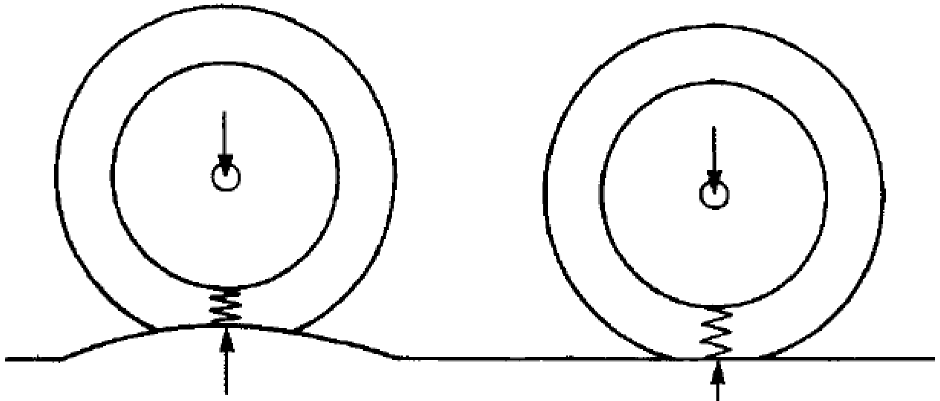
Wrocław
University
of Science
and Technology

Tires road interaction
Rolling resistance

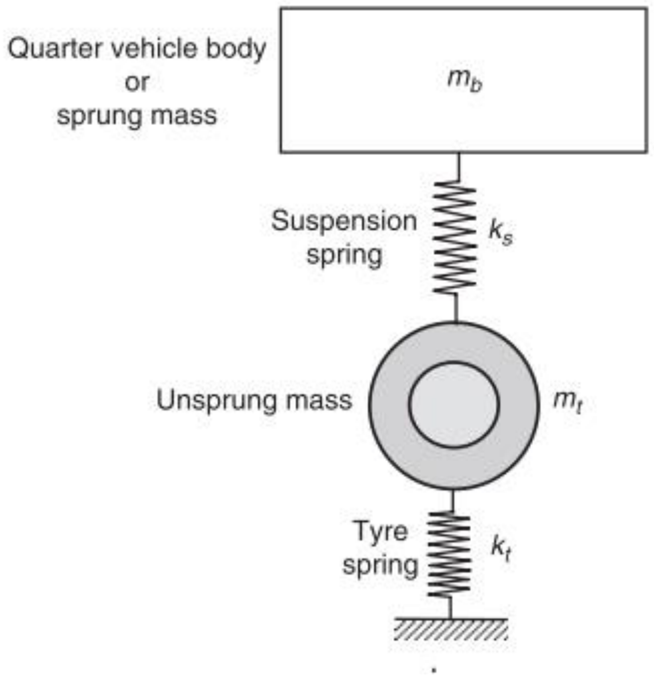
Tires

- When a vehicle is being driven along the road, the tires are acted upon by a complex and variable system of forces that arise in the vertical, longitudinal and lateral directions. The manner in which the tires react to these forces defines their main characteristics.
- The performance of a vehicle is mainly influenced by the characteristics of its tires.
- Tires affect a vehicle's handling, traction, ride comfort, and fuel consumption.
- The main functions of tires.

1. To support the weight of the vehicle and distribute it over the road Surface.
2. To offer the minimum rolling resistance to the motion of the vehicle and thus reduce power absorption.
3. To contribute to the suspension cushioning of impact forces created by road surface irregularities
4. To permit the generation of traction, braking and steering forces on dry or wet road surfaces.
5. To confer safe operation up to the maximum speed of the vehicle.
6. To provide quiet straight-ahead running and freedom from squeal on cornering and braking.
7. To realize an acceptable tread life under varied running conditions.

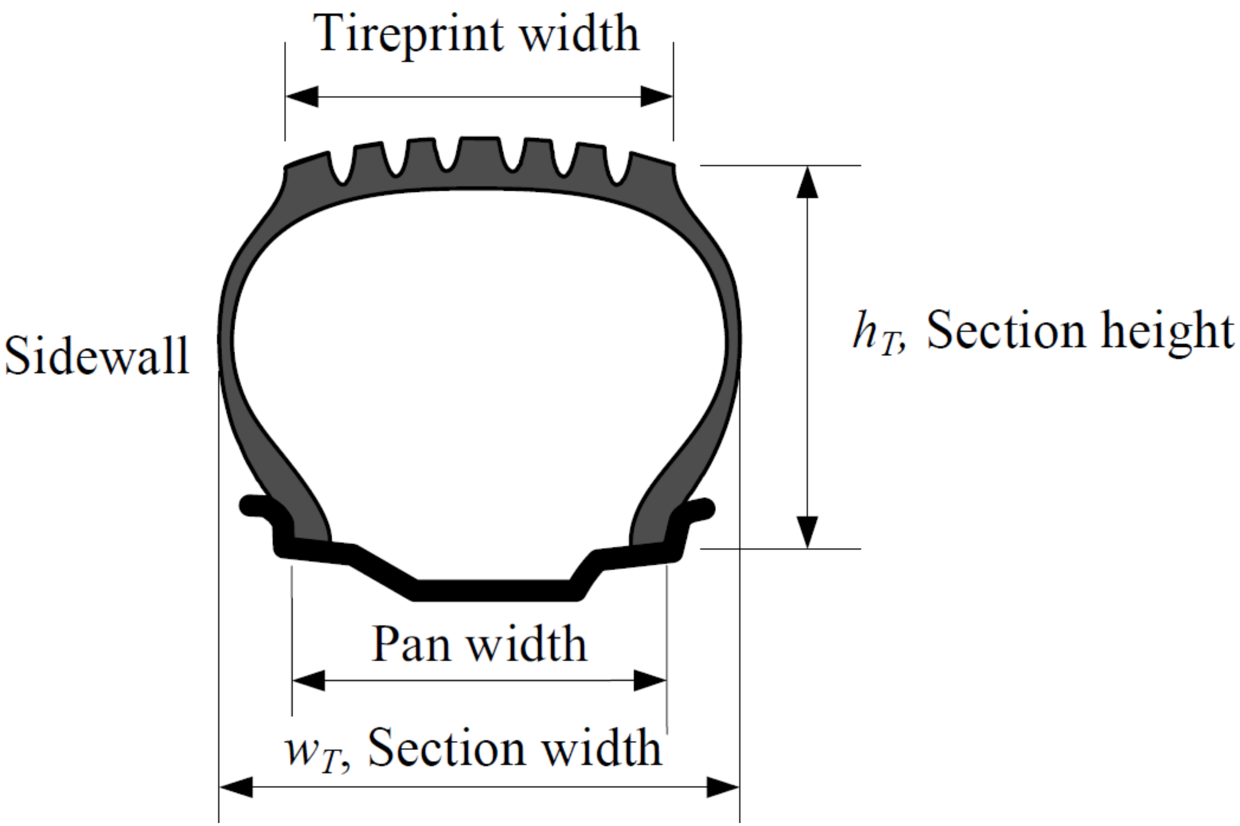


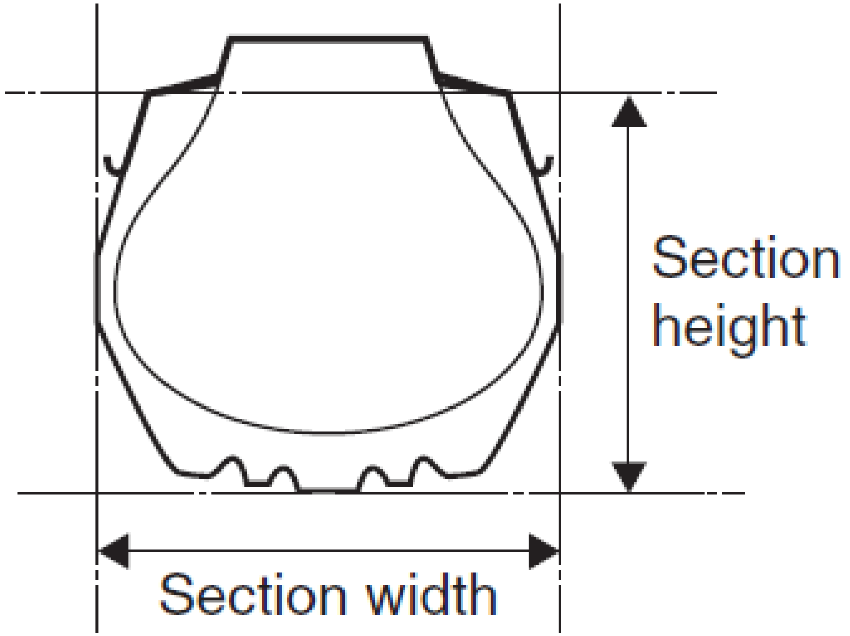
NUNNEY, M. 2015. *Light and Heavy Vehicle Technology*, Routledge.



BLUNDELL, M. & HARTY, D. 2004. *The Multibody Systems Approach to Vehicle Dynamics*, Elsevier Science.

Tires





Aspect ratio is equal to:

$$\frac{\text{section height}}{\text{section width}} \times 100\%$$

60-70% modern practice
95% balloon tires on an earlier era
30-40% high performance cars *(these very low profile tires are related to larger wheel sizes and can be recognized by their almost rubber band-like appearance)*

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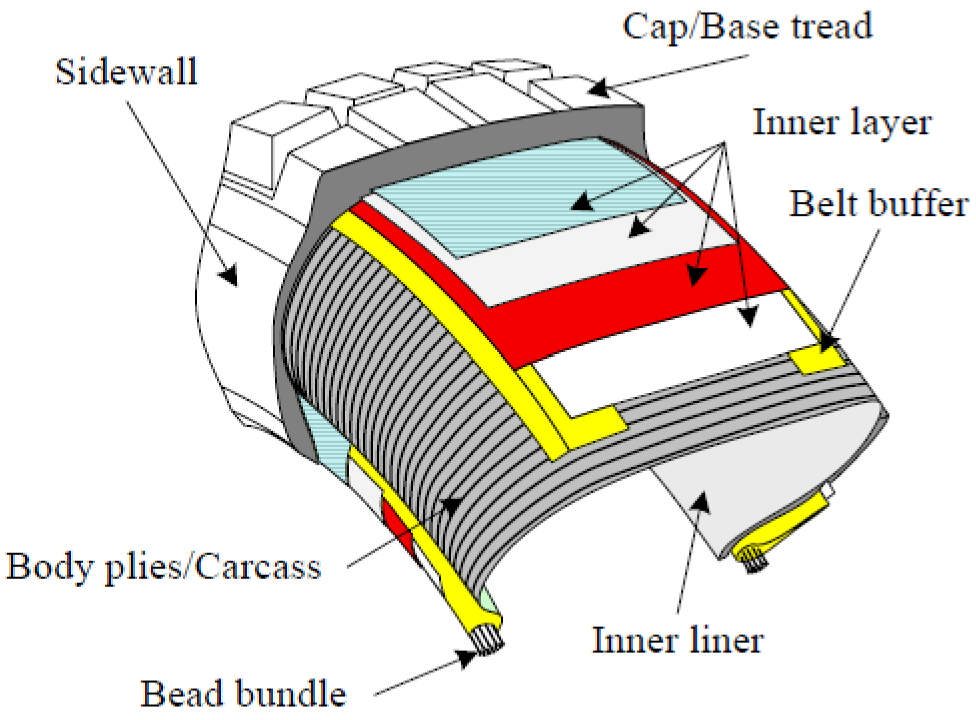

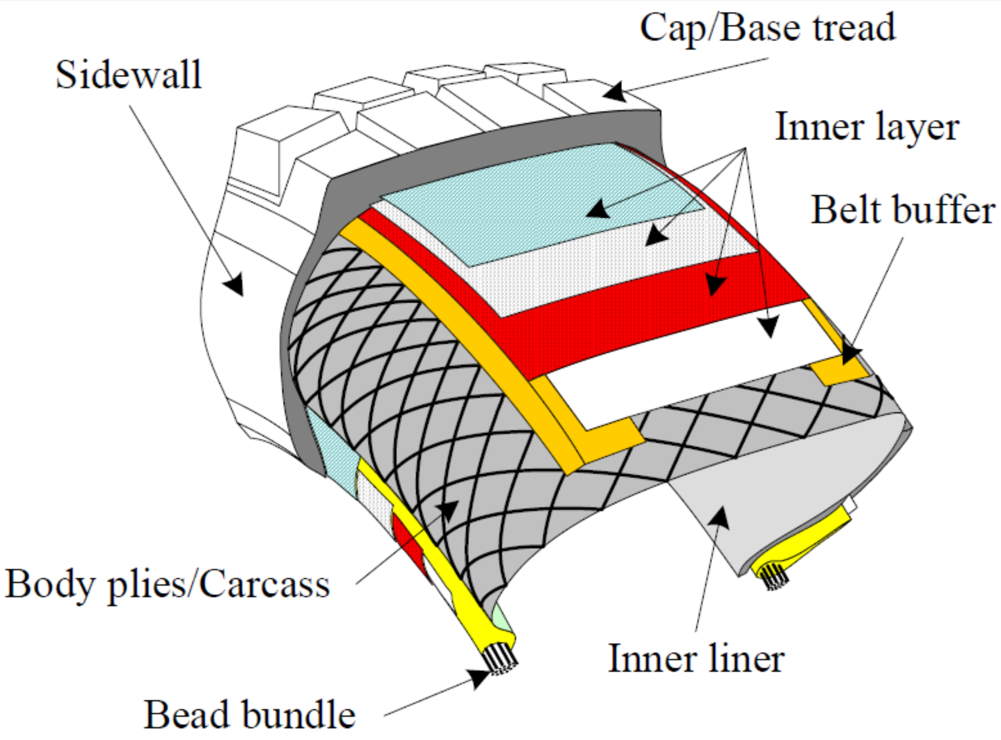

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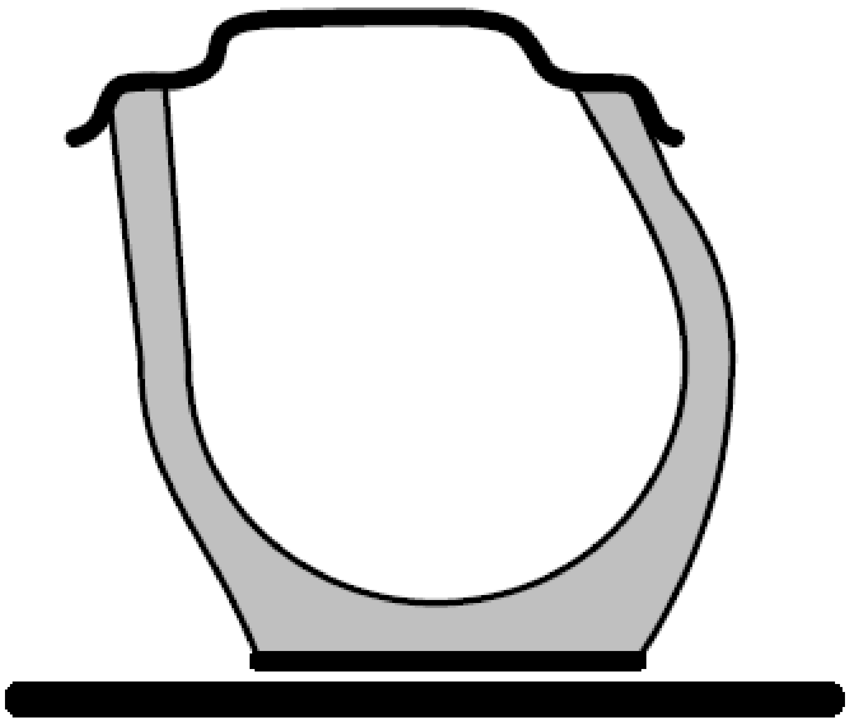
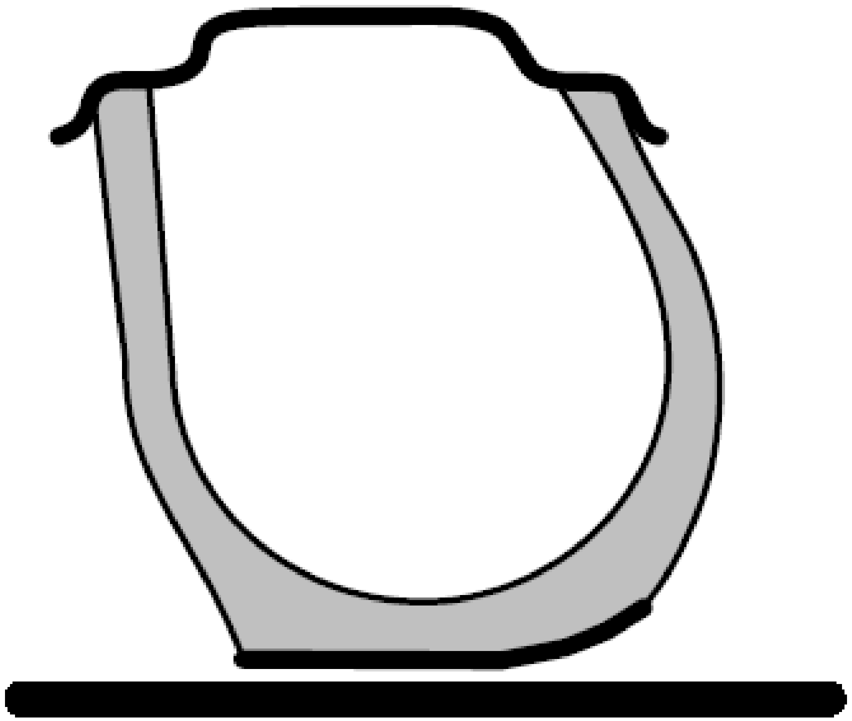
- The ply cords follow the contour of the tire from bead to bead.
- The radial-ply tire is relatively free from internal friction because of the non-criss-crossing of its carcass plies (*cooler running and permits reduced inflation pressures for greater cushioning ability*)
- The rigidity of the stabilizer belt effectively resists contraction of the flattened part of the tread in contact with the road, so there is less tread shuffling and wearing of the tyre.
- A disadvantage of the radial-play tyre is its tendency towards increased ride harshness at low speeds owing to its vibration characteristics,

