Tyre dynamics, tyre as a vehicle component
Part 3.: Rolling resistance

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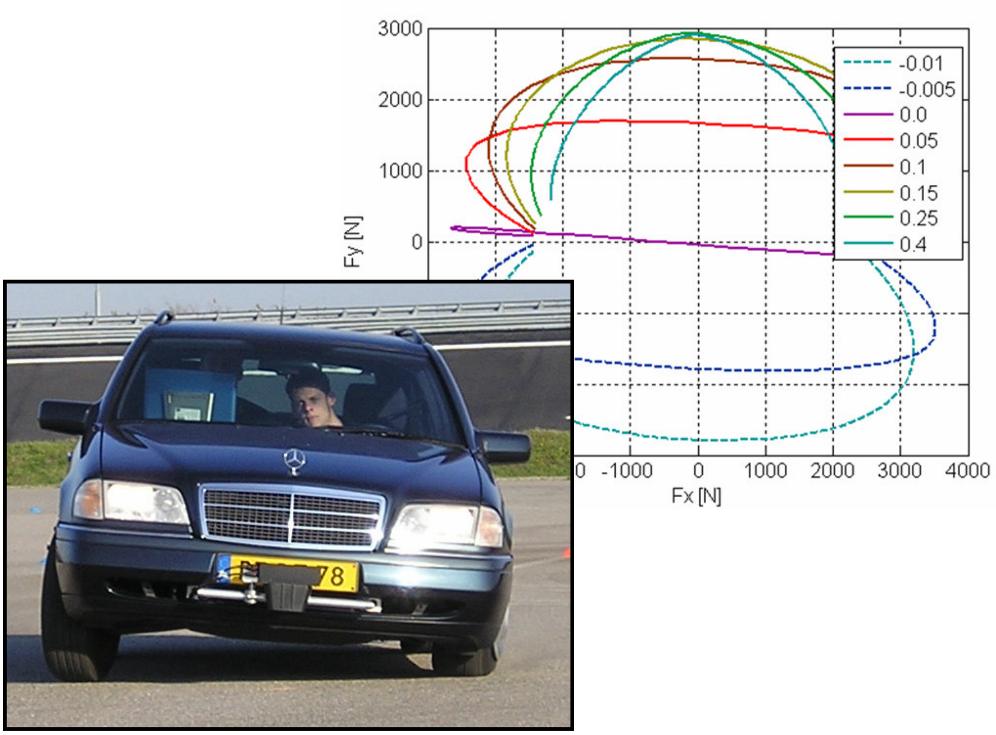

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1. Introductory comments.

Consider a free rolling tyre, schematically depicted in figure 1.
For this free rolling tyre, the following expression is satisfied:

$$F_x = X$$

with -X the required longitudinal force (at the axle) to overcome a resistance force F_x at the contactpatch. This resistance force is referred to as **rolling resistance force** F_R

$$F_R = -F_x$$

In approximation, the rolling resistance force is only depending on the wheelload F_z:

$$F_R = f_R.F_z$$

with rolling resistance coefficient f_R.

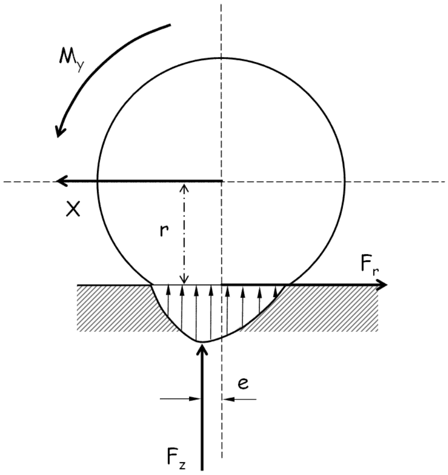

Figure 1.: A free rolling tyre

Because of this rolling resistance force, there must be a driving torque M_y, following from:

$$M_y = F_R.r = F_z.r.f_R \equiv e.F_z$$

with r the loaded tyre radius. As a result, the resulting wheel load acts slightly in front of the projection of the wheel centre on the contact area (see figure). Consequently, the pressure distribution for a free rolling tyre is nonsymmetic.
We observe that the rolling resistance corresponds to the torque M_y.

