Decreasing CO_2 Emissions By Reducing Tire Rolling Resistance

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ABSTRACT: The first motor vehicle was built by Nicolas Cugnot almost 250 years ago and since then there has been a continuous process of motor vehicles' improvements, as well as development of new road pavements. The fuel crisis of the 70s of the 20th century made it clear to vehicle builders that measures should be taken to reduce vehicle fuel consumption and it contributed to an increased interest in electric vehicles. Although significant progress has already been made in reducing fuel consumption by internal combustion vehicles, at the turn of the 20th and 21st centuries, a new challenge has arisen, namely the need to reduce CO_2 emissions. To achieve this, both the need to build more ecological friendly sources of propulsion and to significantly reduce the vehicle's resistance, have to be addressed. This paper deals with one of the most important sources of vehicle resistance - the rolling resistance. Rolling resistance is a phenomenon that occurs at the tire's interface with the roadway and depends on the tire construction, pavement parameters, vehicle operating parameters and atmospheric conditions. The paper presents how big is the influence of rolling resistance on overall energy consumption of road vehicles and how to evaluate rolling resistance, especially in real road conditions.

Rolling resistance is very difficult to measure, so it is common to use simplified methods, which do not always provide representative results. The paper presents an overview of *rolling resistance research methods, their advantages and disadvantages and the impact of the most important parameters of tires, pavement and traffic conditions on tire rolling resistance. Special attention is given to the problem of implementing proper procedures during road measurements of rolling resistance as road measurements are not standardized yet, despite the fact that, if performed correctly, they may give the most representative and precise results leading to improvements of pavements and tires. The results of rolling resistance tests conducted on rubber modified asphalt and on porous surfaces are also presented.*

KEYWORDS: tires, rolling resistance, measuring methods, CO2, fuel consumption, texture.

1. Introduction

In order to move every vehicle must overcome resistive forces acting on it. Those forces control the vehicle's performance and energy consumption. Lower value of resistance means better acceleration, higher speed and lower energy consumption leading also to proportional decrease of CO_2 and other toxic elements emission.

Generally, several resistive forces act or may act on a moving car. They are shown in Fig. 1. Some of the forces act on the vehicle all the time (rolling resistance, drag) some of them may not be present in a certain driving condition (inertia forces, up/downhill force, tow force).

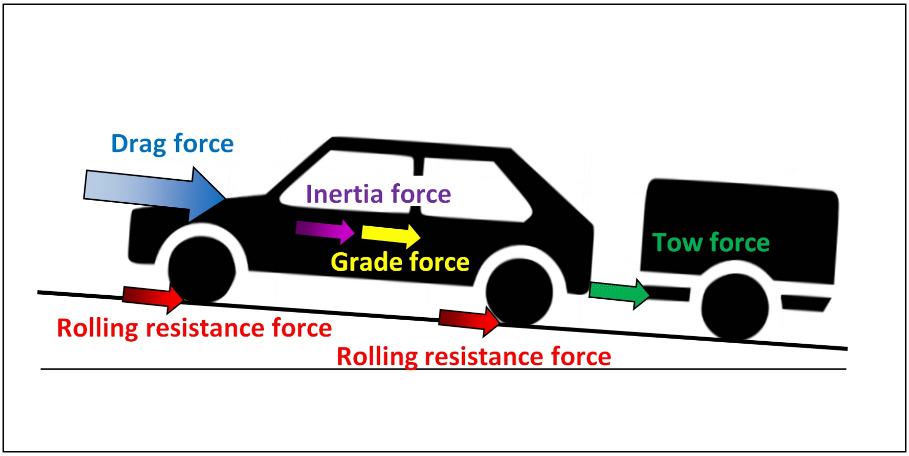

Figure 1: Restrictive forces acting on moving car

Tire rolling resistance is the force resisting the motion of the tire when it rolls on a road surface. It is mainly caused by non-elastic effects in tire and slippage between the tire tread and the pavement, which leads to dissipation of energy. Contrary to early diagonal tires, rolling resistance of modern radial car tires is not very much dependent on the speed. Force of rolling resistance on horizontal road (F_R) is given by the equation (1).

$$F_R = C_{RR} \cdot W \qquad (1)$$

Where:

F_R - Force of rolling resistance [N],
C_{RR} - Rolling Resistance Coefficient [-],
W - Weight of the vehicle [N]

Rolling resistance depends on many factors related to road, tire and operating conditions. The most important influences are given below (☹ - indicates negative influence that is increase of rolling resistance, ☺ - indicates positive influence that is decrease of rolling resistance):

ROAD

- ⥣ Texture = ☹
- ⥣ IRI = ☹
- ⥣ Stiffness = (?) still to be tested
- ⥣ Open voids = ☺

TIRE

- ⥣ Outside diameter = ☺
- ⥣ Width = (?) still to be tested
- ⥥Aspect ratio = (?) still to be tested
- ⥣ Rubber hardness = ☺
- ⥣ Rubber hysteresis = ☹
- ⥣ Tread pattern grooving = ☺
- ⥣ Belt stiffness = ☺
- ⥣ Tread depth = ☹

OPERATING CONDITIONS

- ⥣ Speed = ☹
- ⥣ Inflation pressure = ☺
- ⥣ Load = ☹
- ⥣ Road wetness = ☹
- ⥣ Snow layer = ☹
- ⥣ Temperature = ☺

Vehicle drag resistance is the aerodynamic force that opposes the vehicle's motion through the air. Drag force is dependent on the relative speed of the air flowing around the vehicle, vehicles cross-section, drag coefficient and air density.

The force of inertia "*is the property common to all bodies that remain in their state, either at rest or in motion, unless some external cause is introduced to make them alter this state.*" [1]. Inertia forces act on vehicles when they increase speed (accelerate) or decrease speed (decelerate). Inertia force always opposes the change of speed, so it acts as a resistive force for an accelerating vehicle and as a tractive force for a decelerating vehicle. Using modern technology (electric and hybrid vehicles and ERS) a considerable part of the inertia energy may be recovered.

Grade resistance is proportional to the weight of the car and to sinus of the slope angle. The grade (also called slope) of a road refers to the inclination of the surface to the horizontal in longitudinal direction. Slope is often calculated as a "rise over run" fraction in which run is the horizontal distance and rise is the vertical distance. In many situations and using modern technology a considerable part of the grade energy loses may be recovered.

Tow force exists only when the vehicle tows another vehicle, usually trailer or semitrailer. Tow force is equal to all forces acting on the towed vehicle.

2. Rolling resistance influence on energy consumption and CO_2 emission of passenger cars

2.1. Rolling Resistance Coefficients of modern tires

According to equation (1) the best way to describe rolling resistance force acting on any vehicle is to provide value of the Rolling Resistance Coefficient (C_{RR}). For modern tires this coefficient is fairly independent of speed, at least for typical speed range 30 - 120 km/h but, unfortunately, it is influenced by the tire load and inflation pressure [2], temperature [3] as well as road pavement wetness [4]. An increase of inflation pressure always leads to a decrease of Rolling

Resistance Coefficients, while an increase of the load may influence C_{RR} in both ways. An increase of tire temperature (that is fairly well correlated with air and pavement temperature) leads to a decrease of C_{RR} while pavement dampness always results in increase of C_{RR}.

What follows, any considerations related to rolling resistance must be accompanied by detailed information related to load, inflation, temperature and condition of the pavement. In this chapter it is assumed that all C_{RR} values are obtained or normalized to air temperature of 25ºC, road pavement is dry and tire load as well as inflation pressure are typical for medium class passenger car that is load = 4000 N (≈400 kg) and inflation = 210 kPa (2.1 bar).

Numerous measurements performed by the Technical University of Gdańsk (TUG) on road sections in Europe and the USA indicate that differences between Rolling Resistance Coefficients obtained on different road pavements and obtained for different tires are very big, thus for lowering CO_2 emission proper selection of road pavements and tires is critical. Statistically C_{RR} obtained for typical tires rolling on typical road surfaces has value very close to 0.01. When "the worst" (from the rolling resistance point of view) tires are rolling on "the worst" road pavements C_{RR} value may be as high as 0.015, while combination of "the best", state of the art tire and "the best" pavement may well reduce C_{RR} to as low as 0.004.