- The criss-cross arrangement adopted for the several layers of cords (approx. 40 deg)
- The continuous flexing of its carcass imposes slight fidgeting movements in the rubber layers between the criss-crossed ply cords (*frictional heating which, if generated to excess, can shorten tire life by weakening the ply cords*)
- the vertical deflection of the tire results in contraction of the flattened part of the tread in contact with the road *(a prominent source of tire wear)*



(a) Radial tire



(b) Non-Radial tire

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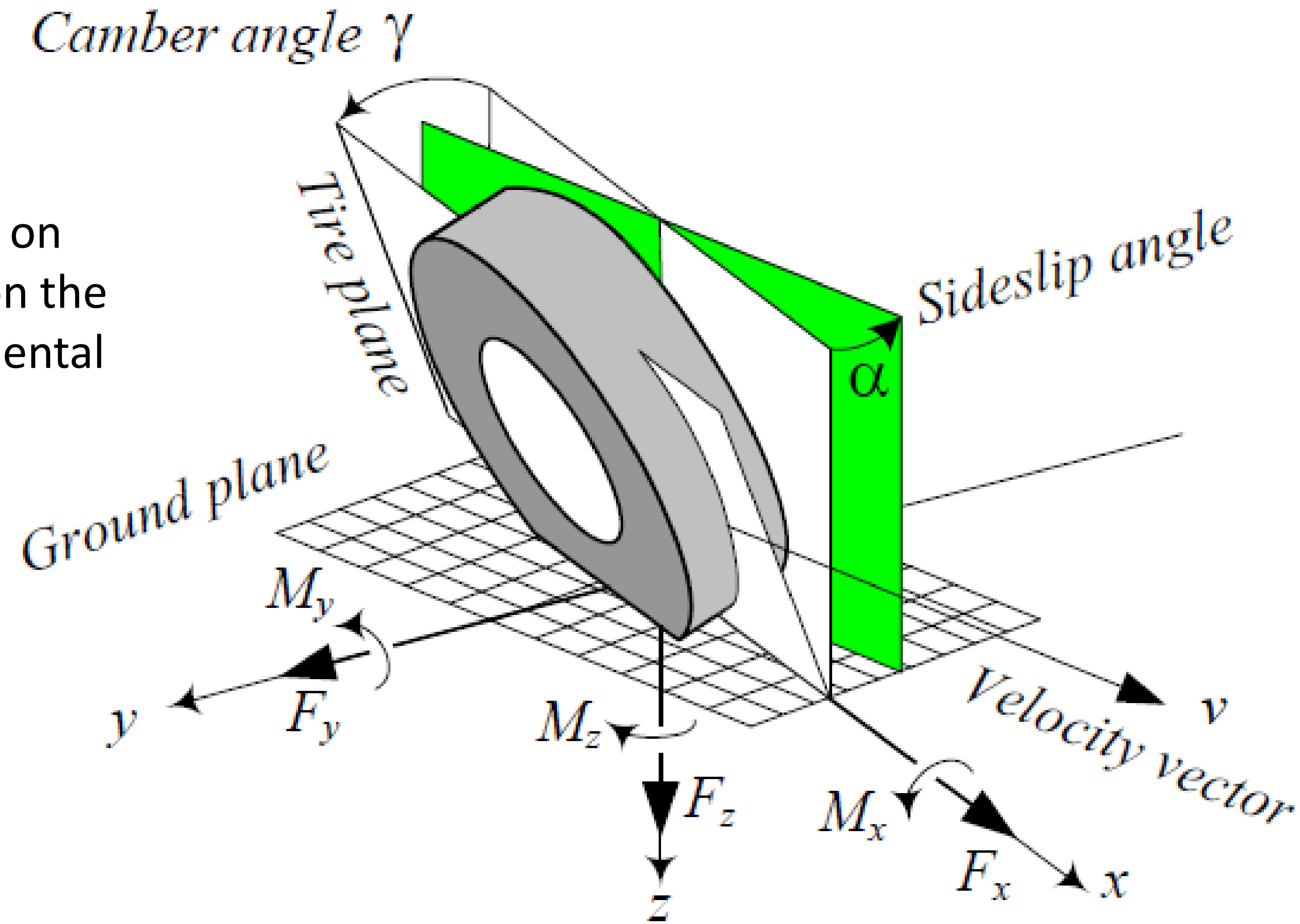
Tires stiffens

Calculating the tire stiffness is generally based on experiment and therefore, they are dependent on the tire's mechanical properties, as well as environmental characteristics

$$F_x = k_x \triangle x$$
$$F_y = k_y \triangle y$$
$$F_z = k_z \triangle z$$



Tires stiffens

When under static load the tire will deflect under the load and generate a pressurized contact area to balance the vertical load F_z

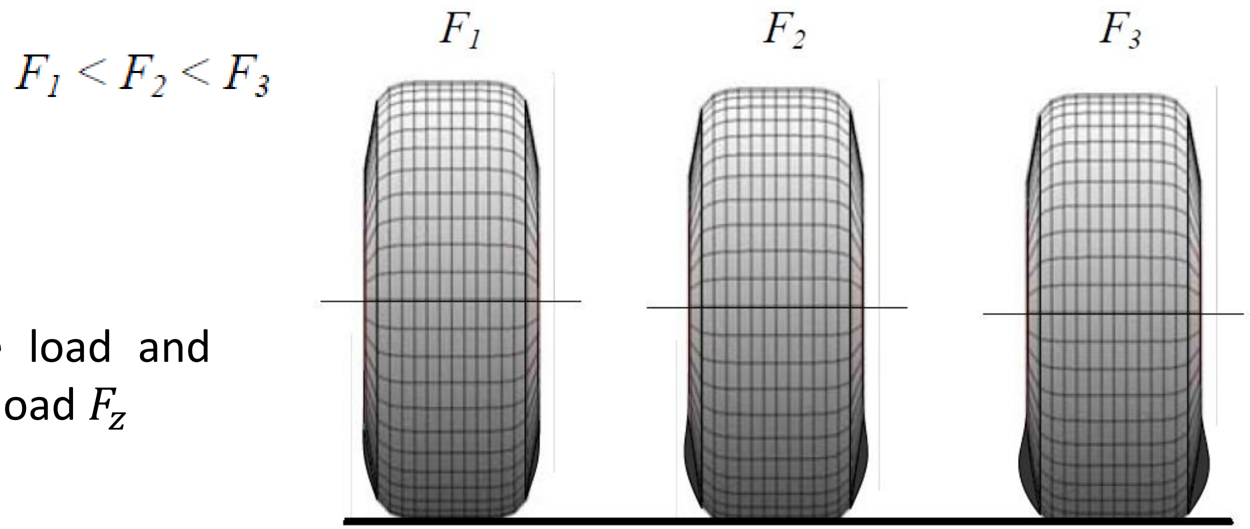
$$F_z = f\left(\triangle z\right)$$

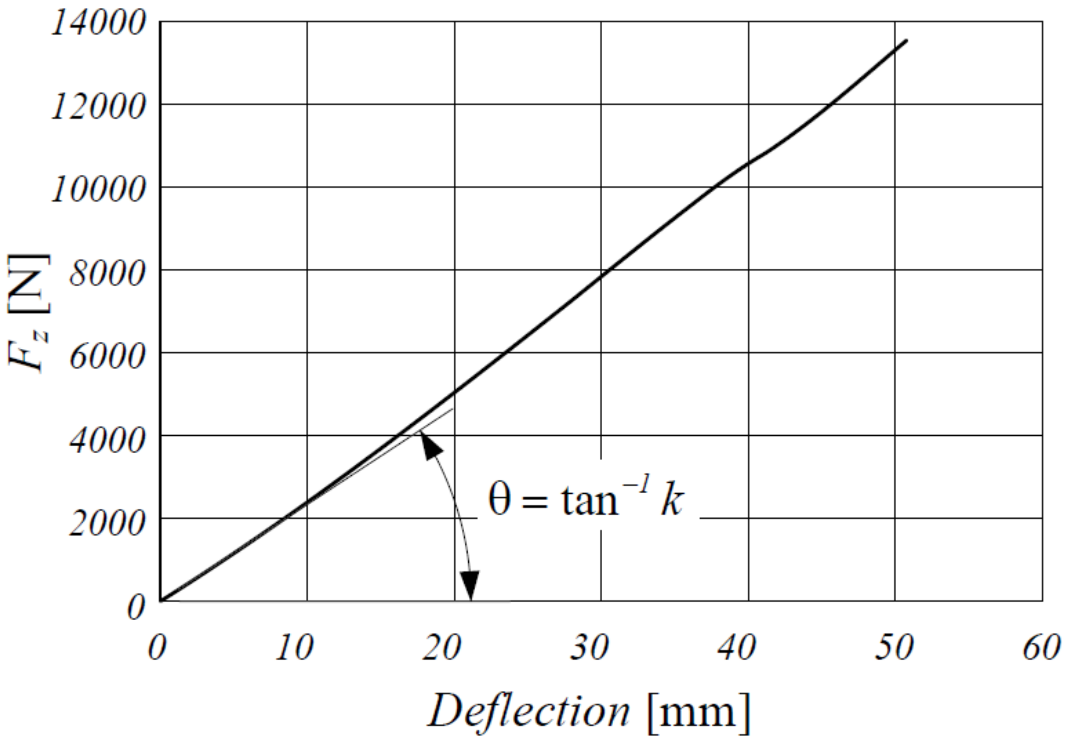
however, we may use a linear approximation for the range of the usual application.

$$F_z = \frac{\partial f}{\partial\left(\triangle z\right)} \triangle z$$

The coefficient $\frac{\partial f}{\partial(\Delta z)}$ is the slope of the experimental stiffness curve at zero and is shown by a stiffness coefficient

$$k_z = \tan\theta = \lim_{\triangle z \to 0} \frac{\partial f}{\partial\left(\triangle z\right)}$$





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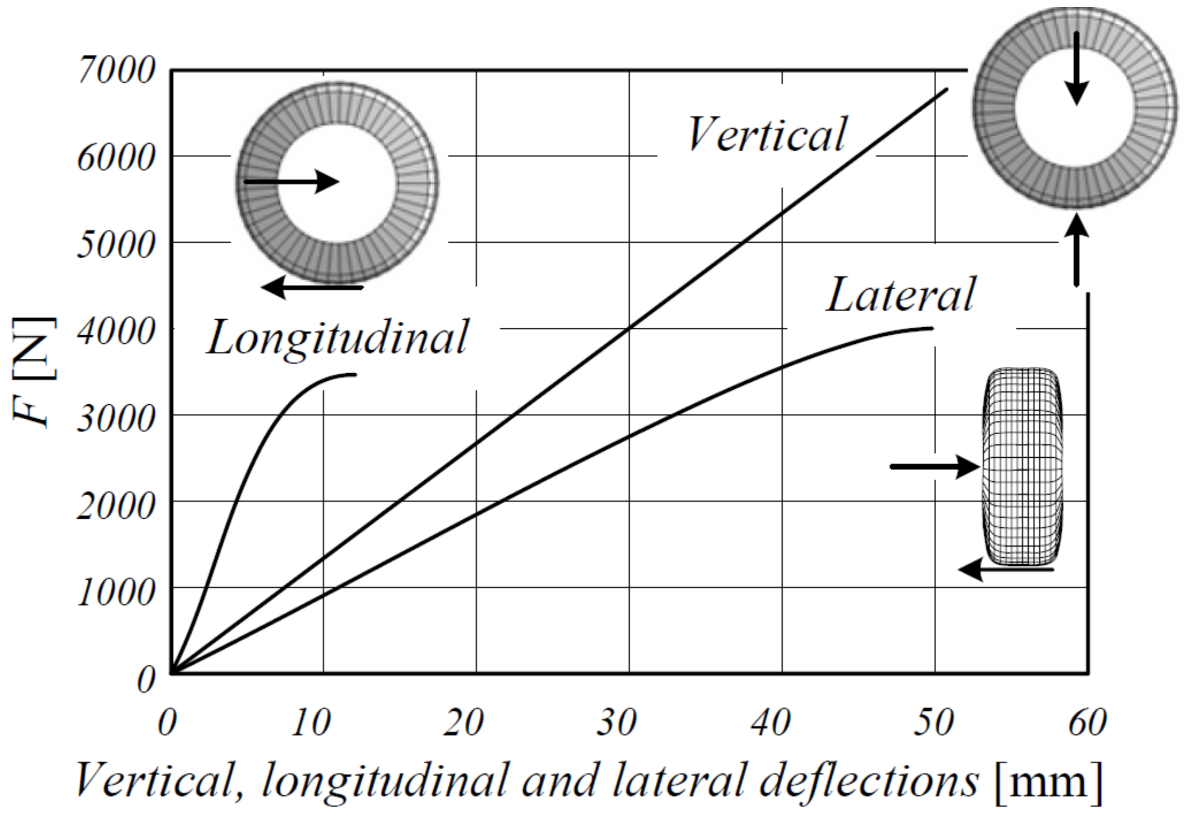
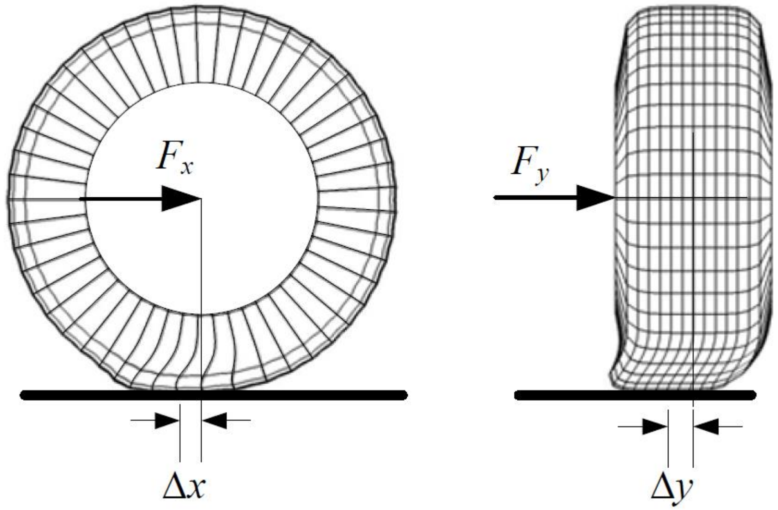
Tires stiffens