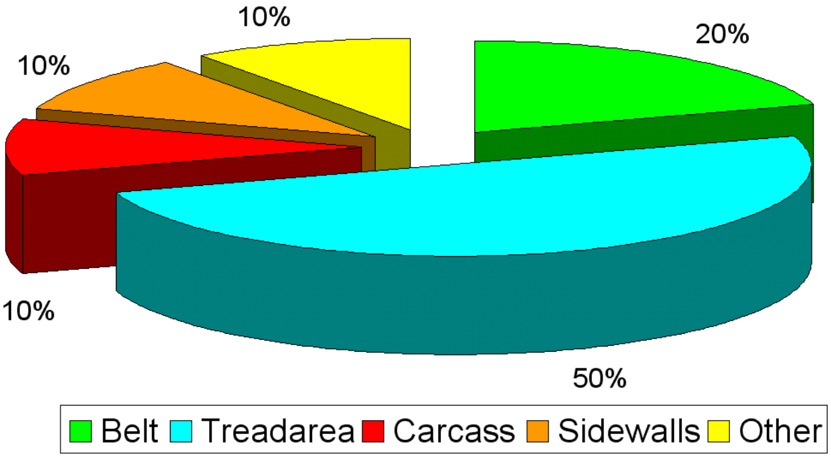

Figure 2.: Contributions tyre parts to energy losses under free rolling conditions

1.1. How can rolling resistance be explained?

For a rolling tyre, deformation of the tyre material occurs while entering the contact patch. The original undeformed conditions are restored when the deformed area leaves the contact patch again. This process involves energy losses, mainly due to

hysteresis of the rubber material. These losses arise in the tread area, in the belt, in the carcass and in the sidewalls.
An overview of the various contributions in this energy loss is shown in figure 2.
These losses together correspond to the rolling resistance force F_R.
As a result, the rolling resistance is reduced for:

- less hysteresis in the tyre material
- less deformation of the tyre

This discussion is related for a rigid flat road. For a deformable (compliant) road, such as soil, the resistance is further increased due to additional friction forces between tyre and soil, and the nonelastic deformation of the soil.

The rolling resistance, being in the order of 0.01 to 0.05 for a rigid road or hard soil may easily increase to 0.35 for a wet saturated soil and to more than 1 for a soft muddy surface. To put it in other words, a wheel on compliant soil attempts to climb out of the pit it is digging itself.
Some areas of the rolling resistance coefficient value are shown in the figure 3 below.

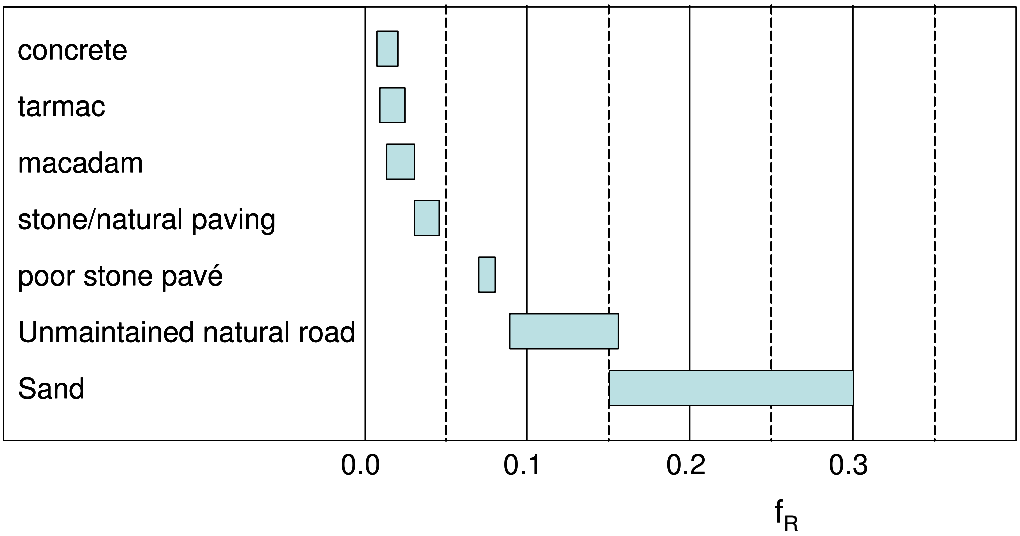

Figure 3.: Rolling resistance values for some road conditions

Other contributions to the overall vehicle resistance include small sliding between road and wheel under normal rolling (adhesion part), aerodynamic drag on the disc (wheel), and friction in the hub.

2. Rolling resistance under driving or braking conditions

The adhesion part is more prominent under driving (tractive force) and braking conditions, leading to higher resistance. The generation of longitudinal forces is always accompanied by some sliding in part of the contact zone. Note that braking and traction also affects the deformation in the contact patch, which may have an impact to rolling resistance, in addition to the occurrence of local sliding.
During small tractive force, the rolling resistance may go down compared to free rolling conditions, up to a level of about 75 % – 85 % of free rolling conditions. An example from [3] is shown below in figure 4..

