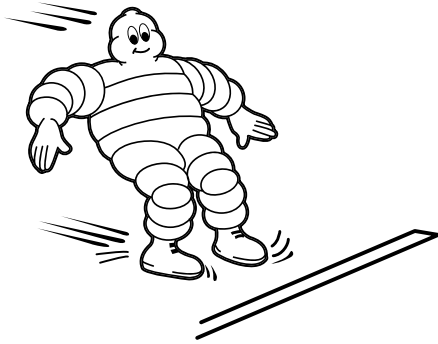
N.B For moderate loads, such as those exerted by vehicles, the friction force X is a linear function of the load Z .



III.2

Longitudinal grip in braking

Braking is essential for the safety of drivers. The contact patch is the ultimate transmission component between the brake pedal and the road surface. Let us look at what happens.



SOURCE OF SLIPPAGE

Consider a vehicle travelling in a straight line at a certain speed. When the driver presses on the brake pedal, braking torque is applied to the four wheels of the vehicle via the braking circuit.

At this moment, the angular speed of the wheels decreases and the rolling speed of the tyre drops below the vehicle speed. To compensate for this difference, the tyres begin to slip on the road at a **slippage rate G**.

During slippage, molecular adhesion and indentation induce a friction force, which opposes slippage, and the vehicle slows down.

Slippage rate G

Wheel slip is a measurement of the difference between vehicle velocity and the rolling velocity of the tyre at its point of contact with the road, which gives the following ratio G, called slippage rate:

$$G = \frac{\omega \cdot R - V}{V}$$

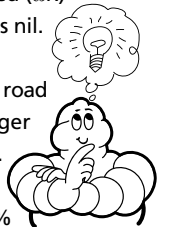
where: ω is the angular speed of the wheel
R, the rolling radius
V, the vehicle's speed
 ωR , the rolling speed of the tyre

Main values for G

G < 0: braking slippage
G > 0: drive slippage
G = 0: free wheeling
G = -1 or -100 %: wheel locked
G = + ∞ : wheel spin - vehicle speed nil

The two extreme cases, "spinning on the spot" and "wheel locked", which we have all experienced on snow-covered or icy road surfaces, enable us to have a better understanding of this concept of slippage.

- When we try to start a vehicle on a hill, or on icy or snowy roads, the wheels very often spin. The wheels go round, but the vehicle does not move forward. The wheel rolling speed (ωR) may be high, but the vehicle's speed (V) remains nil. Slippage is infinite.
- Conversely, when we brake too sharply on an icy road surface, the vehicle's wheels lock (they no longer turn), but the vehicle continues to slide forward. The wheel rolling speed (ωR) is nil, but the vehicle continues to move. Slippage represents 100 % of the distance covered.



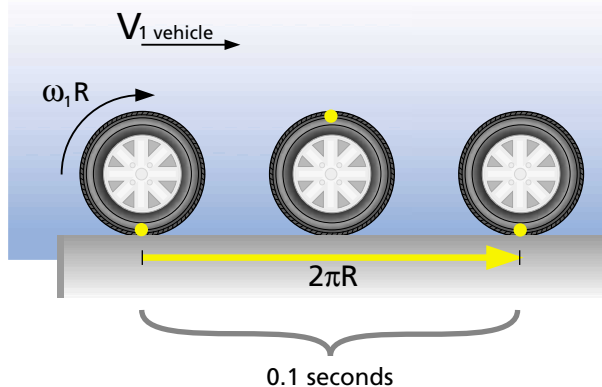
A little more information on...

slippage and braking

**1 BEFORE BRAKING**

It is assumed that the wheel makes one revolution within a length of time t (about 0.1 seconds for a car travelling at 70 km/h).

In 0.1 seconds, the distance covered by the wheel (and thus by the vehicle) is equal to one wheel revolution ($2\pi R$).



$$V_{1\text{ vehicle}} = V_{\text{wheel}} = \omega_1 R$$

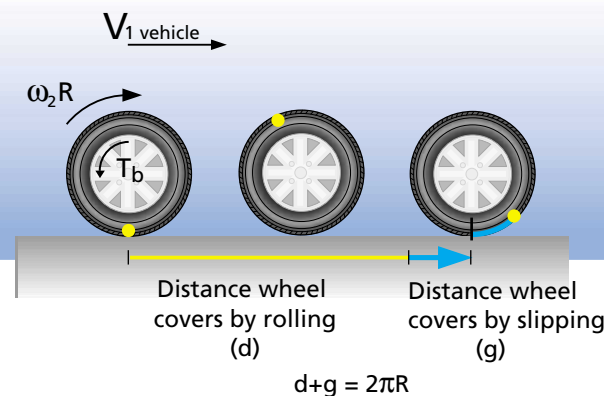
Symbols:

ω : angular speed of the wheel
 R : rolling radius
 T_b : braking torque
 ωR : rolling speed

2 DURING BRAKING

When the driver presses on the brake pedal, the tyre's rolling speed (ωR) drops below the speed of the vehicle.

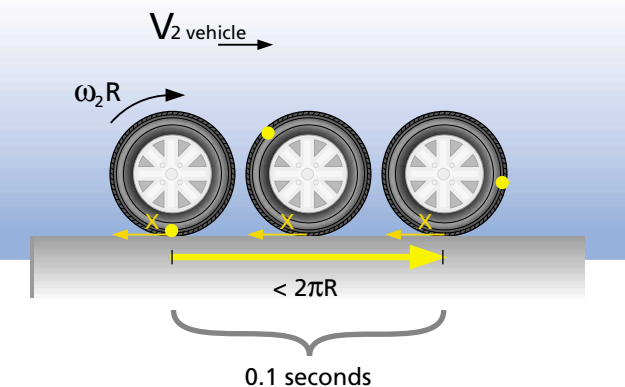
From this moment on, when the vehicle covers a distance equal to $2\pi R$, the wheel no longer does a complete revolution. To follow the vehicle's forward movement, it **rolls** and **slips** on the road surface.



$$V_{1\text{ vehicle}} > \omega_2 R$$

The slippage of the wheel over the road surface excites the grip mechanisms, i.e. molecular adhesion and indentation. Force X opposes slippage and the vehicle slows down (V_{vehicle} decreases, tending towards ωR).

In 0.1 seconds, the wheel now covers a distance of less than $2\pi R$.



$$V_{2\text{ vehicle}} = \omega_2 R$$

If the driver stops pressing the brake pedal, V_{vehicle} once again becomes equal to ωR . Slippage ceases.

■ LONGITUDINAL FRICTION FORCE

This **friction force, X**, depends on the **load, Z**, of the vehicle on the road surface, and on the type of road surface and tread compound. The force is defined by:

$$X = \mu \cdot Z$$

where: X is expressed in daN,
Z is the load of the vehicle on the road, in daN,
and μ , the coefficient of friction of the rubber road interface.

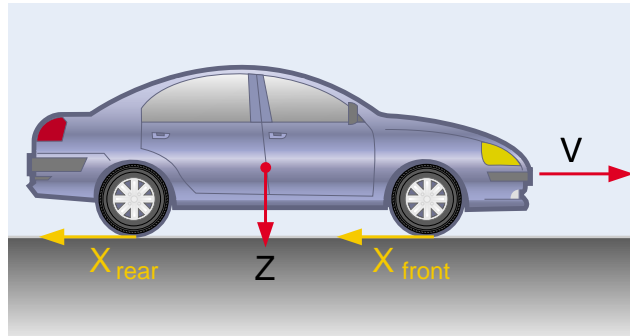
■ LONGITUDINAL FRICTION COEFFICIENT μ

The longitudinal friction coefficient, μ , is thus defined by:

$$\mu = \frac{X}{Z}$$

This coefficient is an abstract notion which illustrates the grip potential offered by a rubber-road interface.

The coefficient μ depends on the nature of the rubber and the road surface, and also on their general condition (temperature, cleanliness, presence of water, etc.). For a given rubber-road surface interface, μ depends very little on the load Z, but varies greatly as a function of the slippage rate G.



V: speed of the vehicle

$X = X_{\text{rear}} + X_{\text{front}}$: overall road surface-vehicle friction force (of all four tyres)

Z: load of the vehicle on the road surface.

Even though this coefficient is an abstract notion, its value can be attached to a real quantity, since it is equal to the deceleration* induced by the friction force X at the time of braking (see opposite).

Symbols:

The symbol μ designates the friction coefficient of a rubber-road interface. However, when we distinguish longitudinal and transversal grip, the symbol μ designates the coefficient of longitudinal grip, as opposed to τ , which designates the coefficient of transversal grip.

* expressed in number of g

A little more information on...



the coefficient of longitudinal friction

THE COEFFICIENT OF LONGITUDINAL FRICTION IS EQUAL TO THE DECELERATION (EXPRESSED IN g)

By applying the fundamental principle of dynamics to the centre of gravity of the vehicle and designating x as the displacement of this point, we have:

$$\mu = \frac{X}{Z}$$

$$X = M\ddot{x}$$

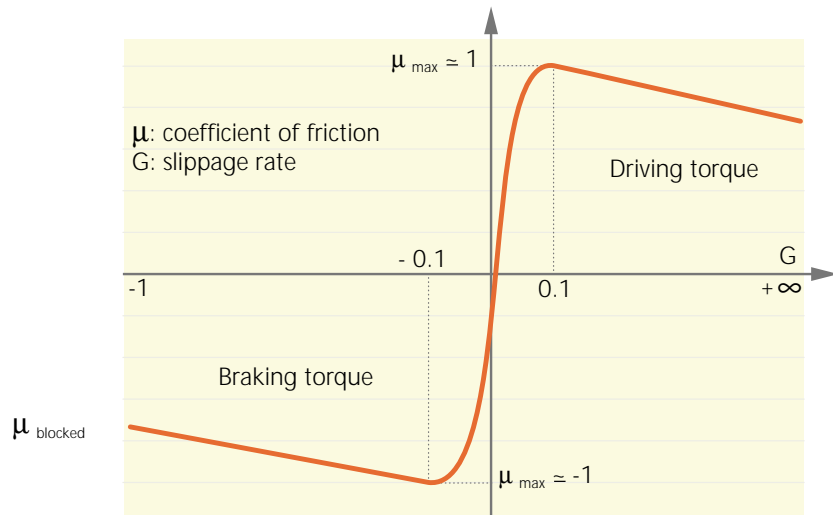
$$\text{and } Z = Mg$$

$$\text{hence } \mu = \frac{\ddot{x}}{g}$$

where \ddot{x} denotes the deceleration, in m/s^2 ,
M is the mass of the vehicle, in kg,
g is the acceleration caused by the force of gravity.

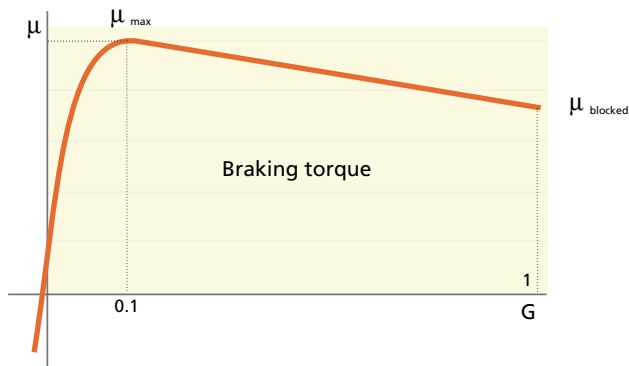
Longitudinal grip in braking

Law $\mu(G)$



N.B.

- For a Car tyre, the form of the curve is identical in both braking and driving torque.
- For a Car tyre, μ_{\max} is generally reached for a slippage rate between 5 and 15 %.
- The slippage rate for which the μ_{\max} is reached decreases when the vehicle's speed increases.



For reasons of convenience, in the rest of the document we will represent the part of the curve corresponding to braking torque in the upper right quadrant of the graph, with G and μ braking expressed in absolute values.

■ THE LONGITUDINAL FRICTION LAW $\mu(G)$

Firm sustained braking consists of 2 phases.

- An increase in deceleration, which corresponds to a rise of the friction coefficient to μ_{\max} , with a slippage rate close to 0.1 (i.e. 10%).



The harder the driver presses the brake pedal, the more the vehicle decelerates. This is the case for gentle braking.

- Then, a deterioration in braking occurs. If the vehicle has no ABS*, the wheels lock and the coefficient of friction drops from μ_{\max} to μ_{blocked} within approximately 0.2 seconds.



At this moment, there is no longer a balance between the driver's braking action and the vehicle's reactions: the wheels are locked and the vehicle skids.

* Anti-locking Brake System

■ GENERATION OF BRAKING FORCES IN THE CONTACT PATCH

Let us observe more closely what happens in the contact patch at the time of braking. As the rolling speed (ωR) of the tyre is less than the vehicle speed (V), the road surface will appear to pull on the tread blocks. Thus, each tread block entering the contact patch is first of all sheared. Then it slips over the road surface before leaving the contact patch.

Shear phase:

The tread of a tyre is deformable, whereas its belt is unstretchable. Consequently, when the driver brakes, the road surface "pulls the contact patch backwards", but only the tread is distorted. The rubber blocks "recline", and this results in a relative movement between the bottom of the rubber block, in contact with the road surface, and the belt. This is **shear** (or **pseudo-slippage**), which appears at the leading edge of the contact patch.

Slippage phase:

As the rubber tread block gets closer to the trailing edge of the contact patch, the stress increases and the rubber block, whilst remaining sheared, goes into **real slippage** with the road surface.

It is these two phases which determine the friction law, $\mu(G)$.

A little more
information on...



THE MAXIMUM SHEAR VALUE OF THE TREAD BLOCK AND THE BEGINNING OF SLIPPAGE

Strain shearing is defined by: $\gamma = \frac{L_{sh}}{h}$

Stress shearing is defined by: $C = \frac{X}{S}$

γ and C are related in the elasticity equation: $C = \gamma \cdot \mathcal{G}$

where \mathcal{G} is the shear modulus.

NB: \mathcal{G} is one third of M , the stretch modulus.

Slippage begins as soon as the shear force X reaches maximum friction $\mu \cdot Z$.

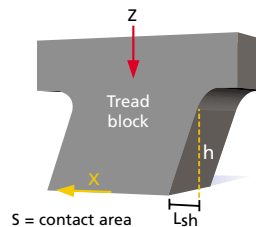
Thus, $X = C \cdot S = \mu \cdot Z$

and since: $Z = P \cdot S$ where P is the pressure of the tyre on the road surface

then: $C = \mu \cdot P$

Shearing has reached its maximum value:

$$\gamma_{max} = \frac{\mu \cdot P}{\mathcal{G}}$$

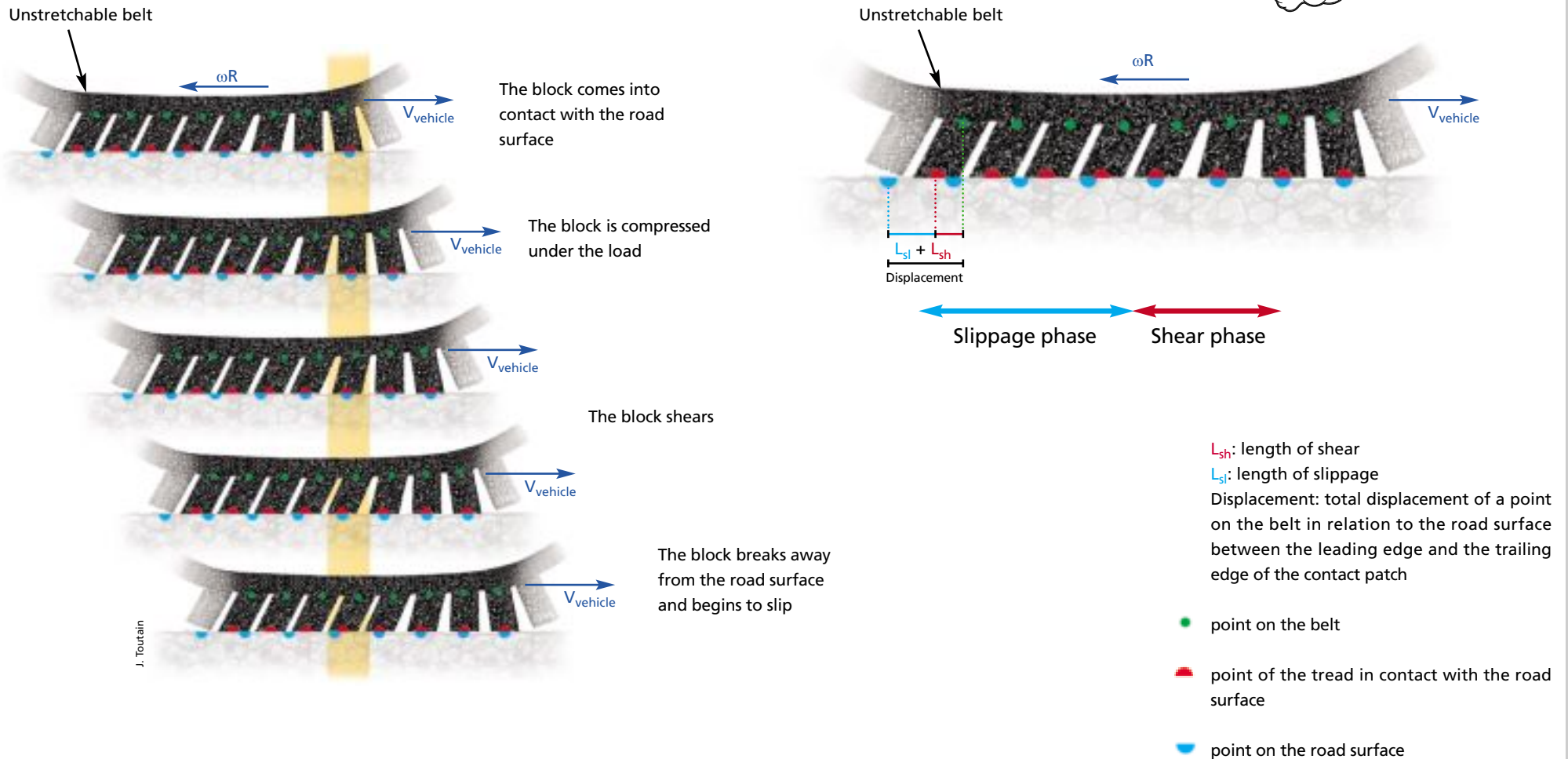


The maximum length of shear L_{sh} is thus defined by:

$$L_{sh} = \frac{h \cdot \mu \cdot P}{\mathcal{G}}$$

Longitudinal grip in braking

Movement of the tread block through the contact patch during braking



■ EXAMPLES OF SLIPPAGE AND SHEAR AS A FUNCTION OF THE COEFFICIENT OF GRIP AND THE SLIPPAGE RATE

Assumptions:

Tread not extensively grooved (rubber tread blocks not very flexible)

Length of the contact patch: $L_{cp} = 10 \text{ cm}$

Vehicle speed: $V = 72 \text{ km/h}$, i.e. 20 m/s

Modulus of the tread rubber: $G = 15 \text{ bars}$

Thickness of the tread: $h = 8 \text{ mm}$

Pressure exerted by the tyre on the road: $P = 3 \text{ bars}$

| | Controlled braking ($G = 10 \%$) | | | Wheels locked ($G = 100 \%$) |
|--|---------------------------------------|---|---|-----------------------------------|
| | Dry road surface $\mu = 1$ | Macrorough damp surface $\mu = 0.5$ | Macrosmooth wet surface $\mu = 0.1$ | All types of road surface |
| Slippage speed ($V_{\text{slip}} = V.G$) | 2 m/s | | | Vehicle speed |
| Δx = length of slippage + length of shear | 11 mm | | | The braking length |
| Length of shear (L_{sh}) | 1.6 mm | 0.8 mm | 0.16 mm | $L_c \ll \Delta x$ |
| Length of slippage (L_{sl}) | 9.4 mm | 10.2 mm | 10.84 mm | \approx The braking length |
| Percentage of pure shear in contact patch | 14.5 % | 7 % | 1.5 % | 0 % |
| Percentage of true slippage in contact patch | 85.5 % | 93 % | 98.5 % | 100 % |

We therefore find that, for a given tyre, when the coefficient of grip diminishes:

- the percentage of pure shear in the contact patch decreases;
- the percentage of true slippage in the contact patch increases;

When the proportion of true slippage tends towards 100 %, the rubber temperature increases greatly and adversely affects grip mechanisms. The friction coefficient should consequently be as high as possible.