- The lateral and longitudinal forces are limited by the sliding force when the tire is vertically loaded.
- A tire is most stiff in the longitudinal direction and least stiff in the lateral direction

$$F_x = k_x \triangle x$$
$$F_y = k_y \triangle y$$

$$k_x = \lim_{\triangle x \to 0} \frac{\partial f}{\partial (\triangle x)}$$
$$k_y = \lim_{\triangle y \to 0} \frac{\partial f}{\partial (\triangle y)}$$





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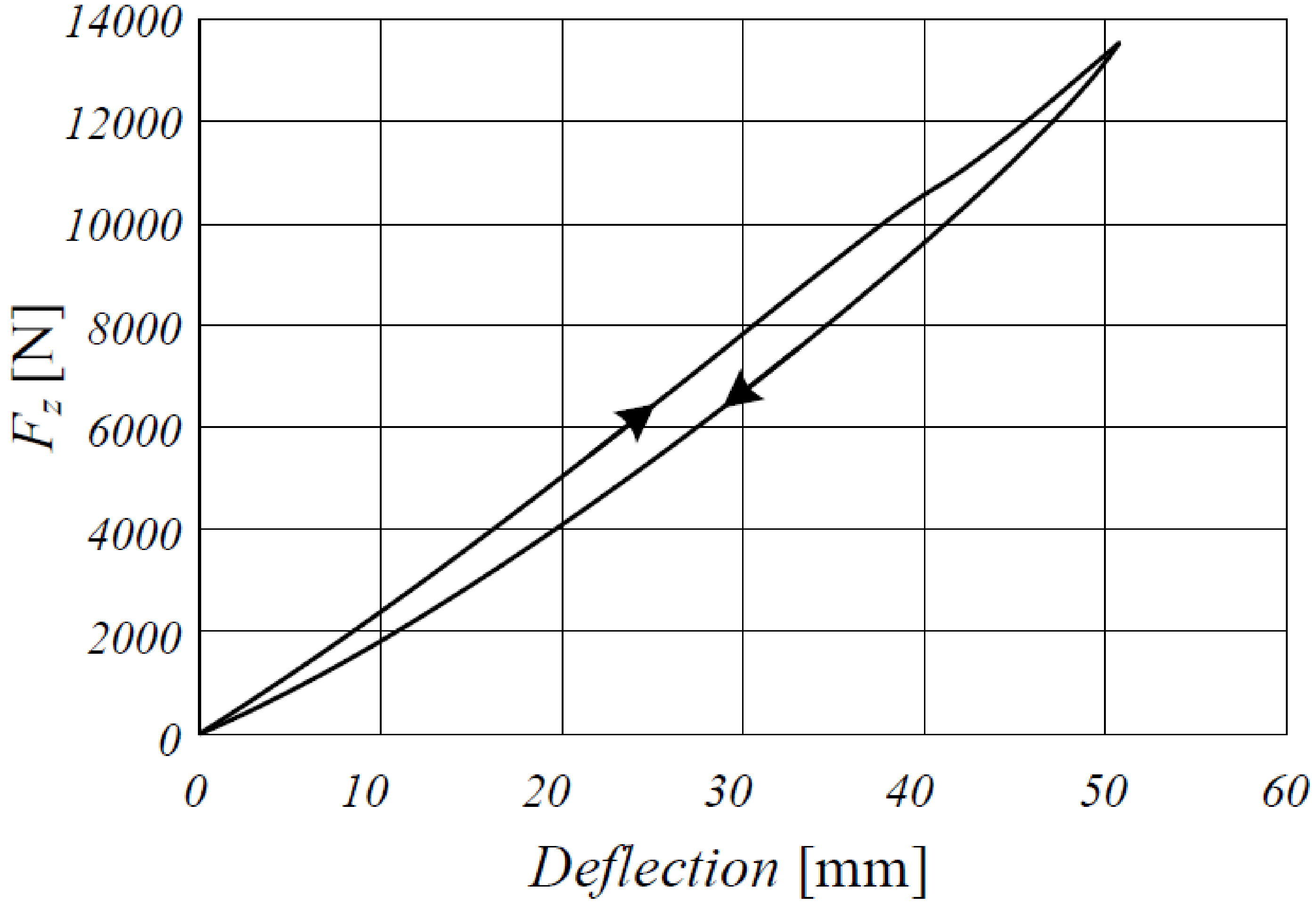
Tires Hysteresis effect
Hysteresis loss



- The loading and unloading stiffness curves are not exactly the same.
- The area within the loop is the amount of dissipated Energy during loading and unloading

- The deformed tire recovers slowly, and therefore, it cannot push the tireprint tail on the road as hard as the tireprint head.
- **The difference in head and tail pressures causes a resistance force, which is called rolling resistance.**

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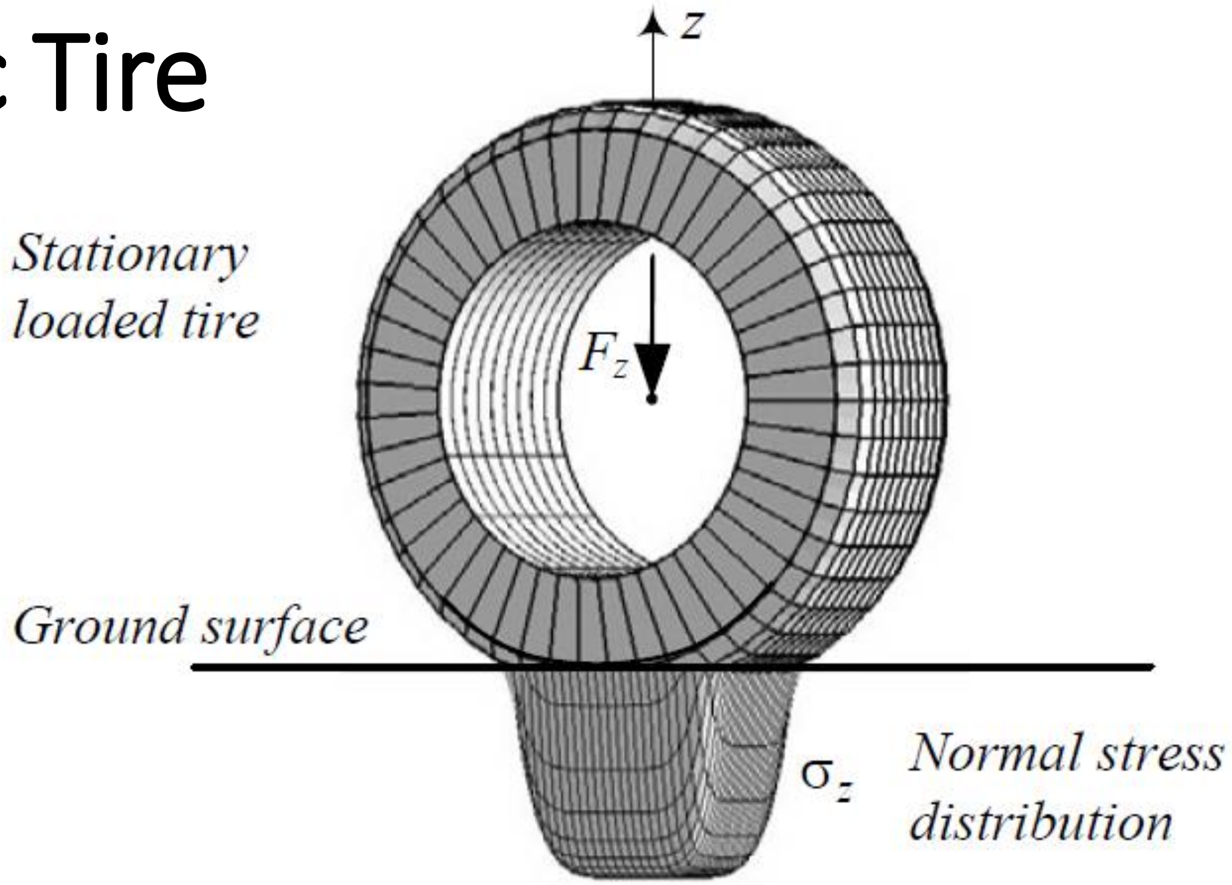
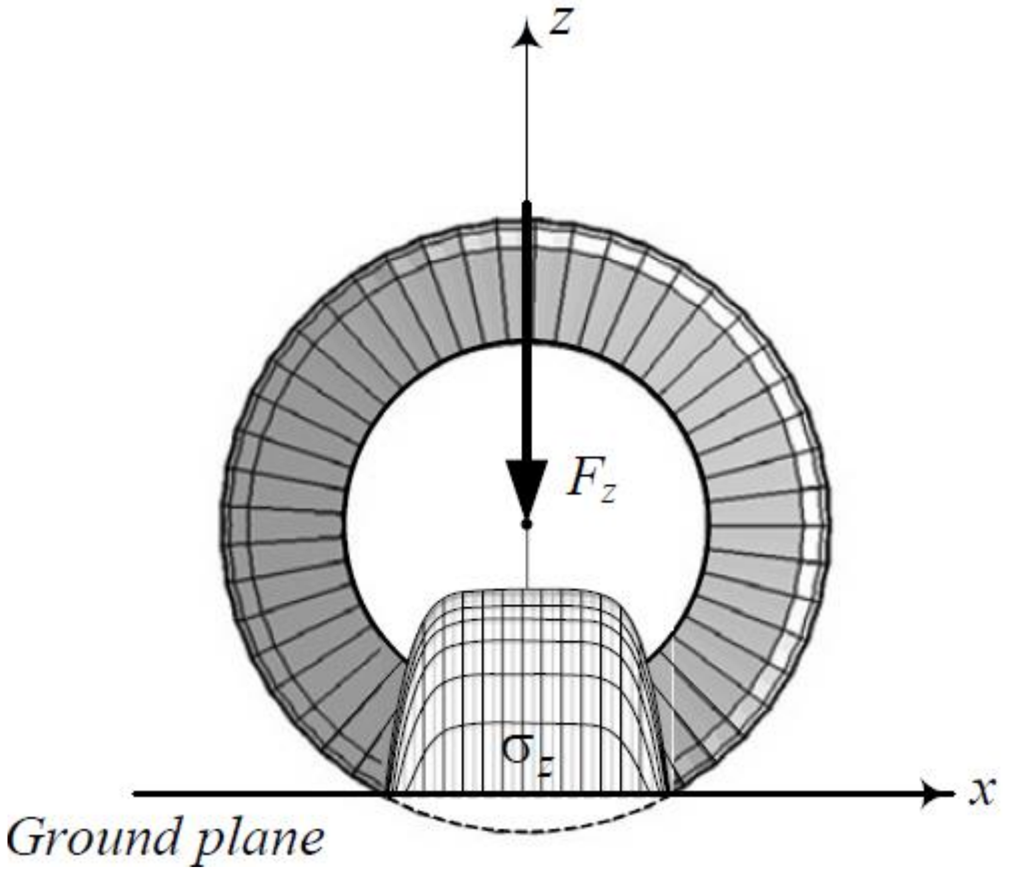
Tireprint
Static Tire





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Tireprint
Static Tire

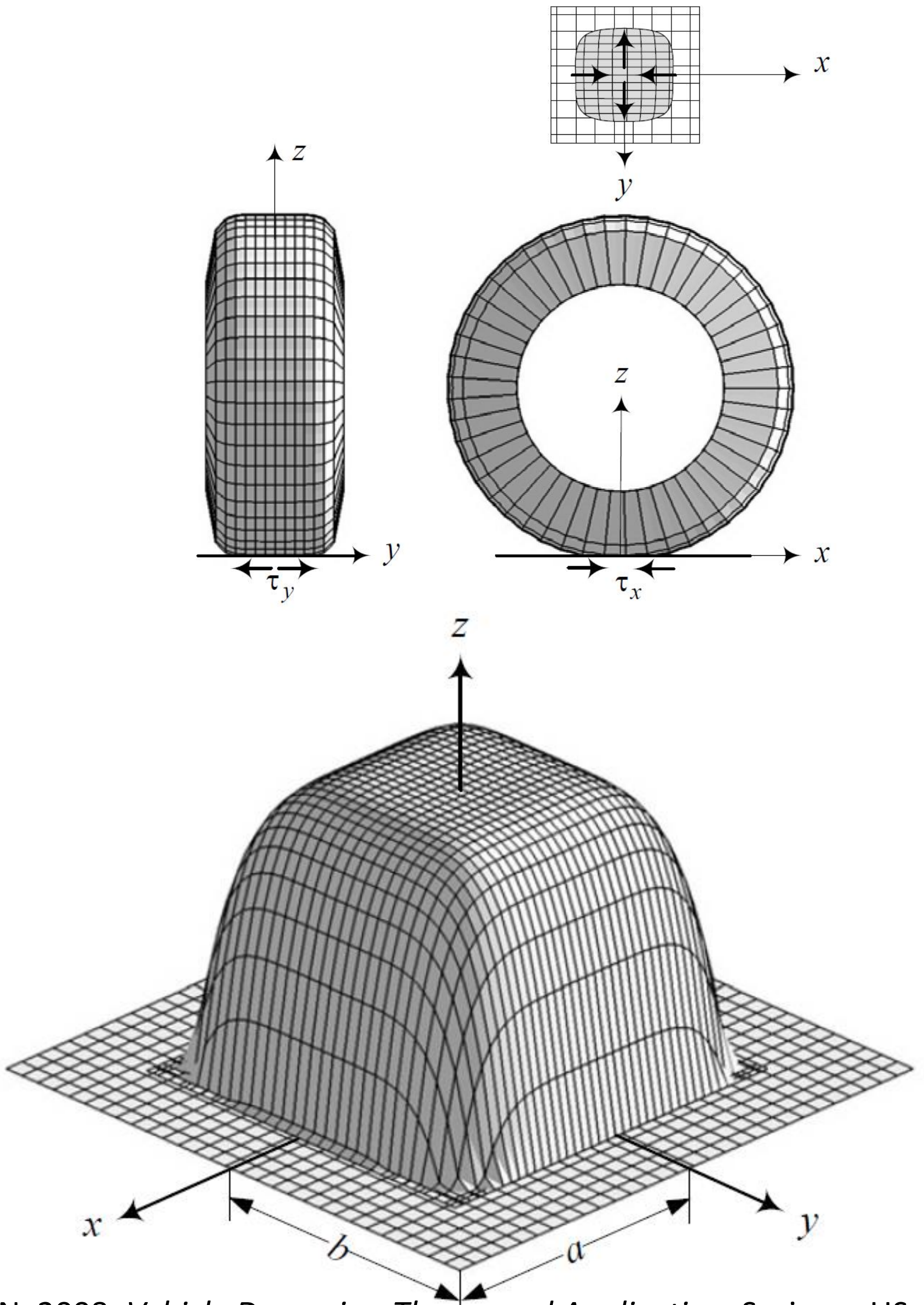
Due to equilibrium conditions, the overall integral of the normal stress over the tireprint area A_P must be equal to the normal load F_z, and the integral of shear stresses must be equal to zero

$$\int_{A_P} \sigma_z(x,y)\,dA = F_z$$

$$\int_{A_P} \tau_x(x,y)\,dA = 0$$

$$\int_{A_P} \tau_y(x,y)\,dA = 0$$

$$\sigma_z(x,y) = \sigma_{z_M}\left(1 - \frac{x^6}{a^6} - \frac{y^6}{b^6}\right)$$



