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CAR TYRES WITH REDUCED ENERGY CONSUMPTION

Marcin Wieczorek, Jerzy Jackowski

Military University of Technology, Faculty of Mechanical Engineering
Institute of Motor Vehicles and Transportation
Gen. W. Urbanowicza Street 2, 00-908 Warsaw, Poland
tel.:+48 261 839877, 261 839565
e-mail: marcin.wieczorek@wat.edu.pl, jerzy.jackowski@wat.edu.pl

Abstract

The objective of this publication is to present the changes that are currently made to the tyre structure in order to reduce its rolling resistance including the rubber compound, tread pattern and tyre support structure. Based on a broad literature review the authors present a history of changes introduced in the construction of tyres aimed at reducing their share in the energy losses needed to overcome the resistance of rolling wheels in the car's movement (at present it reaches even 50%). They indicate a significant conflict resulting from the rubber properties using the data sets available on the labels of summer and winter tyres in which the improvement of wheel adhesion leads to increased rolling resistance. In the next part, the basic factors determining the rolling resistance of tyres are approximated, focusing on those related to their construction. The influence of the rubber loss factor is described which values at different deformation frequency (turning the wheel 10^1-10^2 Hz and its braking at 10^4-10^5 Hz). It determines the interaction of the rubber with the road surface. Various ways of actions are shown to reduce the losses occurring during the deformation of the tyre: the use of silica as a rubber filler and the introduction of nanotechnology to control the rubber crosslinking process, reducing the volume of rubber used to build the tyre coating, simplifying the tread pattern and changing the tyre diameter size to a larger one (treatment used in electric cars). Particular attention was also paid to the weakness of the changes, i.e. the increase of the noise generated by the more elastic coating of the tyre and the possible directions of counteracting this phenomenon were signalled.

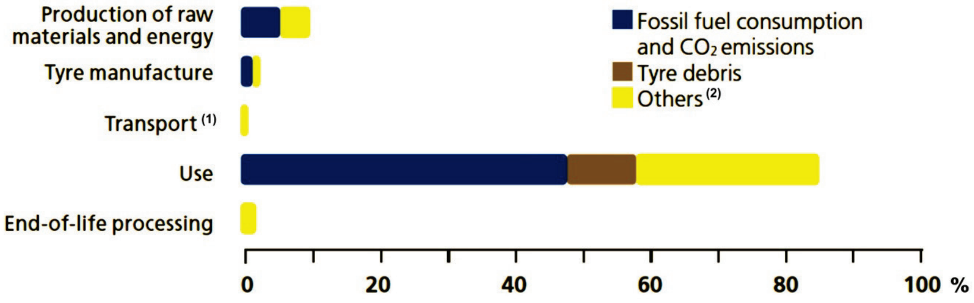
Keywords: *energy consumption, rolling resistance, tyre construction, tyre tread rubber, tread pattern*

1. Introduction

One of the many directions in the car development is to look for opportunities to reduce the energy consumption of its motion. The vehicle becomes lighter its body is streamlined. An important area of such activities is automobile tyres. This is the sole field of a contact between the vehicle and the road. Tyres play the crucial role in the vehicle movement of carrying the vehicle's load, absorbing uneven road surfaces, transmitting the braking and the acceleration forces, steering the vehicle according to the driver's choice and while emitting as little noise and losing as little energy as possible. To satisfy all these functions, tyres have to feature very diverse and important qualities such as endurance, durability and comfort, grip, energy efficiency, precision of steering. Their simultaneous achievement is a big technological challenge because they often contradict each other. The main aim of article is to give a brief outline of the changes that are made to the tyre structure in order to reduce its rolling resistance including the rubber blend, the tread pattern and layout of the tyre supporting structure.

The life cycle analysis of a passenger car tyre (Fig. 1) shows that over 86% of its environmental impact occurs during its use phase (mainly due to rolling resistance). For trucks, this proportion reaches 93%. In regular usage, tyres account for an important proportion of vehicle energy consumption (Fig. 2) [8, 9]. Currently it is estimated at 20% for passenger cars, over 30% for trucks and up to 50% for electric vehicles [18]. It is due partially to the differences in their construction. In the electric car, there are practically no losses associated with the operation of the mechanisms of the propulsion system. Rolling resistance loss arises from the deformation of different components of tyres and from the interaction of tyres with the road surfaces. It comes from a combined effect of component material hysteresis, tyre structure, and inflation pressure and tyre stiffness. Among all tyre components, tread compounds make the largest contribution to the rolling resistance of the tyre, accounting for 40%-50% for passenger tyres and 35-50% of the total rolling resistance loss for truck tyres, depending on tyre aspect ratio and design [15].