A little more
information on...



maximum length of shear and slippage

Δx = length of shear + length of slippage.

The value of Δx depends on the length of the contact patch and the slippage rate:

$$\Delta x = (V - \omega.R) \cdot \Delta t = \frac{V - \omega.R}{V} \cdot V \cdot \frac{L_{cp}}{\omega.R}$$

where V = vehicle speed

$\omega.R$ = tyre rolling speed

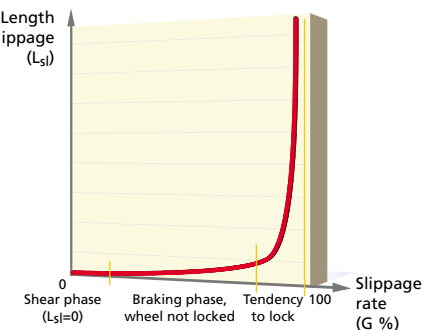
Δt = time tread block spends in the contact patch

L_{cp} = length of the contact patch

Given that $\omega.R = V.(1-G)$

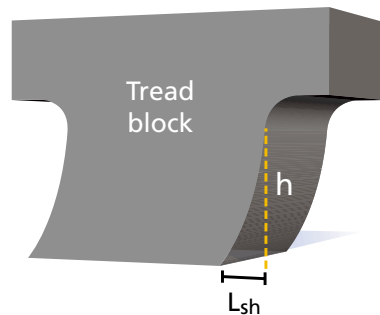
Therefore: $\Delta x = \frac{G}{1-G} \cdot L_{cp}$

The maximum length of shear is actually reached quite quickly. Then the length of slippage increases with slippage rate.



Longitudinal grip in braking

The values given on the previous page are more representative of a competition tyre. For a standard car tyre, we must take account of the flexibility which the tread pattern and sipes give to each rubber block. The shear of the rubber tread block is accompanied by bending, which increases the percentage of the length of shear. This makes calculations somewhat more complex.



Thus, for a standard tyre and a slippage rate of 10 %, pure shear generally concerns 1/4 of the contact patch, as against 3/4 for slippage.



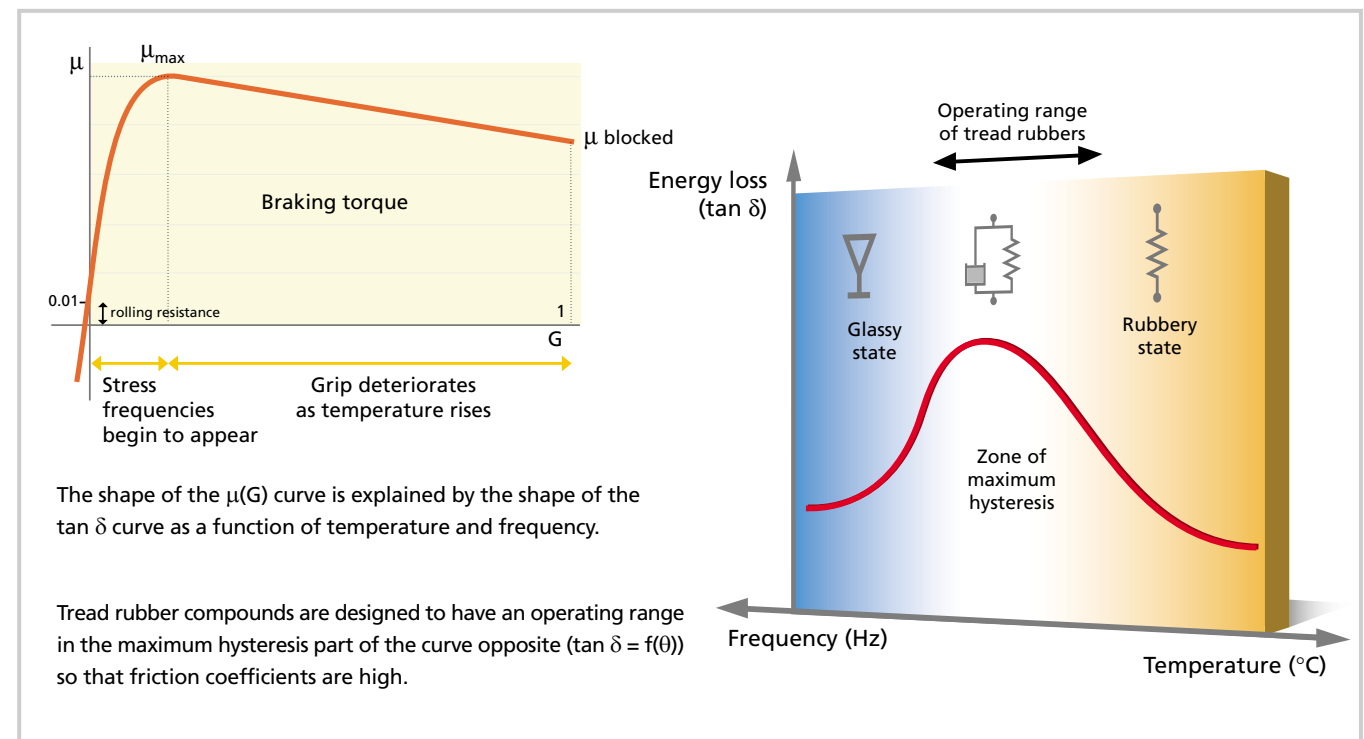
N.B The $\mu(G)$ curve does not pass through 0. For a zero slippage rate (free-rolling), the wheel eventually stops. This is caused by rolling resistance, which comes from the deformation of the tyre at the leading and trailing edge of the contact patch. This deformation presents an equivalent μ of approximately:
 - 0.01 (i.e. 10 kg/t) for a Car tyre,
 - 0.005 (i.e. 5 kg/t) for a Truck tyre,
 i.e. 100 to 200 times less than μ_{\max} .

■ ANALYSIS OF THE $\mu(G)$ CURVE

In reality, the rubber-road surface grip coefficient varies with slippage, particularly because it is affected by temperature.

- In the ascending part of the curve below, the tread is essentially subjected to pseudo-slippage and moderate slippage. The shearing involved elicits the stress frequencies that produce the grip mechanisms observed earlier (molecular adhesion, indentation). At these low rates of slippage, heating is negligible.


- In the descending part of the curve, the percentage of true slippage increases. Heating also increases. If the wheels lock, the contact patch is locked in position too, and the temperature rises even more quickly in the contact patch. At high temperature, rubber hysteresis drops and so does the coefficient of friction. This drop will be all the more important if there is an increase in the slippage speed or in the roughness of the road, or in both.




Consequently, although slippage causes the temperature to rise, a balance must be struck between the rate of slippage and the rise in temperature in order to maintain μ_{\max} at an acceptable value.

In order to obtain the highest possible μ_{\max} , it is vital to:

- firstly, have the highest possible potential μ , by designing compounds with maximum energy losses in the tread rubber's operating range.

 In practice, this results in the use of different tread rubber compounds for Winter tyres and Summer tyres.

- secondly, elicit slippage as soon as possible in the contact patch by using a stiff tread, because of the shape of the $\mu(G)$ curve.

 In racing tyres, the tread rubber is quite thin and there is next to no tread pattern, which provides a maximum friction coefficient (μ_{\max}) at 2 to 3 % of slippage. The stiffness of the tread rubber should be preserved in Winter tyres despite high slipage. This is why self-blocking sipes are used.



*Tread rubber compounds
in Winter tyres are designed
for maximum hysteresis
at low temperatures.*



III.2 Longitudinal grip in braking

0 Before braking occurs, it is assumed that the wheels of a vehicle moves forward by ROLLING only.

1 When the driver presses the brake pedal, the rolling speed of the wheels decreases. To “keep up with” the motion of the vehicle, the wheels ROLL and SLIP over the road surface. The slippage rate, G , is defined as the ratio between the wheel rolling speed at the contact point on the road and vehicle speed. When the slippage rate reaches 100%, the wheel is locked.

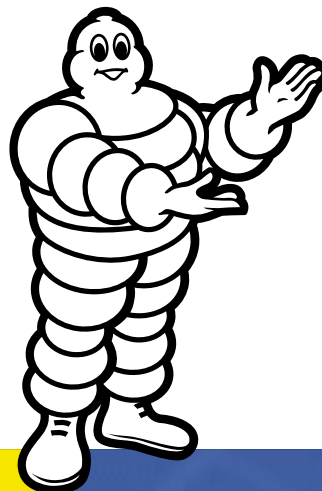
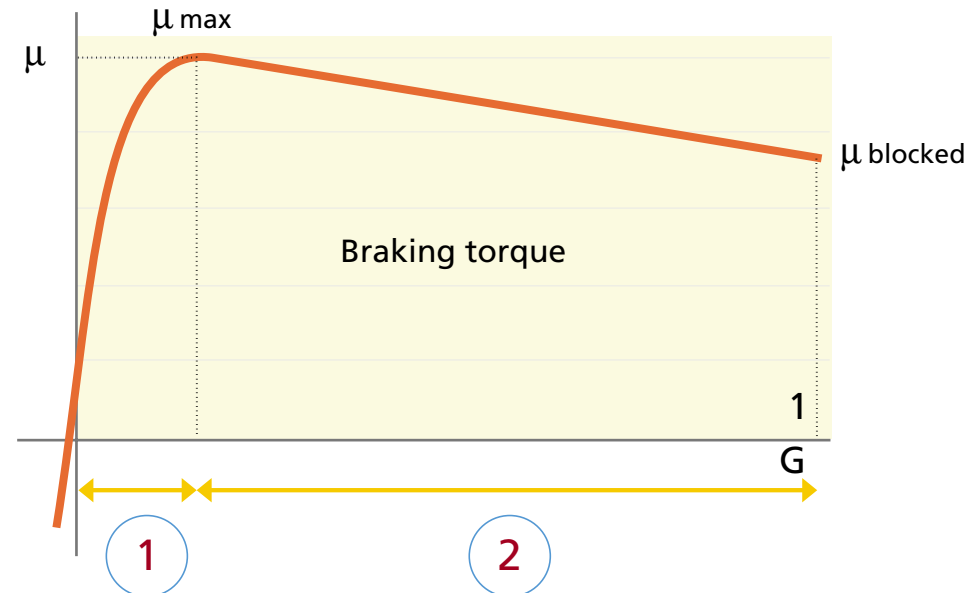
2 Slippage induces a FRICTION FORCE (X), which results from molecular adhesion and indentation.

3 The slippage of tread blocks occurs in two phases: SHEAR (also called PSEUDO-SLIPPAGE) and TRUE SLIPPAGE.

4 $X = \mu \cdot Z$

The coefficient of longitudinal friction of the rubber-road interface is μ . For a given rubber and road surface, it is a function of the slippage rate, G .

5 The $\mu(G)$ law governs braking.



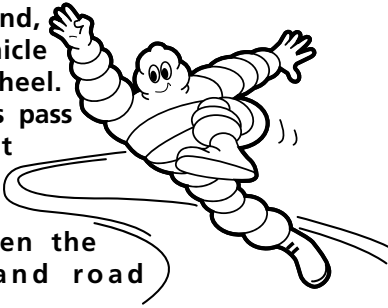
1 Stress frequencies begin to appear on the rubber-road interface. The more the driver brakes, the more the vehicle slows down.

2 Grip deteriorates as temperature rises. The more the driver brakes, the closer the vehicle comes to skidding, and the brakes must be released in order to unlock the wheels.

III.3

Transversal grip in cornering

To negotiate a bend, the driver of a vehicle turns the steering wheel. However, all the forces pass through the contact patch, which is the ultimate point of transmission between the steering wheel and road surface.

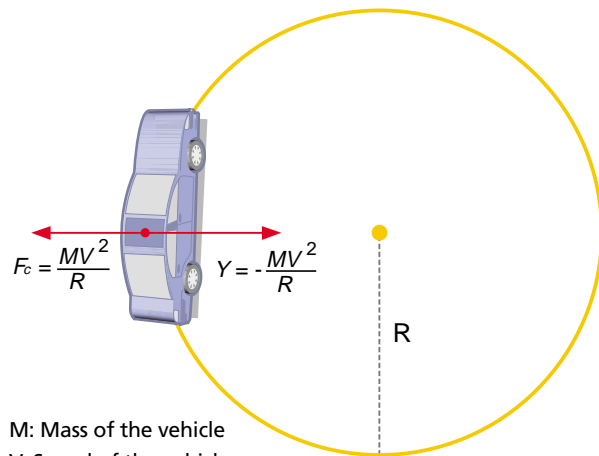


■ SLIP ANGLE


In a bend, the driver sets the turning angle on the vehicle's two front wheels by means of the steering system. In fact, he does not steer the wheels along the vehicle's path, but actually points them towards the inside of the bend. This creates a difference between the direction of the vehicle's motion and the wheels' plane of rotation. The angular difference is known as the **slip angle**. It induces friction between the tyres and the road surface, which generates a **transversal centripetal force Y**.

■ CENTRIFUGAL FORCE

Every vehicle taking a bend is subjected to a **centrifugal force**, F_c , which tends to force it out of its curve. To keep the vehicle on its path, the tyre-road interface must generate a **centripetal force**, Y , equal in value to the centrifugal force.




M: Mass of the vehicle
V: Speed of the vehicle
R: Radius of the bend

 **At very low speed, the centrifugal force is very low, ($MV^2/R \approx 0$) and the turning angle is sufficient for setting the vehicle's path. As the speed increases, so does the centrifugal force. Consequently, the slip angle needed to counteract this force and maintain the vehicle on its required path increases too. Ordinarily, a driver does not use more than a 2° slip angle on the open road and no more than 5° in town.**

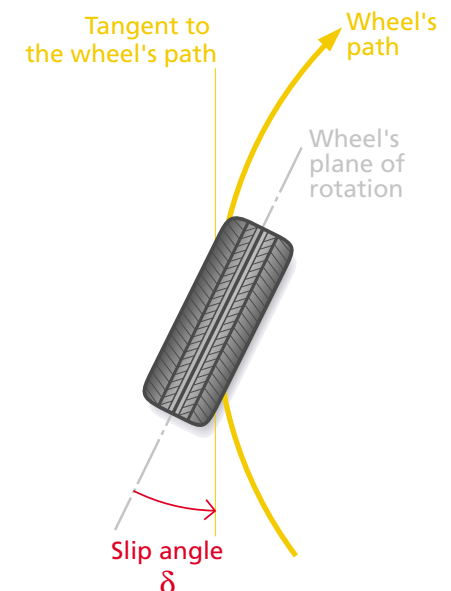
N.B A steering wheel angle of 20° provides an actual turning angle of approximately only 1°.

The slip angle of the tyre is the angle between the wheel's path and its plane of rotation

Let us consider a wheel and tyre assembly which is run "crab-wise" along a given path.

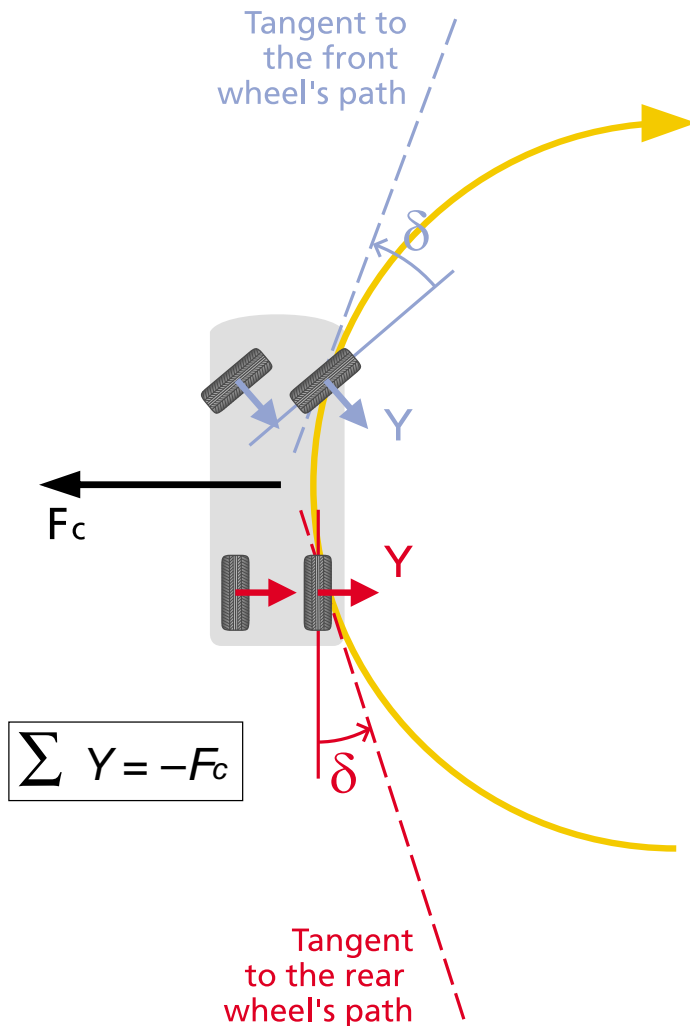
 **The slip angle δ is the angle formed by the plane of the wheel and the tangent to the wheel's path.**

A slip angle may be necessary for keeping a vehicle in a straight line. This is what happens when the vehicle is exposed to a cross-wind. To travel in a straight line, the driver keeps his wheels turned slightly into the wind.



Transversal grip in cornering

Slip angle on the front and rear wheels



On a standard passenger car, the driver adjusts the steering wheel "instinctively" so as to maintain his path by giving the front wheels the required **slip angle**. The rear wheels, which are subjected to a centrifugal force, "naturally" develop a slip angle.

N.B.

In reality, friction force Y is not evenly distributed over the wheels on the inside of the bend and those on the outside. This is called **Tyre Lateral Load Transfer Distribution**.

This **transversal friction force, Y**, depends upon the **load, Z**, applied by the vehicle to the road surface, the state of the road and the tread rubber. In short, force Y depends upon the **friction coefficient of the rubber-road interface**. The letter τ is used to designate the **transversal grip coefficient**.