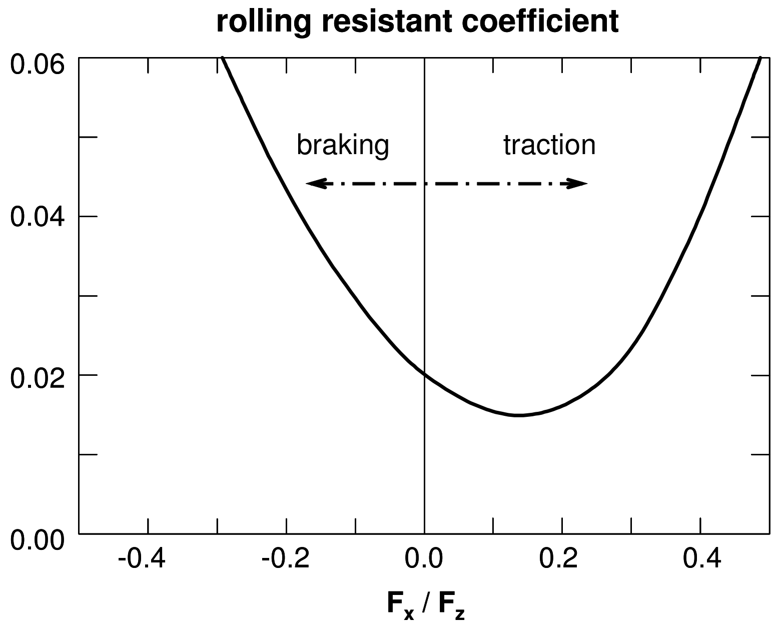

Figure 4.: Rolling resistance under braking and driving conditions

Next to the tyre deflection (deformation), the rolling resistance coefficient f_R also depends on tyre temperature. Both deflection and temperature are affected by the service conditions such as forward velocity, inner pressure and tyre load.

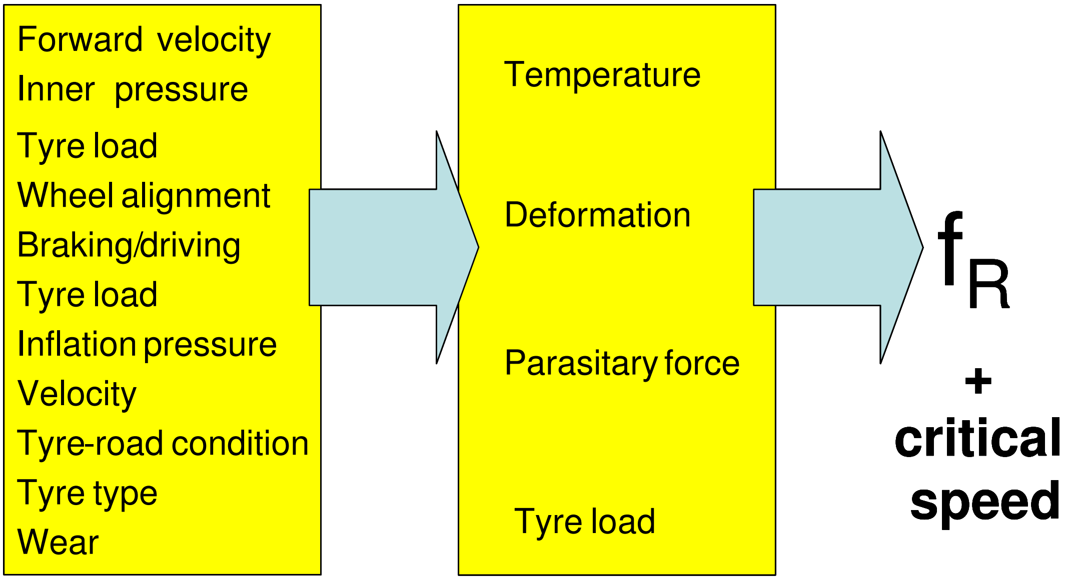

Figure 5.: Relationships with rolling resistance

3. Effect of slipangle and camberangle on rolling resistance

The alignment of the wheel has an impact on rolling resistance. A nonzero slip angle, possibly in combination with some camber will result in a small force acting in the lateral direction, local to the tyre, thus with a component acting in the global forward direction. Slip angle refers here to the angle between the local wheel velocity at the wheel axis and the intersection of the horizontal plane through the wheel axis and the wheel symmetry plane (perpendicular to the wheel axis orientation). When the wheel alignment forces the tyre to have a nonzero slip angle under normal driving conditions, this slip angle is usually referred to as toe angle. The camber angle refers to the angle between the wheel symmetry plane and the global x-z plane, i.e. it describes the rotation of the wheel symmetry plane in x-direction.

