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STUDY OF ROLLING RESISTANCE MECHANISM

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Abstract: *The rolling mechanism is a part of the auto tire, which are the authors conducted over the several years. The underlying idea in most of the programs was to replicate real-life conditions in order to better understand tire behaviour while using the advantage of quasi-controlled conditions. This paper is made because the number of vehicle in use is increasing every year and more vehicles are consuming more fuel. Vehicle manufacturers are making great efforts to develop fuel efficient engines and vehicle designs. In United States, light-duty vehicles (cars & light trucks) are responsible for about 20% of the nitrogen oxides, 27% of the volatile organic compounds, 51% of the carbon monoxide, and roughly 30% of all the carbon dioxide (the main greenhouse gas) emitted from human activities. When a tire rolls on the road, mechanical energy is converted to heat as a result of the phenomenon referred to as rolling resistance. Effectively, the tire consumes a portion of the power transmitted to the wheels, thus leaving less energy available for moving the vehicle forward. Rolling resistance therefore plays an important part in increasing vehicle fuel consumption.*

Keywords: *tire testing, mechanism, rolling resistance.*

1. INTRODUCTION

This main principle is illustrated in the figure of the rolling cylinders. If two equal cylinders are pressed together then the contact area is flat. Consider a particle that enters the contact area at the right side, travels through the contact patch and leaves at the left side. Initially its vertical deformation is increasing, which is resisted by the hysteresis effect [6].

Therefore an additional pressure is generated to avoid interpenetration of the two surfaces. Later its vertical deformation is decreasing. This is again resisted by the hysteresis effect. In this case this decreases the pressure that is needed to keep the two bodies' separate [10].

2. PRESSURE DISTRIBUTION

The resulting pressure distribution is asymmetrical and is shifted to the right [5]. The line of action of the (aggregate) vertical force no longer passes through the centers of the cylinders. This means that a moment occurs that tends to retard the rolling motion.

Materials that have a large hysteresis effect, such as rubber, which bounce back slowly, exhibit more rolling resistance than materials with a small hysteresis effect that bounce back more quickly and more completely, such as steel or silica. Low rolling resistance tires typically incorporate silica in place of carbon black in their tread compounds to reduce low-frequency hysteresis without compromising traction [3]. Note that railroads also have hysteresis in the roadbed structure [2].

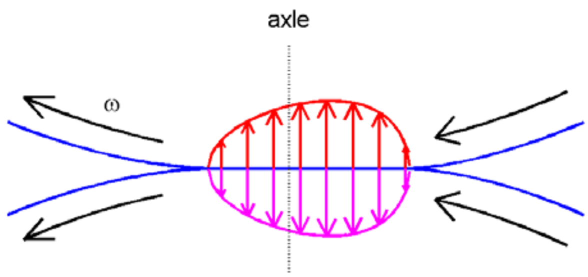

Fig. 1. Tire Contact Area

In the broad sense, specific "rolling resistance" (for vehicles) is the force per unit vehicle weight required to move the vehicle on level ground at a constant slow speed where aerodynamic drag (air resistance) is insignificant and also where there are no traction (motor) forces or brakes applied [8]. In other words the vehicle would be coasting if it were not for the force to maintain constant speed. An example of such usage for railroads is [11]. This broad sense includes wheel bearing resistance, the energy dissipated by vibration and oscillation of both the roadbed and the vehicle, and sliding of the wheel on the roadbed surface (pavement or a rail).

However, there is an even broader sense, which would include energy wasted by wheel slippage due to the torque applied from the engine. This includes the increased power required due to the increased velocity of the wheels where the tangential velocity of the driving wheel(s) becomes greater than the vehicle speed due to slippage [7]. Since power is equal to force times velocity and the wheel velocity has increased, the power required has increased accordingly.

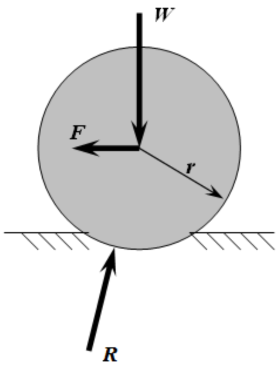

Fig. 2. Tire Rolling Resistance

The pure "rolling resistance" for a train is that which happens due to deformation and possible minor sliding at the wheel-road contact [2]. For a rubber tire, an analogous energy loss happens over the entire tire, but it is still called "rolling resistance". In the broad sense, "rolling resistance" includes wheel bearing resistance, energy loss by shaking both the roadbed (and the earth underneath) and the vehicle itself, and by sliding of the wheel, road/rail contact. Railroad textbooks seem to cover all these resistance forces but do not call their sum "rolling resistance" (broad sense) as is done in this article. They just sum up all the resistance forces (including aerodynamic drag) and call the sum basic train resistance (or the like) [2].

