THE INFLUENCE OF ROAD SURFACE UNEVENNESS ON TYRE ROLLING RESISTANCE

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Summary

The geometric characteristics of road surface substantially affect the interaction between tyre and road. Depending on pavement texture wavelength, the texture chiefly affects tyre/road friction, rolling resistance, interior and exterior noise, tyre wear, and ride comfort. The article presents results of investigations on the influence of road surface unevenness on the rolling resistance of passenger car and truck tyres. The tests were carried out on a roadwheel facility being a part of the test equipment of the Automotive Tyre Testing Laboratory of the Gdańsk University of Technology, where a specially made replica road surface with a sinusoidal unevenness profile was mounted on the drum, and on a test road. The unevenness profile under test was characterized by a wavelength of 0.8 m and amplitude of 10 mm, which corresponded to the road surface type commonly referred to as "washboard". The objective of the experiments was to ascertain whether the increase in rolling resistance observed on uneven road surfaces is exclusively caused by an increase in the energy losses in suspension system damping elements or the energy losses in the tyre actually rise as well. The tests revealed that, on the sinusoidal road surface as defined above in comparison with the "Safety Walk" smooth sandpaper like surface, the rolling resistance of passenger car tyres grew by about 10 % and rolling resistance of truck tyres increased about 30 %.

Key words: tyres, rolling resistance, surface unevenness

1. Introduction

From the tyre point of view, the most important road surface characteristics, decisive for the nature of tyre/road interaction, are unevenness[5] and texture[6], stiffness, and porosity of the wearing course. This article deals with the influence of road surface unevenness on the rolling resistance of passenger car and truck tyres. Fig. 1 schematically presents the wavelength and spatial frequency[7] values for individual texture ranges and indicates the

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[5] Unevenness – operational property, defining the road surface capability to induce shocks and vibrations of a vehicle moving on the road [1]

[6] Pavement texture – deviation of a real road surface from a true planar surface [2]

[7] Spatial frequency – number of unevenness periods per a unit of length

important tyre/road interaction parameters on which the specific ranges have the most significant influence. For tyre/road friction and exterior noise, an increase of the texture may have a favourable effect in specific wavelength ranges (symbolically indicated in the drawing by a green shade) while this effect may be unfavourable in other wavelength ranges (yellow shade).

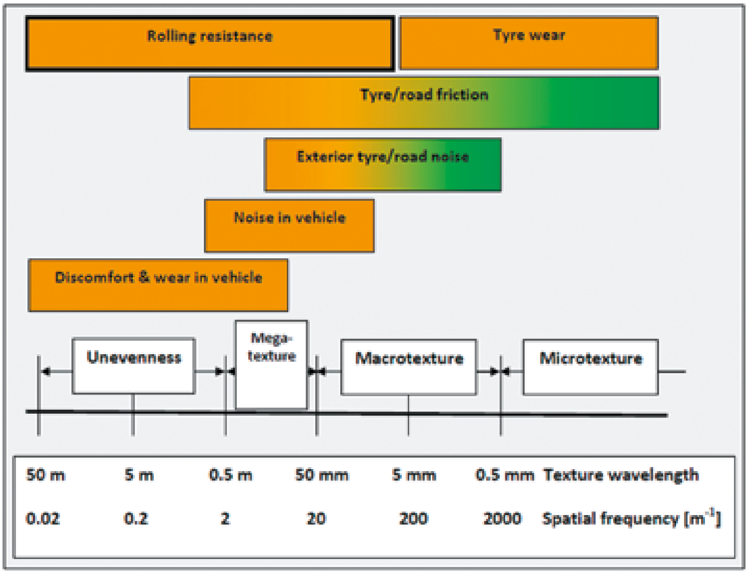

Fig. 1. Influence of pavement unevenness and texture on the tyre/road interaction [7]

It is generally assumed [3] that increase in the texture (commonly described as increase of MPD[8]) results in a considerable increase in the rolling resistance, similarly as it is in the case of a worsening in the pavement unevenness (usually specified in the form of an IRI[9] value). The research works conducted by the authors of this article indicate, however, that the influence of MPD on the rolling resistance is not as significant as it is generally believed [6]. There is no doubt that on road surfaces characterized by high IRI values (i.e. on roads with "uneven" pavement), significant energy losses are generated in the damping elements of the vehicle suspension system, which is directly reflected in an increase of shock absorbers temperature.