■ TRANSVERSAL FRICTION FORCE

The transversal friction force Y is equal to:

$$Y = \tau \cdot Z$$

where: Y is the total friction force developed by the four tyres on the vehicle and expressed in daN;

Z is the load applied by the vehicle to the road, expressed in daN;

and τ is the coefficient of transversal friction of the rubber-road interface.

■ COEFFICIENT OF TRANSVERSAL FRICTION τ

The coefficient of transversal friction, τ , is thus defined by:

$$\tau = \frac{Y}{Z}$$



A little more information on...



the coefficient of transversal friction

THE COEFFICIENT OF TRANSVERSAL FRICTION IS EQUAL TO THE CENTRIPETAL ACCELERATION DEVELOPED BY THE VEHICLE'S TYRES (EXPRESSED IN g).

By applying the fundamental principle of dynamics to the vehicle's centre of gravity and using y to designate the displacement of this point, it can be said that:

$$Y = M \cdot \ddot{y}$$

$$\text{therefore } \tau \cdot Z = \tau \cdot M \cdot g = M \cdot \ddot{y}$$

$$\text{so } \tau = \frac{\ddot{y}}{g}$$

where \ddot{y} denotes centripetal acceleration, in m/s^2 ,
M is the mass of the vehicle, in kg,
and g, the acceleration caused by gravity.



Coefficient τ therefore depends on the nature of the rubber and road surface, and on their general condition (temperature, cleanliness, presence of water, etc.). The coefficient τ also depends on the load. For a given rubber-road interface and a given load, τ varies with the friction force generated by the slip angle, δ .

Even though this coefficient is an abstract notion, its value can be attached to a real quantity. As the formula opposite shows, the **centripetal acceleration*** induced by the friction force Y when the vehicle corners is equal to the transversal coefficient of friction, τ .

* expressed as a number of g

Transversal grip in cornering

A little more
information on...



maximum cornering speed

The maximum speed at which a bend can be taken depends on the transversal coefficient of grip and the radius of the bend.

Since: $\tau = \frac{\ddot{y}}{g}$

and $\ddot{y} = \frac{V^2}{R}$

therefore $V = \sqrt{\tau \cdot g \cdot R}$

where \ddot{y} is the centripetal acceleration, in m/s^2 ,
 g is the acceleration of gravity,
 V is the vehicle speed, in m/s ,
 R is the radius of the bend, in m .



■ EFFECT OF THE BEND RADIUS ON THE MAXIMUM CORNERING SPEED

The maximum speed at which a vehicle can corner therefore depends on the coefficient of grip of the rubber-road interface.

However, the maximum cornering speed also depends on the radius of the bend and so the maximum cornering speed will be less in a tight bend than in a wide curve.




On a flat dry road surface (with $\tau=1$), for a bend with a radius of 100 m, the maximum cornering speed is 32 m/s, or 115 km/h, provided that the vehicle steers perfectly. In the same conditions, if the radius of the bend is 20 m, the maximum cornering speed is only 14 m/s, i.e. 51 km/h!

Of course, this speed can be increased by making aerodynamic "modifications" to the vehicle. This is why racing cars are fitted with spoilers, aprons or skirts, which pin the vehicle to the ground, as if the force of gravity had been increased.


■ LAW OF TRANSVERSAL FRICTION $Y(\delta)$

The friction force, Y , comes from the slip angle between the wheel path and the wheel's plane of rotation. Therefore, it is the **$Y(\delta)$ law** which governs transversal grip in cornering, just as the $\mu(G)$ law determines braking.

The curve opposite shows that force Y increases with the slip angle until Y_{\max} is reached. In passenger cars, this occurs when the slip angle is between 4° and 7° , and in trucks when the slip angle is between 6° and 10° , depending on the tyre's construction, the rubber compound used, the type of road surface, and the inflation pressure.

 During this phase, the vehicle driver strikes a balance between steering action and vehicle direction. The more the driver turns the steering wheel, the more the slip angle increases and the tighter the corner taken by the vehicle.

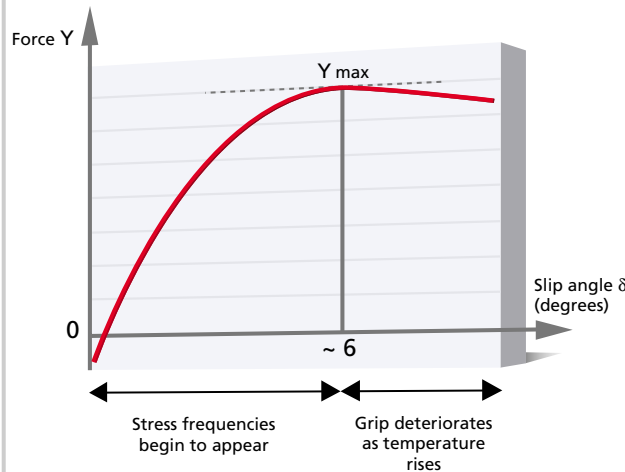
Then Y deteriorates.

 During this phase, the driver finds out that the more he tries to increase the slip angle by turning the steering wheel, the more the vehicle skids. To recover an efficient grip, the driver has to slacken off on the steering wheel.

The $Y(\delta)$ law

Y_{\max} is reached for a slip angle of:

- 4 to 7° for a car
- 6 to 10° for a truck.

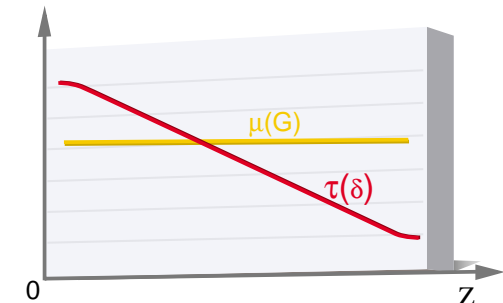


A little more information on... 

the transversal grip coefficient

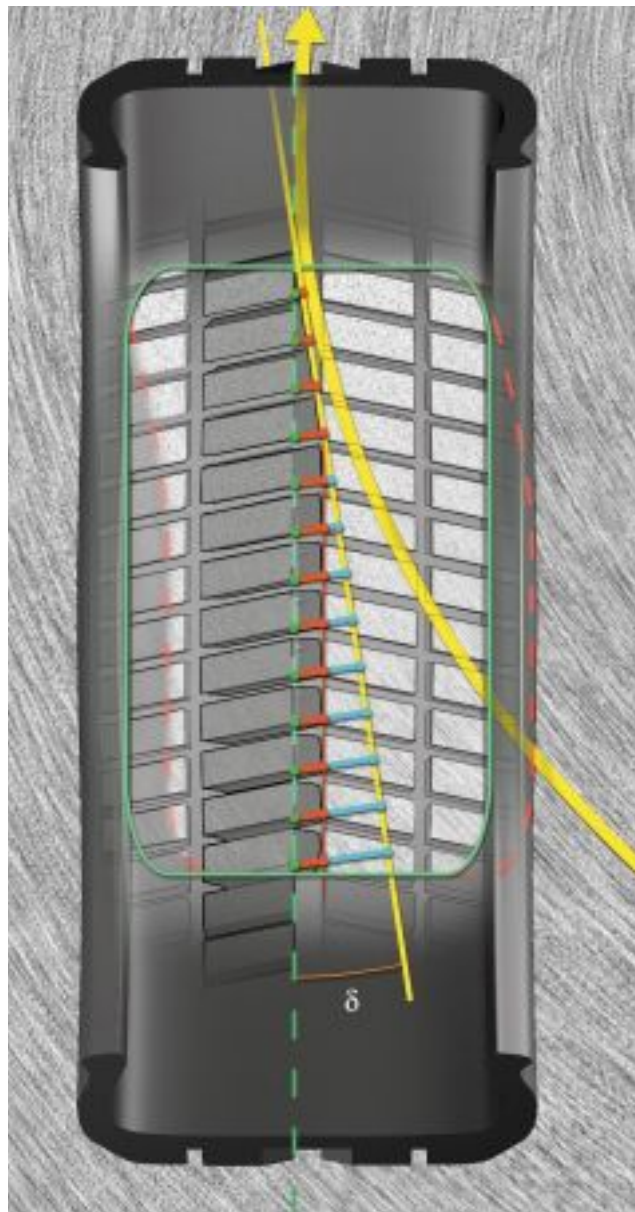
COEFFICIENT τ VARIES GREATLY IN FUNCTION OF THE LOAD UNLIKE μ

This is why either $\mu(G)$ or $X(G)$ can be used to calculate longitudinal friction, whereas $Y(\delta)$ and $\tau(\delta)$ cannot be used as equivalents.



τ decreases when the load Z increases, because the tyre loses transversal rigidity in its contact patch.

Transversal grip in cornering

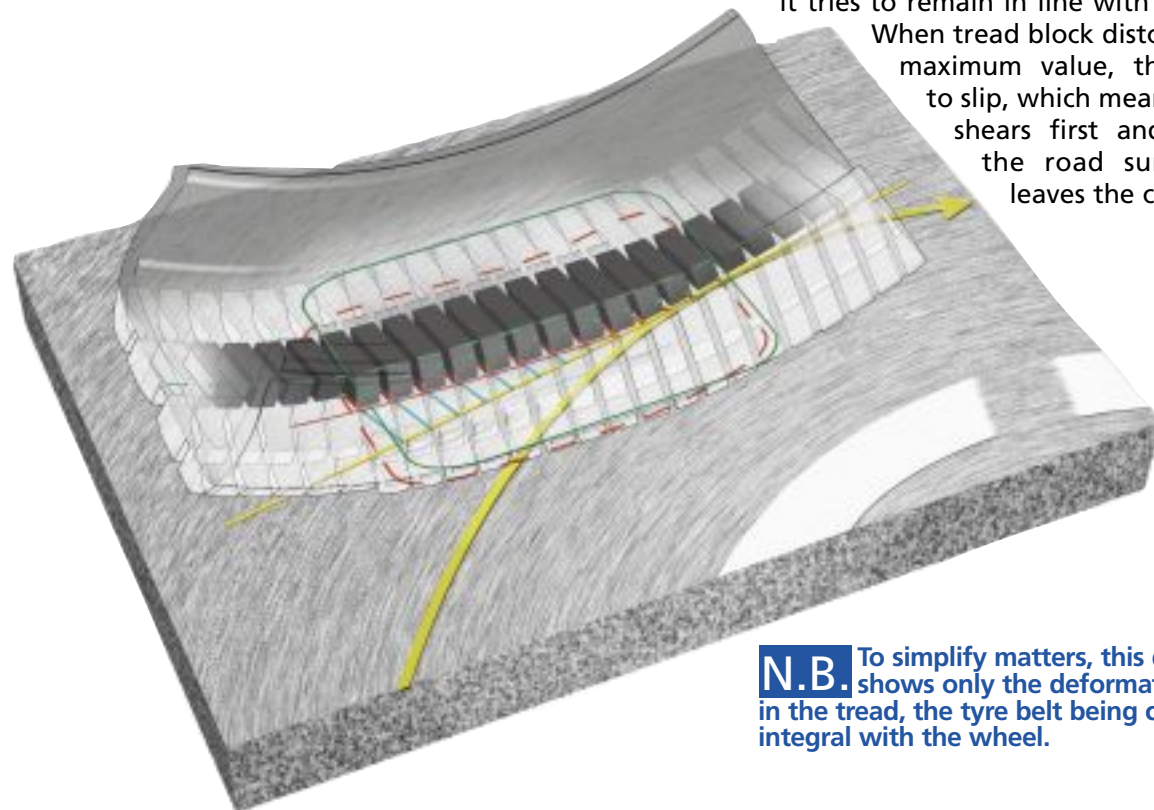


- top of tread blocks
- - - • bottom of tread blocks
- • length of shear
- • length of slippage
- projection of top of tread blocks on road surface
- point on road surface
- tangent to wheel path

■ GENERATION OF TRANSVERSAL FORCES IN THE CONTACT PATCH

Let us consider a tyre subjected to a load, rolling with a slip angle, δ , in relation to its path. At the leading edge of the contact patch, each tread block locates itself vertically on the road surface. As the tread block gets closer to the trailing edge of the contact patch, it undergoes lateral distortion while it tries to remain in line with the wheel path.

When tread block distortion reaches its maximum value, the block begins to slip, which means that the block shears first and then slips on the road surface before it leaves the contact patch.




N.B. To simplify matters, this diagram shows only the deformations occurring in the tread, the tyre belt being considered integral with the wheel.

Shear (or pseudo-slippage) phase

At the leading edge of the contact patch, or for small slip angles (at the start of a bend), the rubber is **sheared** perpendicularly to the tangent to the path.

Slippage phase

For large slip angles, the rubber reaches the maximum shear well before it leaves the contact patch and begins to **slip** over the road surface.

 It is to be noted that, when a slip angle is applied to a wheel, the resultant force of the friction forces developed acts behind the centre of the contact patch. This creates a slip torque, known as **self-aligning torque**, which counteracts the effects of slip angle δ . If the driver releases the steering wheel, the wheels realign themselves along their path.

The shear phase and the slippage phase determine the $Y(\delta)$ law.

■ ANALYSIS OF THE $Y(\delta)$ LAW

As is the case in longitudinal grip, the transversal grip coefficient varies with slippage, particularly because it is affected by temperature.

- In the ascending part of the curve on page 53, the tread is essentially subjected to pseudo-slippage and moderate slippage. This shearing elicits the stress frequencies that produces the grip mechanisms observed earlier (molecular adhesion and indentation). At these low rates of slippage, heating is negligible.

A little more information on... the maximum length of shear and slippage



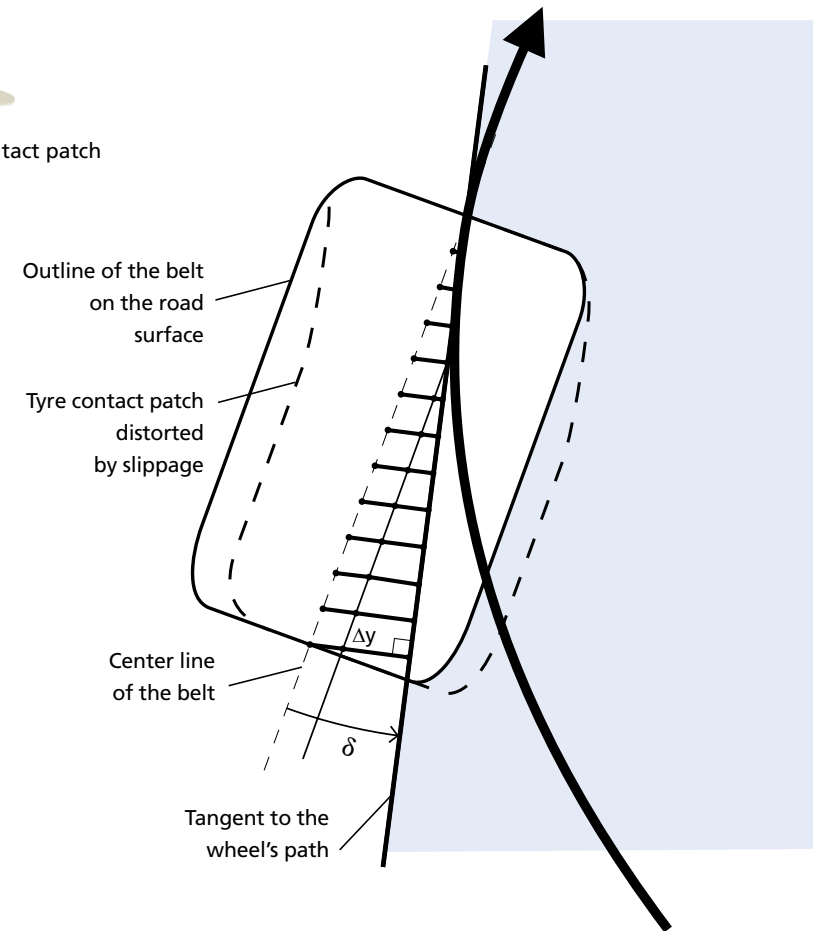
Δy = length of shear + length of slippage

Since $\frac{\Delta y}{L_{cp}} = \sin \delta$, then $\Delta y = L_{cp} \cdot \sin \delta$

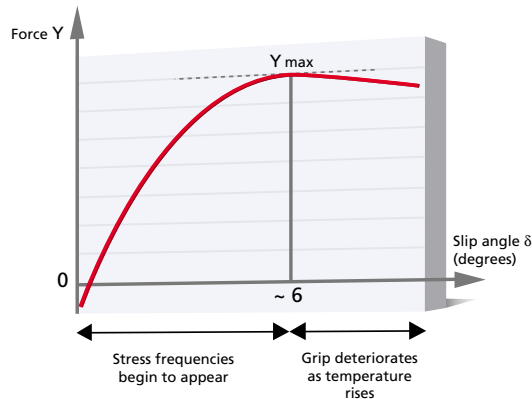
where: L_{cp} designates the length of the contact patch

For example:

If $L_{cp} = 10$ cm and $0 < \delta < 5^\circ$,
then: $0 < \Delta y < 1$ cm



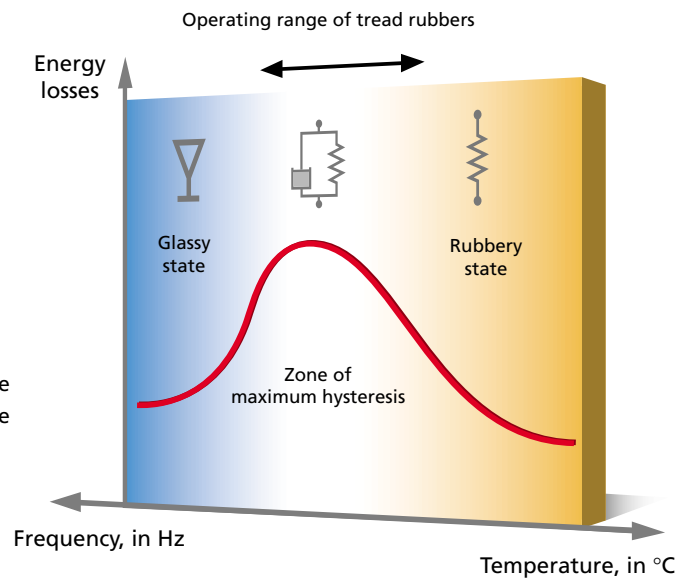
Transversal grip in cornering



The shape of the $Y(\delta)$ curve is explained by the shape of the energy loss curve opposite as a function of the temperature and frequency.

N.B.

When the slip angle is zero, the transversal force is not zero. A slight transversal force is produced by the particular constructional aspects of the tyre, such as plies laid crosswise, dissymetries in the crown area and tread pattern, etc. This transversal thrust represents a force of 1 to 2 daN, or a τ equivalent of 0.01 to 0.02, which is very low.




Tread rubber compounds are designed to have an operating range in the maximum hysteresis part of the curve above so that friction coefficients are high.


- In the descending part of the curve, the percentage of true slippage increases. Heating also increases. At high temperature, hysteresis drops and so does the coefficient of friction.

Consequently, although slippage causes the temperature to rise, a balance must be struck between slippage and rise in temperature in order to maintain Y_{\max} at an acceptable value.

To produce the highest possible value of Y_{\max} , the compounds designed must have the highest energy losses possible in the tread rubber's operating range.

 In practice, this results in the use of different tread rubber compounds for Winter tyres and Summer tyres.

