INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

KKS/ZDMT

Mechanics of driving

Lecture 8

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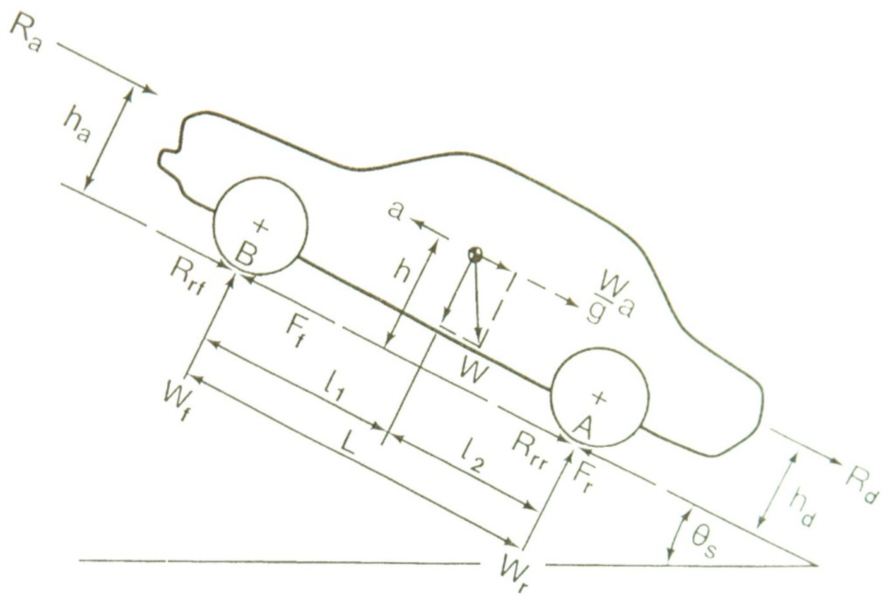
Project CZ.1.07/2.2.00/15.0383
Inovace studijního oboru Dopravní a manipulační technika s ohledem na potřeby trhu práce

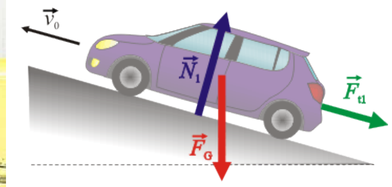
DIAGRAM OF FORCES ACTING ON A VEHICLE IN DIRECTION OF MOVEMENT



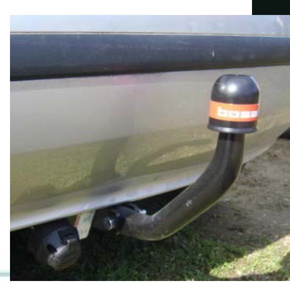
- F drive force on wheel
- R_r rolling resistance
- R_g climbing resistance
- R_a aerodynamic resistance
- R_{ac} acceleration resistance
- R_d towing resistance

DRIVE RESISTANCES

Drive resistances are forces acting against the movement of the vehicle



- Rolling resistance
- Climbing resistance
- Air resistance
- Acceleration resistance
- Towing resistance



ROLLING RESISTANCE

Rolling resistance is caused by:

- Internal (hysteresis) friction of tyre material during deformation (90-95%)
- Friction at contact surface of tyre with road and suction of tread with road (5-7%)
- Standing wave at periphery of tyre at high speeds (heating of tyre)
- Aerodynamic resistance and friction in bearings of pulled wheels (1-3%)

Total rolling resistance in individual vehicle wheels.

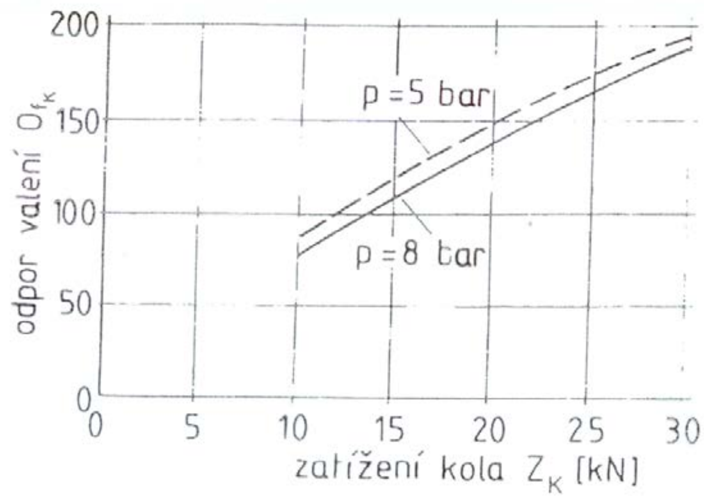
$$R_r = fW \cos\theta_s$$

Where *f* rolling resistance coefficient

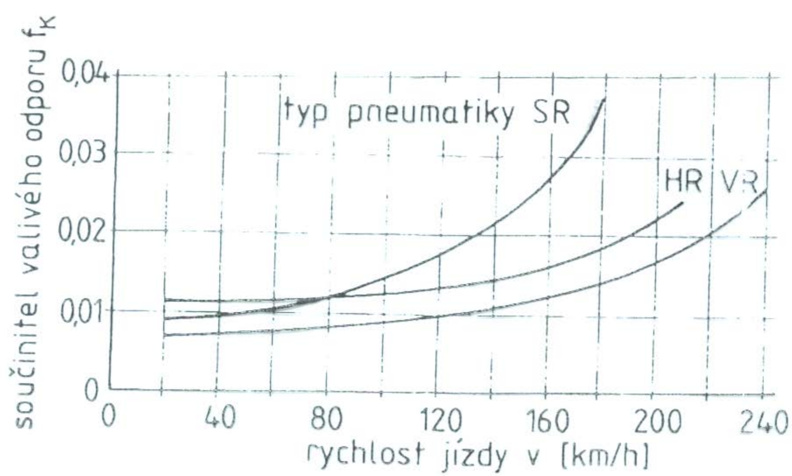
W weight of the vehicle

Surface	f	Surface	f
asphalt	0.01 – 0.02	Grass	0.08-0.15
concrete	0.015-0.025	Deep sand	0.15-0.30
paving	0.02-0.025	Fresh snow	0.20-0.30
tarmac	0.03-0.04	Muddy soil	0.20-0.40
Field track - dry	0.04-0.15	Ice	0.01-0.025
Field track - wet	0.08-0.20		

ROLLING RESISTANCE



Influence of tyre pressure
on rolling resistance



Influence of tyres on rolling resistance coefficient

AIR RESISTANCE

Air resistance is proportional

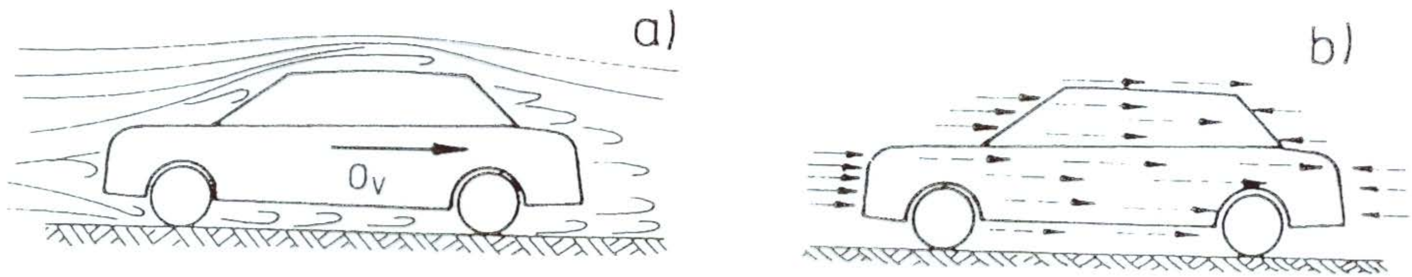
- Dynamic pressure p_d
- End area of vehicle S
- Air resistance coefficient c_D

$$R_a = \frac{\rho}{2} c_D A_f v_r^2 \qquad \vec{v}_r = \vec{v} + \vec{v}_w$$

Where

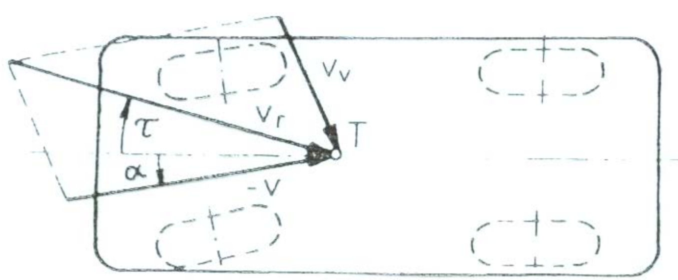
ρ	air density [kg.m^{-3}]
v_r	resistance velocity of air (relative velocity of air and vehicle)
v	vehicle velocity
v_w	wind velocity
A_f	front area – for private automobiles approx. S = (0.7 ÷ 0.85).w.h