For a slip angle α, the contribution of the corresponding local lateral force $F_y = C.\alpha$ (cornering stiffness C, small angle assumed) to the forward direction is $F_y,\sin(\alpha) \cong C.\alpha^2$. For a small slip angle (toe angle) of 1^o and cornering stiffness being conservatively approximated by $C = 15.F_z$, one obtains a contribution to the rolling resistance coefficient of 0.02, being in the order of f_R for a dry concrete road with zero slip angle. Hence, a nonzero slip angle has a large impact on rolling resistance, and care should be taken in measurements of f_R to exclude any lateral parasitary forces.

For similar reasons, camber contributes to rolling resistance. With a wheel not perpendicular to the ground, a local lateral force arises, which can be discussed in a same way as the lateral force for nonzero slip angle. In addition, under combined camber and sideslip conditions, an aligning torque M_z arises, which has a contribution of $M_z.\sin(\gamma)$ to the driving torque M_y.

4. Temperature and rolling resistance.

The internal damping of rubber decreases with increasing **temperature**. As a result, rolling resistance decreases as well. Also, the friction between road and tyre decreases with temperature, resulting in a reduction of the contribution of local sliding in rolling resistance as well. On the other hand, less rolling resistance corresponds to less power dissipation and therefore restricting the temperature rise. Consequently, the decrease of rolling resistance tends to stabilize the temperature of the tyre.

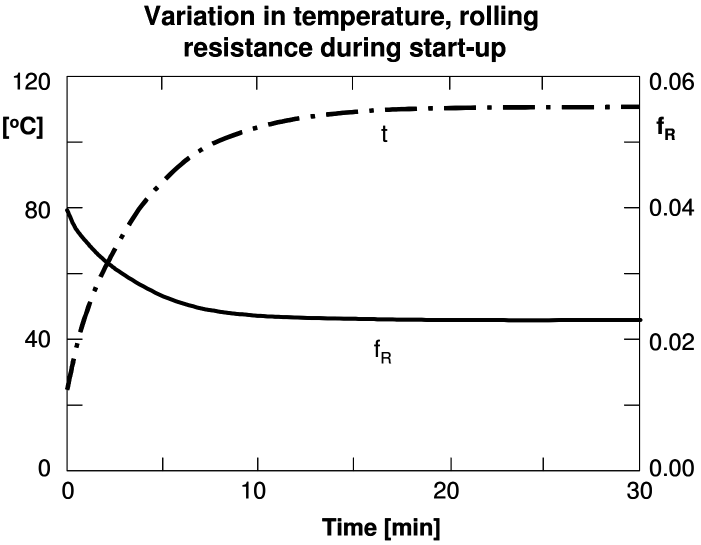

Figure 6.: Saturation of temperature and rolling resistance during start-up process (on a 2.5 m drum).

Some results are shown in figure 6 [3] for a start-up process, taking a certain amount of time before equilibrium in temperature and rolling resistance is reached.

Measurement are carried out with a 7.25-13 radial tyre (184/82R13) on a 2.5 m drum with tyre load 4 kN and tyre pressure 1.5 bar.

5. Varying inflation pressure and tyre load.

Increasing the tyre inflation pressure leads to a stiffer belt and therefore a lower rolling resistance. On the other hand, increasing the tyre load leads to more deformation, and therefore to increased rolling resistance. The critical speed increases with lower rolling resistance in these cases. An increase in temperature leads to an increased inflation pressure which lowers the rolling resistance and corresponding heat dissipation, and therefore has a stabilizing effect regarding temperature.

The SAE suggested an empirical formula for the rolling resistance in dependence of inflation pressure p_i [N/m^2], forward velocity v [m/s] and tyre load F_z [N]:

$$f_R = \frac{K}{1000} . \left(5.1 + \frac{5.5\times10^5 + 90F_z}{p_i} + \frac{1100 + 0.0388F_z}{p_i} \right) v^2$$

The factor K is taken as 0.8 for radial tyres and it is taken as 1 for non-radial tyres. We have plotted curves in figure 7 expressing the rolling resistance against forward speed for varying tyre load and inner pressure, according to this SAE-expression..