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Tireprint
Static Tire

The tireprints may approximately be modeled by a mathematical function

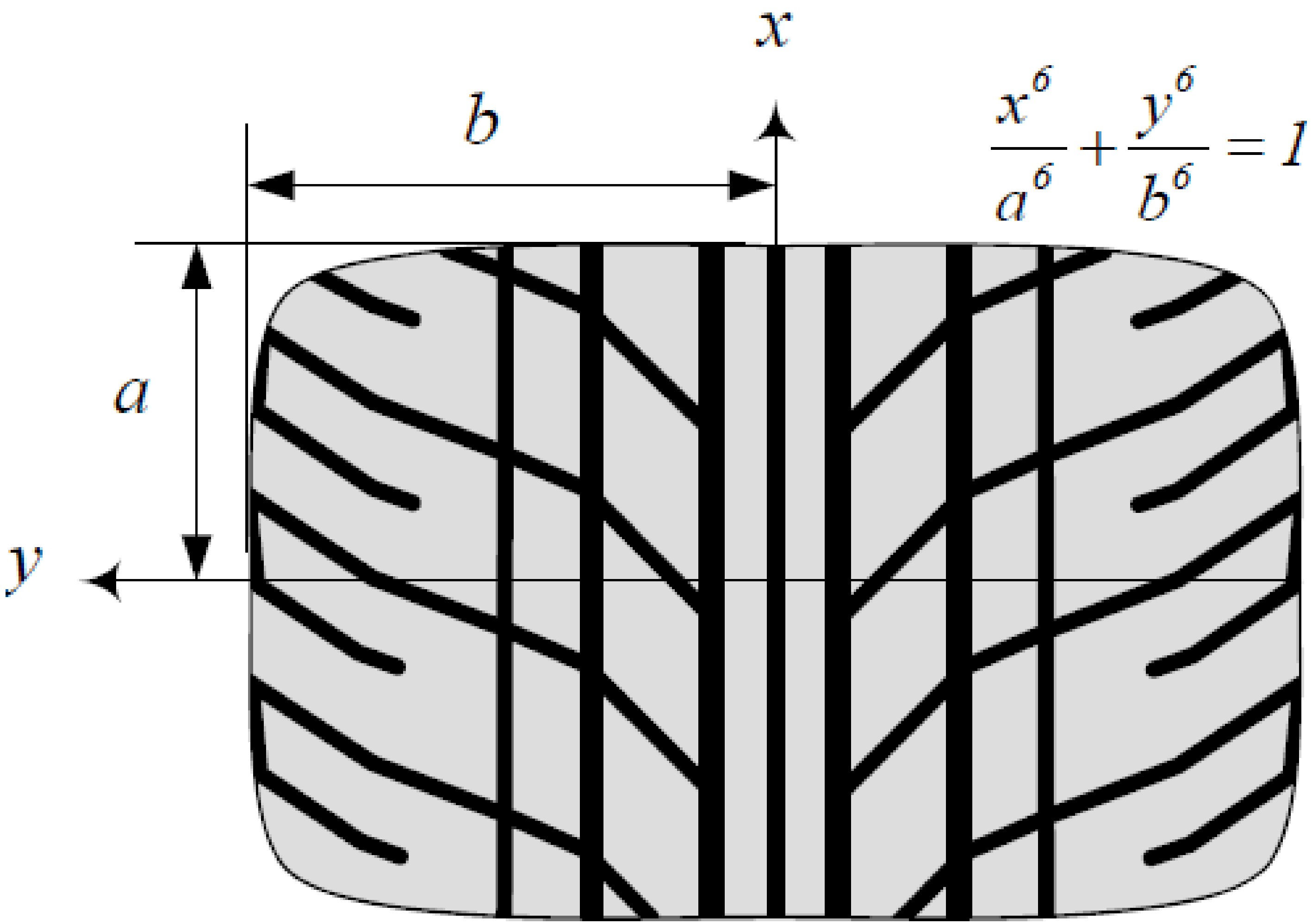
$$\frac{x^{2n}}{a^{2n}} + \frac{y^{2n}}{b^{2n}} = 1 \qquad n \in N.$$

For radial tires, n = 3 or n = 2 may be used

$$\frac{x^6}{a^6} + \frac{y^6}{b^6} = 1$$

For non-radial tires n = 1 is a better approximation

$$\frac{x^2}{a^2} = \frac{y^2}{b^2} = 1.$$



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Tires
Rolling radius

As the tire turns forward, each part of the circumference is flattened as it passes through the contact area.

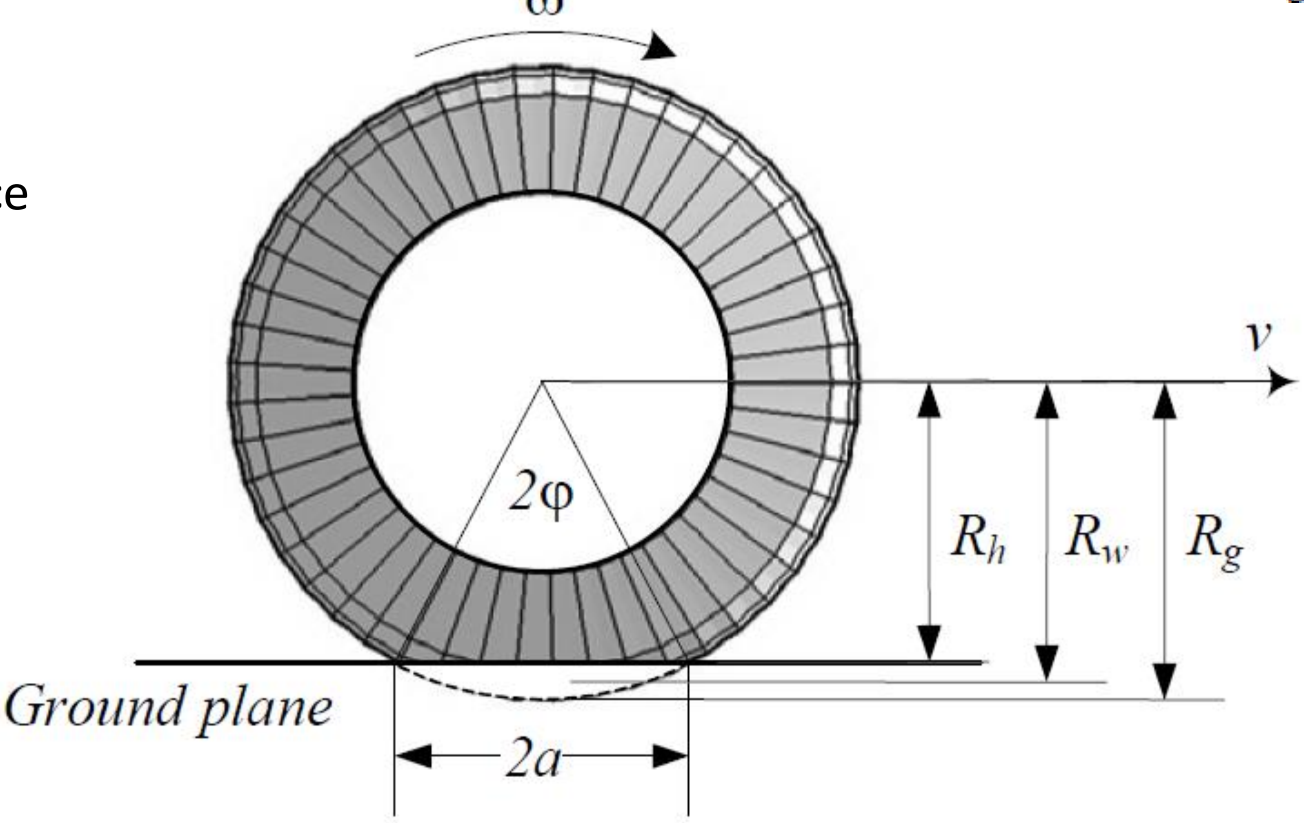
The effective radius of the wheel R_w, which is also called a rolling radius,

$$R_w = \frac{v_x}{\omega_w}$$

The effective radius R_w is approximately equal to

$$R_w \approx R_g - \frac{R_g - R_h}{3}$$

$$R_h < R_w < R_g$$



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Tires

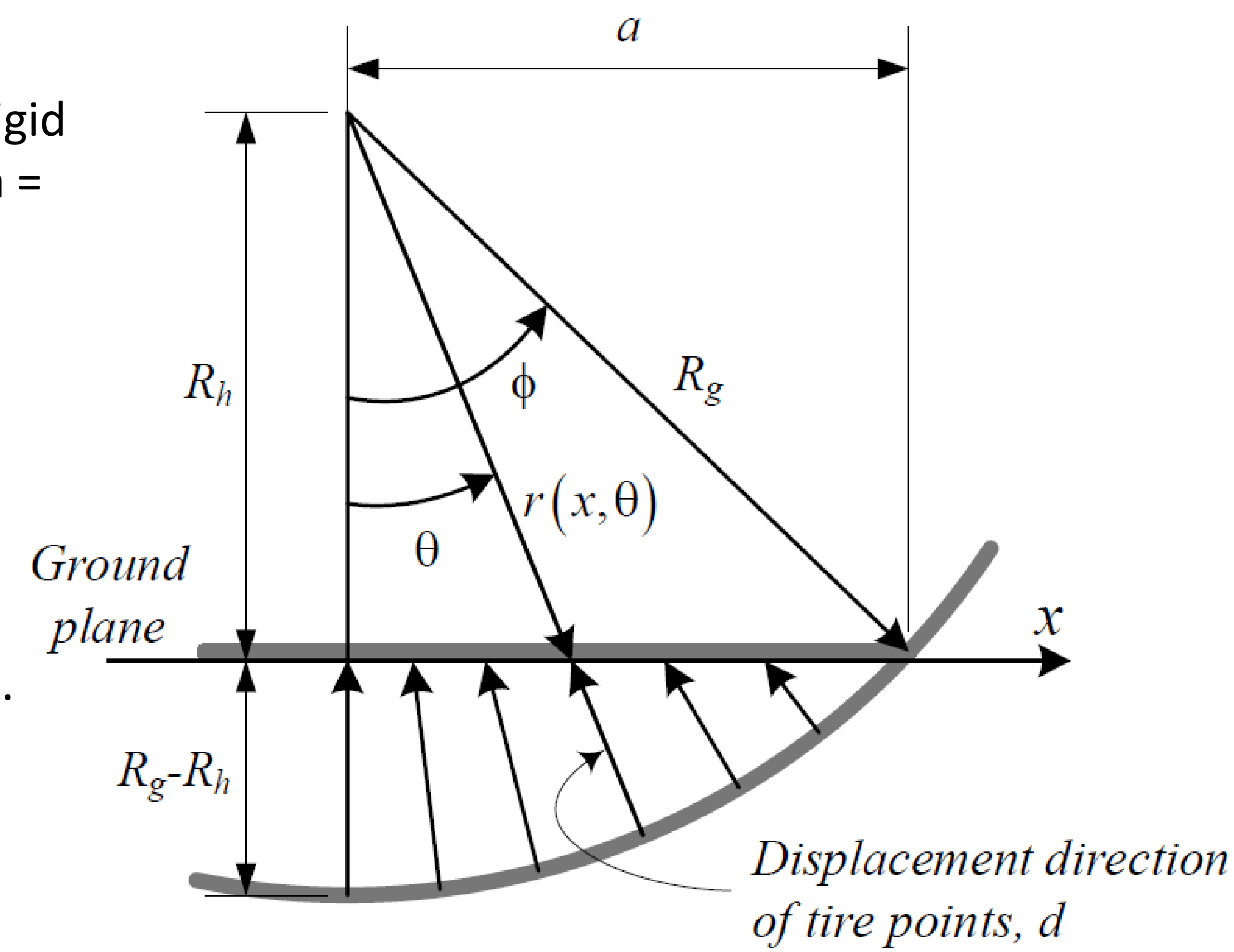
Rolling radius

If the motion of the tire is compared to the rolling of a rigid disk with radius R_w, then the tire must move a distance $a = R_w\varphi$ for an angular rotation φ.

$$a = R_g \sin\varphi = R_w\varphi$$

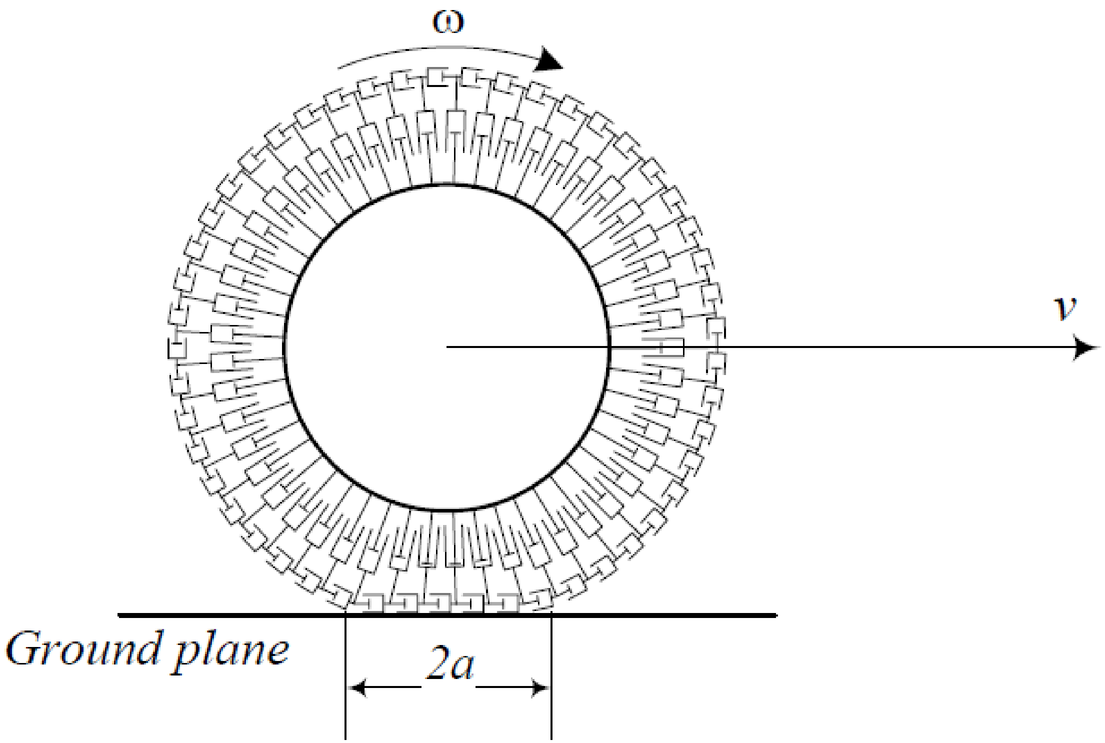
$$R_w = \frac{R_g \sin\varphi}{\varphi}.$$

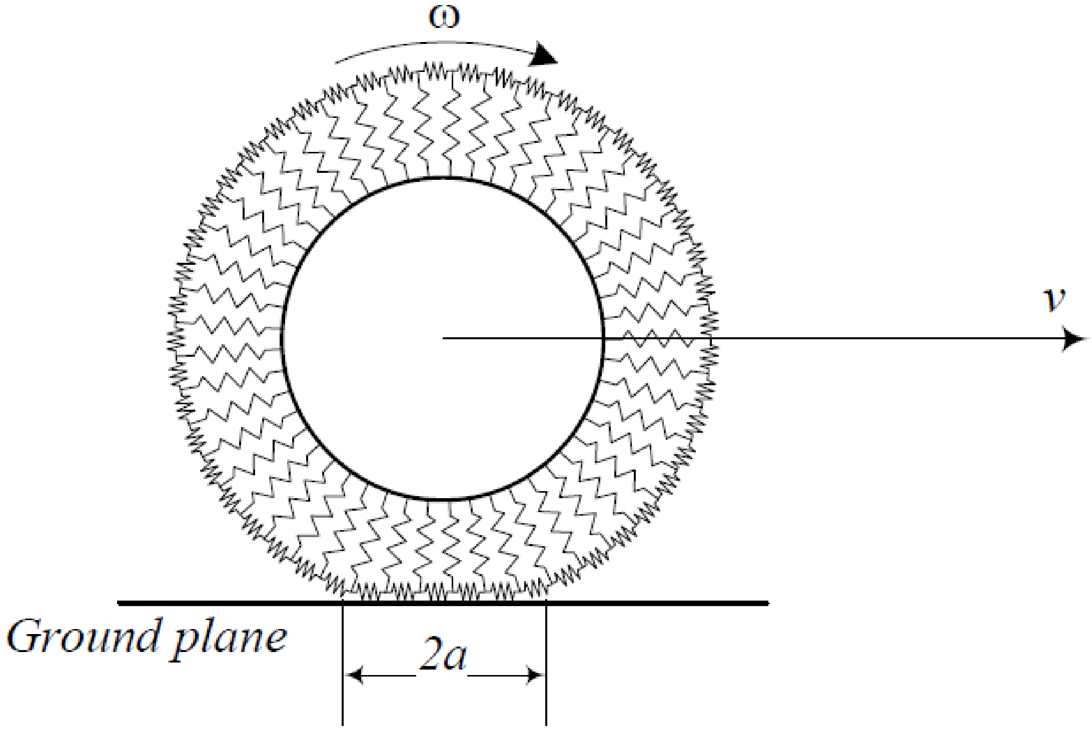
The angle φ is called tireprint angle or tire contact angle.