2.2. *Simulation of Rolling Resistance influence on CO_2 emission*

There are several simulation models used for estimation of energy consumption of light and heavy vehicles. They are usually very complicated and based on numerous input data that are difficult to obtain. In the case of simulations reported in this paper the model is rather simple as the goal was not to predict absolute energy consumption values but to evaluate relative changes of energy consumption due to rolling resistance changes [5]. Due to this simplification it was not necessary to investigate in details particularities of engine and power train efficiency. It is assumed that differences in engine load due to different tire rolling resistance are not big enough to result in different efficiency of the engine and power train. As CO_2 emission is proportional to energy consumption (for given engine type) the model may be used also to evaluate influence of rolling resistance on emission of CO_2 as well as other toxic gases. The model used for evaluation is based on equations (2) and (3).

$$P = \left(F_R + F_D + F_I + F_G\right) \cdot V \quad (2)$$

$$E = P \cdot t \quad (3)$$

Where:

- P Power [W],
- F_R Rolling resistance force [N],
- F_D Drag force [N],
- F_I Inertia force [N],
- F_G Grade force [N],
- V Speed of the vehicle [m/s]
- E Energy [J].

Basic power necessary to drive a vehicle is calculated according to equation (3). If simulation is performed for a conventional vehicle (diesel or petrol engine) the model evaluates when engine braking is present. Most of the vehicles are constructed in such a way that during engine braking fuel consumption is reduced to zero and this behavior is modeled in the algorithm. The algorithm also checks if the speed of the vehicle is below 2 m/s and if so the virtual "idling power" value is used (Pi). In case of electric and hybrid vehicles equipped with KERS it is assumed that 50% of energy during "engine braking" is recovered.

The model has been fed with data obtained for 6 conventional and 4 Low Emission vehicles (electric and hybrid) and simulations were performed for driving with constant speed of 30, 50, 70, 90, 110, 130, 150 km/h as well as for urban driving cycle FTP 75. Energy consumption calculations were performed for Rolling Resistance Coefficients from 0.005 to 0.015 with increment of 0.001. Value of C_{RR} = 0.01 was considered a "typical for present vehicles and road pavements" as it is equal to the average of Rolling Resistance Coefficient that was measured by TUG on numerous road pavements and for numerous tires.

Relative changes of energy consumption averaged for all simulated conventional vehicles are presented in Tab. 1 while corresponding values obtained for hybrid vehicles are presented in Tab. 2. In order to better describe the influence of rolling resistance on overall energy consumption and CO_2 emission for present vehicle fleet and typical pavements (that is in situation where average $C_{RR} = 0.01$) the "Rolling Resistance Impact Factor" (IF_{RR}) was introduced. IF_{RR} shows how much the energy consumption and CO_2 emission are influenced by change in rolling resistance coefficient. For example if $IF_{RR} = 0.3$ the reduction of rolling resistance by half will lead to 15% CO_2 emission reduction (50% * 0.3 = 15%). Impact Factors estimated for conventional and Low Emission vehicles are presented in Tab. 3.

Tab. 3 indicates that CO_2 emission during constant speed driving for conventional and hybrid vehicles is sensitive to rolling resistance in a very similar way, but for urban driving the hybrid vehicles benefit more from low rolling resistance tire/pavement combination than conventional cars. This is because energy to overcome inertia forces is partly recovered in hybrid vehicles.

Table 1: *Relative changes of energy consumption and CO_2 emission for conventional passenger cars*

C_{RR}	Constant speed driving							*FTP -75*
	30 km/h	**50 km/h**	**70 km/h**	**90 km/h**	**110 km/h**	**130 km/h**	**150 km/h**	
0.005	0.77	0.78	0.81	0.85	0.88	0.90	0.92	0.89
0.006	0.81	0.82	0.85	0.88	0.90	0.92	0.94	0.91
0.007	0.86	0.87	0.89	0.91	0.93	0.94	0.95	0.93
0.008	0.91	0.91	0.92	0.94	0.95	0.96	0.97	0.96
0.009	0.95	0.96	0.96	0.97	0.98	0.98	0.98	0.98
0.010	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.011	1.05	1.04	1.04	1.03	1.02	1.02	1.02	1.02

0.012	1.09	1.09	1.08	1.06	1.05	1.04	1.03	1.04
0.013	1.14	1.13	1.11	1.09	1.07	1.06	1.05	1.07
0.014	1.19	1.18	1.15	1.12	1.10	1.08	1.06	1.09
0.015	1.23	1.22	1.19	1.15	1.12	1.10	1.08	1.11

