Road Surface Influence on Tyre Rolling Resistance

Jerzy A. Ejsmont, Grzegorz Ronowski, Beata Świeczko-Żurek, Sławomir Sommer

Technical University of Gdańsk (TUG)
ul. Narutowicza 11/12, Pl 80-233 Gdańsk, Poland
jejsmont@pg.gda.pl
gronowsk@pg.gda.pl
beazurek@pg.gda.pl
slawomirsommer@gmail.com

ABSTRACT: Tyre performance, one of the critical factors for vehicle users, is strongly related to the road surface characteristics, most notably to the pavement texture. Phenomena that occur at the tyre/road interface effect tyre friction (skid resistance), rolling resistance, tyre wear and tyre/road noise. This article deals with relations between surface texture and rolling resistance of light and heavy vehicle tyres. Mean Profile Depth (MPD) is one of the most common descriptors of road surfaces and in many studies it is correlated with rolling resistance of tyres. Results of measurements performed by the Technical University of Gdańsk show that although the correlation exist, it is not very strong and regression between MPD and rolling resistance is not linear. The key reason for this is partial enveloping of the tyre tread interacting with pavement texture. The article presents results of laboratory and road measurements of rolling resistance performed on road surfaces characterized by MPD from 0.20 mm up to 4.75 mm and the correlation of the Rolling Resistance Coefficient with MPD. Certain aspects of texture enveloping and influence of this phenomenon on rolling resistance are discussed.

KEYWORDS: *tyres, rolling resistance, texture, measurements*

1. Introduction

Road surface texture is one of the most important characteristics of the wearing courses of modern roads. It is vital for tyre/road friction often described as skid resistance (that is the ability to carry out tangential forces by the tyre), especially in wet and "dirty" conditions, tyre/road noise (both exterior and interior), vibrations of the suspension, tyre wear and, of course, tyre rolling resistance. On the other hand, tyre rolling resistance is important for overall energy (fuel) consumption of the vehicle, carbon dioxide and toxic gases emissions, performance of the vehicle (top speed) and maximal operational range. The last parameter is a key factor for electric vehicles that at present time, with a few exceptions, provide usually only 120-200 km effective range and their recharge time is rather long.

It is commonly recognized that road surface texture influences rolling resistance considerably (Sandberg *et al.,* 2011(a), Sandberg *et al.,* 2011(b), Sohaney & Rasmussen, 2013) but there is no agreement which parameter characterizing the texture is best correlated with rolling resistance. At present, it seems that MPD (Mean Profile Depth) is the most common descriptor of the road texture (sometimes supplemented by the skewness (Sohaney & Rasmussen, 2013, Rasmussen *et al.*, 2011, Bushan, 2000). For detailed description of MPD evaluation procedure see (ISO 13473-1:1997). Sandberg (Sandberg *et al*., 2011(b)) states that MPD correlates with rolling resistance very well. On the other hand, for evaluation of tyre-pavement interface related phenomena (most notably tyre/road noise) von Meier (von Meier *et al*., 1992) proposes to use MPD modified by the "enveloping" algorithm that accounts for elastic properties of the tyre tread. Many studies (Ejsmont *et al.*, 2016, Cesbron *et al*., 2008) indicate that deformations of the tyre tread are very complicated and that energy loses in the rolling tyre depend on inflation pressure and tyre load in a rather complex way, different on various road surfaces (and that supports hypothesis related to the partial enveloping).

Technical University of Gdańsk (TUG) conducts several research projects related to tyre/road interactions and performs numerous measurements of tyre rolling resistance. The tests include measurements of rolling resistance in laboratory conditions on drums covered with replica road surfaces of very different texture, road measurements of rolling resistance on various European and American roads as well as special laboratory tests of tyre/road interface. In this paper the results of measurements are analysed in respect of road texture influence on rolling resistance.

2. Road texture enveloping by tyre tread

The problem of texture enveloping is very complicated and not solved yet. During interaction with road pavement the tyre tread deflects and tries to follow the shape of the surface. Sometimes it is possible to obtain full contact between tread rubber and outer surface of the road pavement but in most cases the contact between tyre tread and pavement is only partial (see Fig. 1). Tyre tread is pressed and deflected by the pavement “summits”, but stiffness of the rubber compound and tyre belt is so high that instead of floating to the texture cavities the tread rubber forms bridges between adjacent texture peaks, thus air pockets and ducts are created in the area of tyre/pavement foot-print. What is more, the tyre does not “see” the shape of the texture in areas where there is no mutual contact. Two different texture profiles ("*Texture A*" marked with a black solid line and "*Texture B*" marked by a dashed red line in Fig. 1) would deflect tyre tread in exactly the same way, but air pockets and ducts under the tread would be very different. It is obvious that MPD values evaluated for both textures would be very different too.

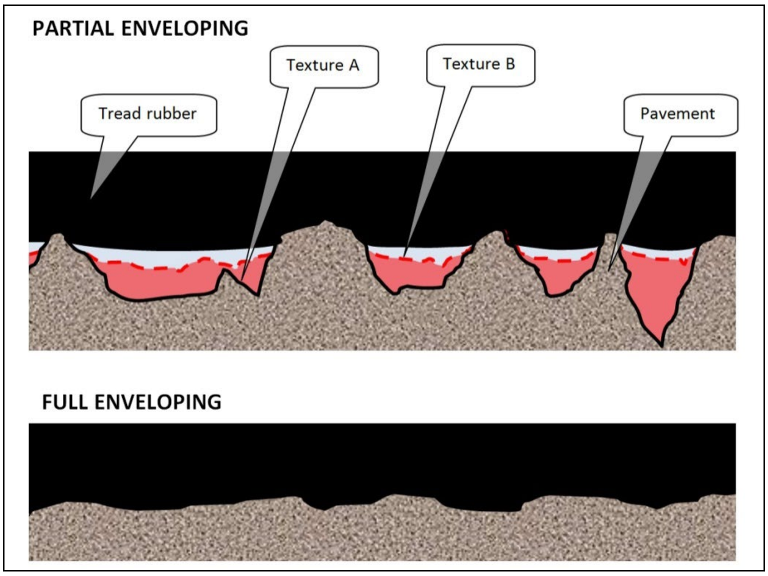


Figure 1. *Interface between tyre and road surface for pavements with different texture*

Generally, whenever possible, it is desired to describe characteristics of any given object by single numerical value. This enables to compare different objects in a relatively easy way. Unfortunately, in the case of road surface texture it is probably impossible to establish a single value parameter that would describe the texture and make it possible to compare the performance of pavements in different respects based on it.