- 80÷90% shape resistance
- 10 ÷15% turbulence
- 4 ÷10% friction



a) Air flow around vehicle

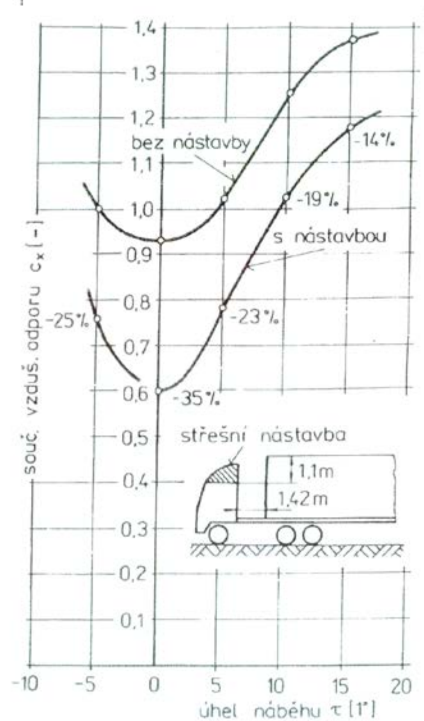
b) Origin of air resistance pressure force (solid arrows) and friction force (dashed arrows)



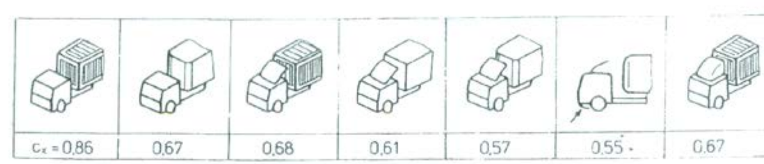
Determining resistance speed of air

Determining end area of vehicle by projection

Type of vehicle	c_x [1]	S_x [m²]
Passenger car	0,3 – 0,4	1,6 – 2,0
Sports car	0,3 – 0,35	1,3 – 1,6
Racing car-uncovered wheels	0,4 – 0,6	0,7 – 1,3
Racing car-covered wheels	0,25 – 0,35	0,8 – 1,5
Truck	0,8 – 1,0	4 – 7
Truck-with cover	0,6 – 0,8	5 – 8
Truck-with trailer	1,0 – 1,2	5 – 8
Truck-with container trailer	1,0 – 1,2	9
Bus	0,5 – 0,7	5 - 7



Obr. 2.14
Součinitel vzdušného odporu c_x pro užitkové vozidlo



CLIMB RESISTANCE

Climb resistance is determined by the weight component of the vehicle parallel to the surface of the vehicle

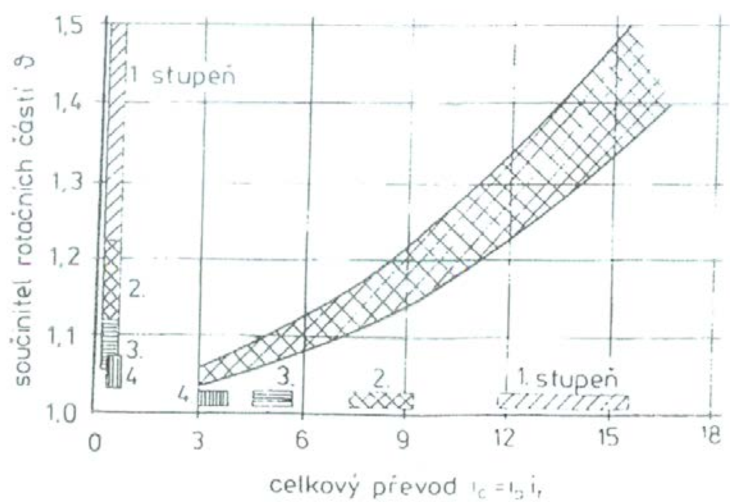
$$R_g = \pm W \sin \theta_s$$

ACCELERATION RESISTANCE

During acceleration the force of inertia acts in the opposite direction to acceleration. This is acceleration resistance