On the other hand, there is no information whether the energy loses in the tyres of a vehicle driven on an uneven road surfaces increase as well. The finding of an answer to this question became one of the primary objectives of the implementation of the

[8] MPD - Mean Profile Depth [4]

[9] IRI – International Roughness Index, defined as the cumulated displacement of the wheel suspension system in the quarter-vehicle model divided by the distance travelled during a simulated vehicle run [5]

ROLRES project. Selected results of the road and laboratory tests carried out in this field in 2013–2015 have been presented below.

2. Results of coast-down road tests

The coast-down road tests were carried out on the TATRA testing ground in the Czech Republic [8]. The said testing ground includes numerous test lanes paved with many special pavement types, characterized by a wide range of MPD and IRI values. For the tests, lanes with smooth asphalt pavement and uneven concrete surface with sinusoidal profile of 800 mm wavelength and 10 mm amplitude were chosen (see Fig. 2). The IRI value calculated for the sinusoidal road profile was IRI = 6.33 mm/m. Three vehicles were tested on the selected pavements: passenger car Ford MONDEO 2.5 L, special off-road vehicle SOF, and truck STAR 944. For the SOF vehicle, the tests were carried out with the use of two shock absorber sets significantly differing from each other in their damping coefficient value. In consideration of very heavy loads developing in the suspension systems of the vehicles driven on the sinusoidal road surface, the tests were carried out with the initial speed being limited to 25 km/h. An additional benefit of adopting this very low initial speed at the vehicle tests was a significant reduction in the aerodynamic drag.

Fig. 2. Test vehicle SOF during coast-down measurements of rolling resistance on a road with sinusoidal profile [8]

Averaged values of the coast-down distance recorded for the test vehicles on roads with very smooth asphalt pavement and sinusoidal concrete profile have been presented in Table 1. The measurement results indicate that the energy losses caused by the vehicle movement on uneven road surface significantly exceeded those observed when the vehicles were driven on the smooth road surface. For the Ford MONDEO car, the distance coasted on the sinusoidal surface was as short as 43% of that measured on the smooth asphalt road. This means that the energy losses caused by the rolling resistance in the broad sense of this term (i.e. by the rolling resistance resulting from the energy losses in both vehicle tyres and suspension system) were more than twice as high. For the STAR 944 truck, the coast-down distance was reduced to 74 %. For the SOF vehicle with low-damping gas shock absorbers, the coast-down distance was reduced to 53%; if high-damping shock absorbers were used, this distance was reduced to 57%. When analysing these results, one should remember that both in the SOF vehicle and in the STAR 944 truck, the drive axles are characterized by relatively high permanent resistance to motion (because both of them have the nature of off-road vehicles), which results in a lower "sensitivity" of the coast-down distance to changes in the tyre rolling resistance. Nevertheless, a statement may be made with a high probability that the influence of road unevenness on the energy losses was significant for all the vehicles under test and that this influence was stronger if the vehicle was provided with a softer suspension system.

Table 1. Averaged coast-down distances recorded for the test vehicles on roads with smooth and sinusoidal surface

Vehicle	Smooth asphalt road surface	Sinusoidal road surface
Ford MONDEO	206.5 m	88.3 m
SOF (with low-damping shock absorbers)	143.0 m	75.3 m
SOF (with high-damping shock absorbers)	133.5 m	75.9 m
STAR 944	161.5 m	120.0 m

In consideration of the results obtained from the tests carried out on the TATRA testing ground, a decision was made to reproduce the sinusoidal road profile on the roadwheel facility used at the Automotive Group of the Gdańsk University of Technology for experimental determining of the rolling resistance of automotive tyres.