The most commonly used pavement surface descriptor MPD was originally developed to replace volumetric path method of texture evaluation and to characterize speed effect in wet skid resistance. There is no doubt that for wet skid resistance the depth of texture cavities is very important as it influences the ability of the pavement to aid water removal from tyre/pavement contact area and provides certain water storage capacity that helps tyre tread to contact pavement summits without water film in between. Thus looking on Fig. 1 one may predict with high confidence that "*Texture A*" with higher MPD will provide better wet skid resistance than "*Texture B*". But it is the same situation with rolling resistance? Definitely it is not. For rolling resistance (but only at dry conditions!) the difference between red and black texture profile in Fig. 1 has no importance as tread deflections (thus also energy loses) are all the same. Of course the situation may change on a wet road, as water film will be different on road with "*Texture A*" and "*Texture B*" (Ejsmont *et al.,* 2015). This leads to the conclusion that MPD is not a very good descriptor of texture in relation to the rolling resistance, especially for very rough road surfaces like, for example, surface dressing or grooved cement concrete where enveloping is always only partial.

At the Technical University of Gdańsk a technique to investigate tyre tread enveloping was developed. The technique is based on silicon rubber moulding made under the tyre footprint on real and artificial road surfaces. The road surface placed in a shallow "pan" is covered by liquid silicon rubber and tyre (usually with smooth tread) is positioned on it. Then required load is applied. The silicon is pressed away from the regions where tread rubber contacts the road surface and stays in regions where there is no contact. After curing the tyre is removed and the silicon casting shows details of enveloping (see Fig. 2). If the texture is very open there is no problem with pressing out the silicon from the texture pockets. However, if the geometry of the surface does not provide adequate drainage, it is necessary to arrange for it by drilling numerous venting holes in the texture pockets. Of course the method gives precise enveloping surface for static conditions only and during driving the local tread deformations may be somewhat different (probably smaller) but the authors believe that nevertheless this method is useful in analysing road texture interaction with tyre tread.

In Fig. 2 enveloping surface obtained for slick tyre loaded to 4000 N and inflated to 210 kPa is shown. It is clearly visible that the best part of the experimental "6 mm pyramids" surface (over 90 %) does not contact the tyre tread at all. In Fig. 3 cross-section through the pyramid's summits in central part of the tyre footprint is presented. The deepest cavities formed by the summits of 6 mm high pyramids indenting into the tread are only 2 mm deep. Nominally, the MPD of the "6 mm pyramids" surface measured over the peaks is equal to 3 mm but at the same time "enveloped" MPD measured for this surface is only 0.45 mm.

The experiments with recording and analysing enveloping surface by silicon rubber method described here is still going on and detailed results will be reported in near future.

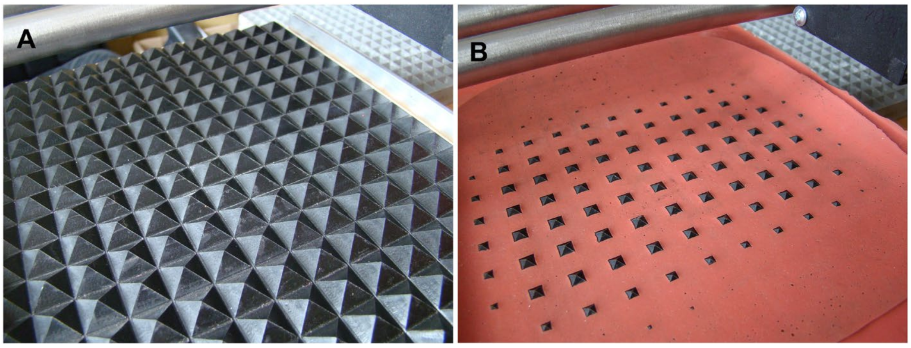


Figure 2. *Experimental surface with uniformly spaced 6 mm high pyramids (A) and the same surface covered by silicone resin that was formed by enveloping tread of smooth tyre*

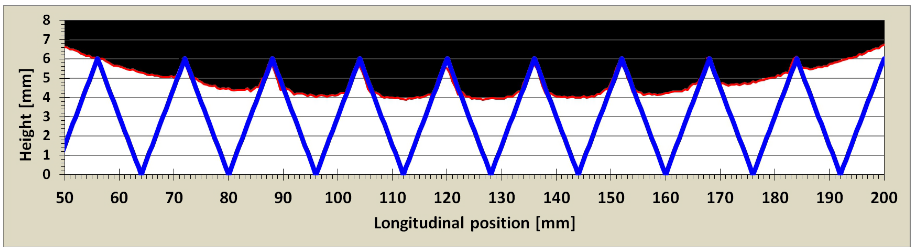


Figure 3. *Longitudinal profile of the enveloping surface in the central region of the smooth tyre footprint interfacing artificial surface with 6 mm high pyramids; tyre load 4000 N, inflation pressure 210 kPa*

3. Test tyres

In this study over 50 passenger car tyres and 10 truck tyres where used. They included both summer and winter tyres of the most common sizes as well as tyres considered by institutes performing rolling resistance measurements as informal reference tyres used to compare different road surfaces. Presenting a full list of test tyres in this article would be meaningless as many of the tyres were used only for statistical comparison and are not specifically addressed here. As a result, in Tab. 1 only tyres that are referenced by their code names in the text or in the figures are described. All tyres were new (less than 18 months old and not run for more than 200 km) and stored in temperature of 4º C in order to preserve original elasticity of the rubber compounds of the tyres.