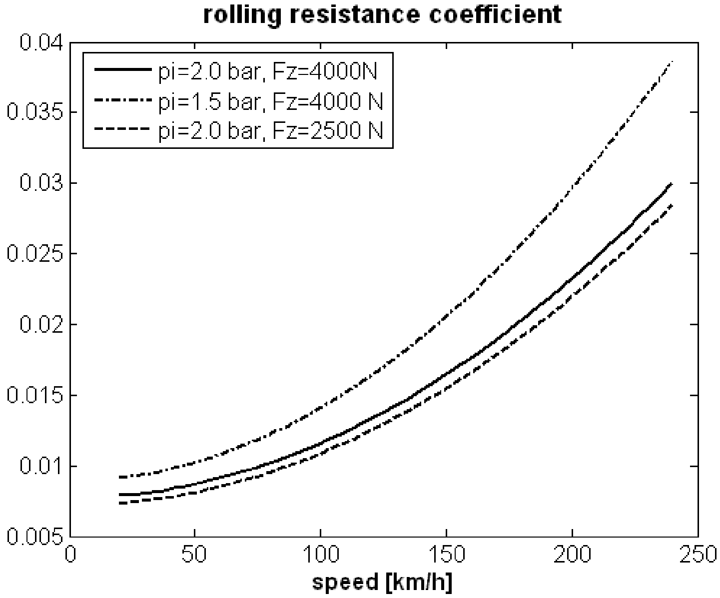

Figure 7.: Rolling resistance for different inflation pressures and tyre load

Other results of the variation of the rolling resistance with inflation pressure are taken from [7] and shown in figure 8. Different inflation pressures are considered on different surfaces. As expected, the effect of increasing the inflation pressure on a soft surface has a more significant effect than on a hard surface such as concrete. Instead of going down, the resistance is increasing with increasing pressure on sand. Lowering the pressure prevent the wheel to 'dig in' in the sand which would lead to a rapidly growing resistance.

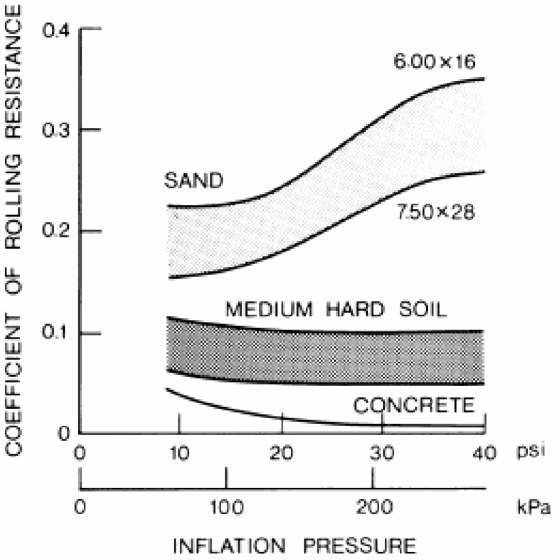

Figure 8.: Rolling resistance coefficient for various
surfaces and inflation pressure

6. Rolling resistance, varying with forward velocity

The dependency of the rolling resistance on forward velocity v can be approximated by a higher order formulation, being second order in the SAE-expression, and suggested to be a fourth-order expression in [4], with the second order term neglected being small compared to aerodynamic forces:

$$f_R = f_{R0} + f_{R1}\cdot\frac{v}{100} + f_{R4}\cdot\left(\frac{v}{100}\right)^4 \quad ; \text{v in km/h}$$

The coefficients f_{R0}, f_{R1}, f_{R4} are shown in figure 9 below as a function of tyre pressure, for three different types of radial (R) tyres:

S : allowable maximum speed of 180 km/h
H : allowable maximum speed of 210 km/h
M+S : tyres, designed for mud and snow (wintertyres)

One observes that the coefficients f_{R0} and f_{R4} decrease with inner pressure, which is a result of the fact that the deformation reduces with increasing tyre pressure, and therefore also the rolling resistance. One also observes that the fourth order coefficient f_{R4} is much smaller for HR tyres than the corresponding values for SR. Clearly, a larger allowable speed requires a lower heat development for the same speed, and this corresponds to a lower rolling resistance and therefore a lower f_{R4}.

We have determined the rolling resistance coefficient for the three tyres treated in figure 9 for nominal pressure and a deviation of + 0.4 bar, based on the mean values of the coefficients f_{Ri}. The results are shown in figure 10. This figure shows the integrated effect of tyre pressure, tyre type (S, H) and speed on rolling resistance. Indeed, for high speed, the HR-tyres show the lowest rolling resistance.