The curve also highlights how important it is to reach Y_{\max} as quickly as possible, with as small a slip angle as possible.

 In practice, this means a tyre which is transversally rigid.

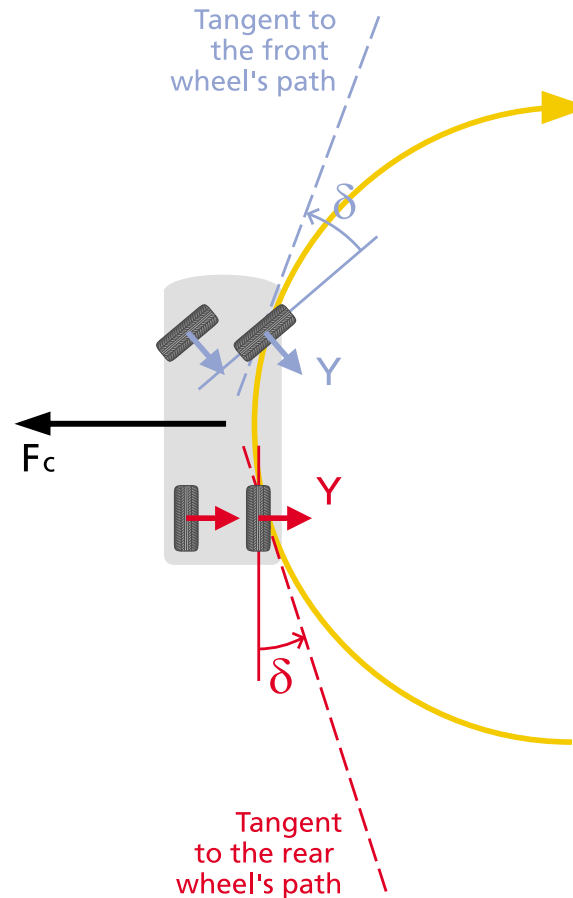
III.3 Transversal grip in cornering

1 When cornering, the vehicle is subjected to a centrifugal force, which must be counteracted by opposing forces in the contact patch.

2 To maintain the vehicle path, the driver "instinctively" applies a slip angle to the wheels. This slip angle causes shear and then transversal slippage of the rubber tread blocks. The mechanisms of molecular adhesion and indentation produce a CENTRIPETAL TRANSVERSAL FORCE Y .

3 $Y = \tau \cdot Z$

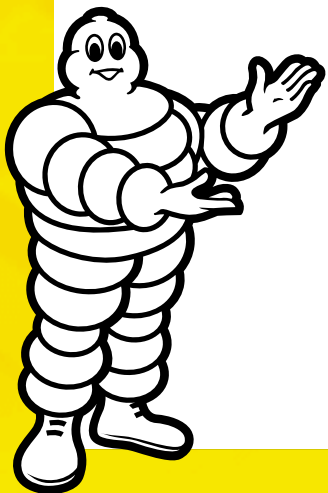
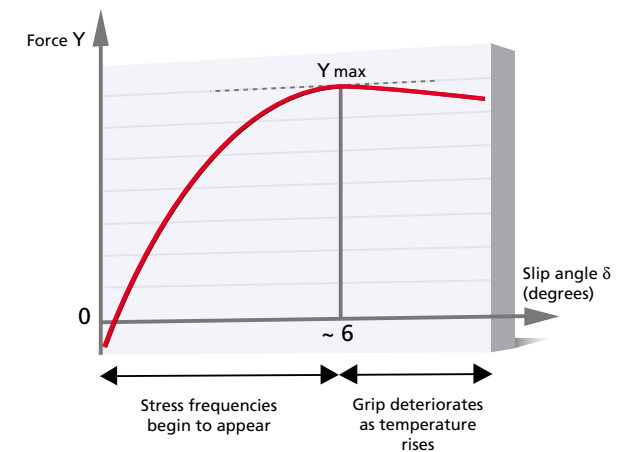
The transversal grip coefficient is τ . For a given rubber, road surface and load, it varies as a function of the slip angle.



$$\sum Y = -F_c$$

4 The $Y(\delta)$ law governs transversal grip.

Y_{\max} is achieved for a slip angle of:
4 to 7° for a car,
6 to 10° for a truck.



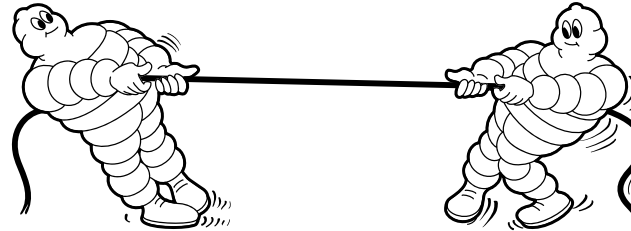
III.4

Sharing the grip potential on the road

A driver very often requires longitudinal grip and transversal grip at the same time. However, the driver cannot have the best of both worlds, as the two forces have to share the grip potential available in the tyre-road interface and consequently compete against each other.

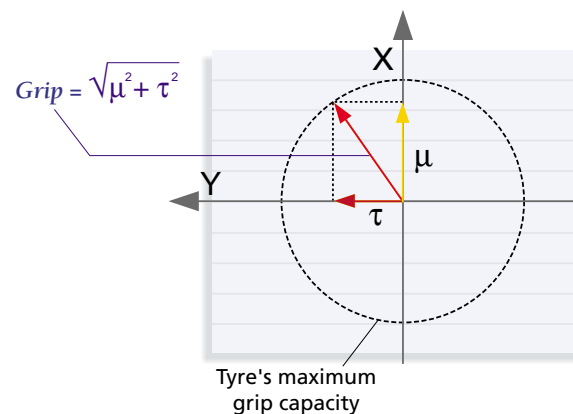
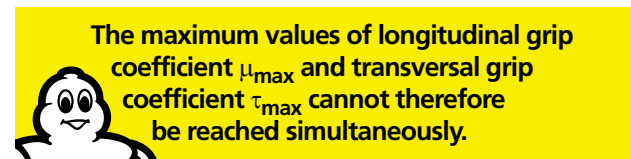
COMBINED GRIP

Brakes are not always applied when the vehicle is in a perfectly straight line and bends are not always negotiated at constant speed. For example, a driver may accelerate in a bend or have to take evasive action whilst braking. A tyre's longitudinal grip and transversal grip are therefore often called upon at the same time.



A POTENTIAL TO BE SHARED

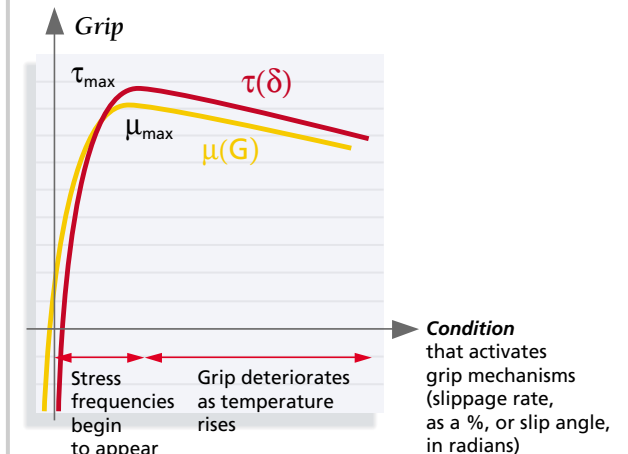
In fact, the tyre-road interface represents a global grip potential delineated approximately by a circle, and available to provide longitudinal or transversal grip or both.



X: Longitudinal friction force
Y: Transversal friction force

Similarities between longitudinal grip and transversal grip


Longitudinal grip and transversal grip are very similar to each other. For a given tyre, in given conditions, the $\mu(G)$ and the $\tau(\delta)$ curves can be easily superimposed.



Thus, if when cornering without acceleration or braking, the driver suddenly decides to brake or accelerate, a longitudinal force component develops and adversely affects the transversal grip potential. Conversely, if when braking in a straight line, the driver turns the steering wheel, longitudinal grip is adversely affected.

However, the adverse effect is not distributed symmetrically. In fact, the application of a driving or braking torque will greatly affect transversal grip, whereas longitudinal grip is not so greatly affected by a slip angle.

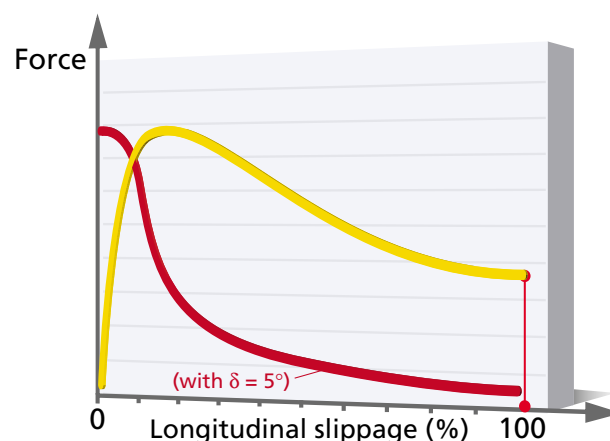
This is explained by the fact that longitudinal slippage induces a sudden drop in the tyre's capacity to generate transversal grip, whereas the production of longitudinal forces is more resistant to an effect of the slip angle.

 **To sum up, when a driver brakes or accelerates suddenly, steering control is impaired. Conversely, in a bend, even a tight one, action on the accelerator pedal will remain relatively effective, but here again steering control will be reduced.**

The ABS* offers a solution to this problem by limiting the slippage rate to around 10 % to 20 %, values at which the transversal forces retain about 50% of their potential. The driver can then steer the vehicle while continuing to brake.

* ABS, Anti-locking Brake System

Acceleration or braking adversely affects directional control

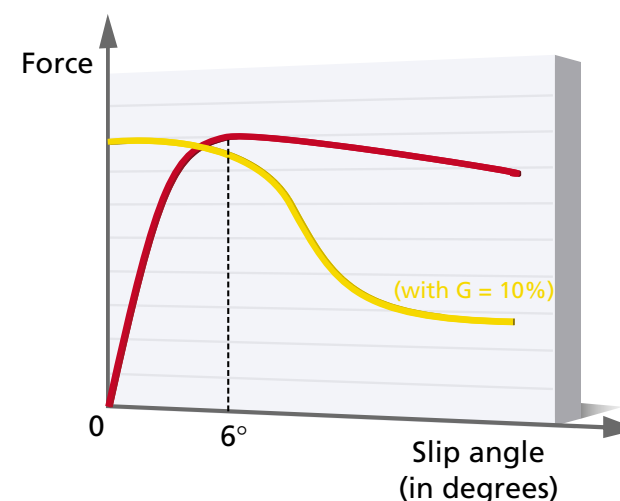


— $X = \mu \cdot Z$ Driving and braking forces

— $Y = \tau \cdot Z$ Steering forces

- When the slippage rate exceeds 15 % (hard braking), the tyre's capacity to develop transversal forces drops sharply (see curve above).

- However, the tyres on a car in a tight bend at high speed, i.e. when the slip angle is about 6° , continue to generate substantial longitudinal forces (see curve opposite).

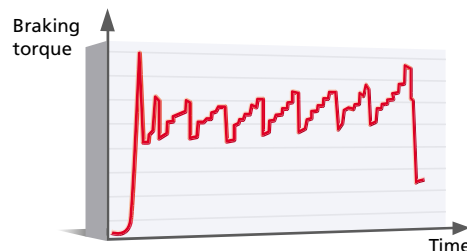


■ ABS

When a driver brakes, the pressure on the brake pedal is adjusted in accordance with visual and sensory perceptions. However, the driver is not in a position to make a precise assessment of the working conditions of the tyres, and there is no guarantee that the wheels will not lock unexpectedly. Remember that the vehicle's transversal grip drops sharply when the longitudinal slippage rate increases. The role of the Anti-locking Brake System is to prevent the wheels from locking, so that the directional stability of the vehicle may be maintained.

How the ABS works

In order to slow down, the driver uses the braking circuit to apply a braking torque to all four wheels of the vehicle. The ABS measures the angular deceleration of each wheel at very close intervals. If this deceleration is moderate, the ABS authorises the **braking torque** to continue to increase. However, if the wheel's deceleration becomes too high, the wheel is on the verge of locking. The ABS then releases the pressure on the brakes, and the braking torque drops sharply, which releases the wheel. The wheel accelerates again and the ABS then authorises the braking torque to increase again, thus repeating the hold-release-reapply cycle.



A little more information on...

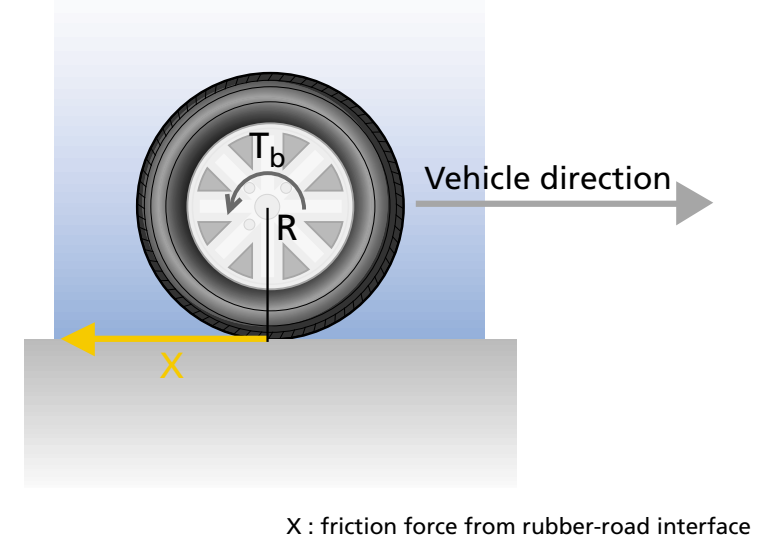
how the ABS works



Wheel locking occurs when the balance is broken between the braking torque T_b and the force X developed at the rubber-road interface.

- When T_b begins to be applied, the wheel decelerates slightly, and slippage starts to occur at the rubber-road interface, generating a braking force X , such that $X.R = T_b$. As long as $T_b = X.R$, the system is balanced.
- If T_b continues to increase whilst X reaches its maximum ($X_{\max} = \mu_{\max} \cdot Z$), then $T_b > X.R$. The wheel decelerates sharply and is on the verge of locking.
- The ABS then releases the pressure on the brakes, and T_b decreases again, with the result that $T_b < X.R$. The wheel accelerates again.
- The ABS then authorises T_b to increase. This is known as the hold-release-reapply cycle.

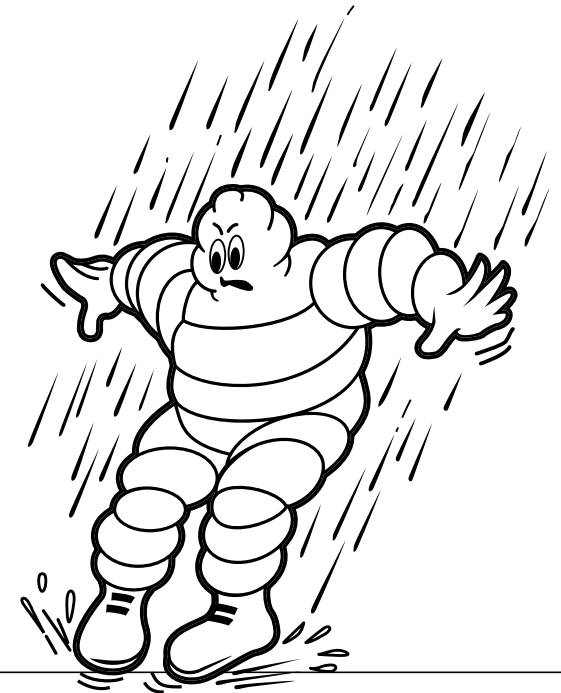
X - and μ - therefore oscillate around their maximum values.





IV *Grip on wet surfaces*

Tyre grip is the result of friction between the tread rubber and the road surface. Therefore, direct contact is required between them. In order for a tyre to grip on a wet surface, it must first disperse the water to restore dry contact.



The presence of water interferes with grip mechanisms. Molecular adhesion can no longer operate if contact between the rubber and road surface is not perfectly clean and dry. Indentation is inoperative if the depth of water covers the tiny bumps in the road surface. In wet weather, maintaining grip therefore involves dispersing the water to restore dry contact between the tread and the road.

The slope of the road, its structure and surface roughness all contribute to water dispersal. However, these factors do not disperse all the water. When the road is wet, water may creep in between the contact patch and the road. The deeper the water and the greater the vehicle speed, the more this effect is amplified, eventually impairing grip potential.

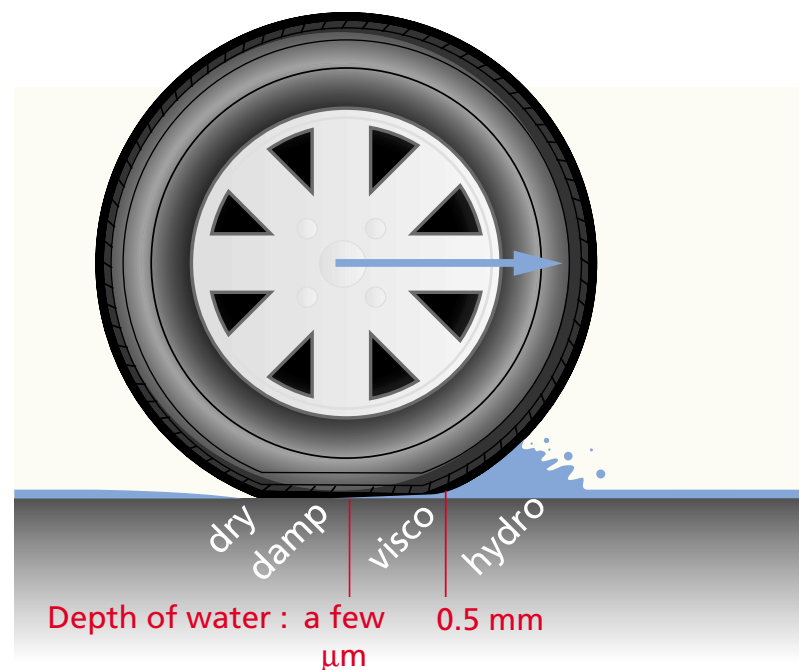
The shape of the tyre's contact patch, its tread grooves and sipes, will **push the water forwards and drain away part of the "bank" of water** builds up in front of the tread. The water still creeping in between the contact patch and the road surface is then **channelled** into the tread grooves where it is **"stored"**. The tread rubber can thus **break through** the residual water film and restore direct contact with the road surface.

These three water dispersal stages occur between the leading and the lagging edge of the contact patch and correspond to three different transition zones called:

- **hydrodynamic** (water depth > 0.5 mm);
- **viscodynamic** (water depth: a few microns to 0.5 mm);
- **damp** (intermittent residual film of water).