$$R_{ac} = \xi m a$$

Where ξ is coefficient of influence of rotating parts



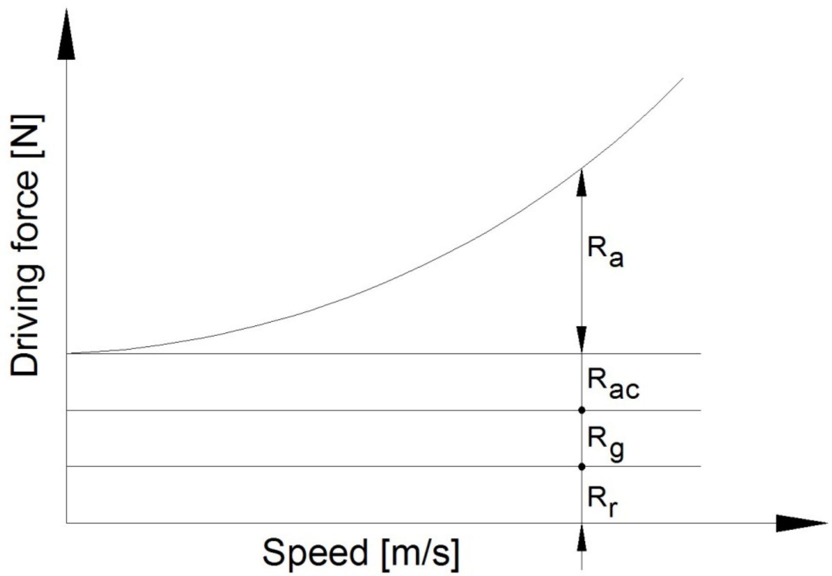
TOTAL DRIVE RESISTANCE
REQUIRED DRIVE FORCE AND POWER

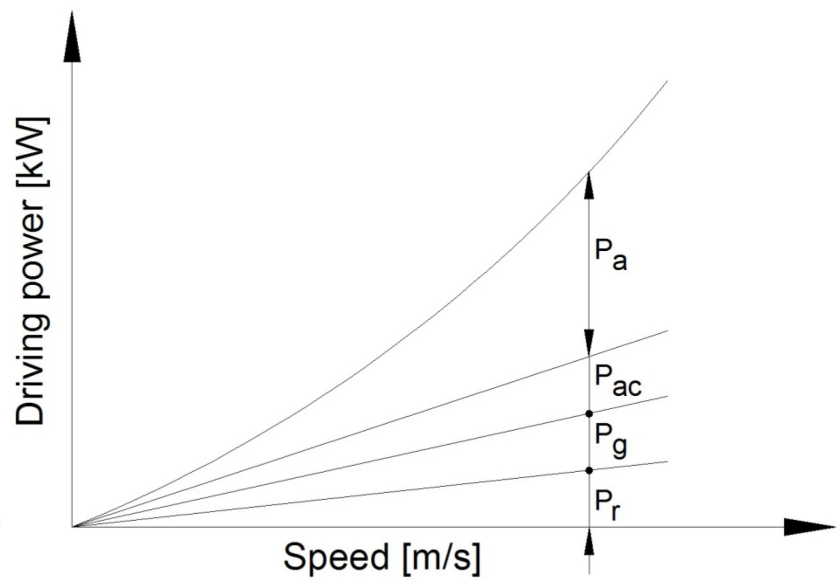
Drive force

$$F = R_{ac} + R_a + R_r + R_g$$

Drive power

$$P = F.v = \left(R_{ac} + R_a + R_r + R_g\right)v$$





ADHESION LIMITS

Maximum allowable peripheral force between wheel and road is

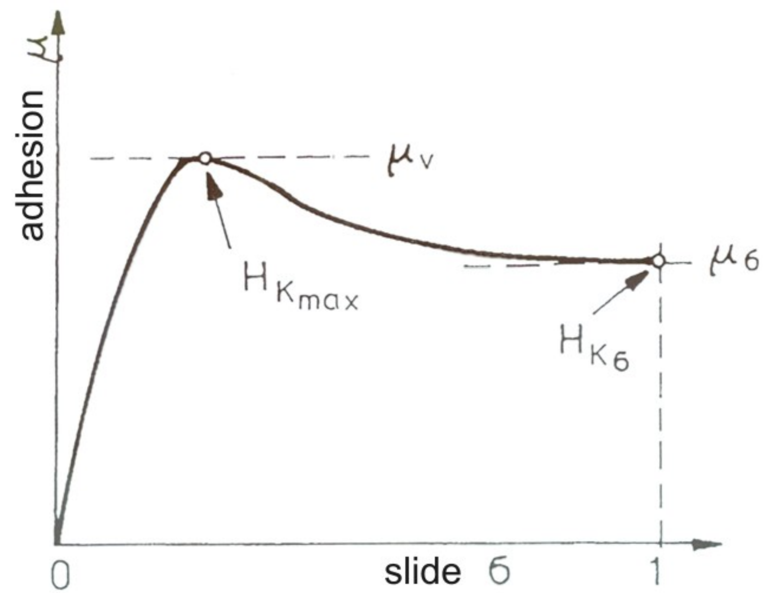
$$H_{K\max} \leq \mu_V . Z_K$$

μ_V - rolling adhesion coefficient
Z_K - vertical wheel load

If longitudinal slip $\sigma = 1$

$$H_{K\sigma} \leq \mu_\sigma . Z_K$$

Where μ_σ is slip adhesion coefficient



SKID AND SLIP

Wheel slip is defined as follows:

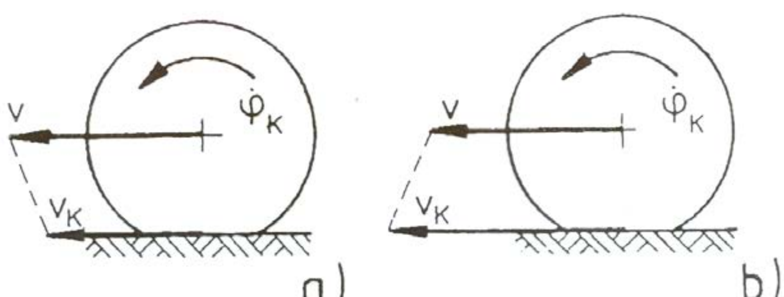
- For driven wheel

$$\sigma_D = \frac{v_K - v}{v_K} = \frac{r_d.\dot{\varphi}_K - v}{r_d.\dot{\varphi}_K} = \frac{r_d - r_K}{r_d} \qquad (v \geq 0, \dot{\varphi}_K \geq 0, v_K \geq v)$$

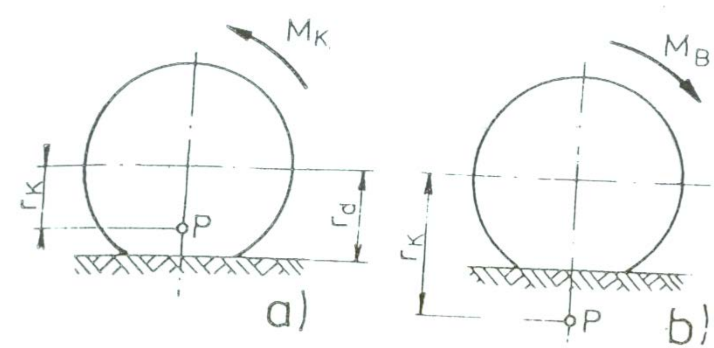
- For braked wheel

$$\sigma_B = \frac{v - v_K}{v} = \frac{v - r_d.\dot{\varphi}_K}{v} = \frac{r_K - r_d}{r_K} \qquad (v \geq 0, \dot{\varphi}_K \geq 0, v_K \leq v)$$

v - vehicle speed
v_K - wheel speed



Kinematics of braked (a) and driven wheel (b)



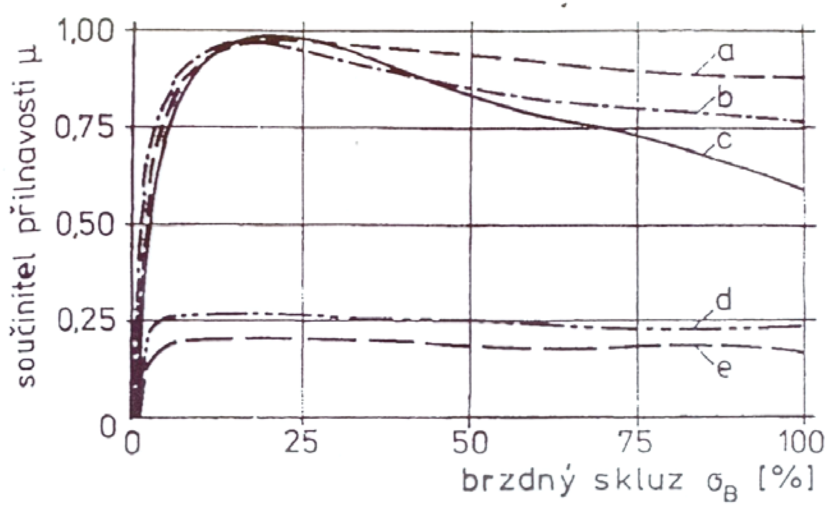
Orientation of poles relative to the movement of wheel in relation to road