Table 1. *Description of selected test tyres*

Code	Producer	Tread	Size	Comments
T1063	Avon	Super Van AV4	195R14C	Informal reference tyre "AAV4"
T1064	Michelin	Primacy HP	225/60R16	Informal reference tyre "MCPR"
T1070	Vredestein	Wintrac Extreme	205/55R16	M+S
T1076	Continental	Blueco	195/50R18	Tyre designed for electric vehicles
T1077	Uniroyal	Tiger Paw	P225/60R16	Informal reference tyre "SRTT"
T1078	Goodyear	Efficient Grip Performance	195/65R15	
T1083	Michelin	Energy EV Green	195/55R16	Tyre designed for electric vehicles
T1092	Avon	Super Van AV4	195R14C	Informal reference tyre "AAV4"
T1107	Debica	Presto	205/55R16	
T1110	Kormoran	Gamma B2	205/55ZR16	
T1112	Pirelli	Cinturato P1	195/60R15	
T1084	Dunlop	SP242	385/65R22,5	Truck tyre
T1085	Bridgestone	R168	385/65R22.5	Truck tyre
T1114	Sava	CIT U3	275/70R22,5	Truck tyre, retreaded
T1115	Giti	GT867	275/70R22,5	Truck tyre, retreaded
T1116	Dunlop	SP372 CITY	275/70R22,5	Truck tyre
T1117	Michelin	XDU	275/70R22,5	Truck tyre, retreaded
T1118	Bridgestone	M758	275/70R22,5	Truck tyre, retreaded
T1119	Dunlop	SP372 CITY	275/70R22,5	Truck tyre, retreaded

4. Results of laboratory tests

Part of the research program performed at the Technical University of Gdansk, was carried in the laboratory using roadwheel facilities designed to test rolling resistance of passenger and truck tyres (see also: Ejsmont *et al.*, 2016) on different replica road surfaces. The replica road surfaces are described in Tab. 2 and shown in Fig. 4.

Table 2. *Description of the replica road surfaces*

Designation	Description	Placement	MPD [mm]
APS4r17	Replica of surface dressing 8/10 mm aggregate. Mineral chippings connected	Roadwheel facility 1.7 m	4.75

	to the polyurethane base layer by the polyurethane resin		
PERSr17	Poroelastic road surface (mineral and rubber aggregate glued by polyurethane resin), 4 mm chipping size	Roadwheel facility 1.7 m	1.53
DAC16r20	Replica of dense asphalt concrete with 16 mm aggregate made as an epoxy laminate	Roadwheel facility 2.0 m	1.33
ISOr20	Replica of ISO reference road surface made as an epoxy laminate	Roadwheel facility 2.0 m	1.06
SMA8r20	Replica of Stone Mastic Asphalt with 8 mm chipping size, made as an epoxy laminate	Roadwheel facility 2.0 m	1.31
STEELr20	Smooth steel surface of the drum	Roadwheel facility 2.0 m	0.42
SWr20	Safety Walk anti slip self-adhesive surfacing with grit size "80" made by 3M	Roadwheel facility 2.0 m	0.84