Maximum grip (μ_{\max}) depending on depth of water and speed.
Examples on a macrorough and microrough road surface

| Depth of water | Speed | |
|-----------------------------------|---------|----------|
| | 60 km/h | 100 km/h |
| 0 (dry surface) | 1 | 1 |
| < 10 μm (damp surface) | 0.8 | 0.7 |
| 1.5 mm | 0.6 | 0.4 |
| 5 mm | 0.5 | 0.1 |



IV.1

The hydrodynamic zone: dispersal and drainage

A little more information on...

the speed at which aquaplaning occurs



The hydrodynamic pressure generated by a slick tyre tread on the "bank" of water can be approximated by Bernoulli's equation:

$$P_{\text{hydrodynamic}} = \frac{1}{2} \rho \cdot V^2$$

where: ρ = density of the water, in kg/m³

V = speed of the vehicle, in m/s

$P_{\text{hydrodynamic}}$ being expressed in Pa (10⁵ Pa = 1 bar)

Experimentally, it can be demonstrated that aquaplaning occurs when the water pressure ($P_{\text{hydrodynamic}}$) and inflation (P) are the same.

The aquaplaning speed can be approximated by the following formula: $V_A = \sqrt{\frac{P}{K}}$ with $K=500$.

In reality, coefficient K depends on the tread pattern and the shape of the contact patch. Today, some high-performance car tyres, when they are new, make it possible to lower K to a value close to 250, i.e. an aquaplaning speed of about 100 km/h.

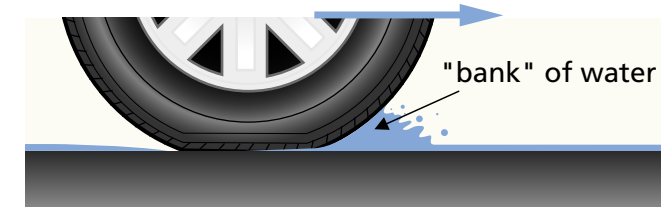
EFFECT OF THE INFLATION PRESSURE ON THE AQUAPLANING SPEED

| Pressure (bar) | Tyre category* | Speed at which aquaplaning begins** (V_A , in km/h) |
|----------------|------------------------------|---|
| 1 | Car tyre (under-inflated) | 50 |
| 2 | Car tyre (properly inflated) | 70 |
| 4 | Light truck tyre | 100 |
| 8 | Truck tyre | 140 |
| 16 | Commercial aircraft tyre | 200 |
| 32 | Fighter plane tyre | 280 |

* slick tyres

** on bituminous concrete

A tyre travelling relatively quickly over a "flooded surface" pushes a little "bank" of water in front of it. The impact of the tread on the water at the front of the contact patch causes a rise in the water pressure (called hydrodynamic pressure).



If this pressure becomes greater than the mean pressure of the tyre on the road surface, the tyre can no longer repel the water and it lifts off the road surface. This is known as **aquaplaning**, or **hydroplaning**. Experimentally, it can be demonstrated that the mean pressure of the tyre on the road surface is approximately equal to the inflation pressure. Thus, **aquaplaning occurs when hydrodynamic pressure and inflation pressure are the same.**



The hydrodynamic pressure increases in proportion to the square of the speed.

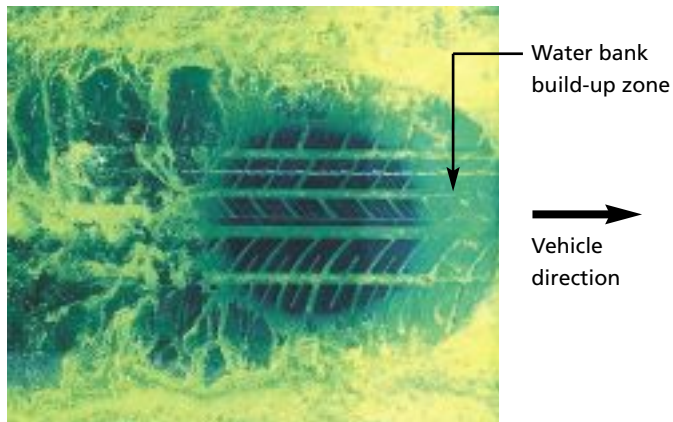
The hydrodynamic pressure produced by a car tyre without a tread pattern is equal to its inflation pressure (2 bars) when the vehicle speed reaches 70 km/h. A "slick" truck tyre (inflated at 8 bars) will produce the same result at 140 km/h. Thus, cars are more exposed to aquaplaning than trucks.



Fortunately, aquaplaning can be warded off by the grooving of the tread and the shape of the contact patch. Today, the aquaplaning speed of a high-performance car fitted with correctly-inflated new tyres exceeds 100 km/h.

■ A ROUNDED FOOTPRINT TO REDUCE THE PRESSURE EXERTED BY THE BANK OF WATER ON THE TYRE

The **bank of water** that builds up in front of the tyre must be quickly dispersed to the side so that the pressure it produces on the leading edge of the contact patch does not exceed the pressure caused by the load of the vehicle on the road surface. A rounded shape of contact patch understandably "ploughs" more easily through the water than a rectangular shape. The phenomena are essentially those involved in fluid mechanics: a flat shape offers more resistance to air than a round shape. Similarly, a ship with a rounded or V-shaped bow "cleaves" through the sea more efficiently than a ship with a rectangular bow. This has been called the "**bow-effect**", or "**stem-shaped effect**".



A little more information on... the rounded contact patch which increases aquaplaning speed



Once again by applying Bernoulli's equation, the pressure exerted by the water at the front of the contact patch at point M can be calculated as follows:

$$P_{\text{impact}} = \frac{1}{2} \cdot \rho \cdot (V \cdot \cos \beta)^2 *$$

where β = leading edge angle at M.

ρ = density of the water, in kg/m³

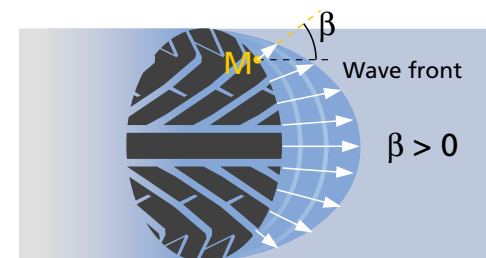
V = speed of the vehicle, in m/s

P_{impact} being expressed in Pa (10⁵ Pa = 1 bar)

The larger β is - i.e. the more "angled" the contact patch - the smaller P_{impact} is, and the higher the speed at which aquaplaning occurs.

* This formula is for a locked wheel.

Rounded contact patch

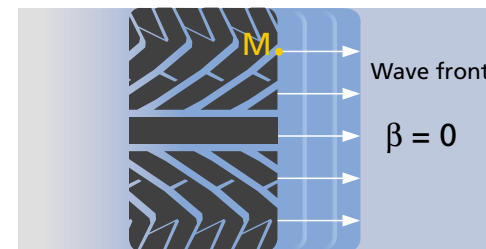


The water is pushed forwards and to the side

Vehicle direction →

The pressure exerted by the water on the tyre decreases when β increases

Rectangular contact patch



The water is thrust forwards

The pressure exerted by the water on the tyre is maximum



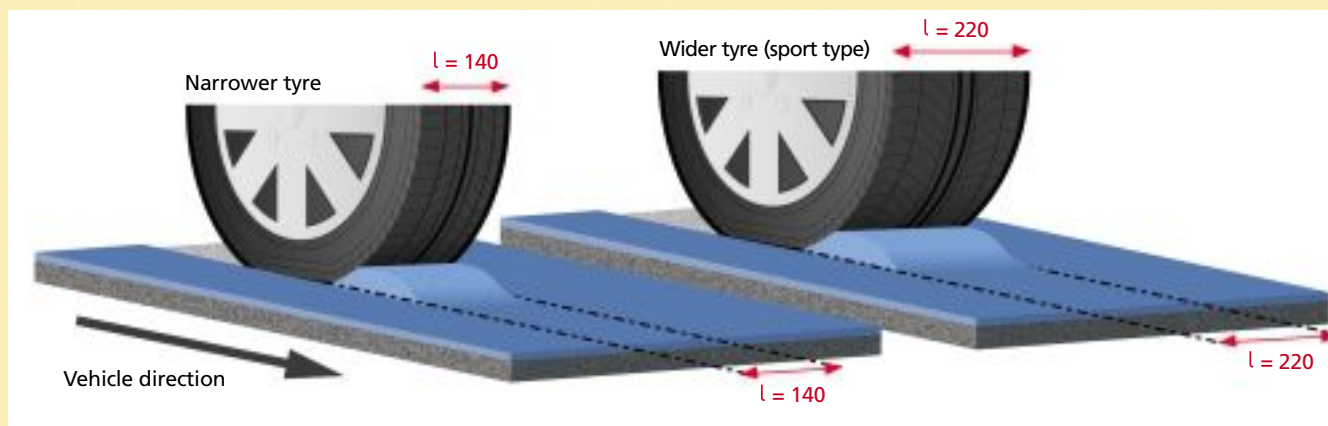
Wide tyres and water dispersal

The tyre overcomes aquaplaning by channelling into the tread grooves the water which manages to creep under the contact patch. If the **flow of water** that can be channelled through the tread grooves is higher than the flow that creeps under the contact patch, the tyre does not lift off the road surface.

At any given depth of water, the narrower the tyre, the smaller the flow of water to be channelled through the tread grooves.

On the one hand, a narrow contact patch therefore reduces the volume of water to be channelled through the contact patch. On the other hand, since wide tyres have to deal with a much greater flow of water, a much greater water dispersal capacity must be built into the tread design.

Effect of the width of the contact patch on the flow of water to be dispersed



$$\text{Flow of water to be dispersed} = V \times l \times h$$

$$V = 80 \text{ km/h}$$

$$h = \text{depth of water} = 3 \text{ mm}$$

$$\text{Flow rate} = 9.2 \text{ l/s}$$

$$\text{Flow rate} = 14.5 \text{ l/s}$$

$$\Delta = + 57 \%$$

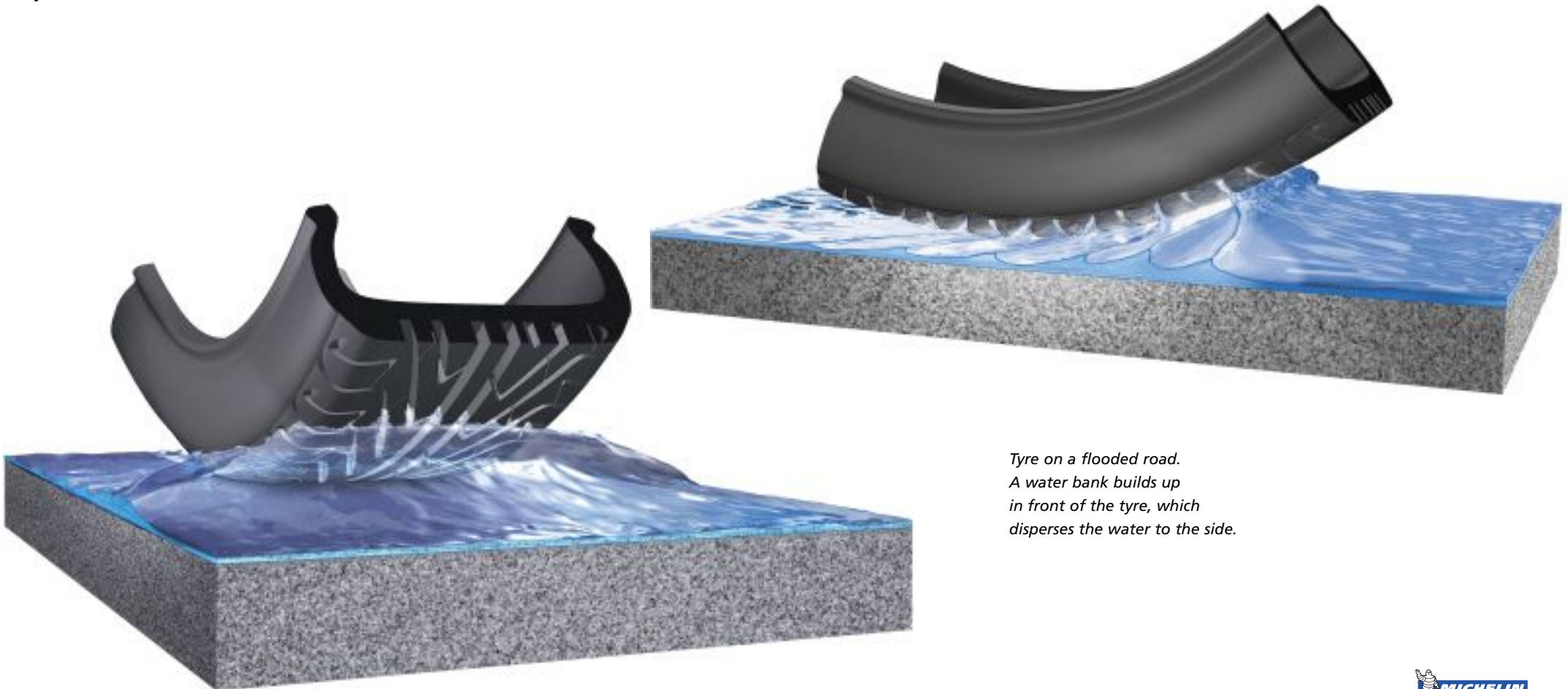
A wide tyre must be designed to deal with a much larger flow of water.

■ ANGLED TREAD GROOVES TO DRAIN AWAY WATER TO THE SIDE

Angled and transversal tread grooves are first of all designed to drain away to the side as much of the water as possible, which has built up in front of the tyre.

Tread pattern terms

| | Standard width for a Car tyre | Depth |
|--------------------|-------------------------------|-----------|
| Circular groove | 8 to 10 mm | 7 to 8 mm |
| Transversal groove | 2 to 7 mm | |
| Sipes | 0.3 to 1.5 mm | |



*Tyre on a flooded road.
A water bank builds up
in front of the tyre, which
disperses the water to the side.*


IV.2

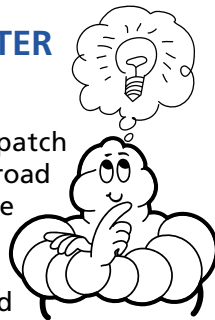
The viscodynamic zone: storing water in the tread grooves.

The tyre design at the front of the contact patch, in the hydrodynamic zone, reduces to about 0.5 mm the depth of water that creeps under the contact patch. The water remaining must be channelled into the tread grooves where it is stored.

■ COMPRESSION OF THE WATER BY THE TREAD BLOCKS

The tread blocks in the contact patch do not roll: they are laid down on the road surface at the leading edge of the contact patch, somewhat comparable to the way we put our feet on the ground as we walk. When the tread blocks then leave the contact patch, they simply lift off. It could be said that tyre tread blocks compress water almost vertically. It is this compression that drives the water towards the tread grooves. There is one condition to be complied with for tread-road contact to be restored: the water compressed must be able to escape to the edge of each block before it leaves the contact patch. If the water cannot escape quickly enough, the tread block does not touch the road surface. The higher the pressure on the film of water and the shorter the distance to the edges of the tread blocks, the shorter the **transfer time** to the storage zone will be. This would appear to mean that the rubber blocks should be small and the grooves large.

 In fact, the layout of the tread grooves must be optimised, in order to reduce the transfer time (small rubber blocks) without affecting the rigidity of the tread (reduced groove density).



A little more information on...

the time for water transfer to the storage zones



We can approximate the time taken to disperse the water to the tread grooves by the following formula, which gives us the compression time of a viscous film by a non-deformable rubber block:

$$t = K \cdot \frac{\eta}{P} \cdot \frac{S}{h_f^2} \cdot \left[1 - \left(\frac{h_f}{h_i} \right)^2 \right]$$

with:

K = geometrical coefficient of tread block section

η = viscosity of the fluid, in Pa.s

P = tyre pressure on the viscous film, in Pa

S = area of the block, in m²

h_i = initial height of the viscous film, in m

h_f = final height of the viscous film, in m

Quantified example:

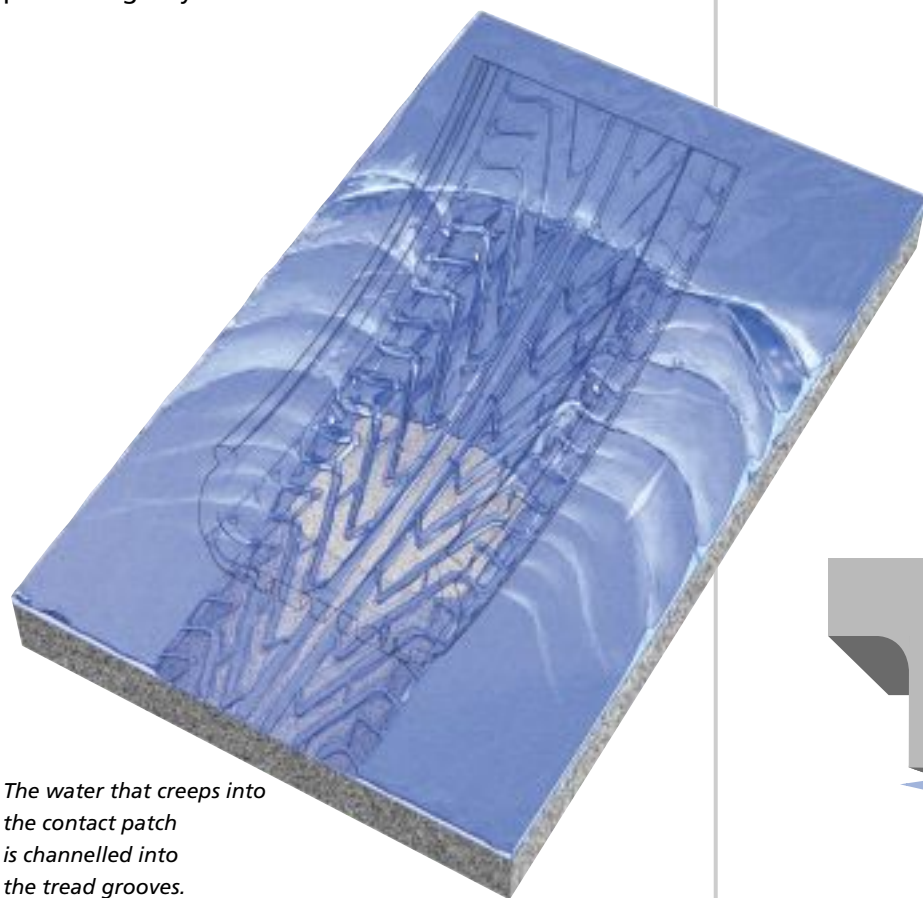
Compression of a film of water 10 µm thick to a residual thickness of 1 µm.

| | | |
|--|-------------------|---------------------|
| Area of the tread block | 7 cm ² | 0.8 cm ² |
| Compression time | 1.4 ms | 0.2 ms |
| Dwell time in the contact patch at 90 km/h | 4 ms | 4 ms |
| % of the footprint in contact with a depth of water exceeding 1 µm | 35 % | 5 % |

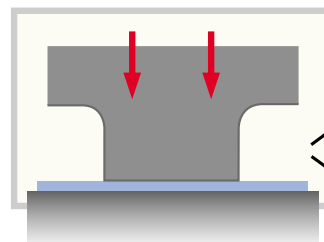
N.B. Length of the contact patch: 0.1 m

A **sipe** system may be added to enhance the tread grooves' dispersal function. These sipes help to channel the water into the tread grooves and their design creates pressure surges along their edges. However, the sipe system must ensure water dispersal without compromising tread pattern rigidity.