a) Driven wheel, b) braked wheel

ADHESION LIMITS FOR SKID AND SLIP

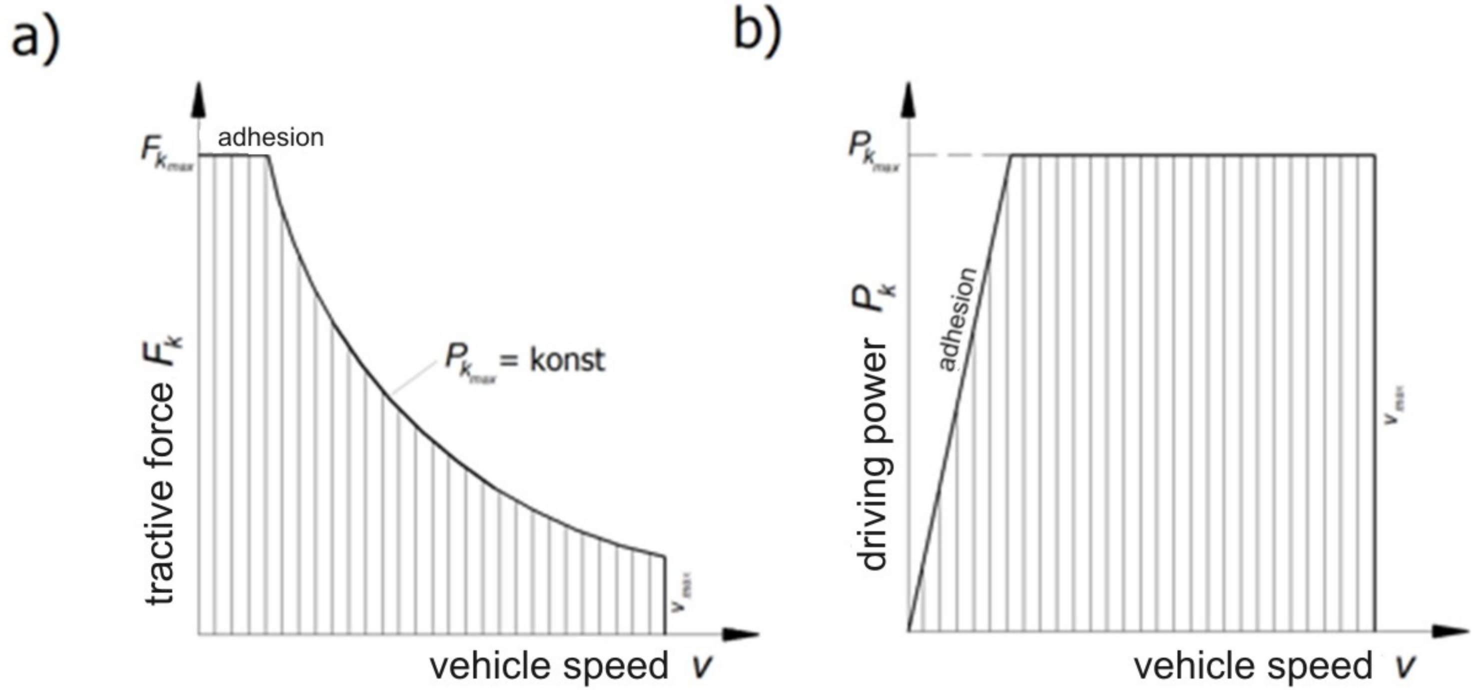
Adhesion coefficients for various road surfaces

Road		Value	Road		Value
Concrete	Dry	0,8 – 1,0	Asphalt	Dry	0,6 – 0,9
	Wet	0,5 – 0,8		Wet	0,3 – 0,8
Paved	Dry	0,6 – 0,8	Tarmac	Dry	0,6 – 0,8
	Wet	0,3 – 0,5		Wet	0,3 – 0,5
Field track	Dry	0,4 – 0,6	Grass	Dry	0,4 – 0,6
	Wet	0,3 – 0,4		Wet	0,2 – 0,5
Deep sand, snow		0,2 – 0,4	Ice		0,1 – 0,3



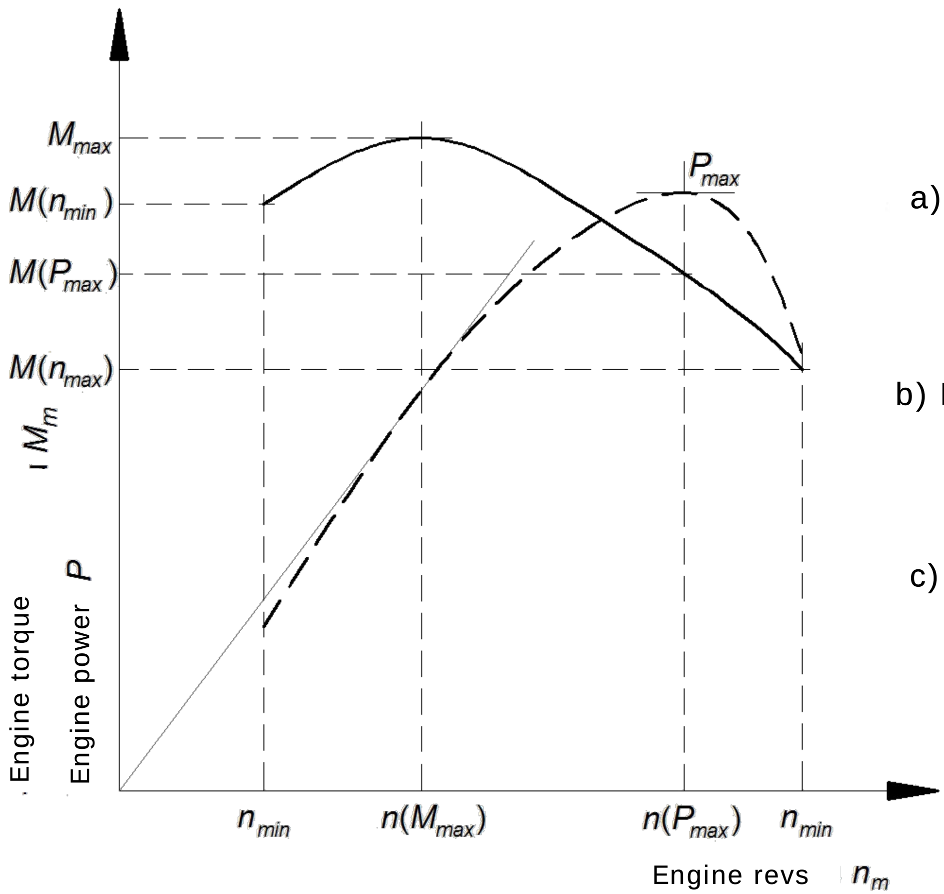
Influence of braked slip on adhesion coefficient: a – dry concrete; b – dry asphalt; c – wet concrete; d – compact snow; e – smooth ice

IDEAL CHARACTERISTICS OF DRIVE MOTOR



Ideal characteristic of vehicle drive (limited with adhesion).
a) For drive force of vehicle, b) for drive power of vehicle