3. Results of laboratory tests carried out on replica road surfaces

The road tests revealed very big influence of road surface unevenness on the rolling resistance of all the tyres under test. Unfortunately, those tests could not give an answer to a question whether the growth in energy losses is exclusively caused by energy dissipation in shock absorbers and other suspension system components or raised energy loses include also additional lost in the tyre, which is subjected to significant cyclic deformations. Although the energy losses in shock absorbers can be evaluated on the grounds of the dynamic characteristics of the suspension system components determined on a test stand, but such a method is not accurate enough, as the shock absorber operation is affected not only by the amplitude and frequency of the excitation applied but also by the shock absorber temperature, while the latter cannot stabilize at the coast-down test because of the test time being too short. Therefore, a decision was made that replica road surfaces with surface profiles identical to those used at the TATRA testing ground should be mounted on the drum of the truck tyre testing machine (see Fig. 3). A test with a standard reference test tyre (SRTT) on a sinusoidal replica road surface mounted on the drum of the roadwheel facility is presented in Fig. 4, where the left and right photos show the tyre in contact with the test surface profile at a place of minimum thickness of the replica, i.e. on the "bottom of a recess", and on the "top of a swell", respectively.

Fig. 3. Roadwheel facility with outer drum of 2.0 m diameter

Fig. 4. Minimum (left) and maximum (right) dynamic deflection of the tyre rolling on the sinusoidal replica road surface

The 2.0 m roadwheel facility has a very heavy hub to which a wheel with the test tyre is fastened and a massive arm on which the tyre-loading weights are placed. In consequence, the inertia of the wheel suspension system is so high that practically no oscillations occur that might be transmitted onto the shock absorber provided in the tyre-loading system, even at the excitation amplitude being as big as 10 mm. Such oscillations would only become significant if the tyre rolled with speeds causing resonance vibrations, but the carrying out of tests in such conditions was considered impracticable because of very high dynamic loads that might result in damage to the testing machine. To determine the impact of sinusoidal unevenness, the tyres were also tested on a steel surface considered as a reference (IRI ≈ 0) and on a standard road surface referred to as "Safety Walk". The tests were carried out at a speed of 50 km/h, for tyres listed in Table 2.

The tyres were tested in thermal stabilization conditions, i.e. after the tyre surface temperatures had stabilized. The passenger car tyres were loaded with a force of 4000 N and inflated to a pressure of 210 kPa. Pursuant to the method adopted at the Gdańsk University of Technology, the inflation pressure in passenger car tyres was kept constant for the whole period of measurements ("regulated inflation pressure"). The truck tyres were loaded with a force of 25 000 N and the tyre inflation pressure, equal to 700 kPa, was set for the tyres being cold ("capped inflation pressure"). For each set of test conditions, the measurement was carried out for 3 min. The construction of the roadwheel facilities at the Gdańsk University of Technology is such that the tyre rolling resistance is measured with the use of the "torque method" [9] and that the rolling resistance force is determined with an accuracy of about 1%.

Table 2. Test tyres used during rolling resistance measurements

Tyre symbol	Make and model	Size	Remarks
T1097	UNIROYAL Tiger Paw M+S	P225/60R16	Tyres used as informal reference tyres
T1064	MICHELIN Primacy HP	225/60R16	
T1087	AVON Super Van AV4	195R14C	
T1116	DUNLOP SP372 CITY / BOSS	275/70R22.5	Retreaded truck tyres
T1117	MICHELIN XDU	275/70R22.5	

Simultaneously with carrying out the rolling resistance measurements, thermograms were taken with the use of a VIGOcam V5 thermographic camera. Based on the thermograms, the temperatures of individual regions of the tyre rolling on various surfaces were determined for each of the tyre regions as the average of the values obtained for six measuring points where markers were placed. The measurement results are given in Table 3.