Rolling Resistance

The distortion of stress distribution is proportional to the tire-road deformation that is the reason for shifting the resultant force forward. Hence, the rolling resistance increases with increasing deformation. A high pressure tire on concrete has lower rolling resistance than a low pressure tire on soil





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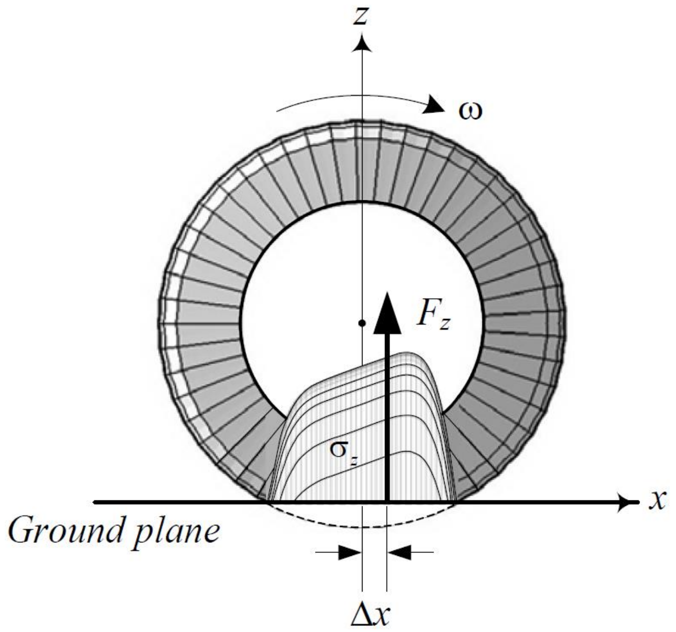
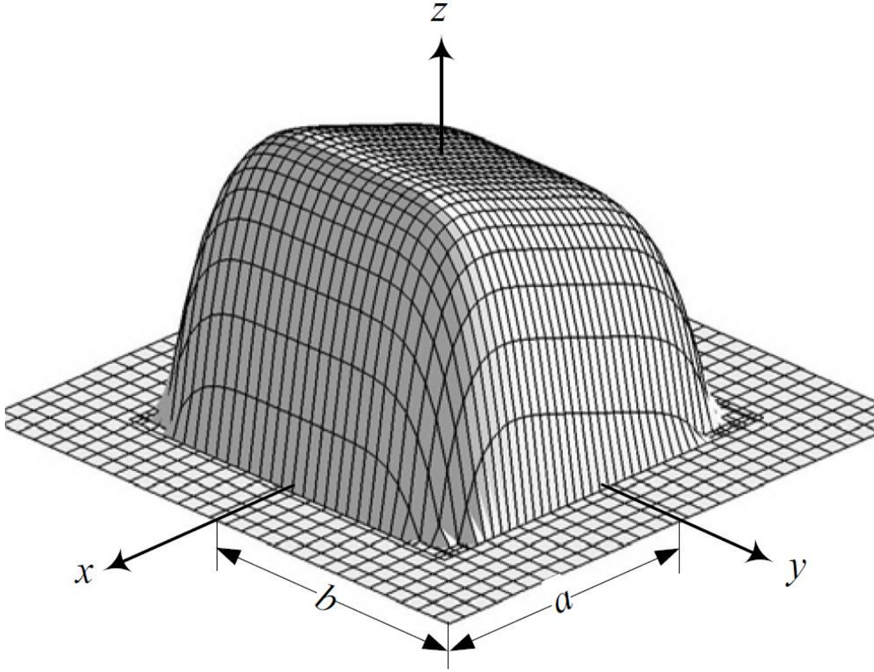
Rolling Resistance

- When a tire is turning on the road, that portion of the tire's circumference that passes over the pavement undergoes a deflection
- Part of the energy that is spent in deformation will not be restored in the following relaxation.
- Hence, a change in the distribution of the contact pressure makes normal stress σz in the heading part of the tireprint be higher than the tailing part**. The dissipated energy and stress distortion cause the rolling resistance.**
- A turning tire on the ground generates a longitudinal force called rolling resistance The force is opposite to the direction of motion and is proportional to the normal force on the tireprint
- The parameter μ_r is called the rolling friction coefficient. Not constant. Dependent on:
    - tire speed
    - inflation pressure
    - Sideslip angles.
    - Camber angles
    - mechanical properties (wear, temperature, load, size, driving and braking forces, and road condition





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Rolling Resistance

- Because of higher normal stress in the front part of the tireprint, the resultant normal force moves forward.
- Forward shift of the normal force makes a resistance torque in the direction, opposing the forward rotation.

$$M_r = F_z \, \Delta x$$

- The rolling resistance moment M_r can be substituted by a rolling resistance force F_r parallel to the $x - axis$.

$$F_r = \frac{1}{R_h} M_r = \frac{\Delta x}{R_h} F_z$$

$$F_r = \mu_r \, F_z$$

Hence

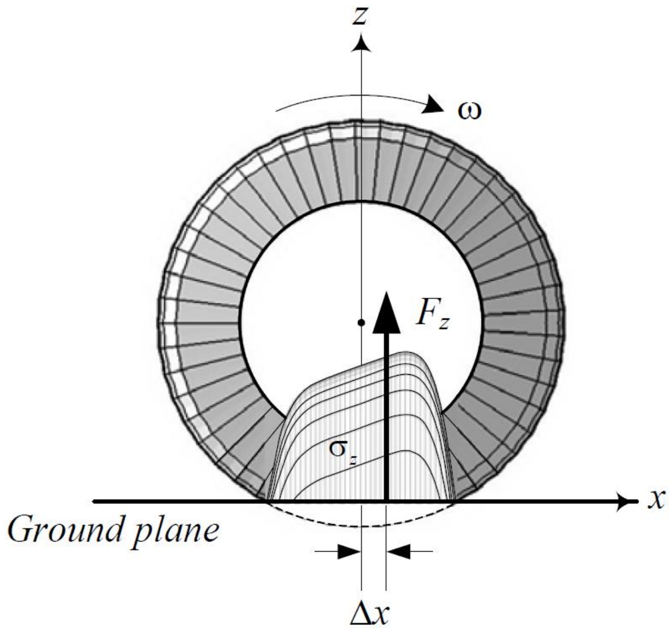
$$\mu_r = \frac{\Delta x}{R_h}$$

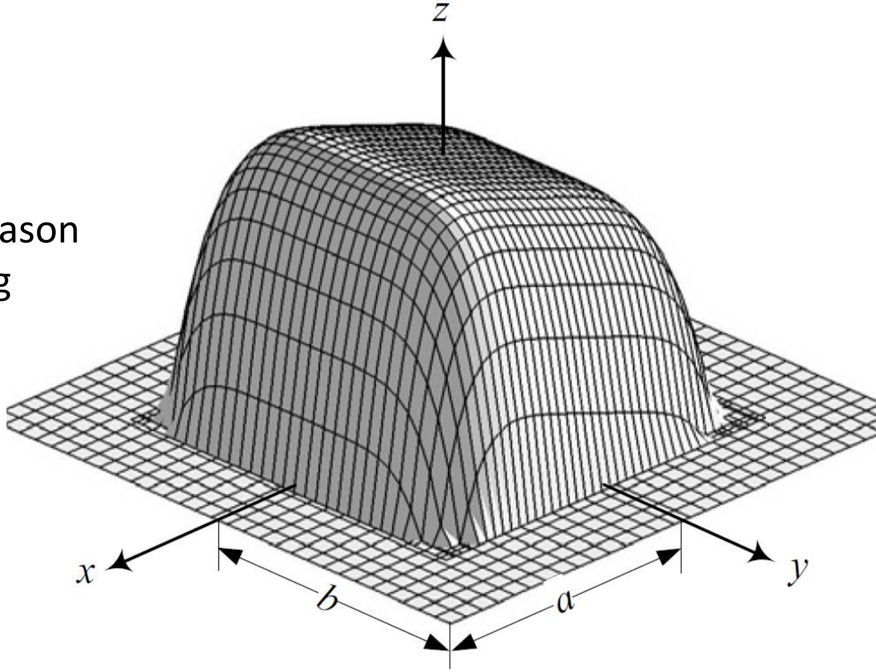
- The distortion of stress distribution is proportional to the tire-road deformation that is the reason for shifting the resultant force forward. Hence, the rolling resistance increases with increasing deformation.
- The rolling friction coefficient increases by increasing speed.

$$\mu_r = \sum_{i=0}^{n} \mu_i \, v_x^i$$

- Practically, two or three terms of the polynomial would be enough. The function is simple and good enough for representing experimental data and analytic calculation.

$$\mu_r = \mu_0 + \mu_1 \, v_x^2$$





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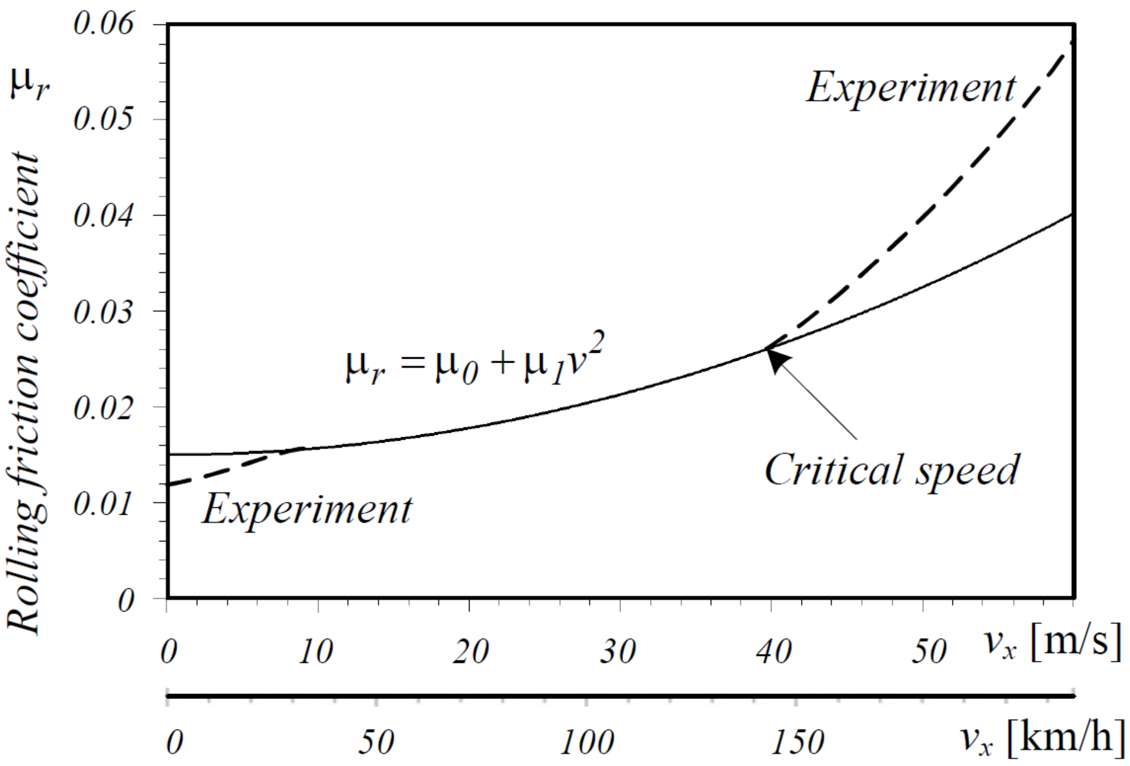
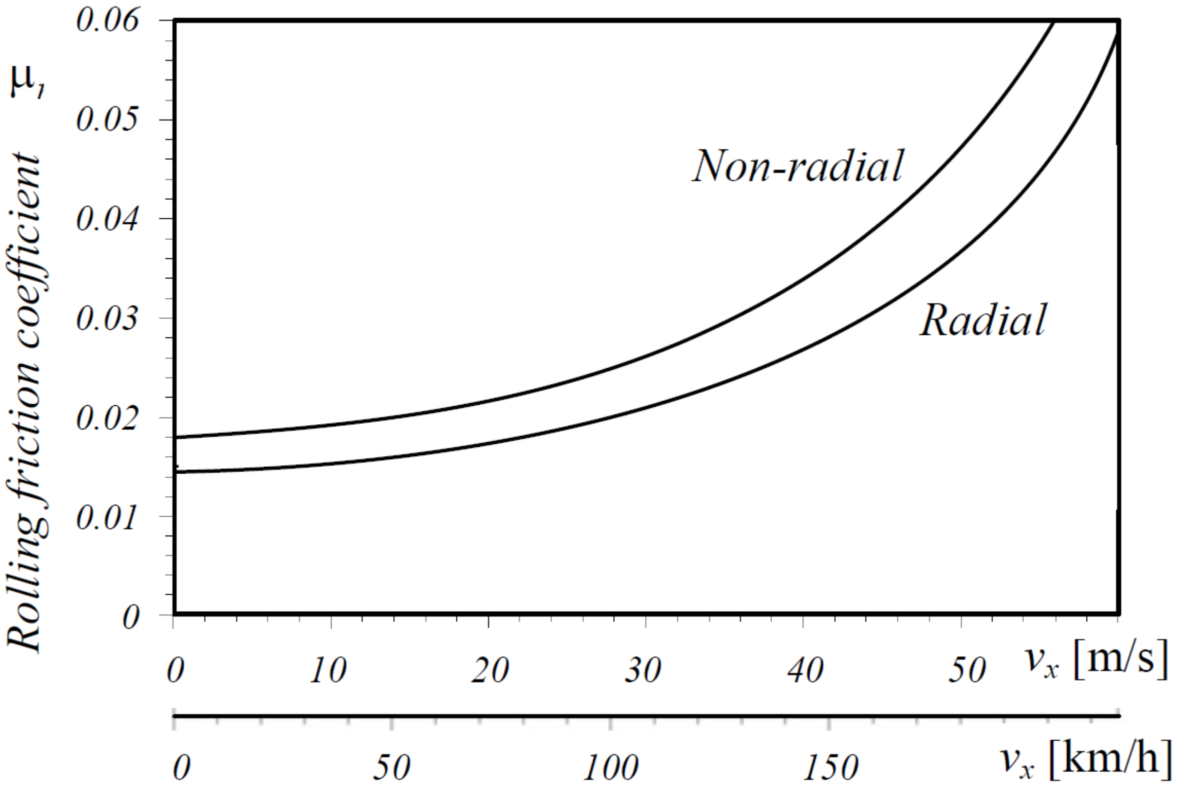
Rolling Resistance





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Rolling Resistance

Road pavement μ_0

$$\mu_r = \mu_0 + \mu_1 v_x^2$$

Road and pavement condition	μ_0
Very good concrete	0.008 – 0.1
Very good tarmac	0.01 – 0.0125
Average concrete	0.01 – 0.015
Very good pavement	0.015
Very good macadam	0.013 – 0.016
Average tarmac	0.018
Concrete in poor condition	0.02
Good block paving	0.02
Average macadam	0.018 – 0.023
Tarmac in poor condition	0.23
Dusty macadam	0.023 – 0.028
Good stone paving	0.033 – 0.055
Good natural paving	0.045
Stone pavement in poor condition	0.085
Snow shallow (5 cm)	0.025
Snow thick (10 cm)	0.037
Unmaintained natural road	0.08 – 0.16
Sand	0.15 – 0.3