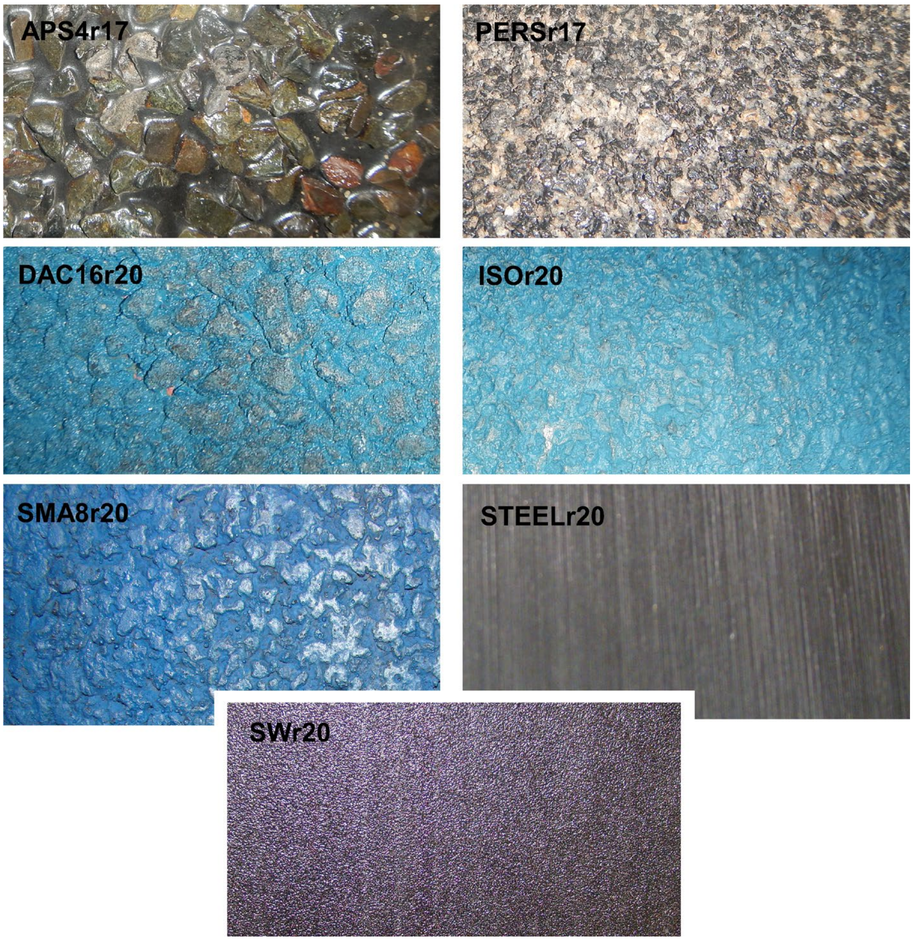


Figure 4. *Replica road surfaces used during the measurements*

Measurements of rolling resistance were performed for speeds 50, 80 and 100 km/h. For passenger car tyres two different load/inflation combinations were used. One designated as "TUG", was based on constant load of 4000 N and regulated inflation pressure of 210 kPa, and the second one designated as "ISO" based on conditions prescribed by ISO 28580:2009 that is load equal to 80% of max load stated by the Load Index and capped inflation pressure of 210 kPa. For truck tyres only ISO 28580 conditions were used so for tested tyres of size 275/70R22.5 the load was 24800 N and capped inflation pressure 700 kPa.

The most common way to present rolling resistance of tyres is to use Coefficient of Rolling Resistance (C_r) that is calculated according to the equation 1.

$$C_r = \frac{F_{RR}}{F_L} \tag{1}$$

Where:

C_r : coefficient of rolling resistance,

F_{RR} : rolling resistance force, N

F_L : tyre load, N

All together 40 passenger car tyres and 10 truck tyres were tested by the drum method. Although most of the tyres were tested at different speeds, only the results of measurements performed at 80 km/h are reported here, as they are in line with results obtained for other speeds. All the results (both obtained in laboratory and on the road) were corrected to the nominal temperature of 25ºC.

In Fig. 5 results of measurements performed according to *TUG* conditions are summarized while in Fig. 6 similar results but obtained for *ISO* conditions are presented. In each figure average Coefficient of Rolling Resistance s obtained for all tyres tested in given conditions are indicated as well as corresponding linear regression lines. In each figure individual results for six selected tyres are also presented. For both measuring conditions clear influence of texture (MPD) on Coefficient of Rolling resistance is observed, but there are also indications that the influence is not linear. This is more pronounced for *ISO* conditions than for *TUG* conditions.

In Fig. 7 polynomial (quadratic) regression lines drown for rolling resistance results obtained for ISO conditions are presented. Unfortunately no replica road surface used by TUG has MPD in range of 2-4 mm, nevertheless the layout of regression lines for all tested tyres is similar, so it seems to support the hypothesis that partial enveloping makes the tyre rolling resistance less sensitive to the increase of MPD after a certain threshold value is reached (for given load and inflation). Grey lines represent selected individual tyres while red lines are related to average rolling resistance obtained for 30 tyres tested at ISO conditions. What is more, there are two regression lines based on averaged results. The quadratic one, marked by the solid line is calculated for whole range of tested MPD's that is from 0.4 to 4.7 mm, while the linear regression line marked by dashed line is calculated for replica road surfaces having MPD ranging from 0.4 to 1.5 mm. It is visible that both lines have very similar layout for MPD values up to 2 mm but for MPD over 2 mm they split considerably, most probably due to partial enveloping.

It is also visible that coefficient of determination (R^2) is rather high when all available data, including results for surfaces with MPD over 4.0 mm are used (R^2 = 0.962 for TUG conditions and R^2 = 0.939 for ISO conditions). When MPD is restricted to a more common range of 0 - 1.5 mm, the coefficient of determination drops down to 0.736 and 0.808 respectively indicating a much worse correlation between MPD and C_r.

However, it must be mention that replica APS4r17 which has MPD = 4.75 mm was manufactured on a special polyurethane base-layer and due to very limited use it has mineral chippings covered all-over by the thin layer of polyurethane, thus it may perform differently in comparison to real road bituminous binder surface dressing. At the same time this replica has a very open structure possible to obtain due to very strong polyurethane bonds between base-layer and the chippings. In opinion of the authors similar surface made with bituminous binder would have lower MPD (probably at about 3 - 3.5 mm) as the chippings would sink more into the binder sprayed on the base-layer.

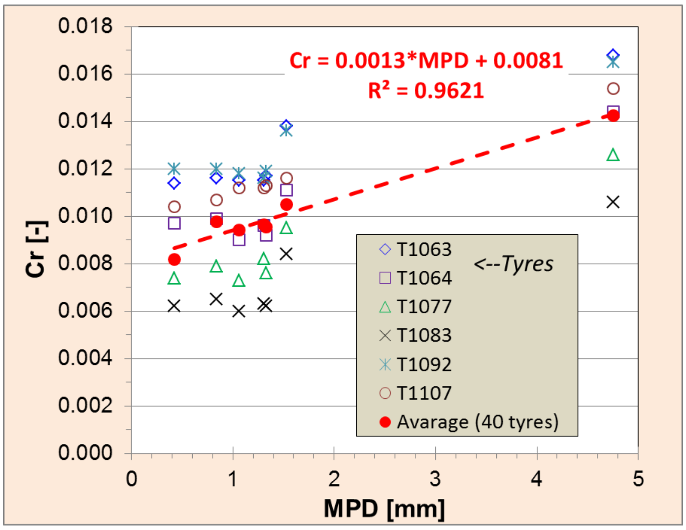


Figure 5. *Influence of MPD on rolling resistance of passenger car tyres tested at TUG conditions*