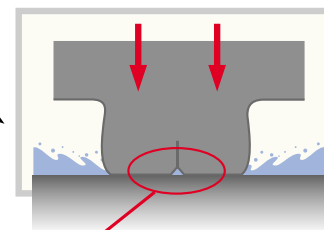
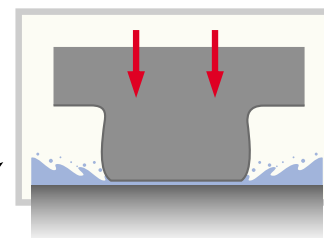
Sipes help to channel water



Tread block compressing water



Tread block without sipes



- Siped tread block:
- greater water channelling capacity
 - shorter distance to tread grooves
 - pressure surges along the edges

Water trapped in the sipes is driven into tread grooves



Sipes and grip on wet surfaces

On wet surfaces, sipes play a key role in restoring grip.

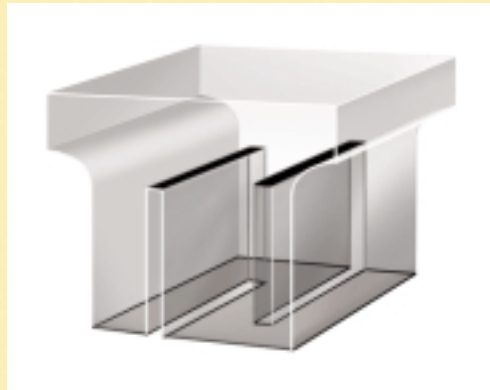
A sipe is defined as a vertical slit forming a void 0.3 to 1.5 mm wide in a tread block. These slits are made by the blade-like inserts fitted into the curing mould.

On wet road surfaces, sipes ensure the following functions:

- The sipes which open out into the tread grooves help to channel the water into the grooves where it is stored.
- Sipes generate pressure surges along their edges, thus breaking through the residual film formed by the water which has not been dispersed or stored. This restores direct rubber-road surface contact.

Because of the importance of the above two functions, a large number of sipes makes the tyre more effective on wet surfaces.

Two types of standard sipes:



The straight sipe

During the 1920s, attempts were made at siping the tread using only straight sipes. However, the load of the vehicle and the forces generated by grip make this sipes splay out and seriously impair the rigidity of the tread pattern.



J. Toutain

The corrugated sipe

As far back as 1930, corrugated sipes brought significant improvement:

- As these sipes are offset against each other, they do not open out as readily as the straight sipes.
- The wavy shape of these sipes makes them effective in all directions.



Sipes and grip on wet surfaces (continued)

There is a drawback in using sipes, since by breaking up the tread block they may reduce its rigidity. Consequently, the tyre responds less quickly and less accurately to the driver's steering action.

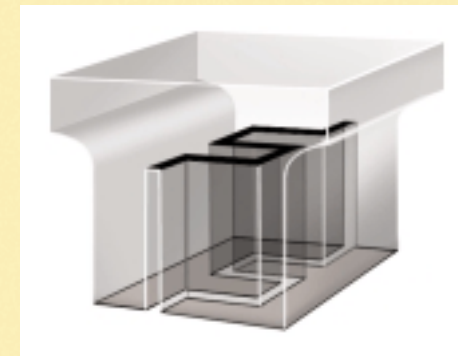
However today, developers and research workers have learned to reconcile grip on wet surfaces and vehicle handling on dry surfaces. The art of sipe design is based on the combination of different sipe shapes which are either set securely within the tread block (quadrangular sipes), or offset against each other (crankshaft sipes) or self-locking (Z sipes). Combining all these sipe shapes, the tread can be siped without compromising its rigidity, which ensures grip and road handling.

Sipes enhancing grip on wet surface without affecting tread rigidity for dry surface grip.



The quadrangular sipe

This sipe is sunk inside the tread block, which ensures little angular variation. It is used mainly in the shoulder area for outward dispersal of water from the contact patch.

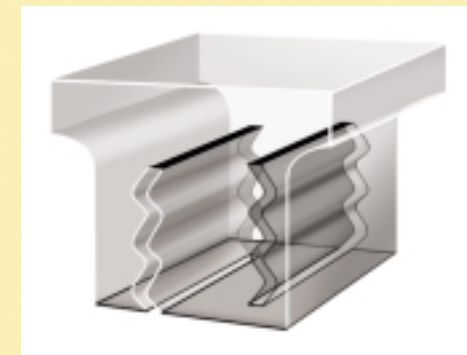


The "crankshaft" sipe

The "double-crenel" shape reduces tread block mobility.

The Z or zigzag sipe

This sipe's self-blocking effect is produced by the vehicle load and the drive torque to maintain tread block rigidity.

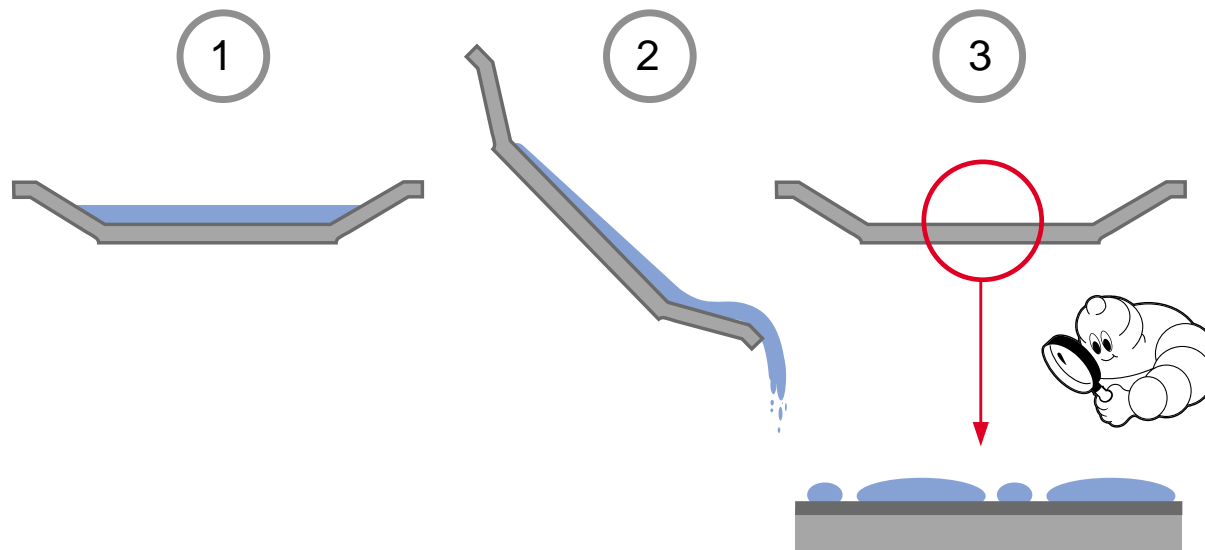


J. Toutain

IV.3

Damp to dry zone: restoring dry contact

What is surface tension?



After a receptacle has been emptied, its surface retains traces of moisture, in the form of a very thin, intermittent film of water, or tiny droplets.

The persistence of these droplets is due to the surface tension of the water.

The cohesive forces between liquid surface molecules are responsible for the phenomenon known as surface tension. These intermolecular forces prevent the liquid from spreading out. It is this phenomenon which enables a glass of water to be filled beyond its rim.



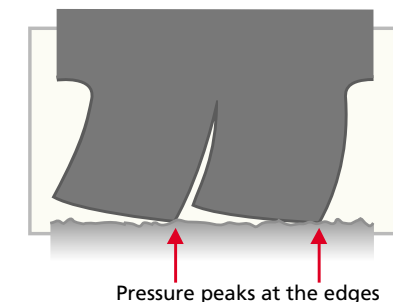
The dispersal of water is not enough to make the road completely dry underneath the tyre. Traces of water remain on the road surface, just as traces of water remain on the surface of a receptacle that has just been emptied.

The surface tension of water causes microscopic drops of water to remain on any surface that has been covered by water. To get rid of them, we have to wipe the surface or leave it to dry. The tyre must therefore find a way of restoring dry contact, in spite of this film of residual water a few microns thick.

■ EDGES TO BREAK THROUGH THE FILM OF WATER

The **edges of the sipes or tread blocks**, combined with the **microroughness** of the road surface, break through the film of water because of the high **pressure surges** they create.

N.B. Consequently, dry contact is restored and indentation and molecular adhesion become fully operative.

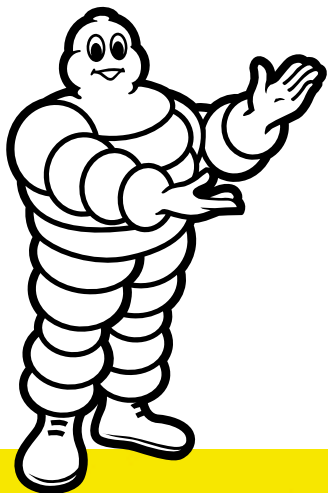


Pressure peaks at the edges

Microroughness varies according to the road surfaces, which explains why grip varies so much in damp conditions.

IV Grip on wet surfaces

TO GRIP ON WET SURFACES, THE TYRE MUST DISPERSE THE WATER TO ENSURE DRY CONTACT.



- 0 • Depth of water on the road MINIMISED by

- water DRAINED AWAY down the road slope and through the road's draining mixes.
- water STORED in the MACROROUGHNESS of the road surface.

- 1 • Water THRUST BACK by

- adequate PRESSURE AT THE LEADING EDGE of the contact patch provided by the INFLATION PRESSURE and the so-called "BOW" EFFECT.

- Water DRAINED AWAY to the side by
- angled TREAD GROOVES.

- 2 • Water CHANNELLED into the tread grooves by

- adequate PRESSURE IN THE CONTACT PATCH (rubber/void ratio + roughness of the road surface) and a SYSTEM OF SIPES opening out into the tread grooves.

- Water STORED in

- the TREAD GROOVES.

- 3 • Residual film BROKEN THROUGH by

- very high PRESSURE SURGES created by the edges of tread blocks and sipes, and the microroughness of the road surface.



V *Grip & vehicle handling*


Grip is not an "isolated" performance of the tyre. It must not be forgotten that it interacts with other types of performance, especially with the way in which the vehicle handles. In this chapter, we shall see how grip is influenced by load transfer and how it affects oversteer and understeer.

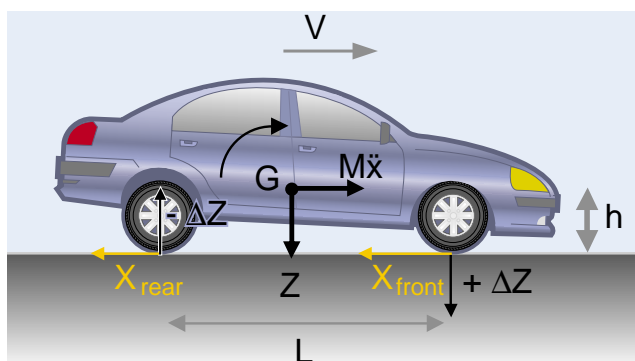


Load transfer

LONGITUDINAL LOAD TRANSFER

Given that a vehicle's centre of gravity is situated at a height, h , above the road and that the friction force, X , of the tyre on the road surface is applied at road surface level, braking creates a **tipping torque** which causes an **overload** ($+\Delta Z$) on the front wheels and a drop in the load ($-\Delta Z$) on the rear wheels. The front end thus gets "heavier" and the rear end "lighter". This is **longitudinal load transfer**. In this situation, if the braking torque was identical on all 4 wheels, the rear wheels would start to lock before the front wheels, and there would be a danger of the vehicle's rear end swinging out, or even spinning round completely.

 To avoid this situation, vehicles are equipped with a brake regulator which ensures the application of greater braking pressure on the front wheels than on the rear wheels.



G: vehicle's centre of gravity,
M: vehicle mass,
 \ddot{x} : longitudinal acceleration,
Z: load,
h: height from centre of gravity to road surface,
L: vehicle wheelbase (distance between the front and rear wheels).

An example of longitudinal overload

Since: $X = X_{\text{front}} + X_{\text{rear}} = \mu Z = M\ddot{x}$

and $X \cdot h = \Delta Z \cdot L$

then: $\Delta Z = X \cdot \frac{h}{L} = \frac{\mu \cdot Z \cdot h}{L}$

Numerical example:

$Z = 1400 \text{ daN}$, i.e., assuming equal distribution of the load, 350 daN per wheel
 $\mu_{\text{activated}} = 1$ (hard braking on a dry surface)
 $h = 0.5 \text{ m}$
 $L = 2 \text{ m}$

This gives:

$\Delta Z = 350 \text{ daN}$, i.e. 175 daN on each front wheel, i.e. an overload of + 50 %.

N.B.

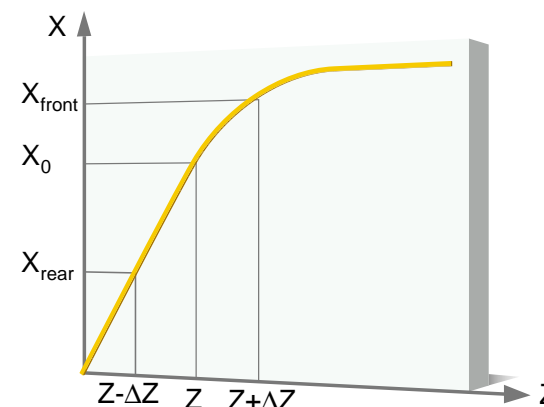
- It is assumed that μ bears little relation to the load
- X is represented as the reaction force of the road surface on the tyre.

A little more information on...




how load transfer affects braking efficiency

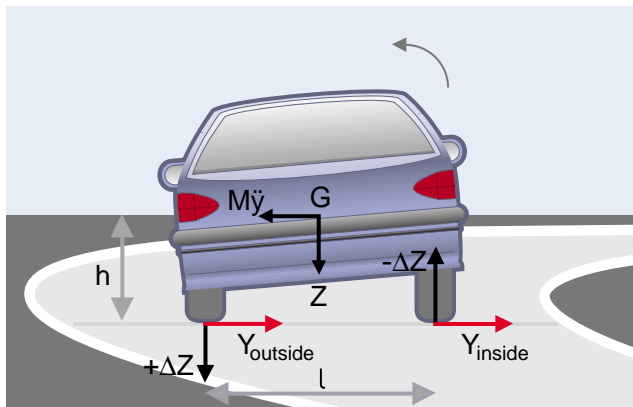
When the load increases and the slippage rate is constant, the longitudinal force developed by a tyre increases to a maximum value and stabilises. When braking occurs, the load transfer therefore leads to an increase in the forces applied to the front tyres (X_{front}) and a reduction of the forces applied to the rear tyres (X_{rear}). If the braking pressure on the rear wheels was not corrected by a brake regulator, the load transfer would lead to the vehicle's spinning round because the rear wheels would lock.



LATERAL LOAD TRANSFER

Given that a vehicle's centre of gravity is situated at a height, h , above the road and that the friction force, Y , is applied to the wheels at road surface level, taking a bend creates a **roll torque**. As a result, the wheels facing the outside of the bend are subjected to an **overload** ($+\Delta Z$), whilst there is a drop in the load ($-\Delta Z$) on the wheels facing the inside of the bend. In this cornering configuration, the sum of the transversal forces on the 4 wheels is less than if all 4 wheels were subjected to the same load: **lateral load transfer adversely affects transversal grip**.

 To minimise the effect of lateral load transfer, vehicle manufacturers have several options. For example, they can increase the vehicle's track and lower its centre of gravity.



G: vehicle's centre of gravity,
M: mass of the vehicle,
 \ddot{y} : transversal acceleration,
Z: load,
 h : height from centre of gravity to the road surface,
 l : vehicle track (distance between the right and left wheels).

An example of lateral load transfer

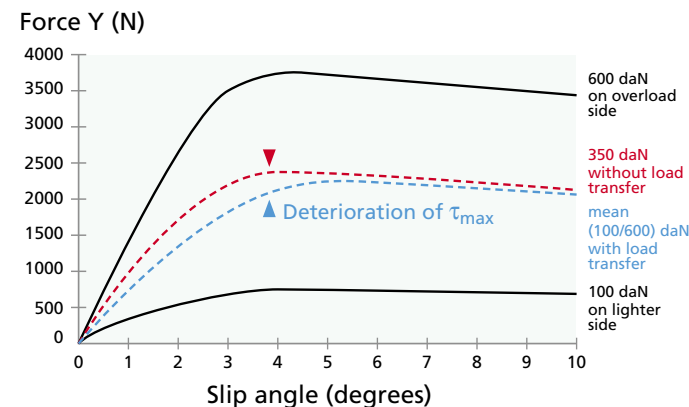
Since: $Y = \tau Z$

and $\Delta Z \cdot l = Y \cdot h$

then: $\Delta Z = \frac{\tau \cdot Z \cdot h}{l}$

Numerical example: for $Z=1400$ daN, i.e. 350 daN per wheel, $\tau_{\text{activated}}=1$, $h=0.5$ and $l=1.5$, the overload is about 250 daN on each wheel on the outside of the bend, i.e. + 71 %, and the load on each wheel on the inside of the bend is reduced by the same amount.

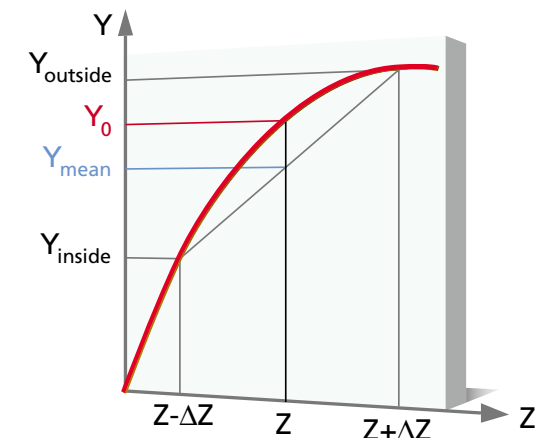
When there is a load transfer (blue curve), the mean of the transversal forces developed by the 4 tyres is smaller than without load transfer (red curve).



A little more information on... 

how load transfer affects cornering

If the slip angle remains constant and the load increases, the transversal force developed by the tyre increases and then reaches a maximum value before dropping away. This is why, in cornering, the load transfer leads to a reduction in the resultant force Y (Y_{mean}).