CHARACTERISTICS OF COMBUSTION ENGINE



External characteristics of combustion engine

a) Moment elasticity

$$e_M = \frac{M_{max}}{M(P_{max})}$$

Ignition engine $= 1{,}07 - 1{,}50$
Compression ignition $= 1{,}03 - 1{,}35$

b) Rev elasticity

$$e_n = \frac{n(P_{max})}{n(M_{max})}$$

Ignition engine $e_n = 1{,}5 - 3{,}5$
Compression ignition $e_n = 1{,}3 - 2{,}0$

c) Total elasticity of engine

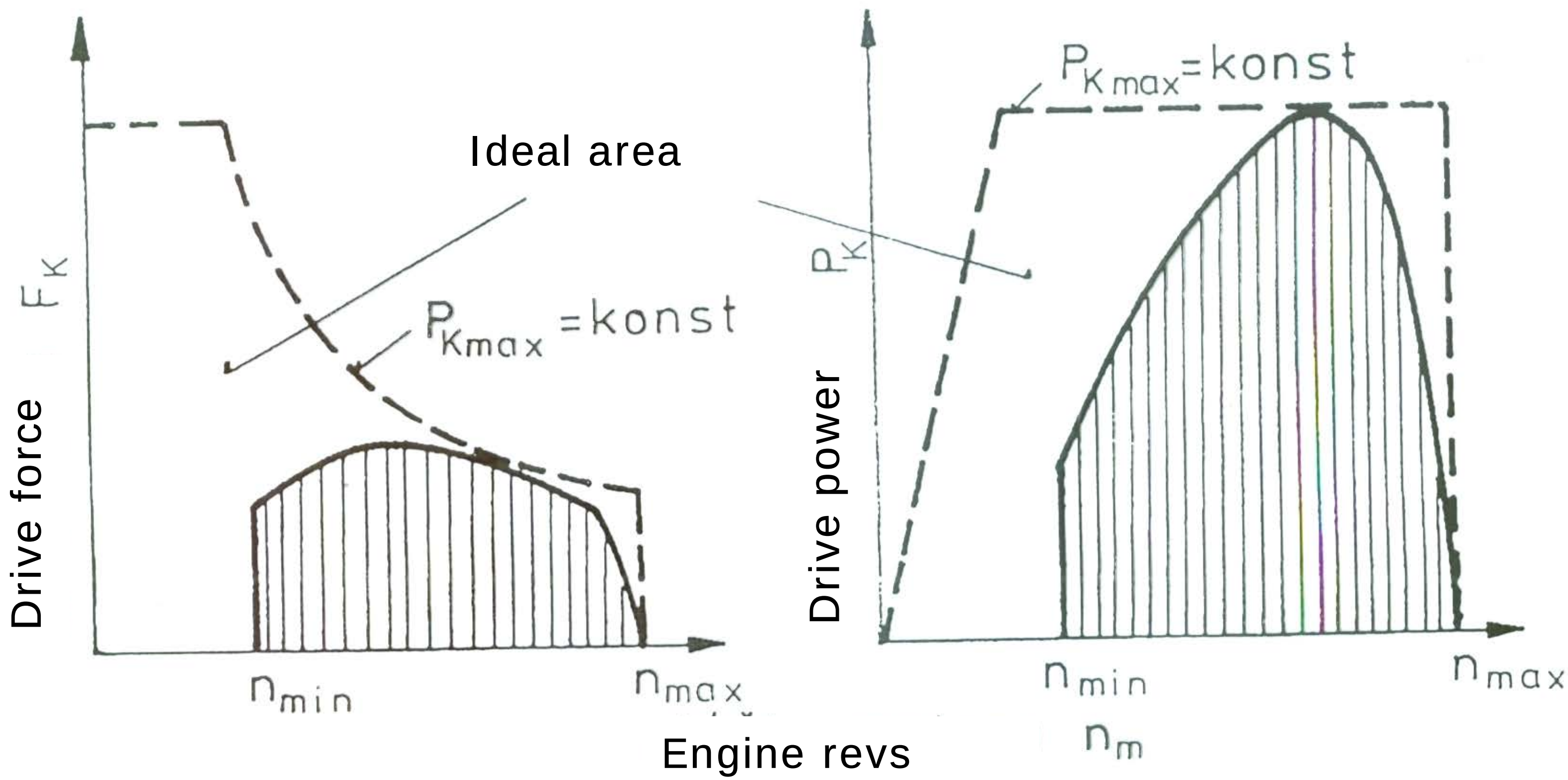
$$e_m = e_M e_n$$

Ignition engine $e_m = 1{,}6 - 5{,}25$
Compression ignition $e_m = 1{,}34 - 2{,}7$

COOPERATION OF ENGINE WITH TRANSMISSION UNIT

It is necessary to change the characteristics of the engine to be as close as possible to the ideal characteristics. For a combustion engine this change must meet 2 conditions:

- Overcome the gap between min. rotations of engine n_{min} and zero rotations of drive wheel, to enable a stationary vehicle to move off
- The curve of torque or engine power must be changed so it is as close as possible to the 'ideal' curve.



COOPERATION OF ENGINE WITH TRANSMISSION UNIT

- **Speed changing device (i.e. clutch)**

Is valid: $M_1 = M_2, \quad n_1 \neq n_2$

- moment $M_1 = M_2$
- efficiency $\eta = \frac{P_2}{P_1} = \frac{n_2}{n_1}$
- clutch slip $s = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$

- **b) torque changing device (and rotations i.e. transmission with axle drive)**

$$M_1 \neq M_2, \quad n_1 \neq n_2$$

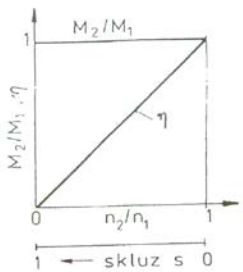
- efficiency

$$\eta = \frac{P_2}{P_1} = \frac{M_2}{M_1}\frac{n_2}{n_1} \qquad \frac{M_2}{M_1} = \eta \frac{n_1}{n_2}$$

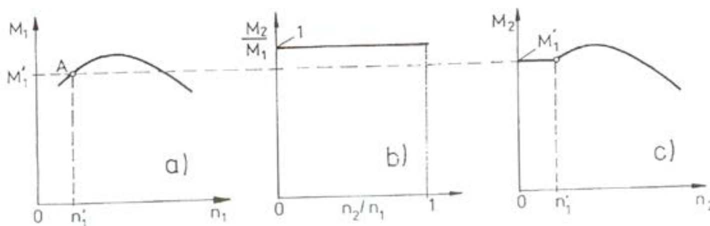
Torque ratio ⇒ two types of torque changers

- Torque changer with continuous transmission ratio, stepped transmission with several gear speeds
- Torque changer with smooth transmission ratio, smooth transmission

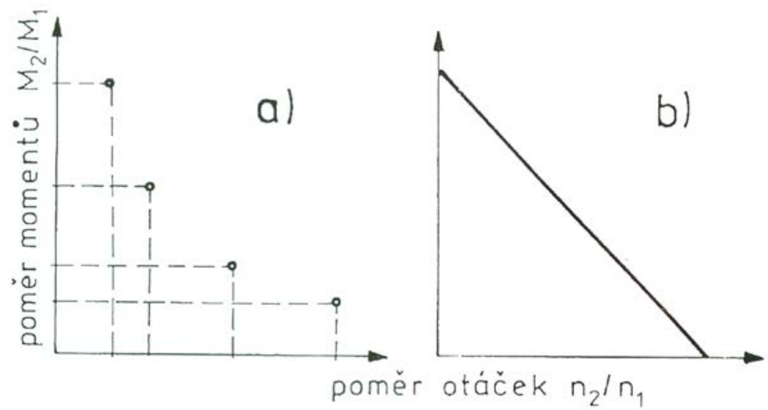
COOPERATION OF ENGINE WITH TRANSMISSION UNIT

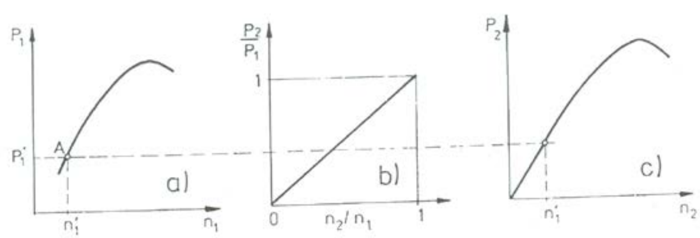


Torque ratio and clutch efficiency



Exceeding rev limits of combustion engine with clutch – torque characteristics: a) engine; b) clutch; c) engine and clutch