A graphic interpretation of the results obtained for passenger car tyres is shown in Figs. 5–7. It can be seen from the graphs that for all the tyres under test, the rolling resistance coefficients (C_r) were the lowest and highest for the steel surface and the sinusoidal surface, respectively. This is also reflected in the temperatures of individual tyre regions,

Table 3. Rolling resistance coefficients and temperature of selected tyre regions

Tyre	Measured quantity	Steel surface	"Safety Walk" surface	Sinusoidal surface
T1064	Rolling resistance coefficient C_r [–]	0.0087	0.0091	0.0097
	Shoulder temperature [°C]	30.3	32.1	34.6
	Sidewall temperature [°C]	29.1	30.1	32.6
	Bead toe temperature [°C]	30.1	31.2	33.9
T1087	Rolling resistance coefficient C_r [–]	0.0107	0.0113	0.0120
	Shoulder temperature [°C]	32.4	32.7	34.9
	Sidewall temperature [°C]	34.3	34.4	37.4
	Bead toe temperature [°C]	35.8	36.6	41.2
T1097	Rolling resistance coefficient C_r [–]	0.0068	0.0076	0.0085
	Shoulder temperature [°C]	28.4	29.3	30.4
	Sidewall temperature [°C]	27.5	28.3	29.8
	Bead toe temperature [°C]	31	31.5	33.9
T1116	Rolling resistance coefficient C_r [–]	0.0054	0.0056	0.0075
	Shoulder temperature [°C]	28.4	29.3	30.4
	Sidewall temperature [°C]	27.5	28.3	29.8
	Bead toe temperature [°C]	31.0	31.5	33.9
T1117	Rolling resistance coefficient C_r [–]	0.0062	0.0064	0.0081
	Shoulder temperature [°C]	32.4	32.7	34.9
	Sidewall temperature [°C]	34.3	34.4	37.4
	Bead toe temperature [°C]	35.8	36.6	41.2

rising with the growing rolling resistance. The interrelations between the temperatures of tyre shoulders, sidewalls, and bead toes are different for all the tyres under test. For the T1097 reference tyre, the highest temperature was recorded for bead toes and the lowest temperature was reached by the sidewalls. For the T1087 reference tyre, the highest temperatures were observed for the bead toes too, but the region where the lowest temperatures were recorded was the tyre shoulders. As regards the T1064 reference tyre, the highest and the lowest temperature values occurred in the tyre shoulders and sidewalls, respectively.

For most of the tyres rolling on the sinusoidal surface, the highest temperature growths were recorded for bead toes, which indicates this tyre region to be the one where the highest energy losses occur due to cyclic tyre loading and unloading by wavy road surface. The differences in the distribution of temperature values in specific tyres can be explained by differences in the internal tyre structure. As an example, the T1087 tyre, which is designed for delivery vehicles, has thick and rigid sidewalls and this causes higher temperature growths in this region.

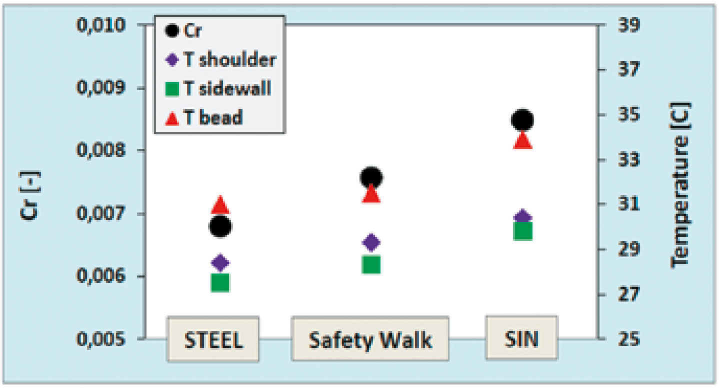

Fig. 5. Comparison of rolling resistance coefficient and temperatures of selected areas of the T1097 tyre