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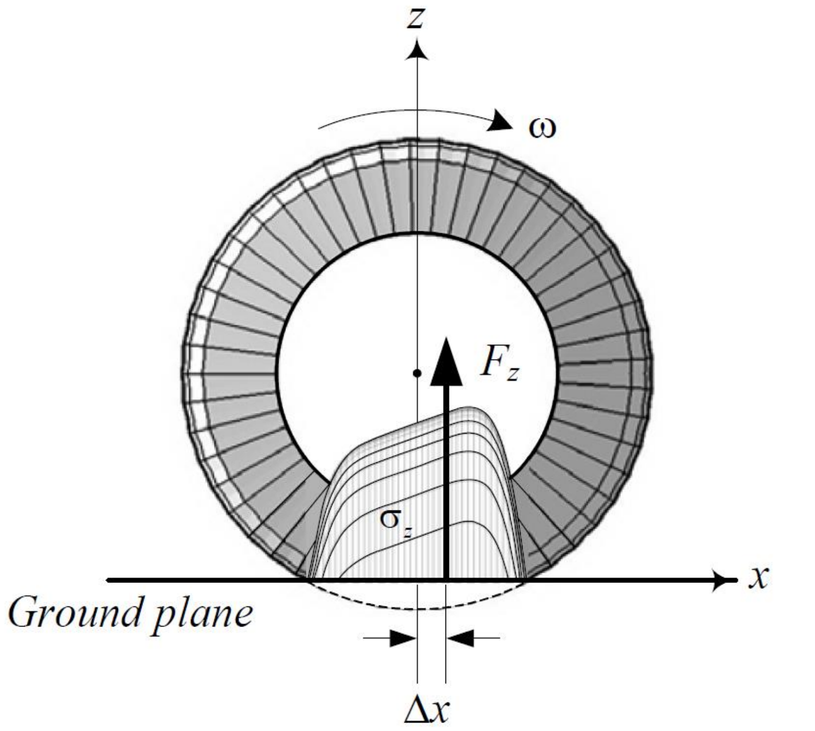
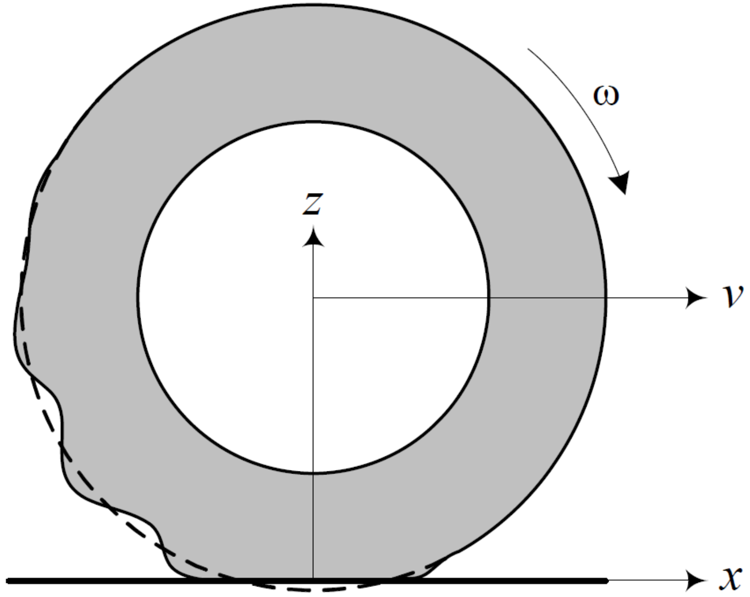
Rolling Resistance

- ***Critical speed*** is the speed at which standing circumferential waves appear and the rolling friction increases rapidly. The wavelength of the standing waves are close to the length of the tireprint. Above the critical speed, overheating happens and tire fails very soon





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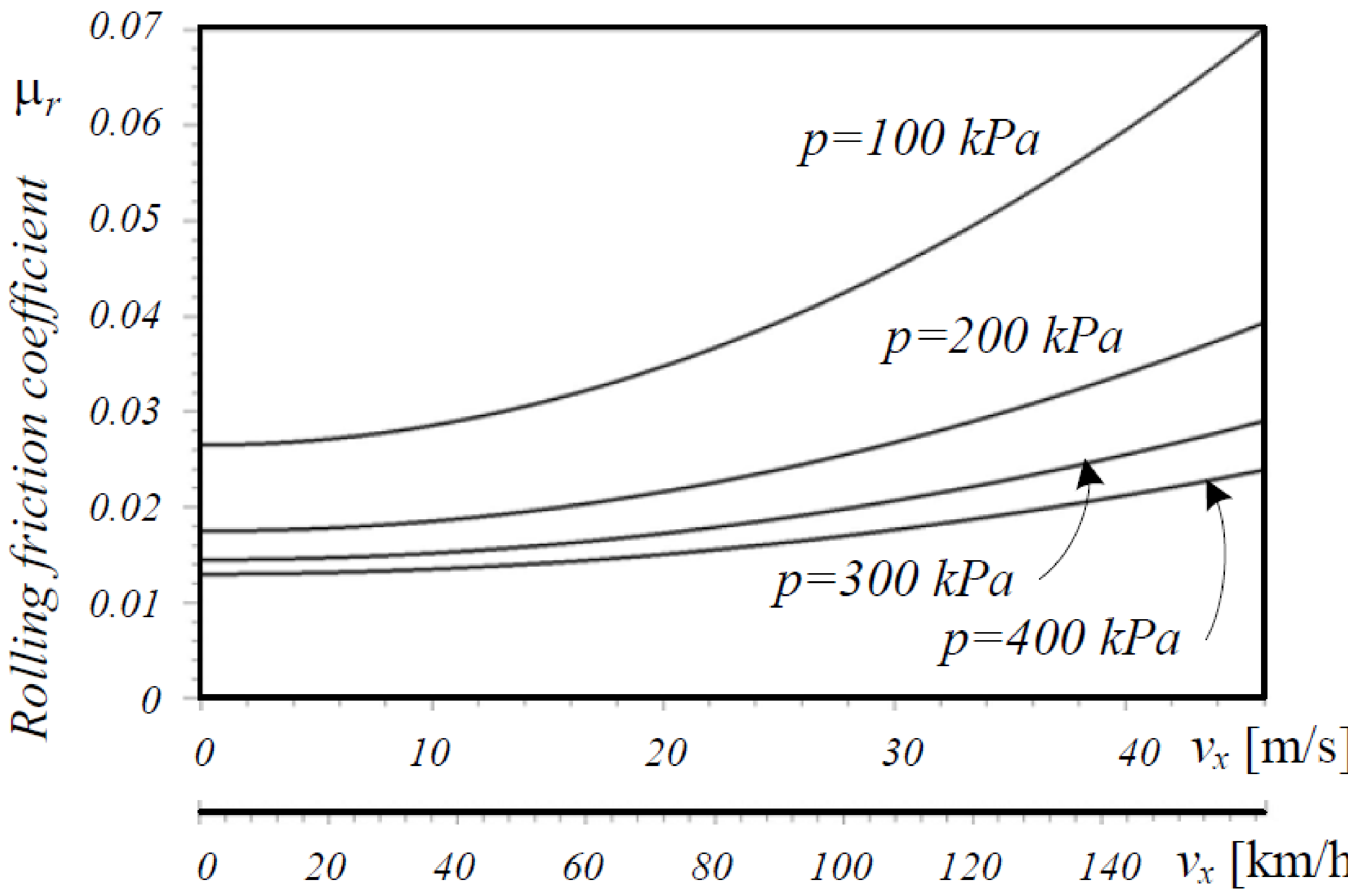
Rolling Resistance

Effect of Inflation Pressure and Load on the Rolling Friction Coefficient

- The rolling friction coefficient μ_r decreases by increasing the inflation pressure p.
- The effect of increasing pressure is equivalent to decreasing normal load F_z
.



$$\mu_r = \frac{K}{1000}\left(5.1 + \frac{5.5 \times 10^5 + 90F_z}{p} + \frac{1100 + 0.0388F_z}{p} v_x^2\right)$$

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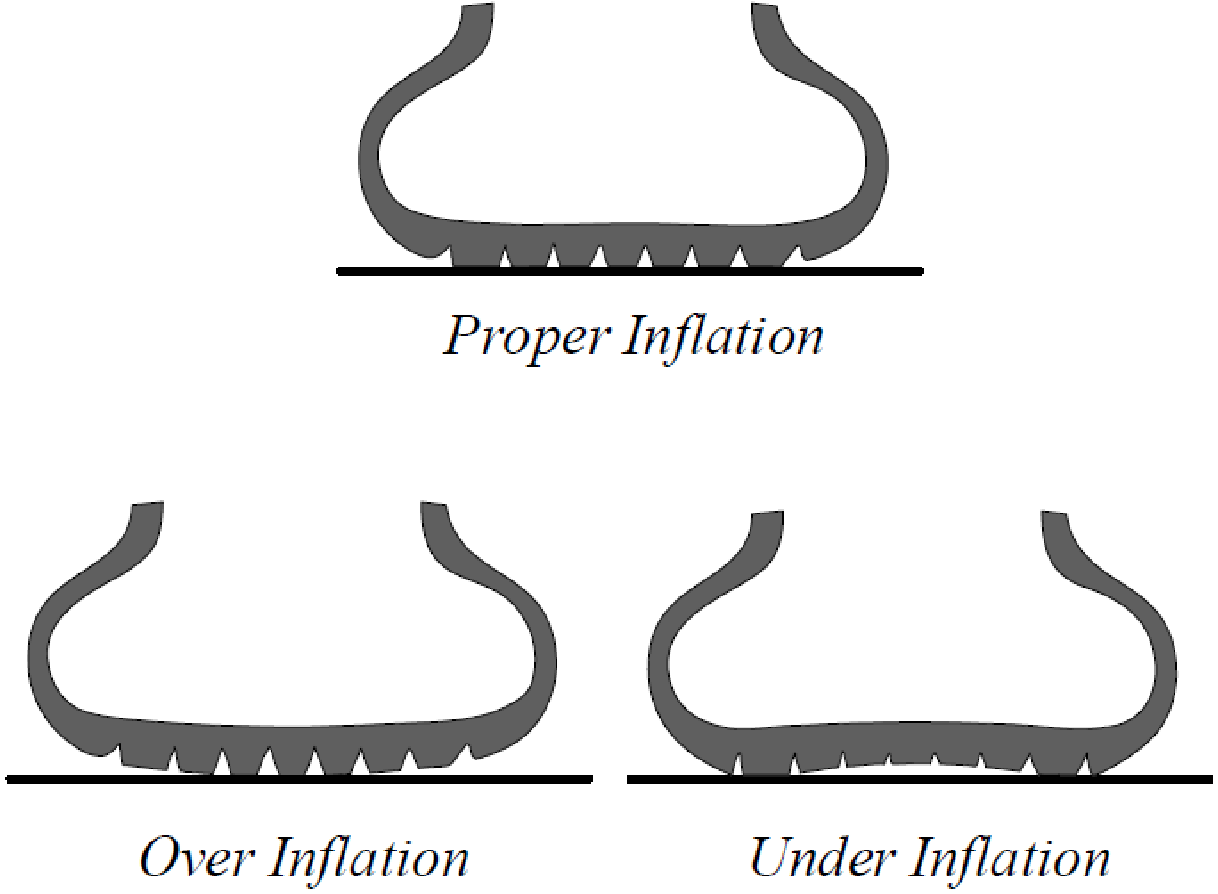
Inflation Pressure and Load

- **High inflation** pressure increases stiffness, which reduces ride comfort and generates vibration
- **Over-inflation** causes the tire to transmit shock loads to the suspension, and reduces the tire's ability to support the required load for cornerability, braking, and acceleration

- **Under-inflation** results in cracking and tire component separation. It also increases sidewall flexing and rolling resistance that causes heat and mechanical failure
- **Under-inflation** results in an overloaded tire that operates at high deflection with a low fuel economy, and low handling.



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Rolling Resistance
Power dissipation

- In the presence of a tractive force, as opposed to free rolling, the normal reaction force moves further ahead of the rotational axis of the wheel and therefor rolling resistance increases. This all means, of course, that some of the energy being supplied to propel the vehicle along the road is wasted, actually in the form of heat due to flexing and internal friction of the tire materials.
- Rolling friction reduces the vehicle’s power. The dissipated power because of rolling friction is equal to the rolling friction force F_r times the forward velocity vx.

$$
\begin{aligned}
P &= F_r \, v_x \\
&= -\mu_r \, v_x \, F_z \\
&= \frac{-K \, v_x}{1000} \left(5.1 + \frac{5.5 \times 10^5 + 90 F_z}{p} + \frac{1100 + 0.0388 F_z}{p} \, v_x^2 \right) F_z
\end{aligned}
$$

Longitudinal Force

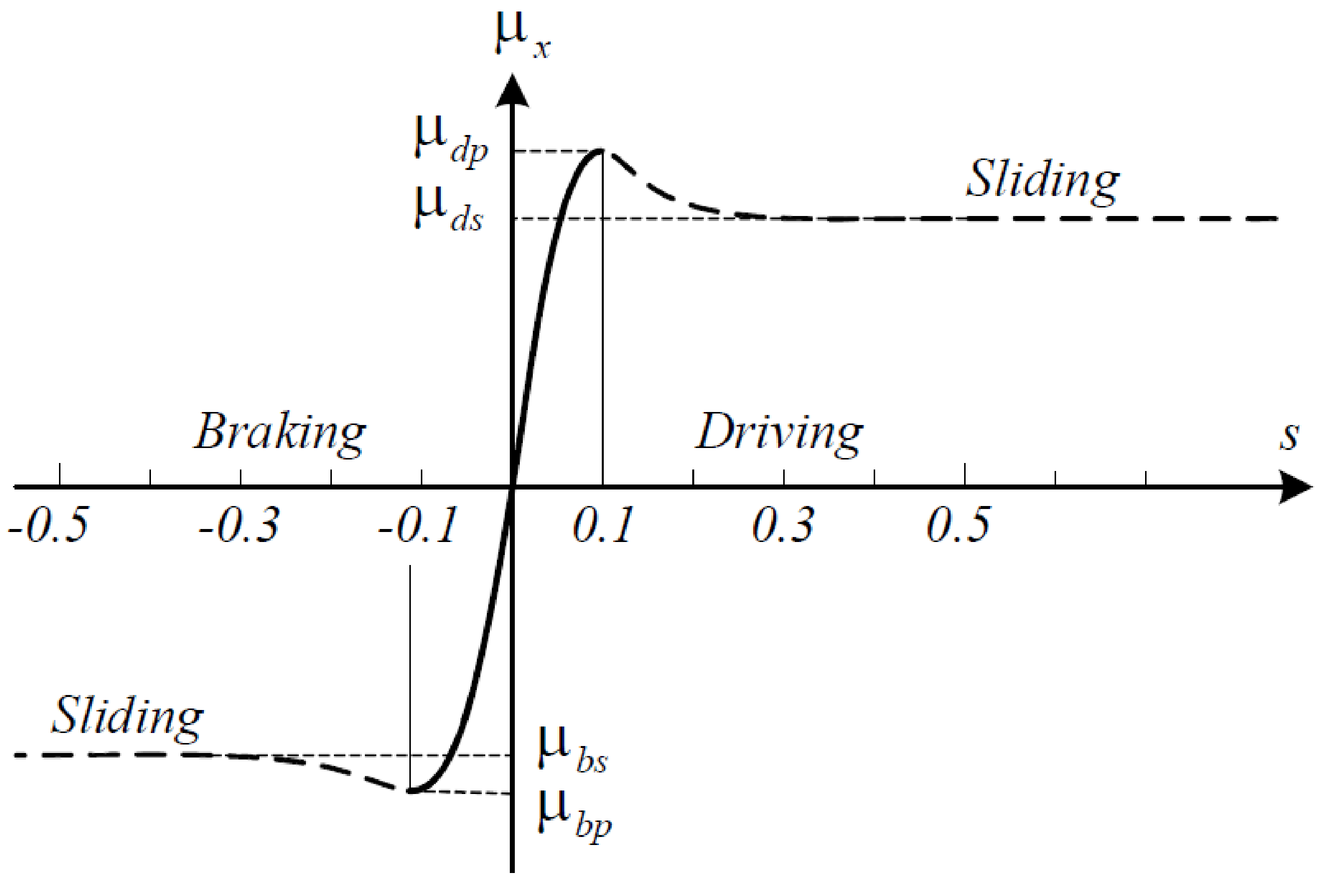
Longitudinal slip ratio

$$s = \frac{R_g \omega_w}{v_x} - 1$$

- When a moment is applied to the spin axis of the tire, slip ratio occurs and a longitudinal force F_x is generated at the tireprint. The force F_x is proportional to the normal force

$$\begin{aligned} \mathbf{F}_x &= F_x \, \hat{\imath} \\ F_x &= \mu_x (s) \; F_z \end{aligned}$$