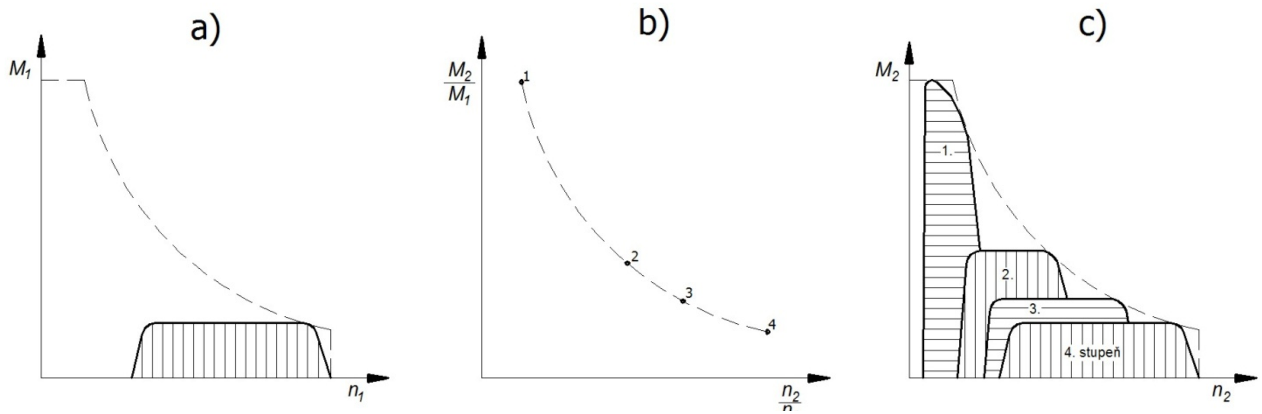




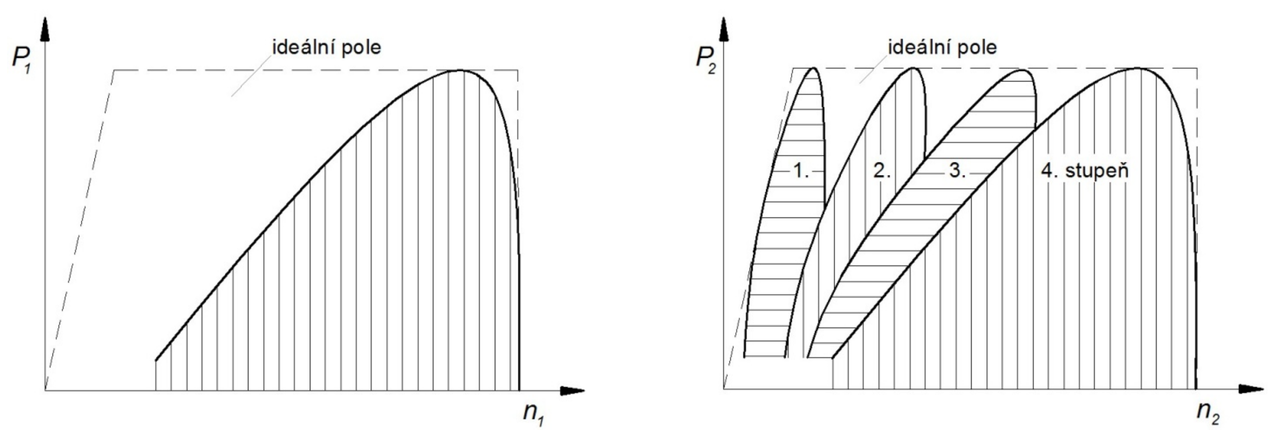
Torque ratio in relation to rev ratio, a) constant transmission (sequential gearbox) ; b) continuous transmission (hydrodynamic converter)

Exceeding rev limits of combustion engine with clutch – performance characteristics

COOPERATION OF ENGINE WITH TRANSMISSION UNIT



Changing torque characteristics of an engine with a four speed transmission a) characteristics of combustion engine; b) characteristics of sequential gearbox; c) torque characteristic at output from transmission.



Changing performance characteristics of an engine with a four speed transmission

WHEEL ROLL THEORY

The wheel is the connecting element between the vehicle and the road. The wheel enables vehicle movement and transfers force to the vehicle and to the road. The wheel has several functions:

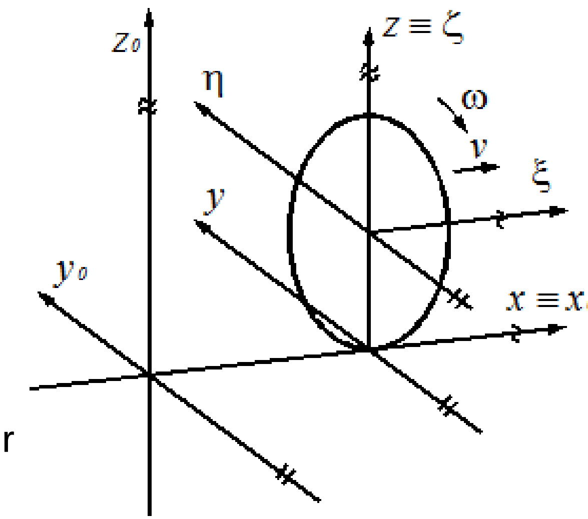
- bearing the weight of the vehicle
- transforming mechanical energy of rotational movement to horizontal movement
- steering element
- suspension element

The requirements of a wheel are thus varied and in many cases contradictory. e.g. the softness of a wheel ensures a comfortable drive, but also leads to big losses of performance due to high rolling resistance. A vehicle wheel comprises a tyre, disk wheel and hub. A disk wheel comprises a rim and disk. They tyre has the biggest influence on the wheel properties.

WHEEL ROLL ON FLAT SURFACE

The starting point for mechanics of a moving wheel is a wheel rolling on a flat plane. The wheel moves so that its plane is identical to the plane x_0, y_0; x, z; ξ, ζ. The basic geometric parameter of a wheel is its radius.

- **nominal radius**
  r_j; radius of unloaded non-rotating wheel
- **Free radius**
  r_0; radius of unloaded non-rotating wheel
- **static operating radius**
  r_S; distance between wheel centre and rigid mount
- **dynamic operating radius**
  r_d; distance between wheel centre and rigid mount for rotating wheel
- **rolling radius**
  r_V; this isn't a geometric parameter, it's kinematic.
- **computational radius**
  r; it's most suitable to take the rolling radius r_V as the computational radius

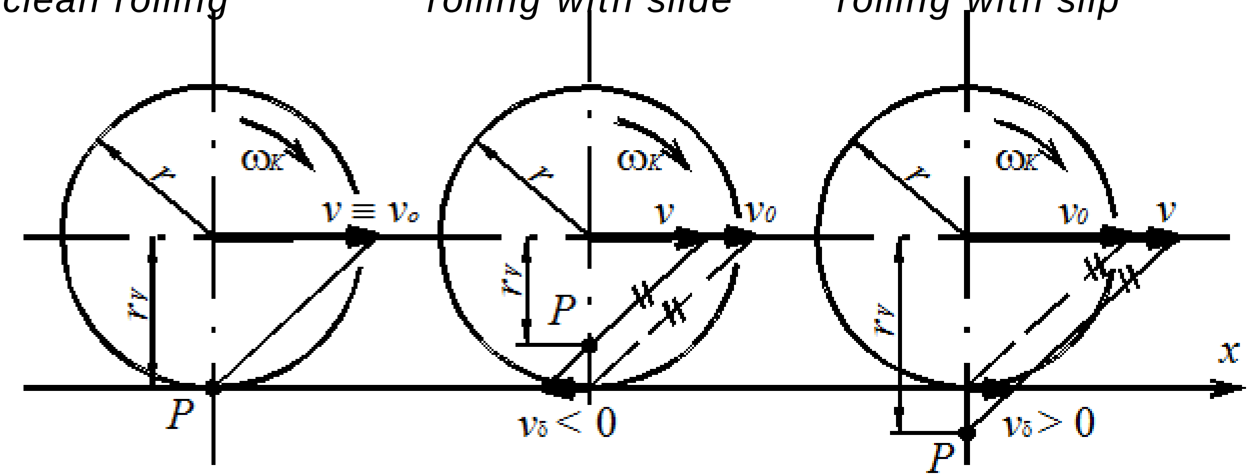


Coordinate system

KINEMATICS OF ROLLING WHEEL

- There are 3 basic cases:

clean rolling | *rolling with slide* | *rolling with slip*



$r_V = r$ | $r_V < r$ | $r_V > r$

$$v = v_o \qquad v = r \cdot \omega_K - |v_\delta| = r_V \cdot \omega_K \qquad v = r \cdot \omega_K + v_\delta = r_V \cdot \omega_K$$