Table 2: *Relative changes of energy consumption and CO_2 emission for electric and hybrid passenger cars*

C_{RR}	**Constant speed driving**							***FTP-75***
	30 km/h	**50 km/h**	**70 km/h**	**90 km/h**	**110 km/h**	**130 km/h**	**150 km/h**	
0.005	0.79	0.79	0.81	0.84	0.87	0.90	0.92	0.84
0.006	0.83	0.83	0.85	0.87	0.90	0.92	0.93	0.87
0.007	0.87	0.87	0.89	0.91	0.92	0.94	0.95	0.90
0.008	0.92	0.91	0.92	0.94	0.95	0.96	0.97	0.94
0.009	0.96	0.96	0.96	0.97	0.97	0.98	0.98	0.97
0.010	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.011	1.04	1.04	1.04	1.03	1.03	1.02	1.02	1.03
0.012	1.08	1.09	1.08	1.06	1.05	1.04	1.03	1.07
0.013	1.13	1.13	1.11	1.09	1.08	1.06	1.05	1.10
0.014	1.17	1.17	1.15	1.13	1.10	1.08	1.07	1.13
0.015	1.21	1.21	1.19	1.16	1.13	1.10	1.08	1.16

Table 3: *Rolling Resistance Impact Factors for conventional and Low Emission cars*

Vehicle	**Constant speed driving**							***FTP-75***
	30 km/h	**50 km/h**	**70 km/h**	**90 km/h**	**110 km/h**	**130 km/h**	**150 km/h**	
Conventional	0.46	0.45	0.38	0.31	0.24	0.19	0.16	0.22
Hybrid	0.	0.43	0.38	0.31	0.25	0.21	0.17	0.32

	42						
Electric	0.35	0.36	0.31	0.25	0.20	0.16	0.13	0.31

Relatively low IF_{RR} values that are calculated for electric vehicles for constant speed driving can be explained by the fact that only one, very small electric car (SMART Fortwo Electric Drive Coupe) was included in the simulation. The values presented in the tables were calculated for "perfect" conditions where all engine power is used to drive the vehicle. In real live conditions considerable energy may be consumed by air-conditioning systems, lights, radio, power steering etc. This lowers the share of rolling resistance in overall energy consumption. Such conclusion is in line with findings presented in [6] where fuel consumption of passenger car Scion FR-Sat was tested at speed 65 mph (105 km/h) with two sets of tires. The difference in rolling resistance between two sets of tested tires was 31.8% and corresponding change of fuel consumption was 5.7%. This gives IF_{RR} = 0.18 that is somewhat lower than presented in Tab. 3.

3. Measuring methods of rolling resistance

3.1. Why is it difficult to measure rolling resistance

Tire rolling resistance is very difficult to measure because it creates a relatively small force acting on the heavily loaded system. For modern car tires rolling resistance constitutes less than 1% of vertical load acting on the tire. More and more often "green" or "blue" tires intended for electric vehicles have rolling resistance coefficient C_{RR} close to 0.005 so the rolling resistance force is in range of 0.5% of the load. If desired accuracy of measurements is in the range of 1%, for typical passenger car tire loaded to 4000 N it is necessary to measure precisely forces in the range of 40 N with accuracy better than 0.4 N (or 20 N with accuracy of 0.2 N for "blue" tires). This task, which is difficult even in the laboratory conditions, becomes extremely difficult in road conditions where many important variables are less controllable.

The following examples show how critical it is to ascertain a perfect alignment of elements in the test facility and how critical it is to control the experiment. If the load provided by the loading system of the laboratory facility or test trailer is not exactly vertical but tilted by angle α, the horizontal component L_h of the loading force L_v is given by the equation (4).

$$L_h = L_V \cdot \sin(\alpha) \qquad (4)$$

Even for an angle as small as 1 angular minute, if the vertical tire load is 4000N the horizontal component spoiling the results of measurements would be 1.16 N, that is typically creating a 3% error. Similar problems arise if the speed during the measurements is not constant. If in test trailer mass associated with the wheel "ahead" of the load cell (that is tire, rim, hub and part of the suspension) is 30 kg and acceleration/deceleration during measurements is only 0.01 m/s^2 the resulted inertia force "seen" by the load cell would be 0.3 N creating a measuring error of 0.75%. In order to eliminate such errors it is necessary to implement very special design solutions and ascertain very high precision of the mechanical structures constituting the test rig.