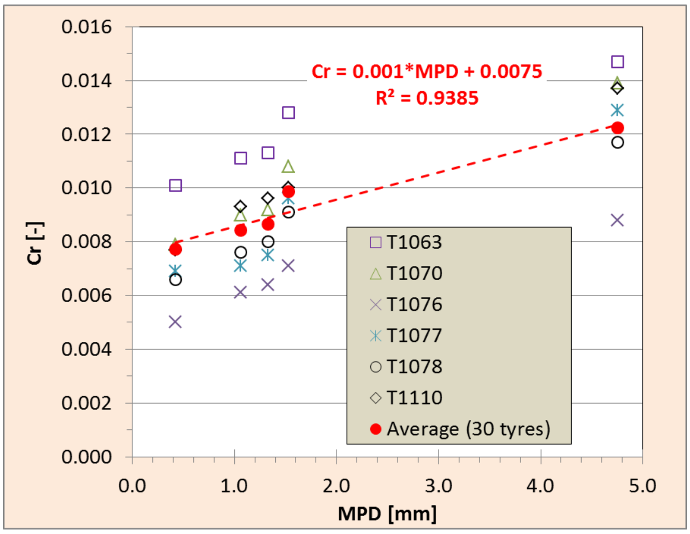


Figure 6. *Influence of MPD on rolling resistance of passenger car tyres tested at ISO conditions*

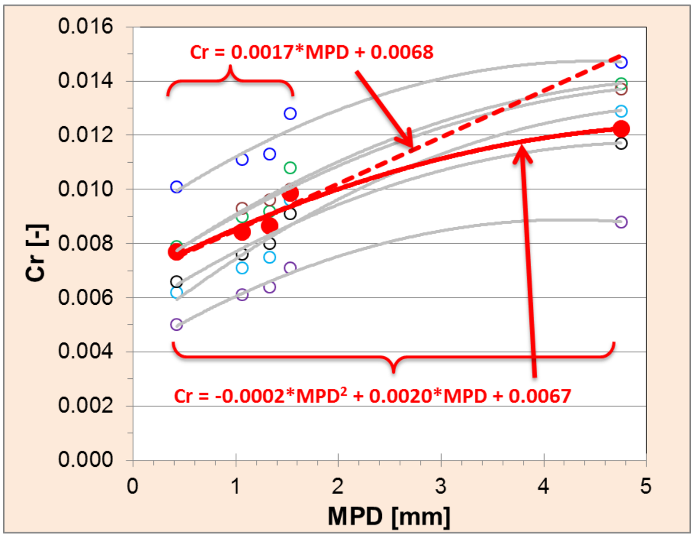


Figure 7. *Polynomial regression lines for texture - rolling resistance relations*

Similar experiments were performed also for truck tyres. As truck tyres may be tested only on TUG's roadwheel facility with drum 2.0 m diameter, the measurements were limited to STEELr20, SWr20, SMA8r20, ISOr20 and DAC16r20 replica road surfaces. In Fig. 8 Coefficients of Rolling Resistance for all those replica road surfaces are presented. It is interesting to note that slope of the regression line for truck tyres is exactly the same as the slope of the regression line calculated for passenger car tyres in MPD range from 0.4 to 1.5 mm.

5. Results of road tests

All road measurements reported in this article were obtained using test trailer R^2 Mk.2 designed and built at the Technical University of Gdańsk. The trailer is described in (Swieczko-Zurek *et al.*, 2016) and presented in Fig. 9. Due to its unique construction the results obtained by R^2 Mk.2 trailer are not influenced by acceleration/deceleration of the test vehicle or by the road inclination. Since 2014 the trailer is equipped with on-board texture measuring system based on OPTOCATOR laser sensor. Typical test conditions used by TUG during road measurements are the same like conditions "*TUG*" used at the laboratory that is load of 4000 N and regulated inflation pressure of 210 kPa.

In order to obtain statistically correct results over 100 different road surfaces were tested. The set of surfaces included cement concrete surfaces, asphalt concrete, Stone Mastic Asphalt, drainage pavements and even experimental poroelastic pavements PERS.

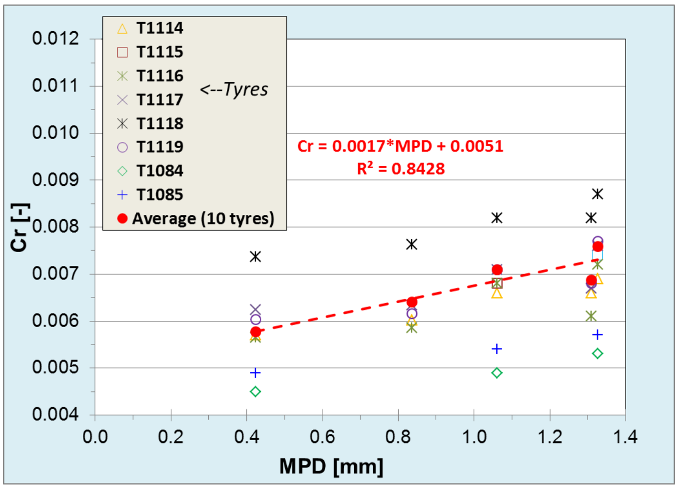


Figure 8. *Influence of MPD on rolling resistance of truck tyres tested at ISO conditions*

Figure 9. *Rolling resistance test trailer R^2 Mk.2*

In Fig. 10 and 11 the results of measurements performed on the road tests sections with MPD less than 2.5 mm are presented. Both for speed of 50 km/h and 80 km/h there is visible increase of rolling resistance due to increase of MPD. As indicated in the figures a linear regression line may be used to approximate relation between Cr and MPD. In Tab. 3 values of the slope coefficient and coefficients of determination R^2 are presented. However, the values of R^2 are rather low (0.3 - 0.5) therefore it is obvious that rolling resistance is not very well correlated with MPD. In the most common range of MPD (0.3 - 1.2 mm) correlation is even worse so the observations made during laboratory measurements are confirmed.