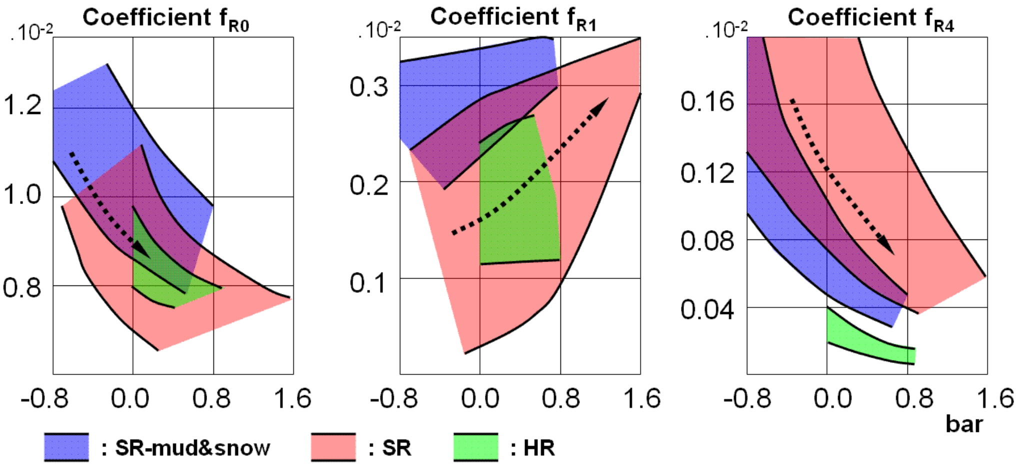

Fig. 9.: Coefficients f_{Ro}, f_{R1}, f_{R4} as a function of the deviation from nominal tyre pressure

The argument about comparison with aerodynamic forces is related to the total resistance for the vehicle. Considering just the rolling resistance, one should include the second order term:

$$f_R = f_{R0} + f_{R2}.v^2, \text{ v in [m/s]}$$

with this expression used in [3], i.e. neglecting the linear term. This is a similar

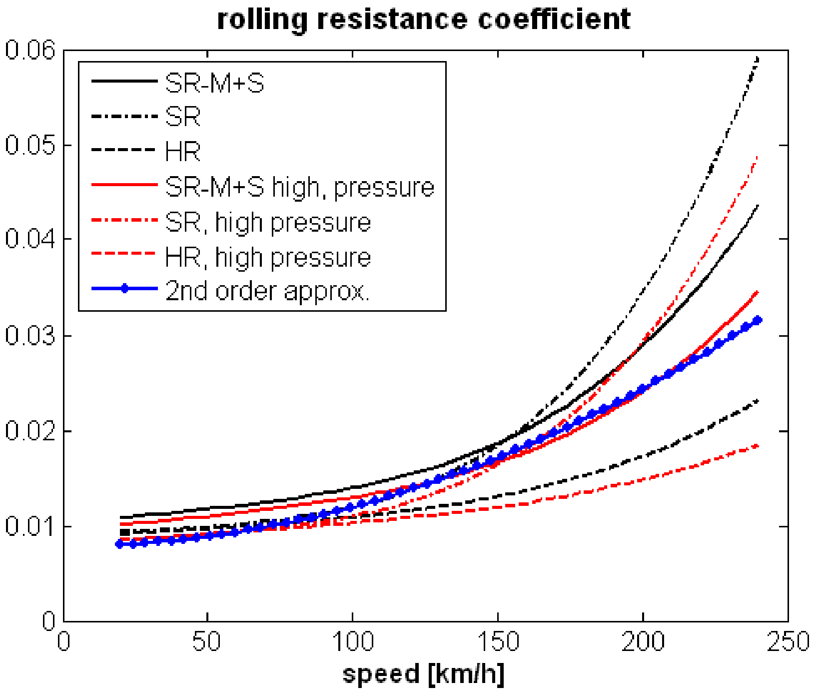

Figure 10.: Rolling resistance factor for some passenger car tyres

expression as introduced earlier, expressing the dependence on tyre load and inner pressure according to SAE. For a radial tyre and conditions with F_z = 3500 N, and inflation pressure 1.85 bar, one finds f_{R0} = 0.0078 and f_{R2} = $5.3.10^{-6}$ s^2/m^2. We have included this graph in blue in the plot with rolling resistance graphs according to the fourth order expression.

One observes that the second order description doesn't show the sharp increase at large speed, as expected. The higher order approximation should therefore be preferred. The progressive increase of the rolling resistance at higher speed is due to the occurrence of standing waves around the tyre circumference, especially at the trailing edge of the contact area. This will lead to a kind of 'lift-off' of the tyre at the rear part of the contact area, with a resulting concentrated contact pressure distribution at the leading part of the contact area. This effect depends on the mass of the tread band. Reducing this mass (resulting in lower rolling resistance) leads to lower centrifugal stiffening and therefore more excessive tyre vibrations. On the other hand, lower mass will increase the natural frequency of the tyre circumferential vibrations, and hence the critical speed. Both effects work against each other. The combined impact on critical speed depends also on the sidewall stiffnesses (being low for radial tyres).