$\mu_x(s)$ is called the longitudinal friction coefficient

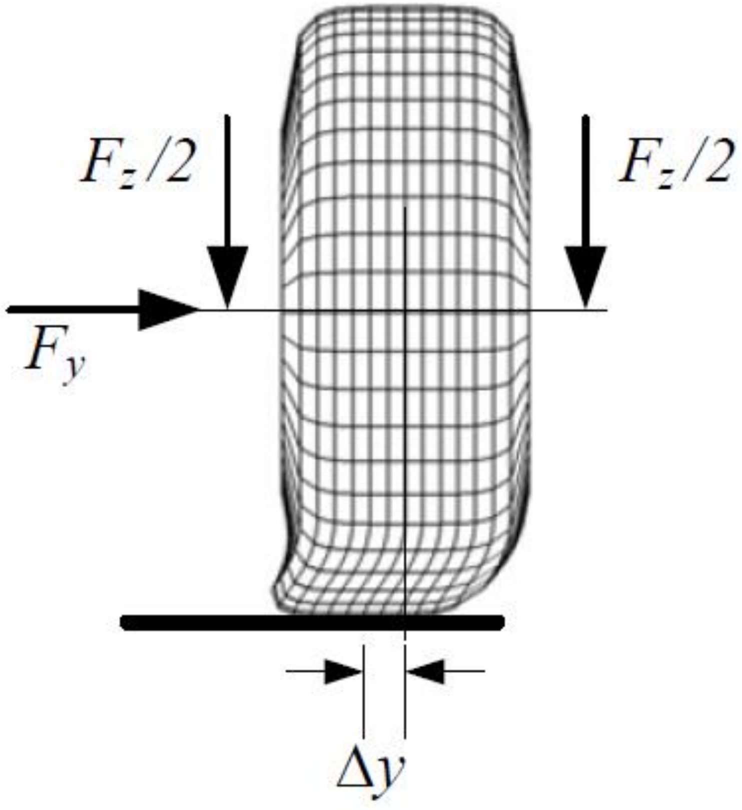


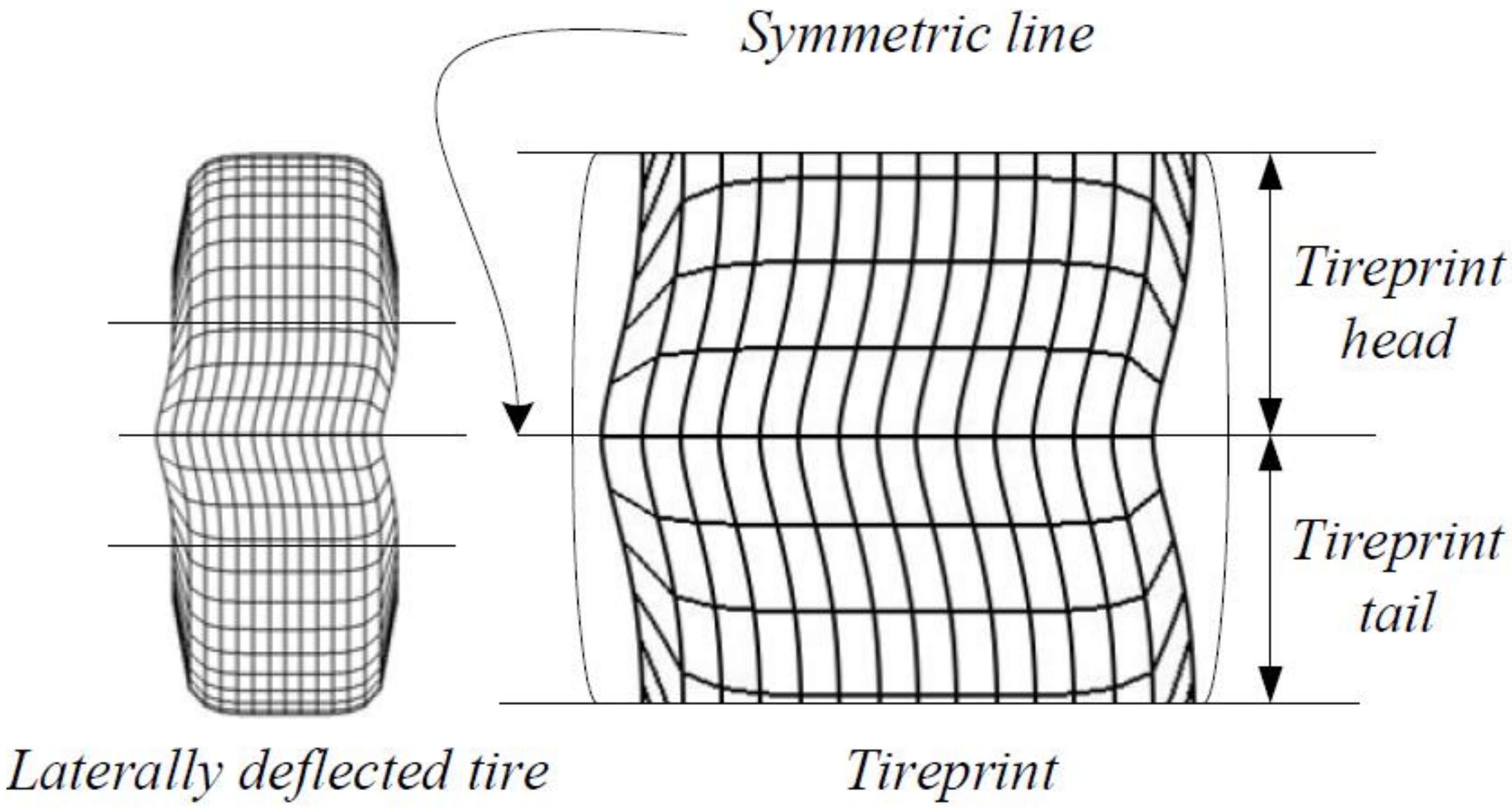
Slip ratio is positive for driving and is negative for braking.

Longitudinal Force

Road surface	*Peak value*, μ_{dp}	*Sliding value*, μ_{ds}
Asphalt, dry	$0.8 - 0.9$	0.75
Concrete, dry	$0.8 - 0.9$	0.76
Asphalt, wet	$0.5 - 0.7$	$0.45 - 0.6$
Concrete, wet	0.8	0.7
Gravel	0.6	0.55
Snow, packed	0.2	0.15
Ice	0.1	0.07

Lateral Force





$$F_y = k_y \, \Delta y$$

The wheel will start sliding laterally when the lateral force reaches a maximum value F_{yM}

$$F_{y_M} = \mu_y \, F_z$$

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Lateral Force

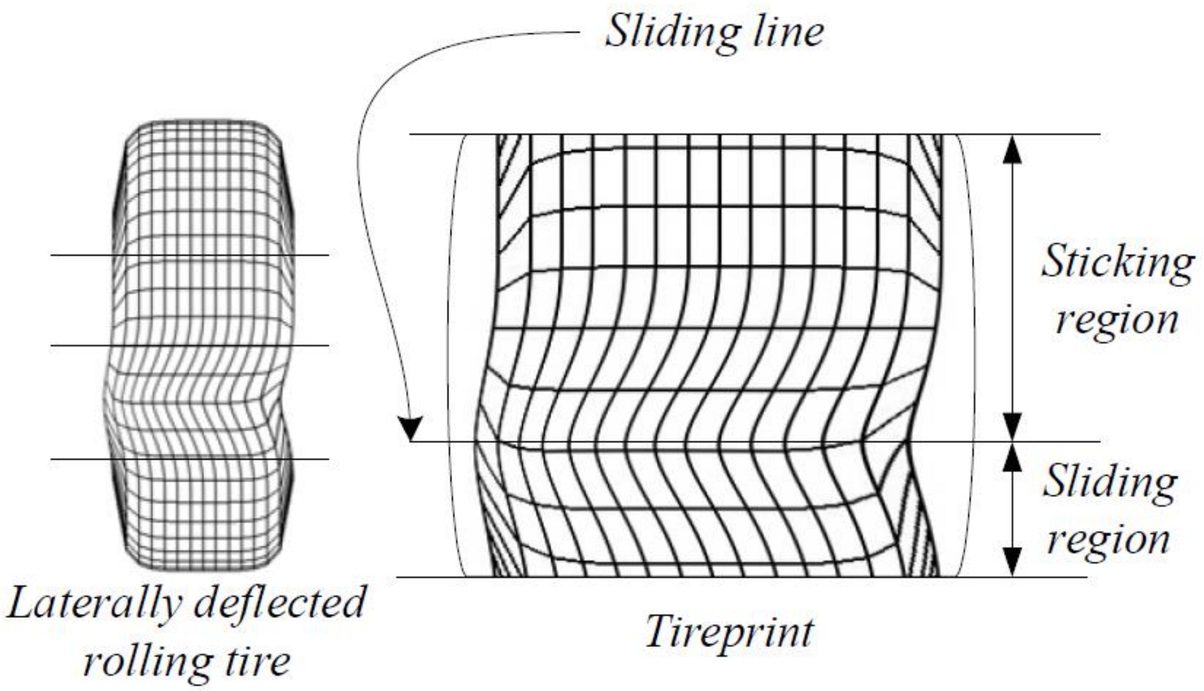
$$\mathbf{M}_z = M_z \hat{k}$$
$$M_z = F_y a_{x_\alpha}$$

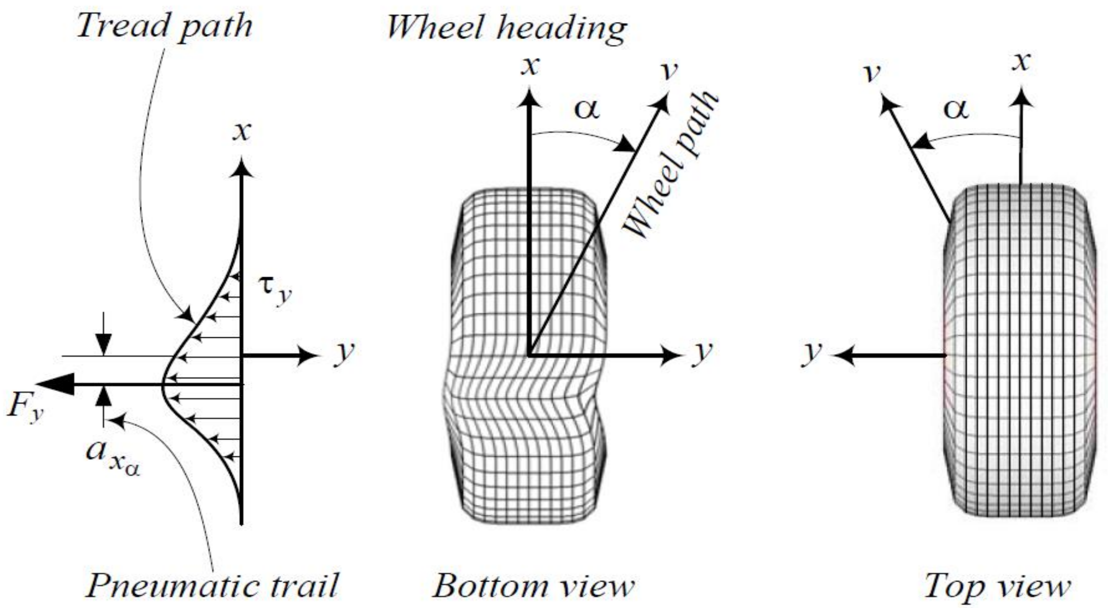
There is also a lateral shift in the tire vertical force F_z because of slip angle α, which generates a slip moment M_x about the forward x-axis.

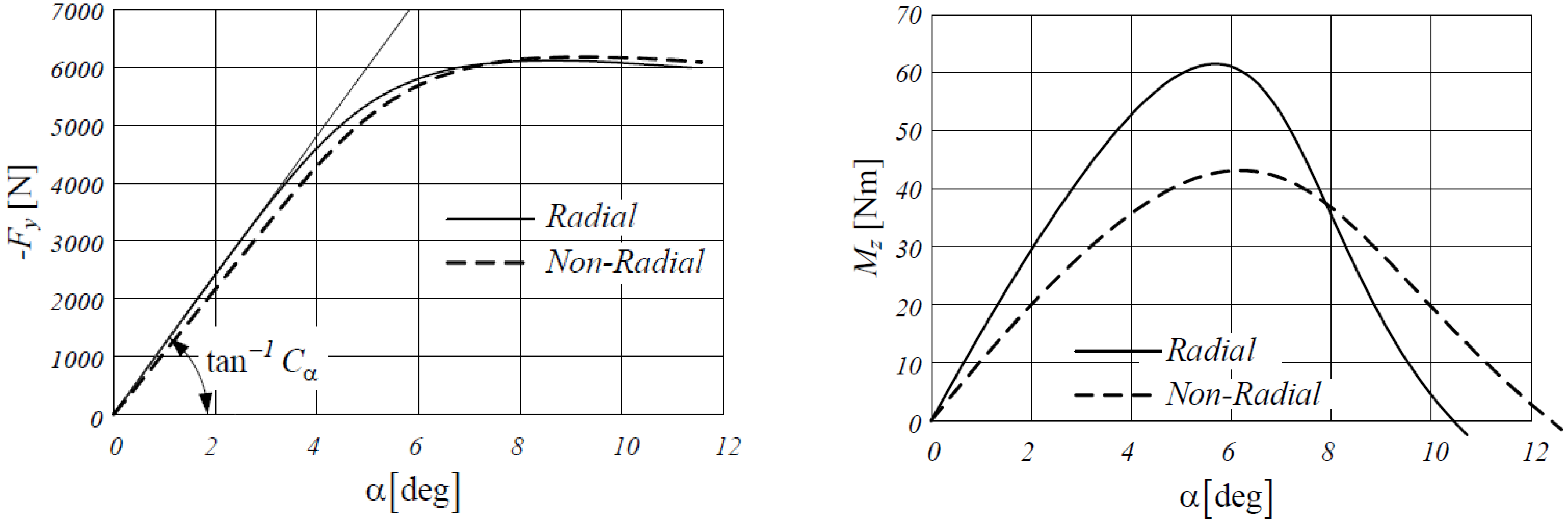
$$\mathbf{M}_x = -M_x \hat{\imath}$$
$$M_x = F_z a_{y_\alpha}$$

We may assume the lateral force F_y is proportional to the slip angle α for low values of α

$$F_y = -C_\alpha \alpha$$
$$C_\alpha = \lim_{\alpha \to 0} \frac{\partial(-F_y)}{\partial \alpha}$$