Pure slide:

$$v = 0 \quad \omega_K > 0$$

$$r_V = 0$$

Pure slip:

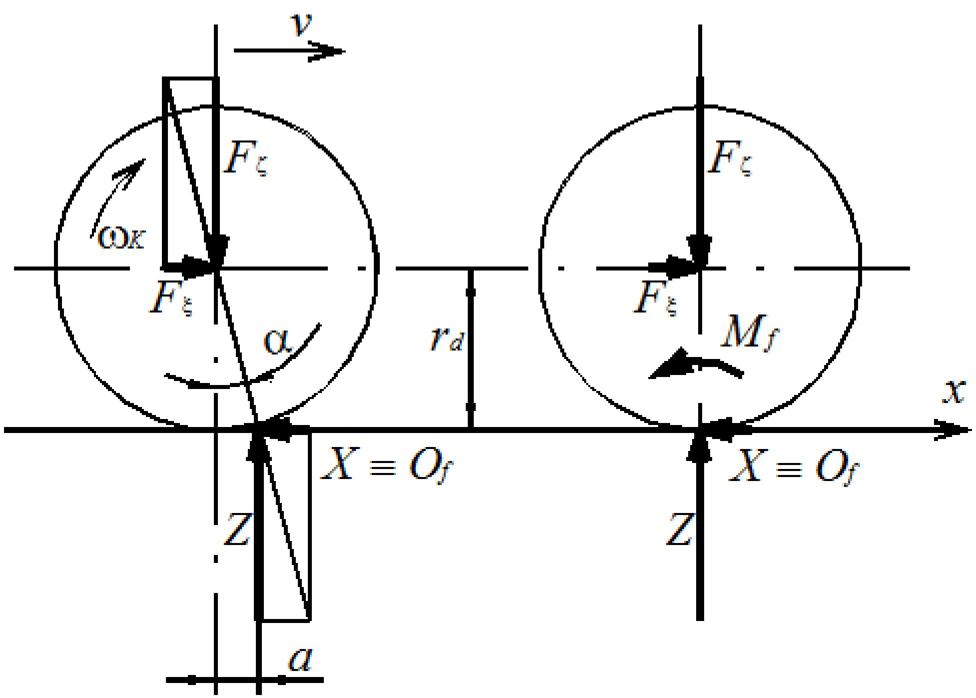
$$v_\delta = v \quad \omega_K = 0$$

$$r_V \to \infty$$

FORCES ON ROLLING WHEEL

For the basic movement states of a wheel, i.e. rolling towed wheel, rolling wheel with slip, rolling wheel with slide, the force ratios of a rolling wheel can be used.

Towed wheel



$$F_\zeta = Z$$

$$F_\xi = X = O_f$$

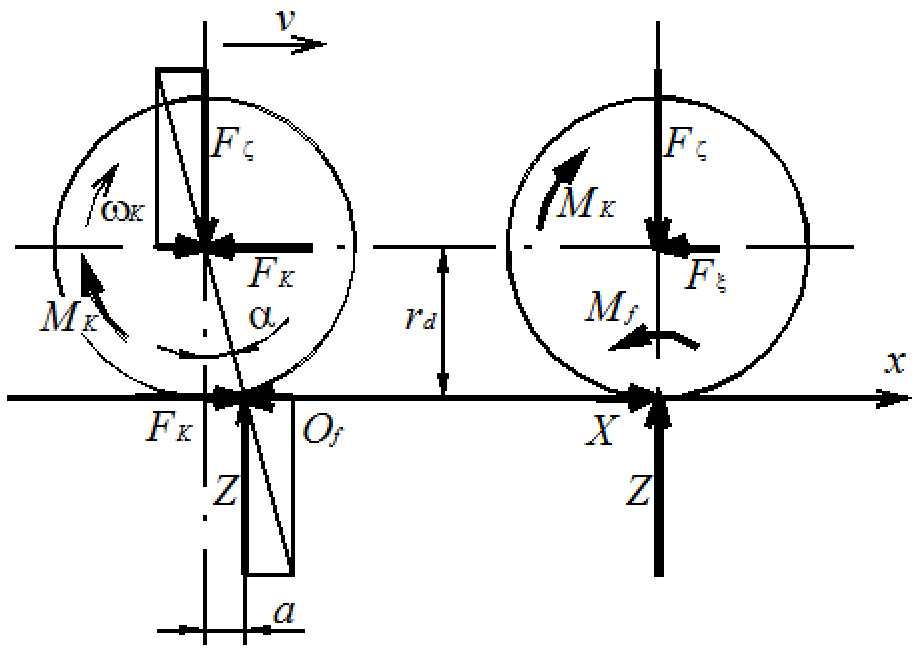
$$O_f = Z \cdot f$$

$$M_f = Z \cdot a = O_f \cdot r_d = Z \cdot f \cdot r_d$$

$$tg\alpha = \frac{a}{r_d} = \frac{O_f}{Z} = f$$

FORCES ON ROLLING WHEEL

Driven wheel



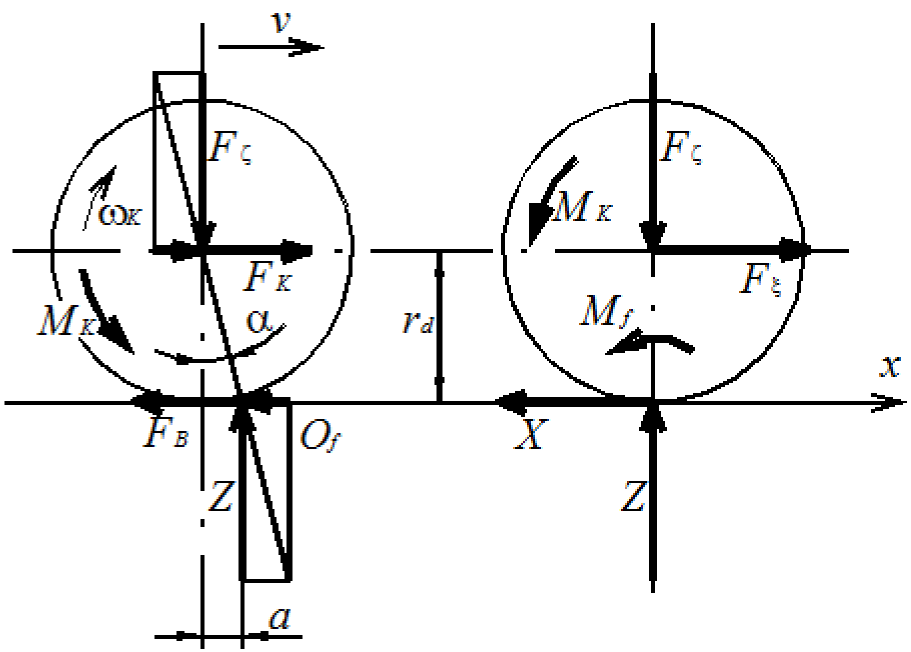
$$F_\zeta = Z$$

$$F_K = \frac{M_K}{r_d}$$

$$F_\xi = F_K - O_f = X$$

FORCES ON ROLLING WHEEL

Braked wheel



$$M_K < 0$$

$$F_K < 0$$

$$-F_K = F_B$$

$$F_\zeta = Z$$

$$F_\xi = F_B + O_f = X$$

From the force analysis of the driven wheel it is seen that the force added to the vehicle is not F_K , but $X = F_\xi$

The relationship between these forces is expressed thus $X = F_K - O_f$

In terms of transformer of mech. energy, the state between *X* and *M is*: $X = \frac{M_K}{r_d} - O_f$