What is more, as it was mentioned in chapter 1, tire rolling resistance is very sensitive to tire inflation pressure and load, surface wetness and temperature [3]. All those variables must be thoughtfully controlled during measurements and if it is not possible to control them (like for example temperature during road measurements), certain corrections must be applied. Generally, tires may be tested according to two different inflation/load schemes. The first scheme is to inflate the tire to the desired pressure at the reference temperature (usually 25° C) and to make rolling resistance measurements with so called "capped" inflation pressure, that is a pressure adjusted at the reference temperature that develops (increases) during the tire warming up process reaching certain equilibrium. The second scheme is to adjust inflation pressure to the desired value when tire temperature reaches its equilibrium during the warming up process. This method is called "regulated pressure" principle. One must observe that results of measurements performed with both schemes are generally different. In the case of capped pressure due to tire warming up process the inflation pressure increases by a few tenths of bar, so the tire is tested at higher pressure than reference pressure. It is not a case for regulated pressure principle. What follows, the results obtained by regulated pressure measurements show higher rolling resistance than results obtained by capped pressure measurements. The typical behavior of inflation pressure for a passenger car tire tested at 80 km/h on a roadwheel facility at the laboratory is presented in Fig. 2.

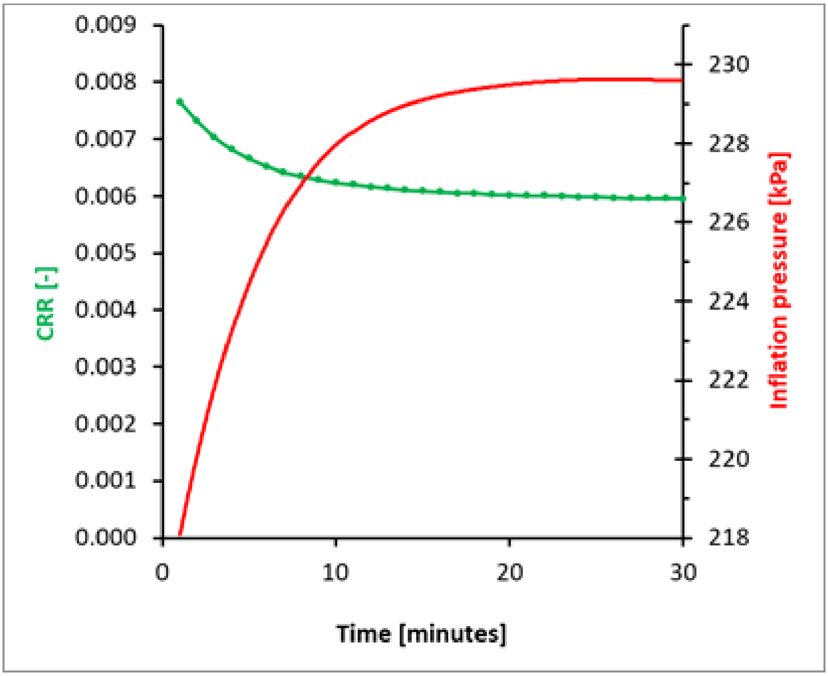

Figure 2: Increase of inflation pressure during tire warming and corresponding changes of rolling resistance

3.2. Laboratory methods

Laboratory methods are based mostly on "outer drum facilities" that utilize steel drums of 2 m or bigger diameter that act as artificial road. One of the drum facilities used at the Technical University of Gdańsk is shown in Fig. 3.

Figure 3: Roadwheel facility with 2.0 m diameter drum at the Technical University of Gdańsk, Poland

Using drum facilities for rolling resistance measurements has many advantages, especially for tire producers, most notably:

- measurements may be carried indoor with full control of ambient conditions,
- measurements are not biased by the driving style,
- easy adjustment of measuring conditions (load, inflation pressure, speed),
- low cost of measurements.