The history of changes in tyre rolling resistance values is illustrated in Figure 3. In 1937, a steel cord was used for Michelin bias-ply truck tyres. This treatment, apart from increasing tyre durability, also reduced the rolling resistance. Another jump is the invention of the radial tyre. The producers have tried many years to reduce the rolling resistance without lowering the grip of the tyre. The progress was made in the 1990 s only after the partial replacement of the soot with silica filler in tread rubber.



(1) transport of new tyres and end-of-life tyre,
(2) other as land use, ore consumption, emissions of carcinogenic substances, acidifiers of eutrophicating substances.

Fig. 1. Distribution of impacts of an average European passenger car tyre throughout its life cycle [18]

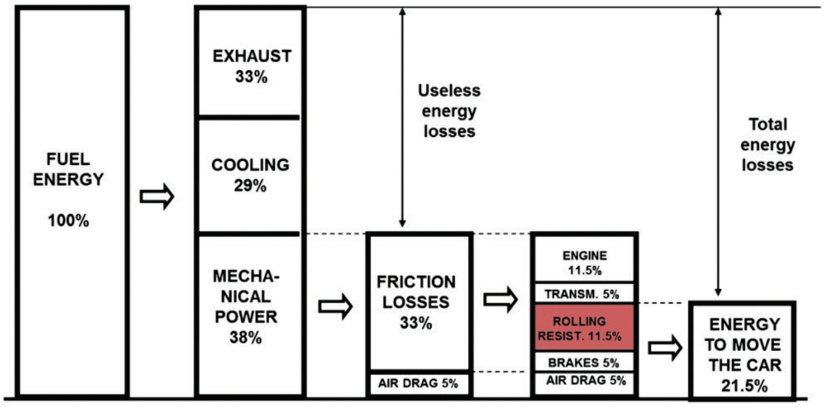


Fig. 2. Distribution of passenger car energy consumption [8]

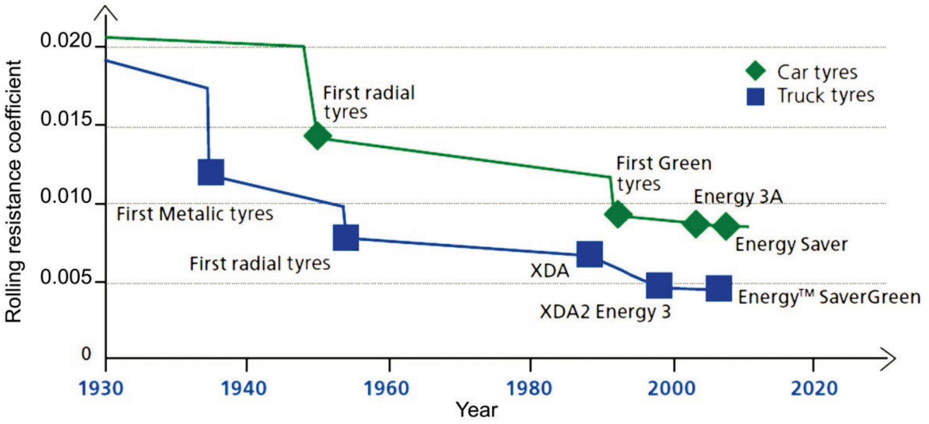


Fig. 3. Evolution of the rolling resistance coefficient [18]

The conflict between the possibility of simultaneous improvement of traction and rolling resistance of summer and winter tyres is shown in Figure 4. It uses the results of studies conducted in accordance with the provisions of Regulation No 117 of the UNECE [16], which are placed on special assessment labels [17]. The letters taken from labels, A (the best properties) to G (the worst properties), was added on the diagram axes next to the detailed measurement values. The drawing also shows the approximate division into economic, medium and premium classes. In this view, improved grip is evident with increasing tyre grade (from E to A) and practically with no change in rolling resistance, (most results are within the E range). In comparison, winter tyres (marked with a blue triangle) are worse. This is due to the specificity of the tread shape and the properties of the rubber, which have to enable low temperature operation, braking and propulsion on snow and ice.