Since railroad rolling resistance in the broad sense may be a few times larger than just the pure rolling resistance [2] reported values may be in serious conflict since they may be based on different definitions of "rolling resistance". The train's engines must of course, provide the energy to overcome this broad-sense rolling resistance.

For highway motor vehicles, there is obviously some energy dissipating in the shaking the roadway and earth beneath, shaking of the vehicle itself, and sliding of the tires. But other than the additional power required due to torque and wheel bearing friction, non-pure rolling resistance doesn't seem to have been investigated, possibly because the "pure" rolling resistance of a rubber tire is several times higher than the neglected resistances [2].

We can imagine the tire being represented by a series of independent springs which resist vertical deformation, as shown in Fig. . As each spring element enters the contact patch, it undergoes vertical deformation. The vertical deformation of the spring reaches its maximum at the center of the contact patch and goes back to zero at the end of the contact patch.

$$\mathbf{F}_r = -F_r \hat{\imath} \quad (1)$$

$$F_r = \mu_r F_z \quad (2)$$

The parameter μ_r is called the rolling friction coefficient. μ_r is not constant and mainly depends on tire speed, inflation pressure, sideslip and camber angles. It also depends on mechanical properties, speed, wear, temperature, load, size, driving and braking forces, and road condition [1] [9]. 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 σ_z in the heading part of the tireprint be higher than the tailing part. The dissipated energy and stress distortion cause the rolling resistance.

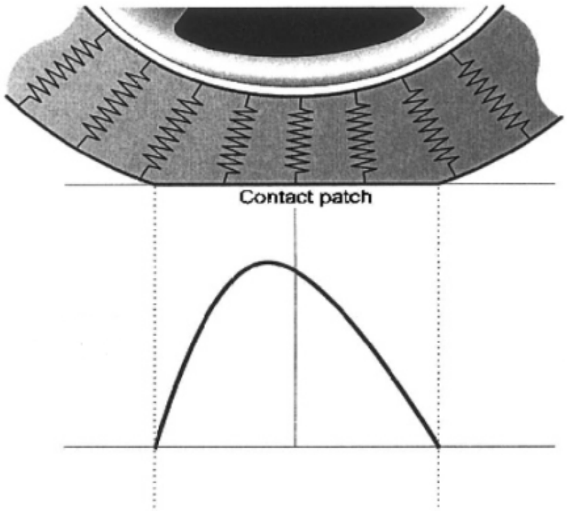

Fig. 3. Normal Force Distribution

Because of higher normal stress in the front part of the tireprint (see 4), the resultant normal force moves forward.

Forward shift of the normal force makes a resistance moment in the $-y$ direction, opposing the forward rotation [1].

$$M_r = -M_r \hat{j} \quad (3)$$

$$M_r = F_z \Delta_x \quad (4)$$

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

$$F_r = \frac{1}{R_h} M_r = \frac{\Delta_x}{R_h} F_z \quad (5)$$

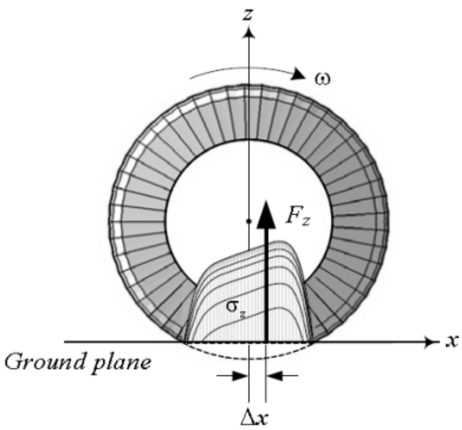

Fig. 4. Normal Stress Distribution and Forces

The test load, speed and inflation pressure vary according to the vehicle manufacturers' requirements. Rolling resistance is significantly influenced by inflation pressure, as illustrated in Figure 1. Since tire rolling resistance can consume up to 25% of the energy required to drive at highway speeds, it is economically wise to keep tires inflated properly.

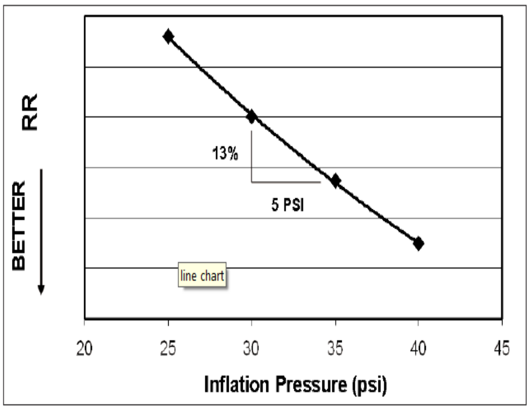

Fig. 5. Rolling Resistance vs. Inflation Pressure

2.1. Rolling Resistance Coefficient

The "rolling resistance coefficient", is defined by the following equation [1]:

$$F = C_{rr} N \quad (6)$$

where F is the rolling resistance force (shown in Figure 2),

C_{rr} is the dimensionless *rolling resistance coefficient* or *coefficient of rolling friction* (CRF), and

N is the *normal force*, the force perpendicular to the surface on which the wheel is rolling.