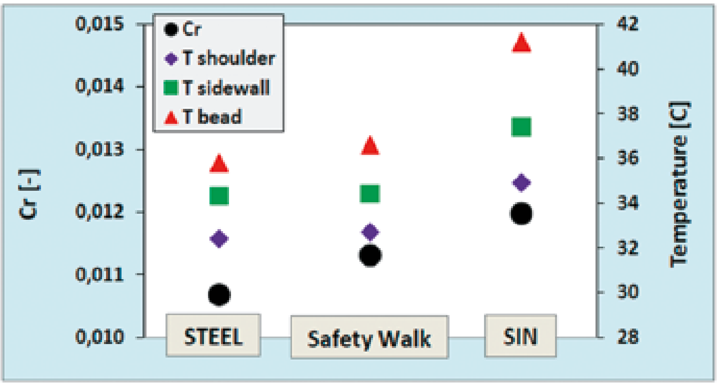

Fig. 6. Comparison of rolling resistance coefficient and temperatures of selected areas of the T1087 tyre

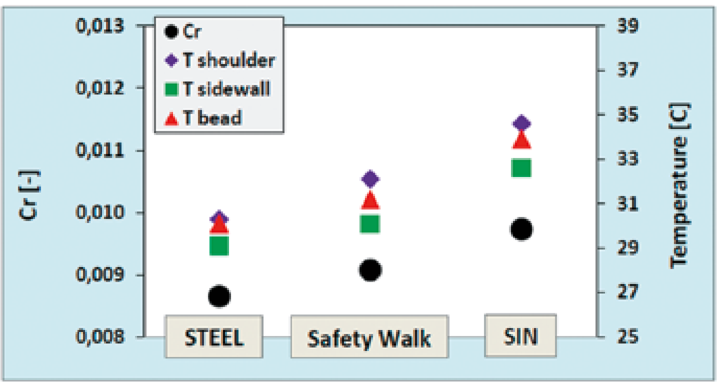

Fig. 7. Comparison of rolling resistance coefficient and temperatures of selected areas of the T1064 tyre

Fig. 8 shows thermograms obtained for the T1087 tyre. On the "C" thermogram, taken when the tyre was rolling on the sinusoidal surface, a significant local temperature growth can be clearly seen in the bead toe region of the tyre, immediately at the wheel rim edge.

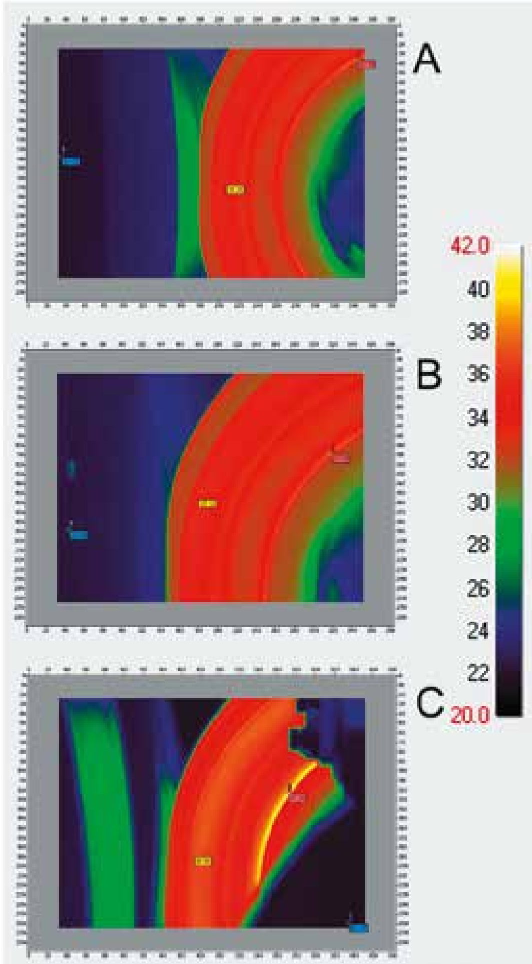

Fig. 8. Thermograms obtained for the T1087 tyre rolling on: A – steel, B – "Safety Walk", and C – sinusoidal surface