As observed before, the rolling resistance is explained from the torque consisting of the resulting net tyre load times the distance of this resulting vertical force to the wheel centre. This torque is increased in case of standing waves. In the trailing zone of the contact area, the tread has the tendency to reduce the local contact pressure and possible to lift-off from the surface. Consequently, the pressure concentrates more locally at the front part of the contact area, i.e. with the tyre load resultant moving forward. This explains the increased rolling resistance, and strong overheating may take place. This will eventually destroy the tyre beyond **a critical speed**.

7. Rolling resistance of truck tyres

For truck tyres, the dependency on vehicle speed appears to be more linear, i.e. the factor f_{R4} can be neglected (see [4]). Important for truck tyres is the relationship with tyre load. Increasing load appears to reduce the rolling resistance coefficient, as indicated in figure 11.

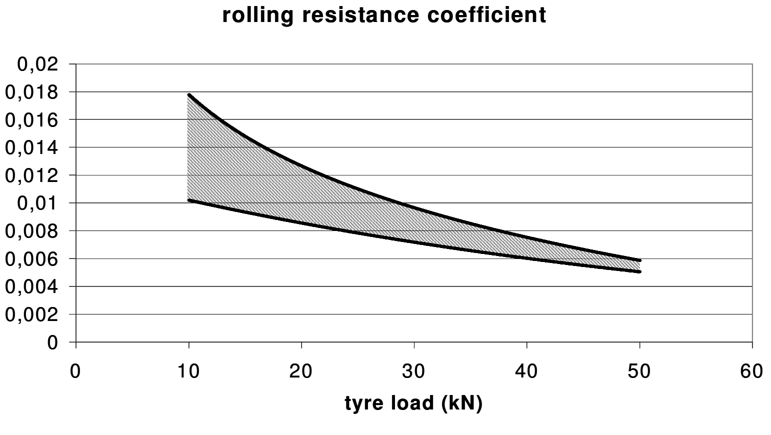

Figure 11.: Rolling resistance coefficient vs. tyre load for a truck tyre, from [4]

Rolling resistance is very important for heavy goods vehicles. About one third of the energy produced by the engine is used to compensate the rolling resistance.
The paper by Popov et. al. confirms that the rolling loss (longitudinal resistance force) is almost linear in the tyre load with the slope slightly increasing with decreasing inner pressure. The rolling loss increases with a decrease in inflation pressure, also leading to a slight increase of the slope (loss versus tyre load). The same tyre deflections correspond with higher rolling loss for higher tyre pressure. Figure 12 was taken from [5].

Wide single tyres have a lower rolling resistance coefficient compared to conventional truck tyres (about 7 % less).

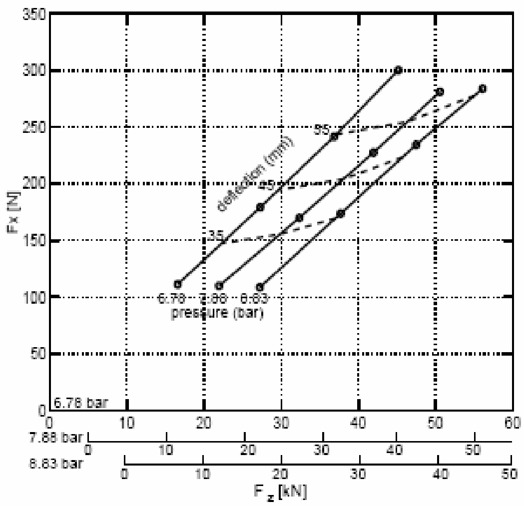

Figure 12.: Rolling loss vs. tyre load, tyre pressure and tyre deflection (from [5])

8. Testing conditions, drum versus flat road.

Results for rolling resistance may be obtained on a flat road or, under controlled testconditions, un a drum in the laboratory with radius usually in the range of 2 – 3 meter. Drum tests may be appropriate for ranking analysis or for investigations in the relative effect of conditions such as load, speed, temperature on rolling resistance. However, the curvature of the drum itself increases the local deformation of the tyre in the contact patch, leading to a larger rolling resistance. With the rolling resistance on the drum f_{RD}, drum diameter D and tyre rolling radius r, the ratio of the rolling resistances on a flat road and on the drum can be expressed as:

$$\frac{f_{RD}}{f_R} = \sqrt{1 + \frac{2r}{D}}$$

This means that with a tyre radius of 0.35 m and a drum diameter of 2 m, the rolling resistance as determined on a drum should be corrected with a factor 0.8607

9. Effect of tyre structure.

Radial tyres normally show a rolling resistance of about 20 % or more lower than bias-ply types, and a higher value of critical speed, see figure 12.