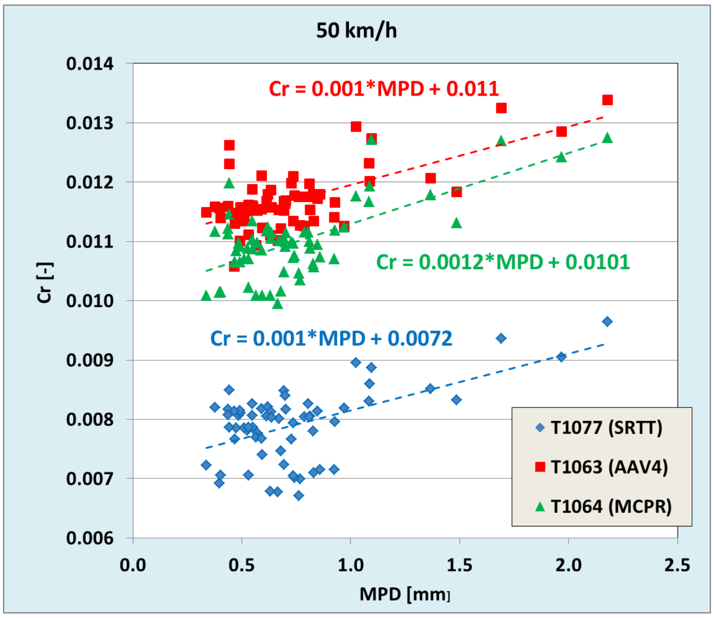


Figure 10. *Results of rolling resistance measurements on road sections - speed 50 km/h*

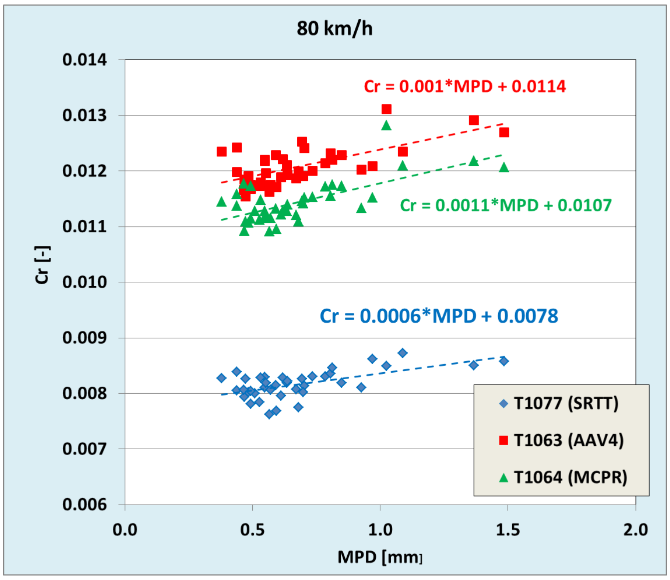


Figure 11. *Results of rolling resistance measurements on road sections - speed 80 km/h*

Table 3. *Slope and R^2 values for linear regression lines drawn for road measurements*

Tyre	Speed [km/h]	Slope	R^2
T1077 (SRTT)	50	0.00096	0.30
	80	0.00061	0.36
T1063 (AAV4)	50	0.00099	0.44
	80	0.00095	0.44
T1064 (MCPR)	50	0.00120	0.46
	80	0.00106	0.45
Averaged	**50**	**0.00105**	
	80	**0.00087**	

Most of the typical road surfaces have MPD below 2.0 mm, nevertheless it is interesting to investigate also coarser surfaces if available. During realization of ROSANNE project (ROSANNE, 2013) one of the experiments included measurements of rolling resistance of tyre T1112 on surfaces with MPD from 0.88 mm up to 2.88 mm. All measurements were performed on the same day. The results are summarized in Fig. 12. Although this measurement covers only fife pavements, the tendency is similar like in the case of results presented in Fig. 7.

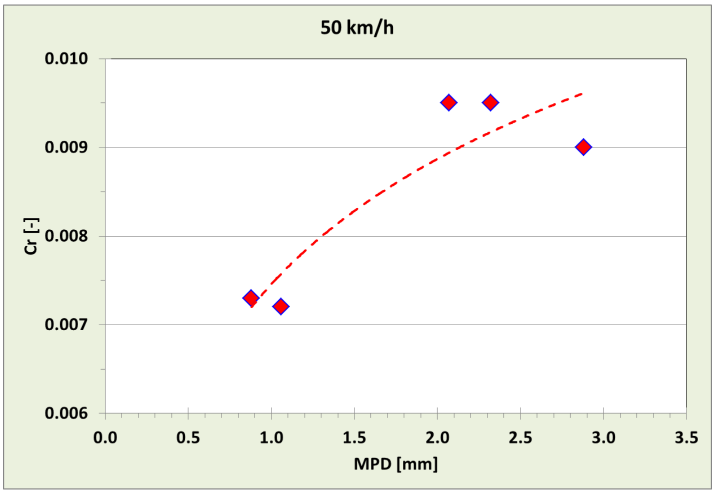


Figure 12. *Results of rolling resistance measurements for passenger car tyre T1112 at speed 50 km/h*

One of the experiments performed together with the Swedish National Road and Transport Research Institute (VTI) included measurements of rolling resistance on a surface that was grinded in order to change its texture (Sandberg, 2015). On the road paved with SMA16 two test sections were grinded by a specially designed grinder. One section designated here as *GR1* was grinded only once while the second section designated as *GR2* was grinded twice. Each grinding process lowered texture summits by about 1 mm in relation to untreated surface designated here as *Ref*. The texture of test section is presented in Fig. 13. Unfortunately results of texture measurements for those surfaces are not available due to the technical problems with the texture measuring device.