A graphic interpretation of the results obtained for truck tyres is shown in Figs. 9–10. It can be seen from the graphs that for both the tyres under test, the rolling resistance coefficients were the lowest and highest for the steel surface and the sinusoidal surface, respectively. Like in the case of passenger car tyres, this is also reflected in the temperatures of individual tyre regions, rising with the growing rolling resistance. The interrelations between the temperatures of tyre shoulders, sidewalls, and bead toes are different for different tyres under test. For the T1116 tyre, the highest temperature was recorded for bead toes and the lowest temperature was reached by the sidewalls. For the T1117 tyre, the highest temperatures were observed for the bead toes too, but the region where the lowest temperatures were recorded was the tyre shoulders. It should be emphasized here that the truck tyres under test were retreaded and their treads were identical but the tyres differed from each other in their carcass structure. For both of the tyres rolling on the sinusoidal surface, the highest temperature growths were recorded for bead toes. Thus, the situation was very similar to that observed for the passenger car tyres.

Fig. 11 shows thermograms obtained for the T1117 tyre. Like in the case of passenger car tyres, a local temperature growth in the bead toe region of the tyre, immediately at the

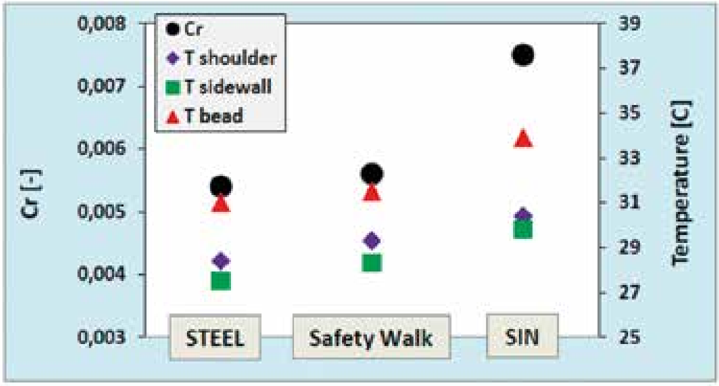

Fig. 9. Comparison of rolling resistance coefficient and temperatures of selected areas of the T1116 tyre

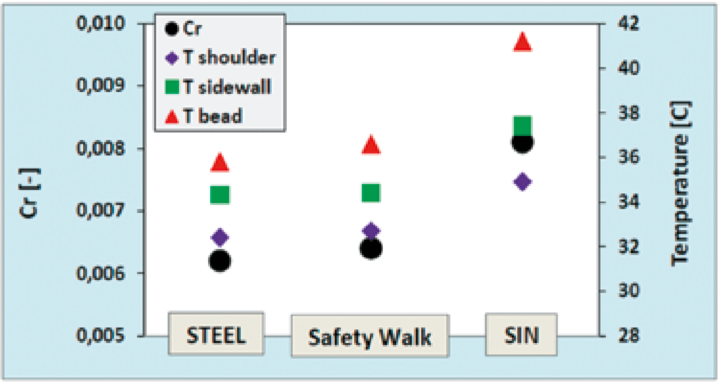

Fig. 10. Comparison of rolling resistance coefficient and temperatures of selected areas of the T1117 tyre

wheel rim edge, can be clearly seen on the "C" thermogram, taken when the tyre was rolling on the sinusoidal surface.

Similar test results were also obtained for other tyres, including tyres of the Run Flat type. For the Run Flat tyres made by different manufacturers, differences only occurred in the intensity of growth in the rolling resistance measured for the tyre rolling on the sinusoidal surface in comparison with the rolling resistance observed for similar tyres but having not been provided with the Run Flat feature.