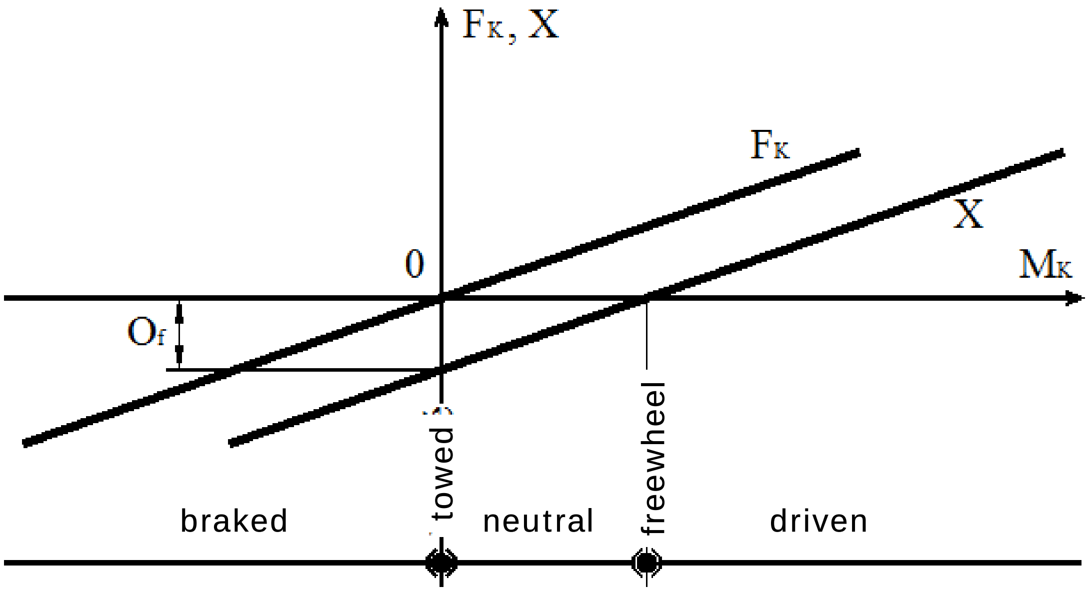
FORCES ON ROLLING WHEEL

Experimental results show that O_f is practically independent of transferred torque, i.e.$O_f(M_K)$ = constant. Graphic representation of this relationship is shown in the following figure. Line $X(M_K)$ is shifted by $F_K(M_K)$ from O_f downwards. This moves the boundary for the driven wheel. For the driven wheel it is necessary to consider $M_K > M_f = O_f \cdot r_d$

A gap thus arises between the state of the towed wheel and the driven wheel. So we can define further states of movement of the wheels: neutral wheel and free wheel.

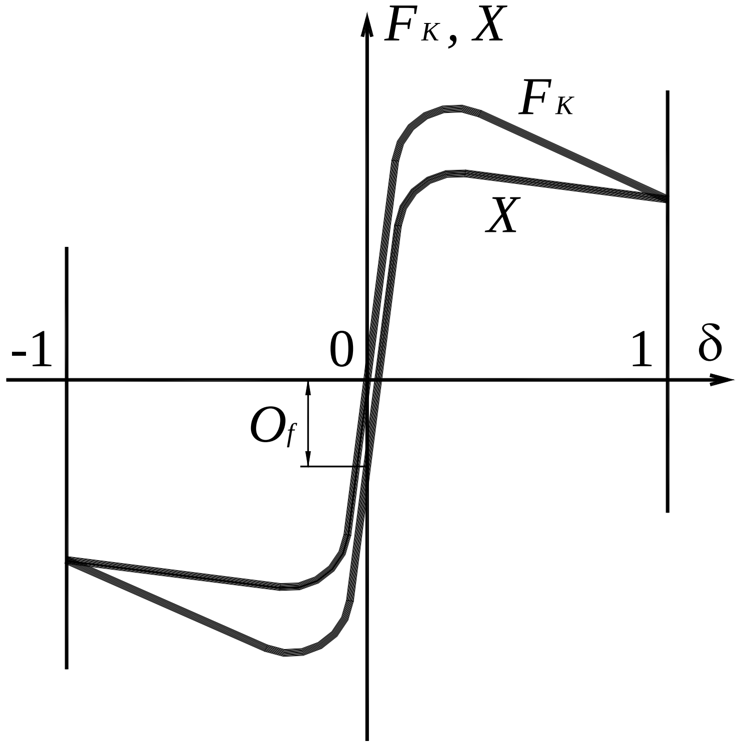
FORCES ON ROLLING WHEEL

Driven wheel	$M_K > M_f$	$F_K > O_f$	$X > 0$	$X = F_K - O_f$
Free wheel	$M_K = M_f$	$F_K = O_f$	$X = 0$	
Neutral wheel	$0 < M_K < M_f$	$0 < F_K < O_f$	$-O_f < X < 0$	
Towed wheel	$M_K = 0$	$F_K = 0$	$X = -O_f$	
Braked wheel	$M_K < 0$	$F_K < 0$	$X < -O_f$	$\lvert X \rvert = \lvert F_K \rvert + \lvert O_f \rvert$



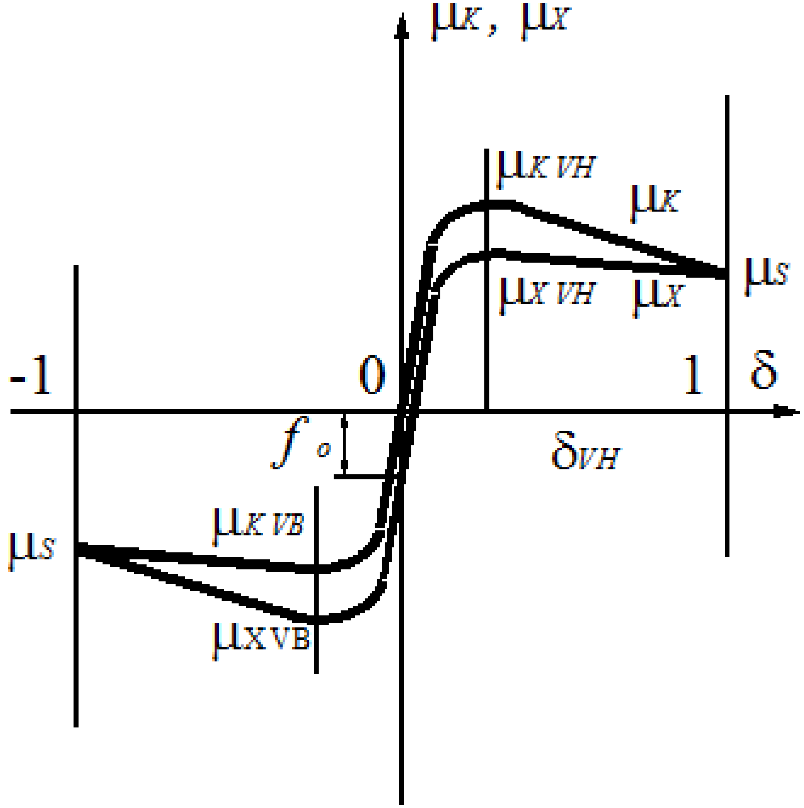
$$X = \frac{M_K}{r_d} - O_f$$

FORCES ON ROLLING WHEEL



For driven and braked wheels, F_K or X cannot be increased at will. The max values are given by the values of wheel adhesion while rolling. The graph shows the typical curve for forces F_K a X relative to slip δ .

FORCES ON ROLLING WHEEL



$$\mu_K = \frac{F_K}{Z}$$

$$\mu_K = \mu_X + f$$

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

More frequently, instead of forces F_K and X we work with dimensionless equivalents of the coefficient of drive force of wheel and the coefficient of peripheral force of wheel μ_X.

The product $Z \cdot \mu_V$ determines max force the rolling wheel is able to transfer to the vehicle whilst both driving and braking. Value μ_S is friction coefficient of adhesion or coefficient of slip adhesion. It is the same for μ_K and μ_X.

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