The test was performed at speeds 50 and 80 km/h. For grinded surfaces very consistence decrease of the rolling resistance was observed both for speed 50 km/h (see Fig 14) and 80 km/h (see Fig. 15).

Figure 13. *View on grinded test surfaces*

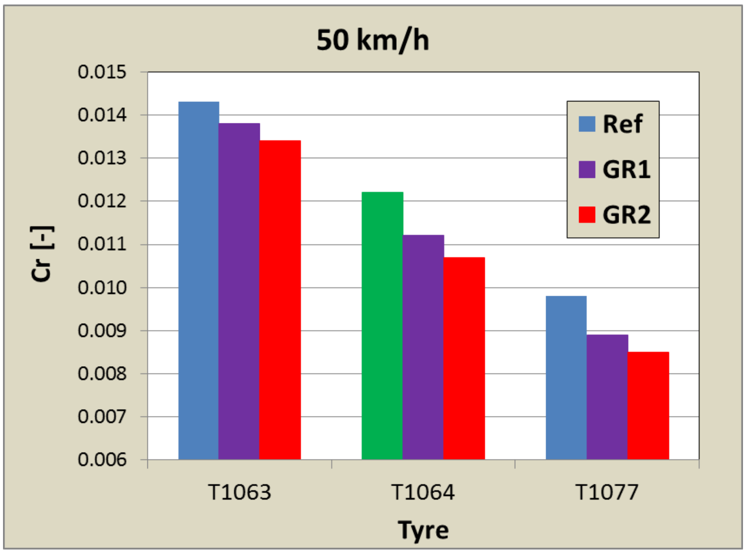


Figure 14. *Results of rolling resistance measurements on grinded surfaces - speed 50 km/h*

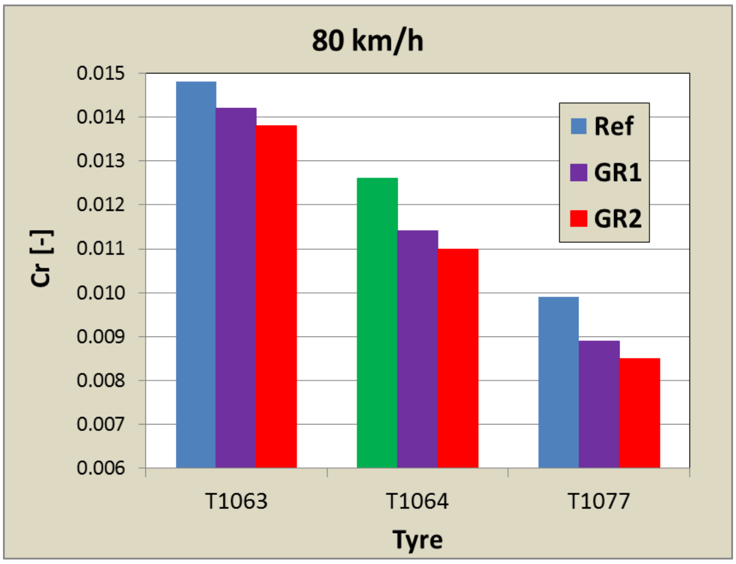
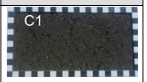
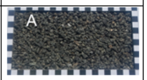
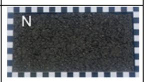
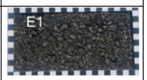
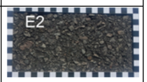
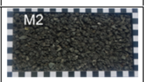
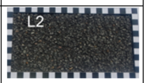
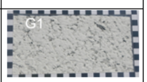
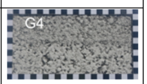
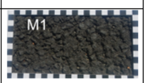
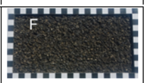


Figure 15. *Results of rolling resistance measurements on grinded surfaces - speed 80 km/h*

In summer of 2015 Technical University of Gdansk together with other partners from ROSANNE consortium (ROSANNE, 2013) performed a very extensive Round Robin Test (RRT) of rolling resistance measuring vehicles on IFSTTAR test track in Nantes, France. As the test track is paved with very different road surfaces TUG decided to extend the measurements over the RRT program and to test additional tyres and test sections with R^2 Mk.2 trailer in order to establish rolling resistance versus road texture relations.

Data describing test sections used during measurements at IFSTTAR are summarized in Table 4. During measurements all surfaces were dry and clean and air temperature was within 20 - 26°C.

Table 4. *Description of the test sections on IFSTTAR test track*

Code	Type of surface	MPD (mm)	Picture
C1	Fine surface dressing	0.4	
C2	Coarse surface dressing 0/14	4.0	
A'	Coarse surface dressing 8/10	3.4	
A	Porous AC 0/6	1.4	
N	ISO „type" – DAC 0/6	0.5	
E1	DAC 0/10 (new)	1.0	
E2	DAC 0/10 (old)	1.2	
M2	VTAC 0/6, class 2	1	
BLOCK	Block pavement	0.9	
L1	Epoxy Resin (smooth)	0.2	
L2	Sand asphalt 0/4	0.8	
G0	Flexible Asphalt Concrete (base course for G1, G2, G3 and G4	1.0	
G1, G2, G3	Flexible Asphalt Concrete with special glass bed painting	0.5	
G4	Flexible Asphalt Concrete with special glass bed painting, very high friction	0.5	
M1	VTAC 0/10, class 1	1.6	
F	High friction surface dressing 1/3 (Colgrip ©)	1.5	

Results of the experiments are presented in Fig. 16 and Fig. 17. Regression line plotted in Fig. 16 for speed of 80 km/h is based on Coefficients of Rolling Resistance averaged for tyres T1064, T1076, T1077 and T1092 obtained for MPD from 0.2 mm up to 4.0 mm and is characterized by the slope of 0.0016 and R^2=0.929. However, when MPD range is reduced to 0.2 - 1.6 mm (see Fig. 17) the slope drops down to 0.001 and value of R^2 is only 0.482.