Unfortunately, this method has also very serious drawbacks, especially if the goal of measurements is to evaluate road surfaces influence on rolling resistance. Most important ones are listed below:

- road surface interfacing the test tire is not flat but has certain curvature,
- there are serious problems with obtaining representative texture of the road pavement and special replica road surfaces must be manufactured (see Fig. 4),

- tires have tendency to wear replica road surfaces and deposit rubber particles on them as there is no natural cleaning provided by variable weather conditions.

There are three commonly used laboratory methods of rolling resistance measurements, namely Force Method, Torque Method and Deceleration Method [7].

Figure 4: Manufacturing of replica road surfaces

Force Method is the most obvious method of measuring rolling resistance force. The principle of this method is based on direct measurements of forces acting on the wheel hub when the tire rolls on the drum. Before relevant measurement is performed the parasitic losses of the system must be establish. Parasitic losses are evaluated during a skim test where the tire load is reduced so much that resulting rolling resistance force is negligible but all parasitic losses (aerodynamic or frictional) are preserved. During measurements the spindle force is measured. The final calculation of the rolling resistance force is done according to the equation that accounts for the drum curvature and tire diameter. The test stand for the force method is very difficult to build, as the method is very sensitive to all imperfections in the measuring system. For example, to ensure acceptable accuracy it is necessary to align the load with precision better than 1 mrad.

Torque Method is based on measuring torque necessary to power the drum during the test. Similarly to the Force Method the parasitic losses must be calculated by a skim test. During the measurements torque necessary to power the drum with constant speed is measured. The final calculation of the rolling resistance force is done according to the equation accounting for drum curvature. The Torque Method is much less sensitive to the geometrical misalignments so it is often preferred over the Force Method. Drums owned by the Technical University of Gdańsk use the Torque Method.

Deceleration Method differs very much from other rolling resistance test methods as the measurement is based on the angular deceleration of the drum during coast-down. In order to account for parasitic losses of the facility it is necessary to perform the deceleration test not only with loaded tire but also for test tire freely costing down as well as drum coasting down without tire. Moment of inertia of the drum and of the tire including rim and hub must be known. Deceleration method does not require very advanced facilities. In fact, most of the drums may be used, but in opinion of this authors it is not as precise as force or torque method.

3.3. Road methods

In contrast to the laboratory methods, the road methods are not so popular as they are very difficult to carry out or the necessary equipment is very expensive. Road methods are best suited for investigation of road surface influence on tire rolling resistance. The most important advantages are:

- tires roll on real road surfaces so the phenomena related to the tire/road interfacing are not distorted,
- road surface is flat.

Despite very important benefits there is a lot of problems related to the road methods. Most important ones are listed below:

- during measurements ambient conditions cannot be controlled,
- there is a lot of sources of measurement errors like wind, road grade or acceleration/deceleration,
- performing measurements is time consuming and/or measuring equipment is very expensive,
- for some road methods it is not possible to make measurements on trafficked roads.

Road measurements may be performed using ordinary cars or trucks (sometimes with special conversions) or by utilizing specially build trailers. In contrast to the laboratory methods there is not a single standard regulating road measurements of the rolling resistance.

There are four basic road methods that may be performed with use of ordinary vehicles. The most popular road method of rolling resistance measurements is Coast Down Method. Just before the measurements, the gearbox of a moving vehicle is shifted to the neutral and the vehicle decelerates due to resistive forces. With certain mathematic procedures [8] it is possible to evaluate the rolling resistance coefficient, provided that the measurements are made in both directions and information about the wind is available. The test vehicle must be in perfect technical condition and the test speed may not be very high, as at very high speeds aerodynamic force clearly dominates rolling resistance force thus, making measurements less accurate. Wind speed and direction may be measured by advanced instruments mounted on the vehicle (or to be precise on a long arm protruding from the vehicle to avoid turbulences) - see Fig. 5, or by roadside sensors.

Figure 5: Car equipped for coast-down measurements of rolling resistance

The second method of road measurements is based on measurements of torque necessary to cruise the vehicle at constant speed. The vehicle must be equipped with precise torque sensor and all information about aerodynamic forces acting on it must be available. This method is only occasionally used as it is difficult to obtain reasonable accuracy with it.

The third method is the indirect method that evaluates tire rolling resistance on the base of fuel consumption. The method is very much influenced by the driving style of the driver and to obtain any meaningful results it is necessary to test tires on a rather long distance, always in the same way, best of all on the test track. The advantage of this method is that results are appealing to the audience as it shows directly the gains or losses in economy and environmental protection.