7000
6000
5000
4000
3000
2000
1000
0
-F_y [N]
0
2
4
6
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α[deg]
Radial
Non-Radial
$\tan^{-1} C_\alpha$
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M_z [Nm]
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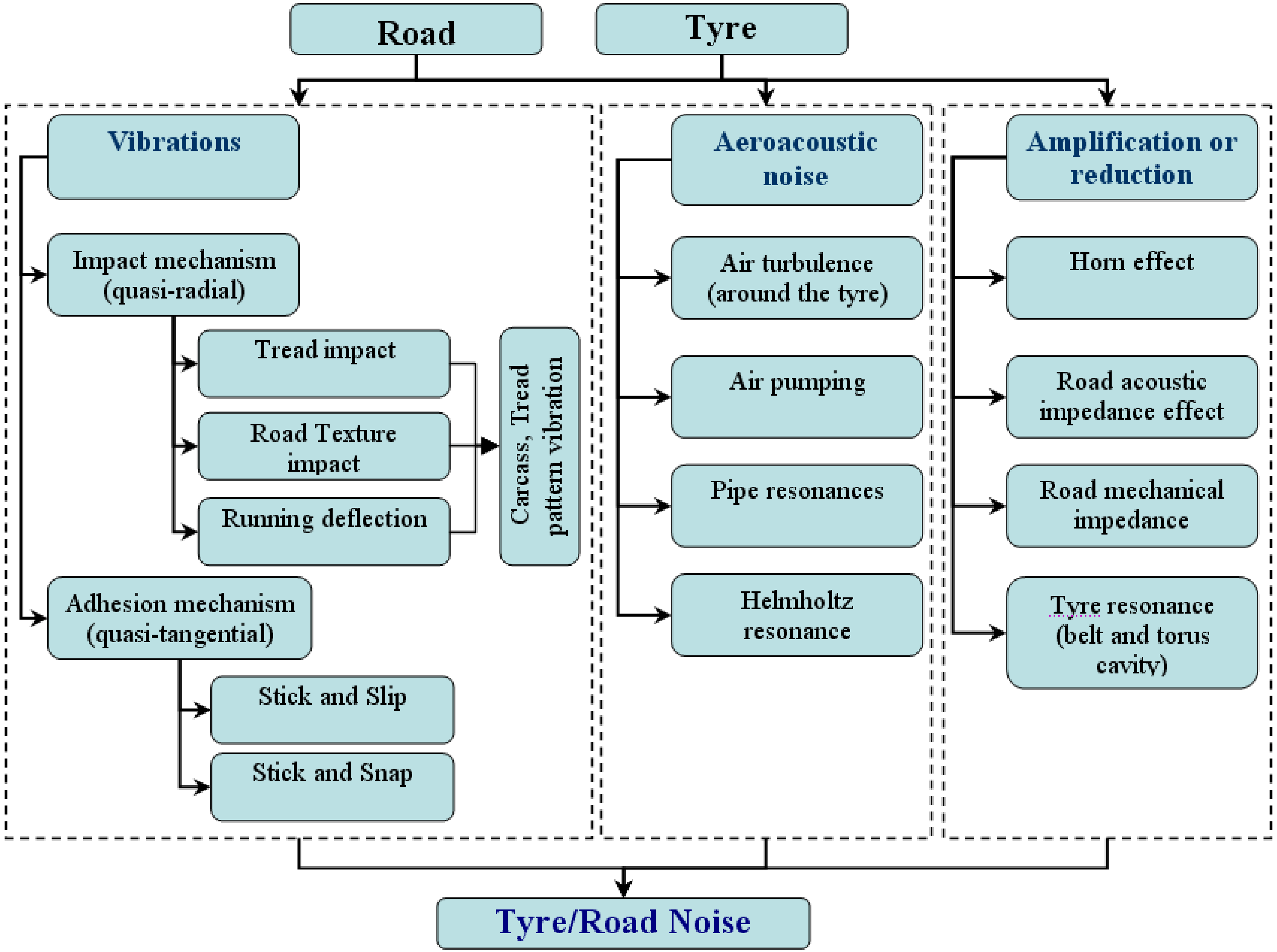
α[deg]
Radial
Non-Radial

Rolling noise



Generation and amplification effects related to tire/road noise

Driver /vehicle

- Driving speed
- Wheel torque
- Vehicle load

Tires

- Tread pattern
- Carcass
- Material
- Pressure/ temperature
- Dimension
- Degree of absorption

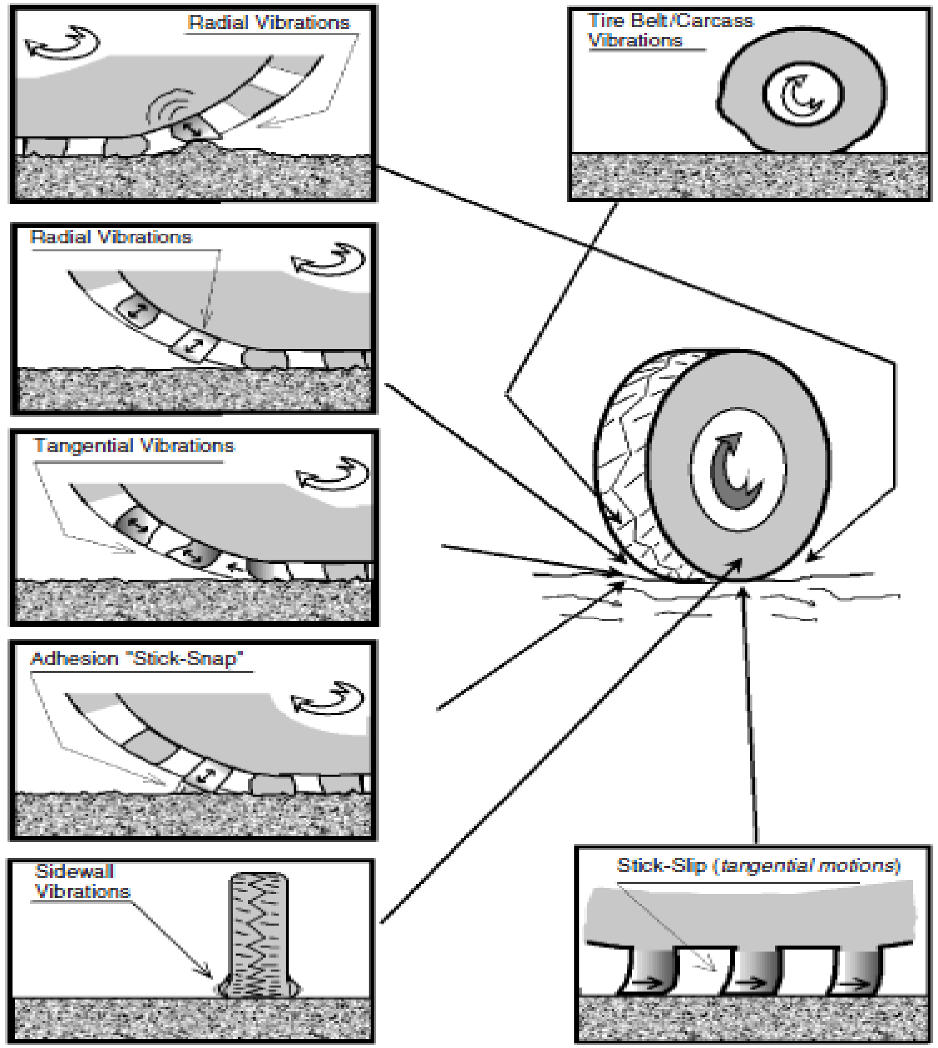
Roadway

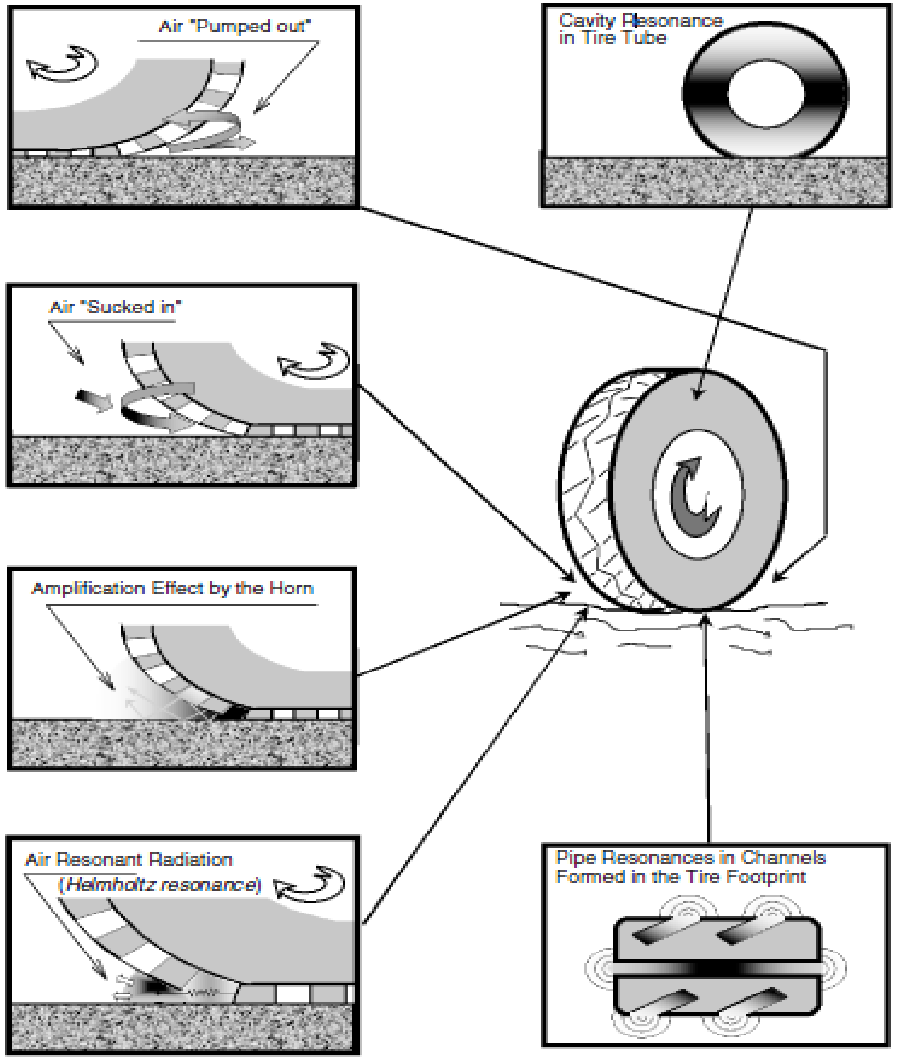
- Coating material
- Roughness
- Weather condition (moisture)
- Porosity
- Elasticity

Tire / road noise generation

Vibration-related mechanisms of tire/road noise generation

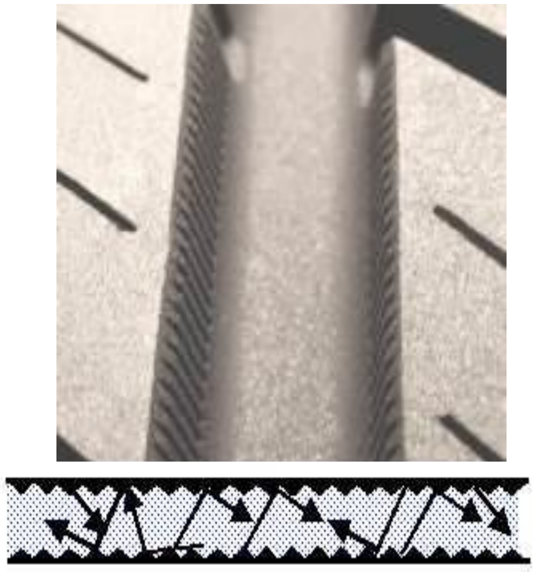
Aerodynamically related generation and amplification mechanisms of tire/road noise

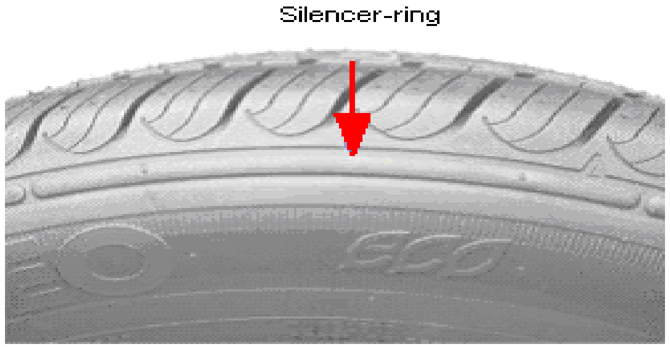


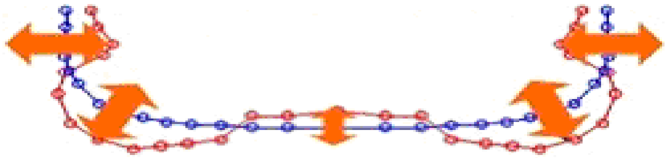


Examples of rolling noise reduction (tires)

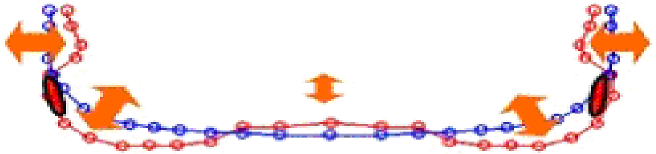
1. The flow is disturbed by the dense perpendicular serrations resulting in noise reduction .
2. Leading air through the groove without distortion. This creates a whistling sound known as “pipe resonance”.
3. Silence ring. Which minimises vibration







Amplitude of vibration is large

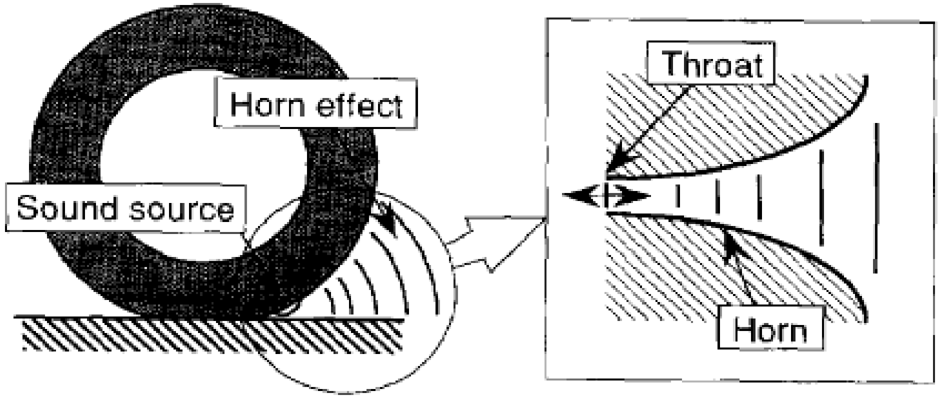


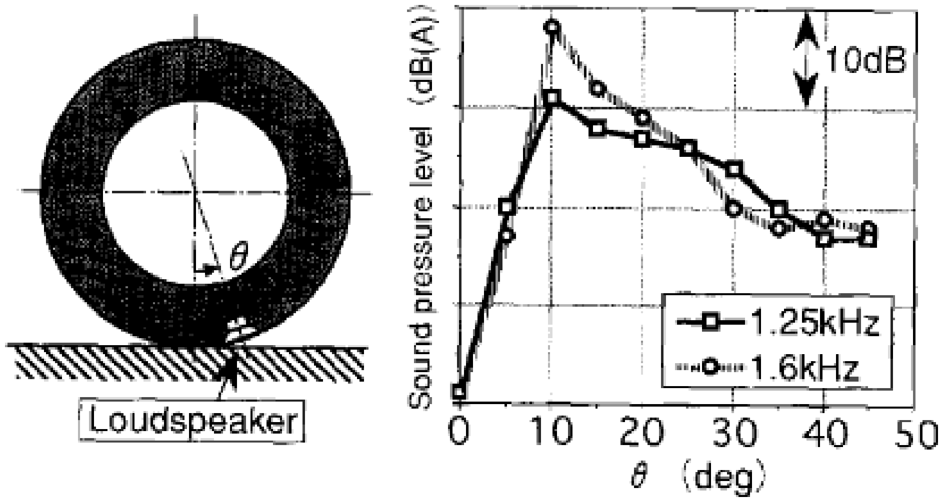
Amplitude decreases by using a silencer-ring

Tire „horn effect”

- The horn shape amplifies the sound pressure.
- The horn effect is a major factor in the radiation of tire-road noise.
- Two kinds of sound sources:
    1. quasi-monopole sources
    2. vibration modes of the surface

- The horn effect and displacement mechanics can be reduced by using thick pours pavement





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