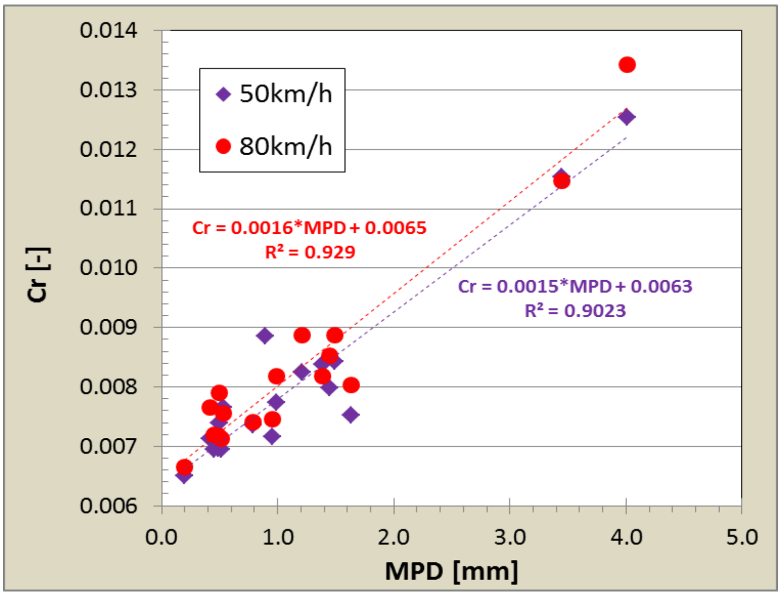


Figure 16. *Results of rolling resistance measurements on IFSTTAR track for all tested pavements*

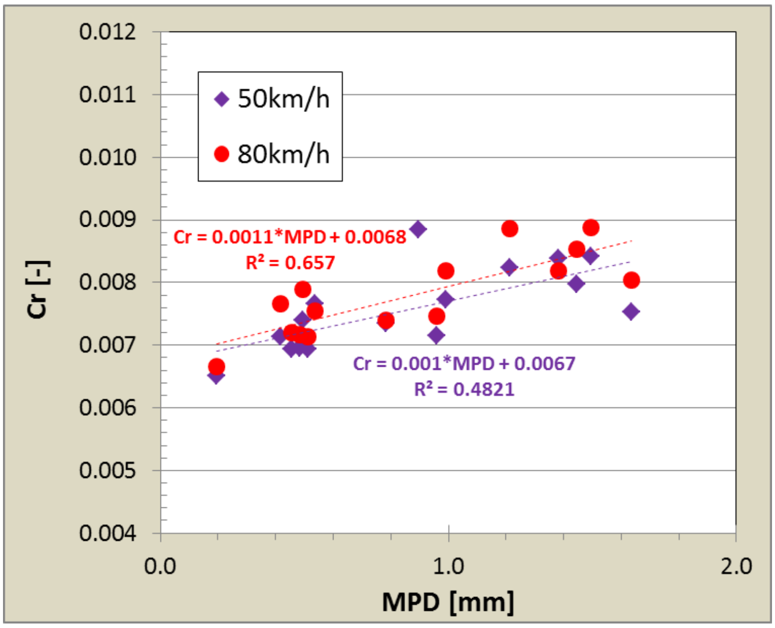


Figure 17. *Results of rolling resistance measurements on IFSTTAR track for tested pavements with MPD from 0.2 to 1.6 mm*

6. Conclusions

Results of road and laboratory tests presented above indicate that pavement texture has a very large impact on tyre rolling resistance. The differences in tyre rolling resistance resulting from surface texture can reach up to 100%. Given that, such differences translate into changes in fuel consumption of up to 20-30% (Ejsmont *et al.,* 2014) it should be considered that optimizing the texture of the surface can lead to a significant reduction in energy consumption by motor vehicles, and, what follows, also significant emission reduction of toxic compounds such as NO_x, CO and SO_x.

In most cases tyre/road interface leads to partial enveloping of the texture by tyre tread rubber. This means that tread rubber contacts the pavement only in certain regions located around peaks of the texture. Due to this, the shape of the texture summits is of utmost importance for rolling resistance, while influence of the shape and depth of cavities is negligible.

Mean Profile Depth does not characterize pavement correctly concerning rolling resistance since it does not take into account the enveloping phenomenon. Nevertheless, if a wide range of surfaces is concerned (including extremely rough surfaces with high MPD) the correlation between MPD and rolling resistance is very high. In such a case the slope of the regression line calculated for C_r [-] versus MPD [mm] is typically at about 0.0017. However, if pavements are restricted to more common smoother types with typical values of MPD in range 0.4 - 2.0 mm, the correlation is weak and slope is reduced to about 0.001 for car tyres. In the authors' opinion, this is due to the phenomenon of enveloping that is not sufficiently taken into account by MPD. Rough pavements that are characterized by high values of MPD (e.g. surface dressing) usually have very sharp texture peaks which, not the depth of cavities, is the reason for rolling resistance increase. This is well illustrated by comparison of pavement "A" and "M1" (see Table 4). Both pavements have very similar MPD but pavement "A" has very sharp summits and edges, while pavement "M1" is much less "aggressive". Value of C_r for tyre T1064 at 50 km/h measured on aggressive pavement "A" is 0.0101 while on pavement "M1" it is only 0.0087.

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