4. Conclusions

The test results presented herein indicate that road surface roughness of large wavelength ("unevenness") causes both increased energy amounts to be lost in the

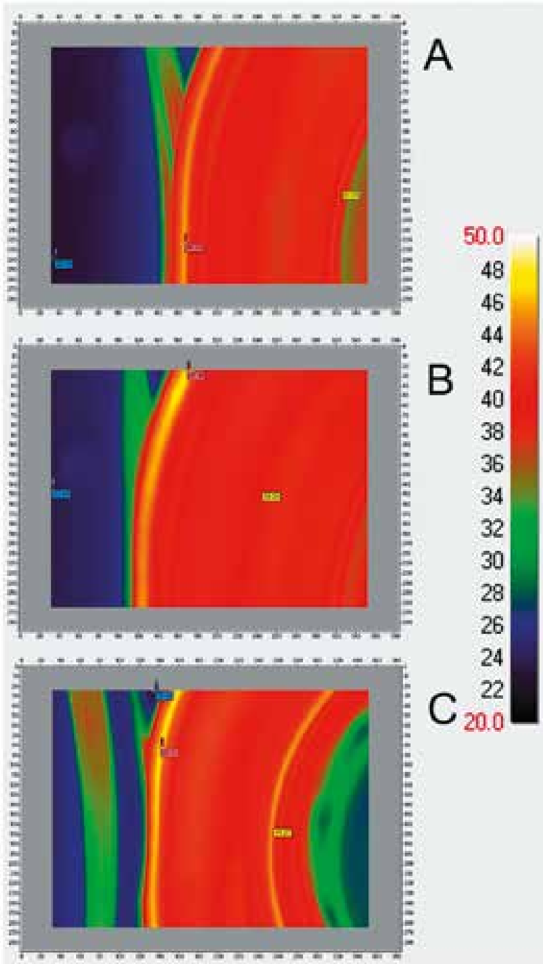

Fig. 11. Thermograms obtained for the T1117 tyre rolling on: A – steel, B – "Safety Walk", and C – sinusoidal surface

tyre as such and significant energy losses to occur in the damping elements of the vehicle suspension system. For vehicles of different kinds, the distribution of the energy losses between the tyre and the suspension system may vary enormously.

For the passenger car subjected to the tests, the coast-down distance on the sinusoidal road surface was as short as 43% of that measured on the smooth road. This means that, with some simplifying assumptions, the resistance to motion on the road with the sinusoidal profile was by about 230% higher in comparison with that occurring on the even road surface. At the same time, a comparison of the rolling resistance coefficient for passenger car tyres, determined during laboratory tests on the "Safety Walk" and sinusoidal surface profiles, revealed differences of merely about 10 %. This means that in a passenger car moving on a road surface with a high IRI value, i.e. on a road surface popularly defined as uneven, the increased resistance to motion is chiefly caused by a significant growth in the energy losses in suspension system components.

For the truck, the coast-down distance on the sinusoidal road surface decreased by only about 30 % in comparison with the distance achieved on the even road. The measured growth in the rolling resistance of truck tyres (sinusoidal road surface as against the "Safety Walk") was also about 30 %. This means that for the truck driven on an uneven road (with a high IRI value), the most important reason for the growth in energy losses is the energy loss in tyres instead of suspension system components.

The above research results were obtained from tests carried out on an uneven road surface with a relatively short wavelength (0.8 m) and it is not certain that they would well represent the situation where the vehicles would be driven on an uneven road surface with a large wavelength. For research results of more general nature to be obtained, tests must be carried out on test roads with sinusoidal profiles where the wavelength would be of several meters (e.g. 3 m or 6 m, as such wavelengths can be represented on the drum of the roadwheel facility). Unfortunately, a test road with such characteristics is unavailable for the authors of this paper. Nevertheless, a modification of the testing machine is planned, in result of which the wheel under test will be mounted on a suspension system whose characteristics (masses and geometry) would be close to those of a typical suspension system of a motor vehicle. This will make it possible to carry out simultaneous measurements of rolling resistance and energy losses in the shock absorber, which is expected to facilitate further analysis of the influence of road unevenness on energy losses in the tyre and in the wheel suspension system.

An analysis of the thermograms indicates that during tests on uneven road surfaces, the greatest energy losses occur in the bead toe region in most of the tyres. This phenomenon has been observed in both passenger car and truck tyres.

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