C_{rr} is the force needed to push (or tow) a wheeled vehicle forward (at constant speed on the level with no air resistance) per unit force of weight [1].

For the US railroads, lb/ton has been traditionally used which is just 2000C_{rr}. Thus they are all just measures of resistance per unit vehicle weight. While they are all "specific resistances" sometimes they are just called "resistance" although they are really a coefficient (ratio) or a multiple thereof. If using pounds or kilograms as force units, mass are equal to weight (in earth's gravity a kilogram a mass weighs a kilogram and exerts a kilogram of force) so one could claim that C_{rr} is also the force per unit mass in such units. The SI system would use N/tonne (N/T) which is 1000 g C_{rr} and is force per unit mass, where g is the acceleration of gravity in SI units (meters per second square) [1].

The above shows resistance proportional to C_{rr} but does not explicitly show any variation with speed, loads, torque, surface roughness, diameter, tire inflation/wear, etc. because C_{rr} itself varies with those factors. It might seem from the above definition of C_{rr} that the rolling resistance is directly proportional to vehicle weight but it is not.

The coefficient of rolling friction for a slow rigid wheel on a perfectly elastic surface, not adjusted for velocity, can be calculated by

$$C_{rr} = \sqrt{\frac{z}{d}} \tag{7}$$

Where:
z is the sink age depth;
d is the diameter of the rigid wheel.

Empirical formula for C_{rr} for cast iron mine car wheels on steel rails.

$$C_{rr} = 0.0048 \left(\frac{18}{D}\right)^{\frac{1}{2}} \left(\frac{100}{W}\right)^{\frac{1}{4}} \tag{8}$$

Where:
D is the wheel diameter in [in].
W is the load on the wheel in [lbs].
As an alternative to using C_{rr} one can use b which is a different rolling resistance coefficient or coefficient of rolling friction with dimension of length, It's defined by the following formula [2]:

$$F = \frac{Nb}{r} \tag{9}$$

Where:
F is the rolling resistance force (shown in Figure 2),
r is the wheel radius,
b is the rolling resistance coefficient or coefficient of rolling friction with dimension of length, and
N is the normal force (equal to W as shown in Fig.).

The above equation, where resistance is inversely proportional to radius r. seems to be based on the discredited "Coulomb's law". Equating this equation with the force in rolling resistance coefficient, and solving for b, gives

$$b = C_{rr} r \tag{10}$$

Therefore, if a source gives rolling resistance coefficient (C_{rr}) as a dimensionless coefficient, it can be converted to b, having units of length, by multiplying C_{rr} by wheel radius r.

2.2. Effect of Inflation Pressure and Load on the Rolling Friction Coefficient

The rolling friction coefficient μr decreases by increasing the inflation pressure p. The effect of increasing pressure is equivalent to decreasing normal load Fz [9].

$$\mu_r = \frac{K}{100}\left(5.1 + \frac{5.5 \times 10^5 + 90F_z}{p} + \frac{1100 + 0.388F_z}{p} v_x^2\right) \tag{11}$$

The parameter K is equal to 0.8 for radial tires, and is equal to 1.0 for nonradial tires. The value of F_z , p, and v_x must be in [N], [Pa], and [m/ s] respectively[4].

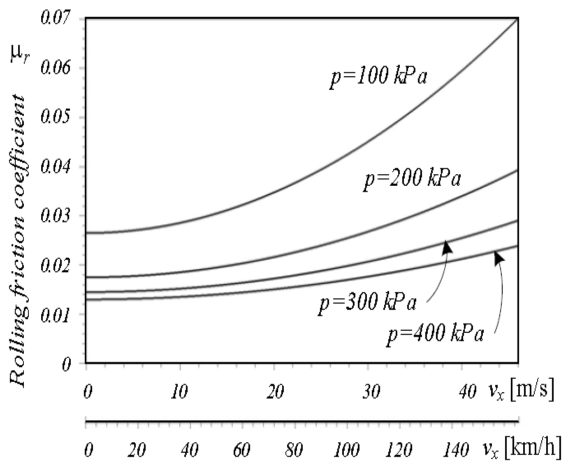

Fig. 1. Rolling friction coefficient

3. CONCLUSIONS REGARDING THE DISSIPATED POWER BECAUSE OF ROLLING FRICTION

Rolling friction reduces the vehicle's power. The dissipated power because of rolling friction is equal to the rolling friction force Fr times the forward velocity vx. The rolling resistance power is:

$$P = F_r v_x = -\mu_r v_x F_z \tag{12}$$

$$P = -\frac{K v_x}{1000}\left(5.1 + \frac{5.5\times10^5 + 90F_z}{p} + \frac{1100 + 0.0388F_z}{p} v_x^2\right) F_z \tag{13}$$