The fourth method is based on towing the test vehicle by another vehicle and measuring towing force simultaneously. To decrease sensitivity of the method to aerodynamic forces very often the test vehicle is enclosed in a capsule that isolates it from the air flow. This method is obsolete and nowadays it is used only to evaluate rolling resistance of tractor tires rolling on soft soil.

The most promising road measurement method is so called trailer method that is based on specially designed test trailers that are towed by cars or trucks. There are only a few test trailers of this type as construction of trailers is fairly complicated. Probably the most advanced trailer was built at the Technical University of Gdańsk and it is called R^2 Mk.2 [9]. The idea of its measuring system is presented in Fig. 6 and the trailer is shown in Fig. 7. The trailer is equipped with many sensors that control its position in relation to the road surface, road grade, acceleration tire inflation pressure and speed.

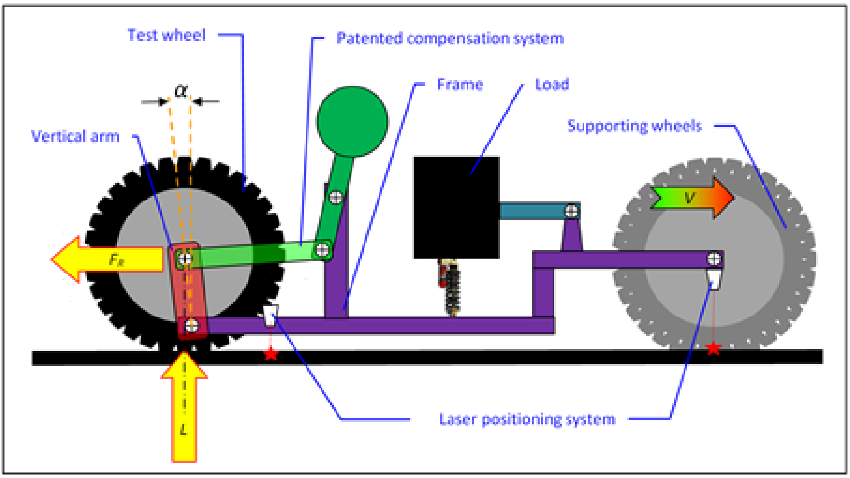

Figure 6: Principle of R^2 Mk.2 trailer measuring system

Figure 7:

Figure 8: Trailer R^2 Mk. 2 during measurements at MnRoad facility in USA

Trailer R^2 Mk.2 is used to make evaluation of road pavements in many European countries and in the USA. It may be used both in dry and wet conditions, on test tracks and on trafficked roads.

4. Road pavement influence on tire rolling resistance

Tire performance is strongly related to the road surface characteristics, most notably to the pavement texture and to some extent also to the road stiffness and damping. Mean Profile Depth (MPD) is one of the most common descriptors of road surface texture and in many studies it is correlated with tire rolling resistance. Results of measurements performed by the TUG show that although the correlation exists, it is not very strong and regression between MPD and rolling resistance is not linear [10]. The key reason for this is partial enveloping of the tire tread. This phenomenon is presented in Fig. 8. In the left part of the picture a very simple geometrical texture (6 mm high pyramids) is presented while in the right part it is shown which part of this texture has real contact with smooth tread tire. Only the summits of pyramids interface tire tread and the depth of the local tread deflections is only 2 mm (in comparison to the pyramids height of 6 mm). As MPD accounts for whole texture shape from the very top of "summits" to the very bottom of "valleys" it cannot correlate well with rolling resistance.

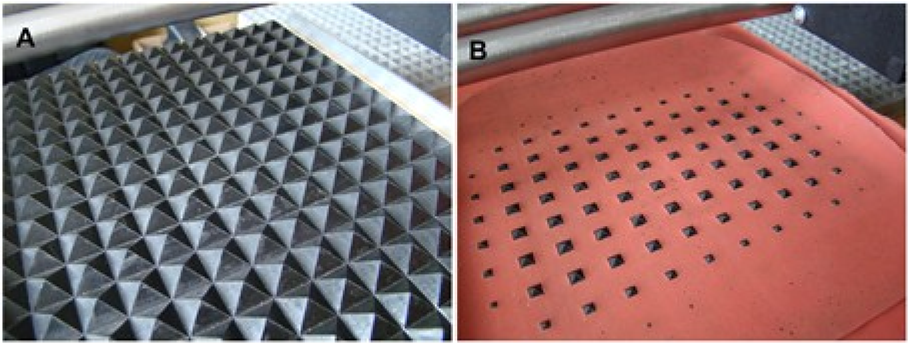

Figure 9: Experimental surfaces with uniformly spaced 6 mm high pyramids (A) and the same surface covered by silicone resin that was formed by enveloping tread of smooth tire (B)