This can be explained by the tyre structure design, leading to less rubber deformation energy for the radial tyre, compared to the bias-ply tyre. This effect is increased by the introduction of low rolling resistance tyres, some years ago, where reduction of 40 % has been claimed with respect to conventional radial tyres, i.e. ending up with half of the rolling resistance of bias-ply tyres.

Other design aspects have an impact to rolling resistance as well, such as the number and orientation of plies, the choice of rubber compounds and the design of treads. Natural rubbers have lower damping compared to synthetic rubbers, leading to lower rolling resistance however at the cost of lower critical speed and smaller lifetime.
Patterned treads measurably increase rolling resistance over slicks, because tread rubber bulges and deforms into voids in the tread pattern when the tire bears on the road. This effect is called tread squirm.

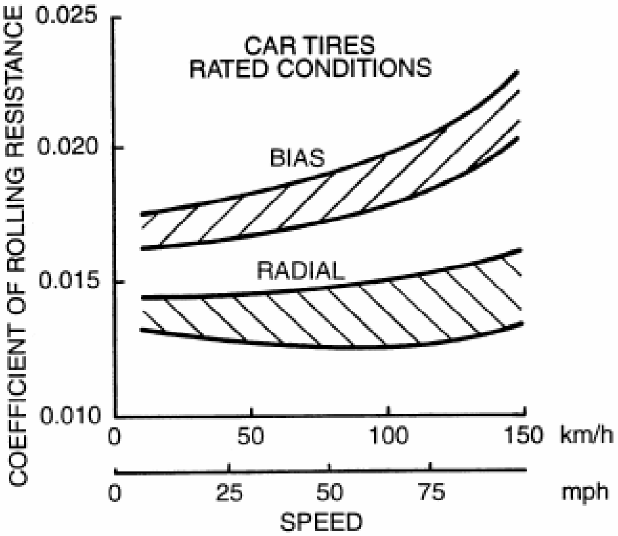

Figure 11.: Rolling resistance coefficient for bias and radial ply tyres (from [6])

10. Rolling resistance on a wet road.

With a significant amount of water on the road, the tyre has to push away this water leading to a larger rolling resistance, depending on the water height h [mm], the tyre speed v [km/h] and the tyre width b [cm]. This resistance will increase with speed up to the level where the full tyre is floating on the water. Beyond this point, the resistance will not increase further with speed.
As shown in [2], the effect of speed on the resistance force F_{RW} can be expressed as:

$$F_{RW} = A.b.v^n \text{ [N]},$$

with exponent n approximately equal to n = 1.6 if h > 0.5 mm
For h = 0.2 mm, n can be approximated by n = 2.2.
The value of A depends on waterheight h. Some results for rolling resistance under aquaplaning conditions are shown in figure 14

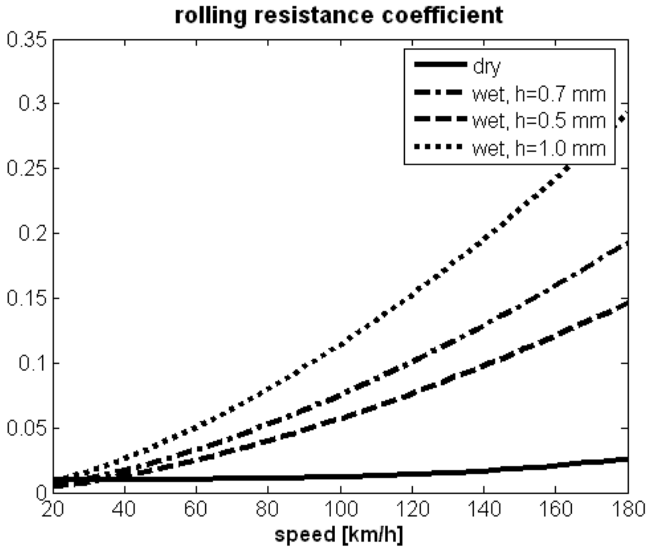

Figure 14.: Rolling resistance under aquaplaning conditions

11. Wear and tyre size.

Rolling resistance decreases with wear. Hysteresis losses occur mostly in the tread band. Hence, reducing the tread band material will result in lower resistance.

The two tyre geometrical parameters having an effect on rolling resistance are:

- Tyre radius
- Aspect ratio (section height / tyre width)

Rolling resistance is decreased for a larger tyre radius or a lower aspect ratio (low profile tyres). Hence, smaller tyres have a larger rolling resistance coefficient. However, such tyres are usually used for lighter cars with lower tyre load and therefore lower rolling resistance force.

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