The resultant power P is in [W] when the normal force F_z is expressed in [N], velocity v_x in [m/ s], and pressure p in [Pa]. The rolling resistance dissipated power for this type of tires is:

$$P = \begin{Bmatrix} \left(0.0085 + \frac{1300}{p} + \frac{2.0606}{p} v_x^2\right) v_x \le 46\, m/s (165\, km/h) \\ \left(\frac{1300}{p} + \frac{3.7714}{p} v_x^2\right) v_x F_x ; \quad v_x > 46\, m/s (165\, km/h) \end{Bmatrix} \tag{14}$$

For example, If a vehicle is moving at 100km/ h ≈ 27.78m/ s ≈ 62 mi/ h and each radial tire of the vehicle is pressurized up to 220 kPa ≈ 32 psi and loaded by 220 kg, then the dissipated power, because of rolling resistance, is:

$$P = 4\times\left(\frac{5.1 + 55\times10^5 + 90F_z}{} p + \frac{1100 + 0.0388F_z}{p} v_x\right) F_x = \\ = 2424.1W \approx 2.4kW \tag{15}$$

To compare the given equations, assume the vehicle has tires with power loss given by Eq. (14).

$$P = \left(0.085 + \frac{1800}{p} + \frac{2.0606}{p} v_x^2\right) v_x F_z = \\ = 5734.1W \approx 5.7kW \tag{16}$$

The important conclusion is, and it shows that if the vehicle uses this type of tires, it dissipates more power.

References:

[1] Bogdan L, Albrechcinski TM. Characterisation of Tire Partiulates. Buffalo, NY: Arvin Calspan; 1981.

[2] Clark SK, DodgeRN. A Handbook of Rolling Resistance of Pneumatic Tires. Ann Arbor: Institute of Science and Technology, The University of Michigan; 1979.

[3] Committee for the National Tire Efficiency Study NRC. Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance -- Special Report 286. The National Academies Press; 2006.

[4] Cossalter V. Motorcycle Dynamics. Greendale: Race Dynamic Publishing; 2002.

[5] Dugoff H, Fancher PS, Segel L. An analysis oftire traction properties and their influence on vehicle dynamic performance. SAE 700377; 1983.

[6] General Motors Corporation. Comments on Tire Rolling Resistance to U.S. Environmental Protection Agency. Environmental Protection Agency; 1978.

[7] Genta G. Motor Vehicle Dynamics, Modeling and Simulation. Singapore: World Scientific; 2007.

[8] Janosi ZJ, Kamm IO, Wray G. Tire turning forces under on- and off-road conditions. Calgary: Conf. I.S.T.V.S; 1981.

[9] Jazar RN. Vehicle Dynamics. Theory and Applications. Riverdale, NY: Springer Science + Business Media; 2008.

[10] Noor AK, Tanner JA. Advances and trends in the development of computational models for tires. Computers & Structures; 1985.

[11] Vollebregt DiEAH. User guide for CONTACT, Vollebregt & Kalker's rolling and sliding contact model. VORtech Computing; 2012.

Studiul mecanismului de rezistență la rulare

Rezumat: *Mecanismul de rulare este parte componentăa pneului autovehiculului, cu care autorii s-au ocupat câțiva ani. Cea mai importantă idee este aceea că se caută soluții în viața reală, pentru o mai bună înțelegere a condițiilor în care lucrează pneul precum şi avantajele utilizării condițiilor cvasi-reale. Această lucrare a fost făcută, pentru că un număr foarte mare de vehicule sunt scoase din uz în fiecare an, iar vehiculelel consumă tot mai mult combustibil. Producerea vehiculelor se face cu mare efortşi de aceea se caută soluții de reducere a consumului şi astfel să se eficientizeze motorul şi proiectarea vehiculelor. În Statele Unite ale Americii, vehiculele grele, de mare tonajsunt responsabile pentru 20% oxid de azot, 27% comnponenti organici volatili, 51% monooxid de carbon şi aproape 30% din tot dioxidul de carbon existent în activitatea umană. Când pneul rulează pe şosea, energia mecanică este convertită în căldură ca rezultat al rezistenței la rulare. Efectiv, pneul consumăo parte din energia transmisă, astfel micşoreazăenergia disponibilă pentru deplasarea vehiculului pe traseu. Rezistența de rulare loacă asfel un rol important în descreşterea consumului de combustibil al autovehiculului.*

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