A new procedure of texture evaluation based on enveloping properties of tire tread is being developed at the Technical University of Gdańsk, but it is not finished yet, so the following example of assessment of road pavements (see Tab. 4) is compiled with MPD as the texture descriptor.

Table 4: *Coefficients of Rolling Resistance (C_{RR}) obtained at 80 km/h for tire SRTT rolling on selected road pavements*

Type of surface	**MPD (mm)**	**$C_{RR\ (25C)}$**
Epoxy Resin (smooth)	0.20	0.0058
Fine surface dressing	0.42	0.0068
ISO „type“ – DAC 0/6	0.54	0.0069
Sand asphalt 0/4	0.78	0.0064

DAC 0/10 (new)	0.99	0.0073
DAC 0/10 (old)	1.21	0.0081
Porous AC 0/6	1.38	0.0076
VTAC 0/6, class 2	1.45	0.0079
High friction surface dressing 1/3 (Colgrip ©)	1.49	0.0080
VTAC 0/10, class 1	1.64	0.0070
Coarse surface dressing 8/10	3.44	0.0109
Coarse surface dressing 0/14	4.01	0.0134

Values presented in Tab. 4 indicate that texture of the road pavement has very substantial influence on tire rolling resistance. Due to this observation in many countries special "energy saving pavements" with small aggregate are being developed nowadays.

Road pavement stiffness may have important influence on tire rolling resistance but only for non-conventional pavements that are classified as "elastic" or "poroelastic". Stiffness of conventional pavements like asphalt concrete or cement concrete is so much higher than stiffness of tire tread that overwhelming the majority of deflections created at the tire/road interface occur in tire (tread and sidewalls). The situation is different for poroelastic road surfaces (PERS) containing rubber aggregate that deflect considerably, especially under the pressure exerted by truck tires.

Fig. 9 presents results or laboratory rolling resistance measurements performed for passenger car tire on very smooth steel surface (STEEL), replica of very rough surface dressing (APS) and on poroelastic material (PERS-HET) at 80 km/h. The picture indicates that rolling resistance of poroelastic road surfaces for passenger car tires is more than acceptable. Unfortunately, for truck tires rolling resistance on PERS is considerably higher than on conventional, rigid road pavements. For example, on typical dense asphalt concrete tested truck tires at 80 km/h had C_{RR} at about 0.0055 while on PERS the C_{RR} was at about 0.0090. This is because pressure exerted by truck tires on the pavement creates considerable deflection of PERS and corresponding energy losses that occur in the deflected pavement.

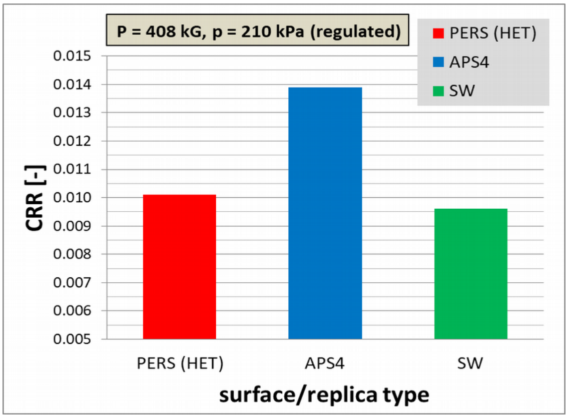

Figure 10: Results of rolling resistance measurements for different road surfaces including PERS

5. Conclusions

Rolling resistance is a very important parameter describing quality of tire/pavement interface. In order to reduce rolling resistance it is necessary to develop reliable and internationally standardized measuring methods and put a lot of effort into the development of tires and pavements. It seems that there is still potential to decrease CO_2 emission and fuel consumption by at least 15% just by reducing rolling resistance of tires.

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