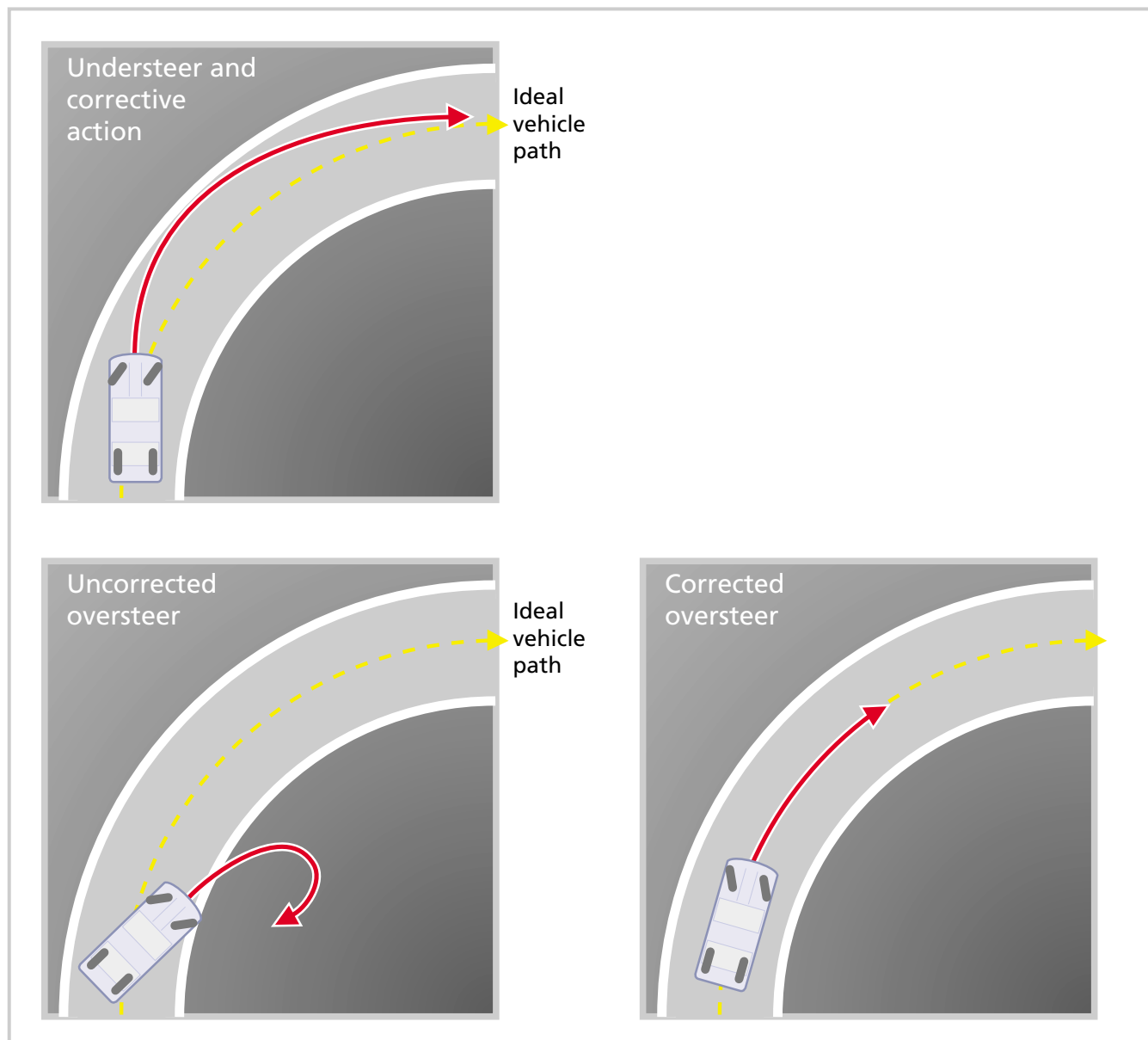
Understeer and oversteer

A vehicle which **understeers** tends to “travel in a straight line” when the driver is negotiating a bend. In more accurate terms, the vehicle will want to travel in a shallower curve than the intended one. This effect is amplified as the cornering speed increases. To counteract the “straight line” tendency, the driver of an understeering vehicle has to increase the steer angle or slow down, or do both.





A vehicle which **oversteers** has a tendency to take a path which is tighter than the intended bend. This effect is amplified when the speed increases. In fact, at high speed, the rear of the vehicle “swings out” and the front of the vehicle ends up pointing towards the inside of the bend. To correct the direction of travel, the driver must reduce the steer angle and, if the vehicle has front-wheel drive, accelerate.







Front-wheel drive vehicles are naturally rather prone to understeer. Rear-wheel drive vehicles have fairly neutral steer characteristics at constant speed, although they oversteer slightly in the event of sharp acceleration.

For safety reasons, vehicle manufacturers prefer to design understeering vehicles. In a bend taken at too high a speed, the corrective action to take on such vehicles is to increase the steer angle and slow down. This is an instinctive reaction for the driver, whereas reducing the steer angle and accelerating are not. Racing drivers, on the other hand, prefer vehicles that oversteer, as this enables them to corner as close as possible to the inside of the bend.



How transversal force variations influence vehicle handling

| Vehicle status | Y_{front} | Y_{rear} | Effect on the vehicle's general handling characteristics* |
|--|---|---|---|
| Load shift towards the rear axle (car boot full) |  |  | <i>understeer</i> |
| Rear tyres under-inflated | |  | <i>oversteer</i> |
| Narrower rear tyres | |  | <i>oversteer</i> |

| Handling the vehicle | Y_{front} | Y_{rear} | Effect on the direction of travel** |
|---|---|---|--|
| Accelerating on front-wheel drive vehicle |  | | <i>bend not so tight</i> |
| Accelerating on rear-wheel drive vehicle | |  | <i>bend tighter</i> |
| Decelerating slightly |  | | <i>bend tighter</i> |
| Braking too hard |  | | <i>bend not so tight</i> |
| Increasing steer angle |  | | <i>bend tighter</i> |
| Front tyres hit ice |  | | <i>vehicle follows a straight line !</i> |

* For a neutral steering vehicle

** All other parameters being unchanged

Understeer and oversteer are due to the development of different transversal forces (Y) at the tyre-ground interface on the front and rear axles.

If $Y_{\text{rear}} > Y_{\text{front}}$, the vehicle understeers (the steering wheels have less directional power).

If $Y_{\text{front}} > Y_{\text{rear}}$, the vehicle oversteers (the rear end may swing out due to centrifugal force).

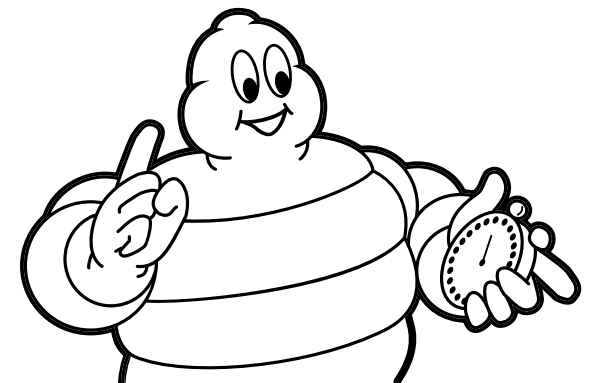
The factors which can influence oversteer and understeer are those on which force Y depends:

- the load, Z , which may vary from one axle to another depending on the position of the centre of gravity and on load transfers;
- the coefficient of grip, τ , which may vary from one axle to another if the tyres are not of the same type or exhibit different degrees of wear, or if the road surface is different. The coefficient of grip is also altered by the slippage rate induced by acceleration and deceleration.
- the slip angle, δ , which varies on the front and rear axles as a function of the driver's action on the steering wheel, the accelerator or the brake pedal.



VI *Testing tyre grip*

Grip tests are designed to check that the construction, tread pattern and compounds used comply with the user's requirements.



Grip is a general safety requirement for any vehicle, whatever the conditions may be, in winter or summer, in the dry or in the wet, on rough or smooth road surfaces, out on the motorway at high speed or on country roads.

A tyre manufacturer should therefore have a comprehensive battery of grip tests that effectively include the full spectrum of end-user conditions. In addition, these tests must be reproducible and discriminating. The results of these tests are used for the development of new tyres and their certification by vehicle manufacturers and the authorities.

The parameters taken into account in a grip test protocol are as follows:

- the **stress** imposed on the tyre:
 - **stress mode** (longitudinal, transversal or composite);
 - **slippage rate** (braking with anti-locking brake system, braking with wheels locked);
 - **slip angle**;
 - **vehicle speed, acceleration or deceleration**;
 - **inflation pressure**;

- the **test conditions**:
 - the **type of surface**: macroroughness, microroughness, thermal properties;
 - the **condition of the surface**: dry, damp, wet, flooded, but also snow-covered or icy, as well as its temperature;
 - the **type of vehicle** (weight, load transfers, over- or under-steering characteristics, laboratory vehicle, etc.) or the **test machine**;
- the **measurement mode**: speeds, braking distance, travelling time, acceleration, deceleration, slippage rate, forces, etc.

What about the driver?

The driver only has a very slight influence on the results obtained in the course of these tests. In fact, professional test drivers are capable of adjusting their driving to make it highly reproducible. The professionalism of the test driver eliminates almost all driver effect.



Test driver at the wheel of a vehicle equipped with instrumentation during a transversal grip test

VI.1

Analytical tests



Road simulator in operation. Here, the tyre is running on the inside of the drum.



Road simulator in operation. Here, the tyre is running on the outside of the drum.



Flat road-surface simulator.

These are tests in which stress is applied to a tyre isolated from the vehicle context, making the tyre run on a machine called a road simulator or rolling rig, or using a laboratory vehicle equipped with a wheel connected to instrumentation.

ROAD SIMULATORS

A rolling rig consists of a "drum", coated with an artificial road surface or a replica of a real road surface. The tyre rolls on this rotating drum. On some of these machines, the tyre runs inside the drum, on a slightly concave surface, whereas on others, the tyre runs on the outside of the drum, on a slightly convex surface. The combination of the two types of machine gives a more accurate insight into the service conditions on a flat road surface.

Other machines, which are less widespread and more sophisticated, are designed to test tyres on a flat surface.

Tests on a rolling rig have the major advantage of controlling a certain number of parameters which cannot be controlled on a test track, such as:

- ambient temperature or tyre temperature,
- atmospheric conditions,
- load,
- drive torque or brake torque,
- maintaining speed despite brake pressure.

These tests produce graphs of the coefficient of grip as a function of the load, slip angle, slippage rate, speed and temperature.



■ LABORATORY VEHICLES

Laboratory vehicles are used on test tracks and are fitted with on-board instrumentation connected to an additional wheel operating independently of the others.

Test principle

The vehicle travels at constant speed, in a straight line and over a surface considered to be regular. The tyre on the measurement wheel is subjected to a given load and inflated to a specific pressure.

Brake and drive torque are applied to the wheel gradually over a set scale of time, making it possible to scan the slippage rate (G) from 0, when the torque is nil, to 100%, when the wheels are locked. A fixed or variable slip angle (δ) can also be set on the wheel.

During analytical tests, the on-board equipment measures the longitudinal force (X) and the transversal force (Y) on the hub as well as the slippage rate (G).

By computing all the parameters selected and the measurements made, the longitudinal and/or transversal grip coefficients μ and τ can be calculated as a function of the slippage rate and/or the slip angle.

Analytical tests are essential to the understanding of the operating mechanisms of tyres. However, they are not representative of the combined stresses to which the vehicle's tyres are subjected on the road. To reproduce these real stress conditions, vehicle track tests are necessary.

*Laboratory vehicle,
equipped with a
measurement wheel.
This wheel, located at
the centre of the vehicle,
operates independently
of the other
4 wheels.*



Measurement wheel connected to instrumentation

Test conditions controlled:

- type of surface
- load on the 5th wheel
- drive/brake torque on the 5th wheel
- slip angle on the 5th wheel
- tyre inflation pressure
- depth of water
- speed
- temperature

Values measured:

- longitudinal force X
- transversal force Y
- slippage rate G

Values calculated:

- coefficient of grip μ and τ as a function of the slippage rate and slip angle.



VI.2

Vehicle track tests



Test tracks at Ladoux, Clermont-Ferrand, France.

Vehicle tests are performed on outdoor tracks.

What characterises these tests is the number of parameters over which there is little control: wind, sunshine, rain, ambient temperature, track temperature and the inevitable differences between vehicles which appear to be the same. In order to obtain usable results, track tests are always performed against a set of **reference tyres**. In addition, each test is usually run with several different types or versions of the tyre, thus providing not only measurements but also a tyre classification. In order to obtain reliable statistics for classification, each type of tyre goes through the same test several times.

Example of a grip test sequence on a test track for three types of tyres

| 1 | 2 | 3 | 4 | 5 |
|------------------------------------|-----------------|-----------------|-----------------|------------------------------------|
| Reference set of tyres n/2 runs | Set A n runs | Set B n runs | Set C n runs | Reference set of tyres n/2 runs |

- Each set makes several consecutive runs in order to make several measurements.
- The reference runs at the start and at the finish indicate how test conditions may have changed.
- The sequence is reproduced for each type of surface.

■ TESTING LONGITUDINAL GRIP

One way for assessing longitudinal grip consists in measuring deceleration in order to evaluate braking efficiency. This test is performed on tracks that cover most of the range of real-life driving conditions.

Test principle

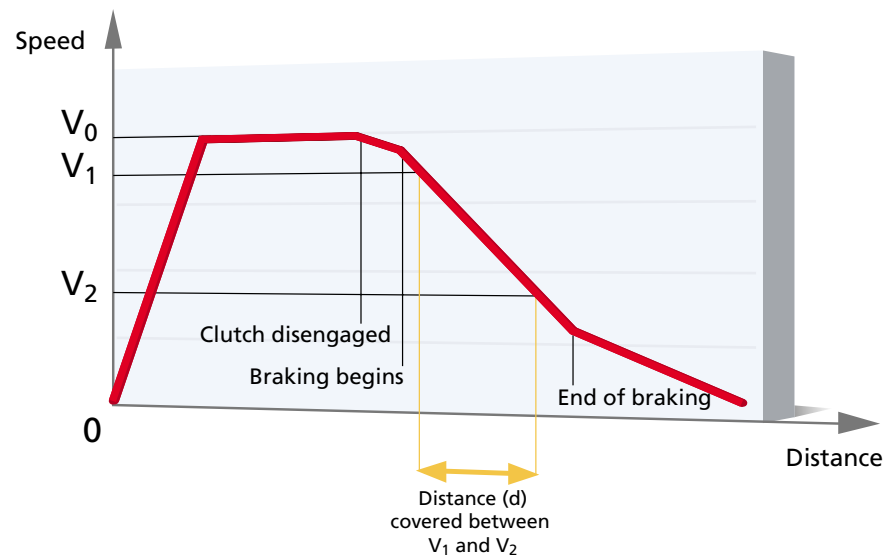
The test driver of a vehicle travelling at a speed V_0 over a specific type of road surface locks the brakes on the front wheels*. The vehicle, which may or may not have an ABS**, is equipped with a system for measuring speed and distance***. This system records the **braking distance**, d , while the speed drops from V_1 to V_2 ($V_1 < V_0$ and $V_2 < V_1$).

Then the mean **longitudinal coefficient of grip**, μ , is calculated using speeds V_1 and V_2 and the braking distance, d .

* On vehicles which are not equipped with ABS, the rear brake circuit is disconnected in order to maintain straight-line directional stability during braking.

** For the tests with an ABS, speed V_2 is never less than 10 km/h, as the system functions differently at low speed, and this could give misleading test results.

*** This system consists of a fifth wheel or a radar, connected to an on-board computer.



Wheel for measuring distance and speed, mounted at the rear of a test vehicle

Test conditions controlled:

- depth of water
- vehicle load
- tyre inflation pressure

Test conditions measured:

- wind speed and direction,
- track temperature

Values recorded:

- distance covered between V_1 and V_2

Value calculated:

- longitudinal coefficient of grip μ

A little more information on... calculating the coefficient of grip μ



The energy dissipated over the braking distance d is equal to the vehicle's kinetic energy loss:

$$\frac{1}{2} M.V_2^2 - \frac{1}{2} M.V_1^2 = M.\ddot{x}.d$$

From this, we directly deduce \ddot{x} , which denotes the vehicle's deceleration in m/s^2 .

This deceleration is due to two components: the "natural" deceleration of the vehicle (overall aerodynamic resistance, various types of friction and rolling resistance) and the force generated in the contact patch by the brake torque applied. Therefore:

$$F_{fw} + \mu.Z = M.\ddot{x}$$

where: F_{fw} is the deceleration force of the free-wheeling vehicle, or natural drag
 μ , the average coefficient of friction of the braked tyres,
 Z , the load applied to the tyres,
 M , the total mass of the vehicle.

For a braking test with "two front wheels locked", Z is the load supported by the two braked wheels. This is the load on the front axle, to which the load transfer is added:

$$Z = Z_{front} + M.\ddot{x} \cdot \frac{h}{L}$$

where: Z_{front} is the load on the front axle
 h is the height of the vehicle's centre of gravity
 L is the vehicle's wheelbase.

The mean value of the coefficient of friction is determined from the two previous equations:

$$\mu = \frac{M.\ddot{x} - F_{fw}}{Z_{front} + M.\ddot{x} \cdot \frac{h}{L}}$$

F_{fw} is given experimentally by an equation written as follows:

$$F_{fw} = M.(A + B.V^2)$$

In practice, a mean value is used to calculate the distance:

$$F_{fw} = M. \left[A + B. \left(\frac{V_1 + V_2}{2} \right)^2 \right]$$

Parameters A and B characterise the natural drag F_{fw} . They are assessed in the course of a prior deceleration test using a "free-rolling" vehicle.

Knowing the speeds V_1 and V_2 and the braking distance d we can therefore obtain the value of μ :

$$\mu_{mean} = \frac{M. \left(\left[\frac{V_2^2 - V_1^2}{2d} \right] - \left[A + B. \left(\frac{V_1 + V_2}{2} \right)^2 \right] \right)}{Z_{front} + M. \left(\frac{V_2^2 - V_1^2}{2d} \right) \cdot \frac{h}{L}}$$

For a braking test with "4 wheels braked", front and rear load transfer effects cancel each other out. Consequently:

$$\mu_{mean} = \frac{M. \left(\left[\frac{V_2^2 - V_1^2}{2d} \right] - \left[A + B. \left(\frac{V_1 + V_2}{2} \right)^2 \right] \right)}{Z_{total}}$$

Types of road surface

The tests are carried out on dry surfaces, damp draining mixes, polished concrete and asphalt concrete with water depths of either 2 or 5 mm. Each surface represents a real-life driving condition.

- Polished concrete with a water depth of 2 mm corresponds to heavy rain on very compacted and worn road surfaces which do not drain away water very well;
- Asphalt concrete with a 5 mm depth of water corresponds to puddles or ruts on roads and motorways in wet weather.
- Damp draining mixes correspond to very small depths of water frequently encountered on roads.

■ TRANSVERSAL GRIP TESTS

There are three types of transversal grip tests: tests on a wet or damp circular track, aquaplaning tests in bends or combination tests on a circuit.

Tests on water-sprayed circular tracks

The purpose of these tests is to evaluate and measure the level of transversal grip of various sets of tyres on wet or damp circular tracks.

Test principle

The test vehicle does several laps of the track at maximum speed, i.e. just below the grip breakaway point.

The time taken to cover a lap, or a section of it, is carefully measured.

The lap time and the curve radius are used to calculate the vehicle's average speed and transversal acceleration.

Types of surface

- The tests are carried out on macrosmooth surfaces, covered by 1 to 2 mm of water, which corresponds to a wet, worn road surface.

Test conditions controlled:

- curve radius
- depth of water
- vehicle load
- tyre inflation pressure

Test conditions measured:

- temperature of the air and track surface
- wind speed

Values recorded:

- lap time



Truck on water-sprayed circular track

Aquaplaning test in a bend

The aim of this test is to evaluate and measure transversal grip when the vehicle passes through a considerable depth of water, such as might be encountered during a downpour or when going through a rut full of water.

Test principle

The test is performed on a circular track, that has a 20 metre-long trough filled with water to a depth of 7 mm. Every time the test vehicle laps, all four wheels go through this water trough, while the driver maintains the steering wheel at the same angle.

Each lap of the track is done at constant speed. The test driver increases the vehicle speed at the beginning of each new lap, until vehicle grip in the water trough reaches its breakaway point and the vehicle travels in a straight line. The transversal acceleration of the vehicle is measured just before it reaches the trough and while it goes through it.

The transversal acceleration is then plotted against the vehicle speed so that the following can be calculated:

- the mean level of transversal acceleration;
- at what point the vehicle begins to break away from its intended path;
- the maximum acceleration and the corresponding speed;
- the "danger speed" (when aquaplaning is total and the vehicle travels in a straight line);
- the progressiveness of the change from maximum transversal acceleration to total aquaplaning.

Test conditions controlled:

- depth of water
- tyre inflation pressure
- speed before the water trough
- steering angle

Values recorded on each run:

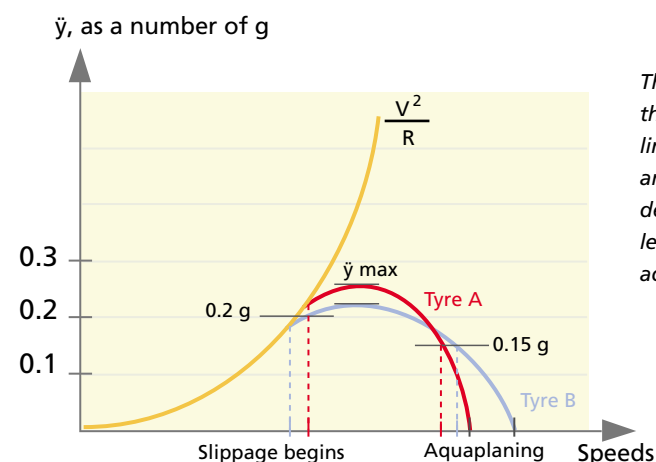
- time taken to go through the trough
- average acceleration before and in the trough

Values calculated:

- vehicle speed through the trough
- area beneath the curve (mean transversal acceleration)
- maximum transversal acceleration
- speed at max. transversal acceleration.
- speed at zero transversal acceleration ("danger speed")
- slope of the curve after max.transversal acceleration.



Transversal acceleration plotted against speed



Tests on a combination circuit

The purpose of these tests is to provide a comprehensive picture of the tyre and vehicle performance, which is measured and evaluated using a marking system.

Test principle

These tests are carried out on a circuit comprising a succession of bends of decreasing radius (from a wide curve to a hairpin bend), and different road surfaces. The tests simulate very severe driving conditions.

The lap time and the time taken to cover each section of track are measured. These sections are known as transversal, wet, transversal damp, longitudinal with deep water and wet slalom.

At the end of the test, the test driver marks the vehicle's handling on a wet surface according to a calibrated marking table (drive, braking, sensitivity to puddles in straight lines, steerability, transversal grip, quality of driving and vehicle balance). The driver also rates how progressively the tyre reaches maximum grip, which no analytical test can reflect.

N.B. In most of these tests, the influence of the vehicle is very important. The test driver's appreciation of vehicle handling is consequently a crucial factor in understanding the results.

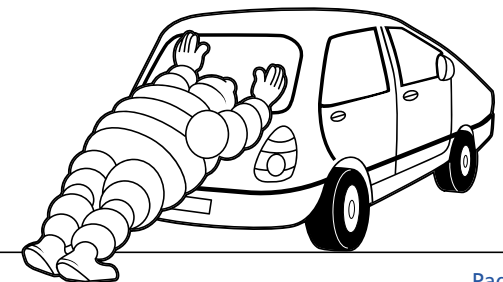


Combination circuit at the Ladoux test centre, France, called the "Duck" (Canard) circuit because of its distinctive shape. This circuit alternates between wide bends, tight bends and straight stretches.



VII *Grip & rolling resistance*

Like grip, the rolling resistance of tyres is due to the visco-elasticity of the rubber, which implies an energy loss each time the material undergoes distortion. Persistently looking for more grip and less rolling resistance therefore may seem contradictory. It can be demonstrated that these two types of performance are compatible.



It has already been shown that the mechanisms of grip are all based on rubber's hysteresis, which is its ability not to revert immediately to its initial shape after being subjected to deformation. This is why the tyre's tread blocks wrap around the rough spots in the road surface asymmetrically, so as to generate forces which counteract skidding. Hysteresis also amplifies the effect of the molecular adhesion forces.

But, has it not already been stated that hysteresis and a loss of energy inevitably go together? Might it not be tempting to wonder whether by laying the emphasis on grip, rolling resistance is not increased? Conversely, might it not be said that passenger safety suffers if grip potential is discriminated in any way because rolling resistance is reduced?

Below, the reader will see how grip and rolling resistance no longer affect each other as they used to.

While grip and rolling resistance do have hysteresis and energy loss in common, they are totally different mechanisms because of the frequencies at which they occur. Once this difference had been understood, both good grip and low rolling resistance could be made to coexist.

Rolling resistance



- Structural distortions
 - Low frequencies
 - Energy spent to no effect
- Deflection and then flattening

Grip (resistance to skidding)



- Surface distortions
 - High frequencies
 - Energy spent profitably
- Road roughness effect (indentation)

■ WHERE DOES ROLLING RESISTANCE COME FROM?

As the tyre rotates, the load distorts the tyre over its entire width and thickness in the contact patch. It is this **structural distortion** at both the leading and trailing edge of the contact patch which generates the energy loss corresponding to rolling resistance.

Grip, which counteracts sliding or even skidding, comes from the **distortion of the tyre's surface** (indentation) or even from molecular distortion (adhesion).



■ MAXIMISE GRIP AND MINIMISE ROLLING RESISTANCE: A CHALLENGE IN PHYSICAL SCIENCE

A simple comparative analysis may be performed on grip and rolling resistance to assess the **energy loss**.

An approximate figure of the energy lost in visco-elastic mechanisms every second is given by the following equation:

$$E_{\text{lost instantaneously}} \cong V \times h \times A \times Fr$$

with:

V: volume of rubber distorted

h: hysteresis of the rubber

A: amplitude (extent) of the distortion

Fr: stress frequency

Energy dissipated by the mechanisms of grip and rolling resistance

| | V | h | A | Fr | Instantaneous energy loss $V \times h \times A \times Fr$ |
|--------------------|----|---|----|-----|--|
| Grip | 1 | 1 | 1 | 100 | 100 |
| Rolling resistance | 10 | 1 | 10 | 1 | 100 |

V: volume of rubber distortion

A: amplitude of the distortion

h: energy loss due to rubber hysteresis

Fr: stress frequency

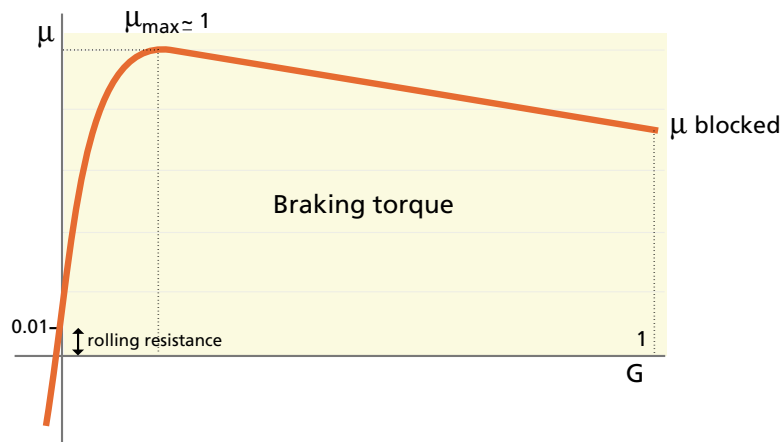
Approximately 1 mm is the estimated thickness of rubber affected by surface distortion caused by "indentation", whereas deflection and flattening in the contact patch affect the entire thickness of the tread pattern, which to simplify matters, will be considered to be 10 mm. Consequently, the ratio between the volumes (V) affected by the two types of distortion is 1 to 10.

In addition to this, the ratio of amplitude (A) between surface distortion and distortion of the entire tread pattern is also 1 to 10.

On the other hand, the stress frequency (Fr) produced by the mechanisms of grip as opposed to that produced by the mechanisms of rolling resistance is 100 to 1 in normal service conditions.

Calculations then show (see table opposite) that the action of grip usually produces as much energy loss as rolling resistance.

$\mu(G)$ law in braking



The curve does not pass through 0. For zero slippage (free-rolling), the wheel eventually stops. This corresponds to rolling resistance, which comes from the distortion of the tyre at the leading and trailing edges of the contact patch each time the wheel rotates. This distortion generates a μ value of:

- 0.01 (i.e. 10 kg/t) for a car tyre;
- 0.005 (i.e. 5 kg/t) for a truck tyre.

As has already been demonstrated, both grip and rolling resistance are directly related to hysteresis. On the basis of these conclusions, it would therefore appear impossible to reduce rubber hysteresis in order to obtain less rolling resistance without compromising the tyre's grip. This conclusion would seem to be further reinforced by the fact that grip generates far greater forces than rolling resistance.

An analysis of the grip curve shows that a passenger car tyre's rolling resistance corresponds to a μ braking value of 0.01 (see opposite).

The force produced by rolling resistance on the contact patch is therefore 100 times smaller than maximum longitudinal grip force.

If rolling resistance is decreased, will this not elicit a corresponding reduction in the force generated by grip? An in-depth examination of frequencies provided the key to this puzzling antagonistic reciprocation.

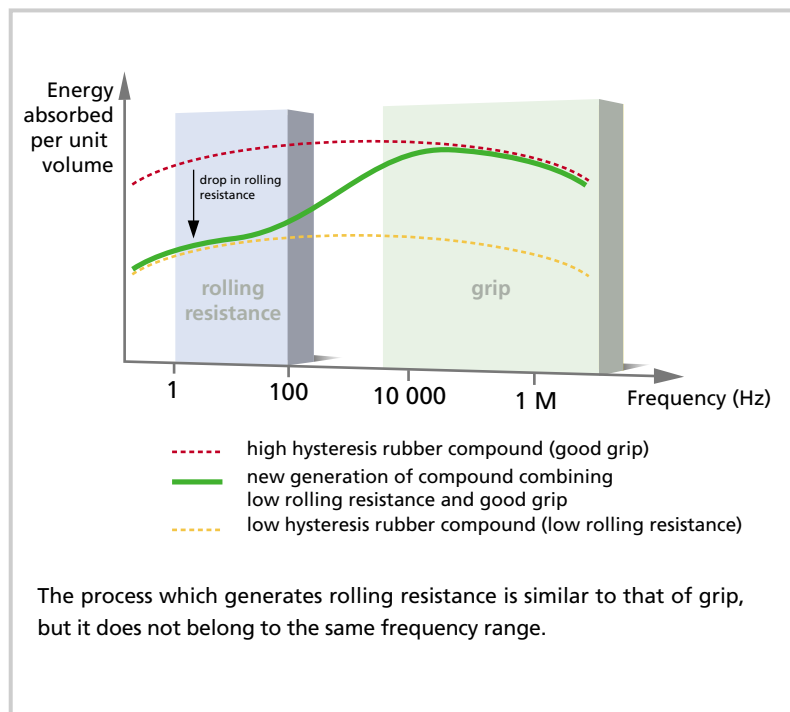
■ TWO DIFFERENT FREQUENCY RANGES

The distortion of the tyre's surface that generates grip occurs at frequencies between 10^3 and 10^{10} Hz. Structural distortion of the tyre, however, occurs every time the wheel rotates, which on a passenger car happens about 15 times every second (15 Hz) when the vehicle is travelling at 100 km/h (see frequency table opposite). Grip and rolling resistance relate to vastly different frequency ranges.


Once again another question comes to mind. Could rubber with high hysteresis in the grip frequency range not prove to be self-defeating, because it also exhibits high energy losses in the rolling resistance frequency range? This used to be true.

The use of silica has made it possible to separate grip from rolling resistance.

Until recently, rubber compounds gave the tyre a relatively flat energy absorption curve. As a result, what was gained in grip was lost in rolling resistance, and vice versa. The new compounds manufactured today have brought the answer. Their energy absorption curve rises sharply in the frequency range contained between 100 and



10,000 Hz, which means that the required levels of performance in both grip and rolling resistance can be combined and delivered in the manufactured tyre.

 **The Silica rubber compounds developed since 1993 and that are part of “green tyre” or Green X technology ensure 20% less rolling resistance without the slightest compromise in grip.**

*Green X tyre
with tread
containing silica*



A, B, C...

**A**

ABS: pp. 28, 39, 56, 57
Acceleration, accelerate: pp. 33, 56
Adhesion: see Molecular adhesion
Aggregates: p. 24
Aquaplaning, hydroplaning: pp. 61, 62
Aquaplaning test in a bend: p. 85

B

Bank of water: pp. 61, 62
Bernoulli's equation: pp. 61, 62
Binder: p. 24
Bituminous concrete: pp. 24, 29, 31
Bow effect: see Stem-shaped effect
Braking, deceleration: pp. 33, 38, 56, 72
Braking distance: pp. 82, 83
Braking torque: pp. 57, 72
Break (through the residual water film): pp. 29, 60, 70

C

Centrifugal force: pp. 46, 47, 54
Centripetal acceleration: p. 48
Centripetal force: pp. 46, 54
Channel: pp. 60, 64, 66, 67, 70
Circular groove: p. 64
Circular track: pp. 84, 85
Coefficient of friction, coefficient of grip: pp. 23, 26, 27, 29, 30, 31
Coefficient of longitudinal friction, coefficient of longitudinal grip, longitudinal friction coefficient, longitudinal grip coefficient: pp. 26, 38, 43, 45, 55, 83

Coefficient of transversal friction, coefficient of transversal grip, transversal friction coefficient, transversal grip coefficient: pp. 26, 48, 50, 54, 55
Combination circuit: p. 86
Contact patch: pp. 33, 60, 61, 63, 65, 70
Cornering: pp. 33, 46, 56
Coulomb's friction force: p. 35

D

Damp zone: pp. 60, 69
Danger speed: p. 85
Deceleration: see Braking
Depth of water: p. 60, 63
Dispersal (of water), disperse: pp. 61, 62, 63, 70
Drainage, drain: pp. 22, 23, 29, 61, 63, 70
Draining mix: pp. 24, 29, 31

E

Elastic, elasticity (see also Visco-elastic): pp. 8, 11, 13, 14
Elastomer: pp. 11, 17
Energy loss: pp. 9, 10, 12, 19, 88, 89

F

Fines: p. 24
Flow of water: p. 63
Friction coefficient: see Coefficient of friction

G

Glass transition temperature: pp. 14, 15, 16, 19
Glassy state, vitreous state: pp. 13, 14, 15, 16, 19

Grip coefficient: see Coefficient of friction
Grip tests: Chap. VI

H

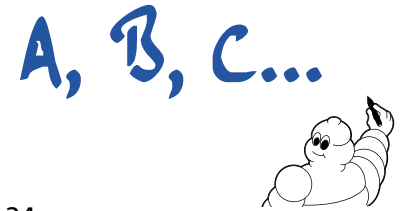
Hydrodynamic pressure: p. 61
Hydrodynamic zone: pp. 60, 61, 65
Hydroplaning: see Aquaplaning
Hysteresis: pp. 8, 9, 10, 12, 13, 14, 15, 19, 43, 53, 88

I

Ice: p. 30
Indentation: see Road roughness effects
Indenter: see Rough spot

L

Laboratory vehicle: p. 80
Lateral load transfer: pp. 47, 73
Length of shear: pp. 34, 40, 41, 42
Length of slippage: pp. 34, 41, 42
Load bearing surface: pp. 23, 25, 28
Longitudinal friction coefficient, longitudinal grip coefficient: see Coefficient of longitudinal grip
Longitudinal friction law: p. 39
Longitudinal grip: Chap. III.2
Longitudinal load transfer: p. 72
Loss of energy: see Energy loss



M

Macrorough: pp. 27, 31

Macroroughness, macrotexture: pp. 17, 23, 27, 28, 29, 70

Macrosmooth: pp. 27, 31

Macrotexture: see Macroroughness

Maximum cornering speed: p. 49

Measurement wheel: pp. 80, 82

Microrough: pp. 27, 31

Microroughness, microtexture: pp. 17, 23, 28, 29, 69

Microsmooth: pp. 27, 31

Microtexture: see Microroughness

Modulus: pp. 12, 13, 14, 15

Molecular adhesion: pp. 17, 18, 20, 22, 28, 29, 31, 60, 88

Molecular mobility: pp. 13, 14

Molecular velocity: p. 15

O

Overload: pp. 72, 73

Oversteer: pp. 74

P

Phase angle: pp. 10, 12

Piston: pp. 9, 10, 19

Polymer: pp. 11, 12

Pseudo-slippage (see also Shear): pp. 34, 35, 40, 43, 45, 52

R

Reference tyre: p. 81

Relaxation: p. 13

Rigidity: see Modulus

Road roughness effects, indentation: pp. 17, 20, 22, 23, 28, 31, 60

Road simulator: see Rolling rig

Road surface: Chap. II

Roll torque: p. 73

Rolling resistance: p. 43, Chap. VII

Rolling rig, road simulator: p. 79

Rough spot, indenter: pp. 17, 20, 22, 23, 25, 88

Rubber: Chap. I

Rubbery state: pp. 13, 14, 15, 19

S

Sand: p. 24

Self-aligning torque: p. 52

Shear (see also Pseudo-slippage): pp. 34, 40, 42, 43, 45, 51, 52, 54

Silica: p. 90

Sipe: pp. 60, 64, 66, 67, 68, 69, 70

Slip angle: pp. 46, 47, 50, 54, 56

Slippage, slip: pp. 34, 35, 36, 37, 40, 42, 43, 45, 51, 52, 53, 54

Slippage rate: pp. 36, 45, 56

Snow: p. 30

Speed of deformation: p. 15

Spinning on the spot: p. 36

Spring: pp. 8, 10, 19

SRT pendulum: p. 26

Standardised sand: p. 23

Stem-shaped effect, bow-effect: pp. 62, 70

Storage (of water), store: pp. 22, 23, 29, 60, 65, 67, 70

Stress frequency: pp. 15, 16, 17, 18, 19

Structural distortion: pp. 88, 90

Sulphur bridges: pp. 11, 12, 14

Surface coating: p. 24

Surface distortion: pp. 88, 90

Surface tension: p. 69

T

Temperature: pp. 13, 14, 15, 43, 44, 52, 53

Tipping torque: p. 72

Transfer time: p. 65

Transversal friction coefficient, transversal grip coefficient: see Coefficient of transversal grip

Transversal friction law: p. 50

Transversal grip: Chap. III.3

Transversal groove: p. 64

Tread grooves: pp. 60, 64, 65, 70

U

Understeer: p. 74

V

Van der Waals bonding: p. 18

Viscodynamic: pp. 60, 65

Visco-elastic, visco-elasticity: pp. 8, 9, 13, 14, 17, 18, 19, 88

Viscosity, viscous: pp. 8, 9, 11, 12, 13

Vitreous state: see Glassy state

Vulcanised: p. 11

W

Wave front (see also Bank of water): p. 62

Wheel locked: pp. 36, 43, 57, 72

WLF equation: pp. 15, 16