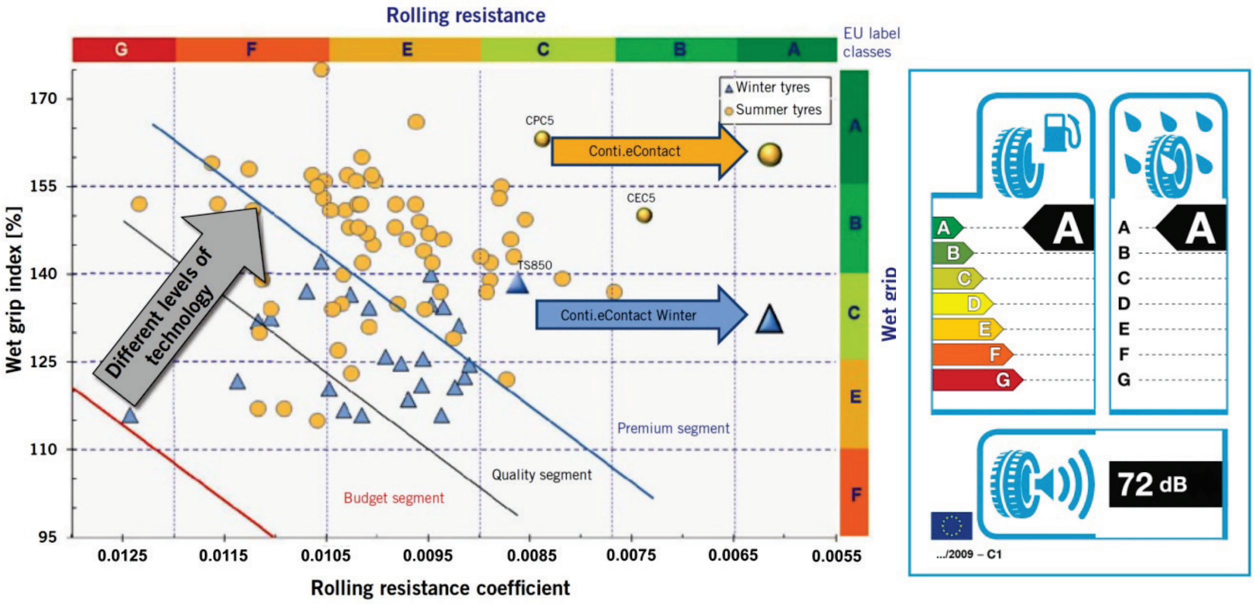


Fig. 4. Comparison of summer and winter tyres (2012) in the conflict of goals between wet grip and rolling resistance in different classes of the EU tyre label (example on right) [10, 13, 17]

2. Basic factors affecting tyre rolling resistance

2.1. Rubber

The level of energy loss from viscoelastic rubber compounds used in the tread under dynamic deformation depends not only on the viscoelastic properties of the tread compounds, but also on the mode of deformation. Hence, the energy loss H for the rolling resistance for sinusoidal deformation can be described by the following volume integral over deformation and hysteresis [13, 15]:

$$H = \pi \cdot \int \sigma \cdot \varepsilon \cdot tg(\delta)\, dV\,, \qquad (1)$$

where:

σ – amplitude of stresses,
ε – amplitude of deformation,
$tg(\delta)$ – rubber loss factor (tangent of phase angle between stress and strain, figure 5),
V – volume of rubber.

The equation (1) shows that for a maximum reduction of the rolling resistance all of these influencing parameters have to be minimized.

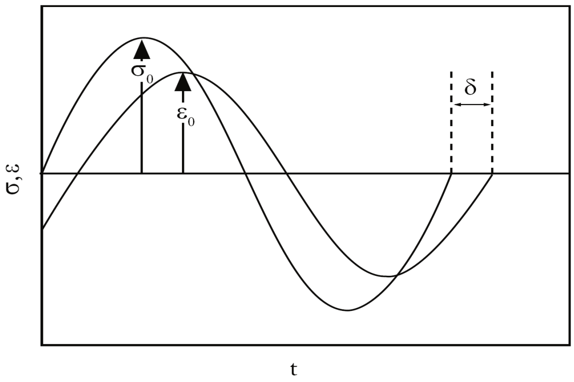


Fig. 5. Changes in stress and deformation of a rubber sample subjected to an oscillating signal as a function of time

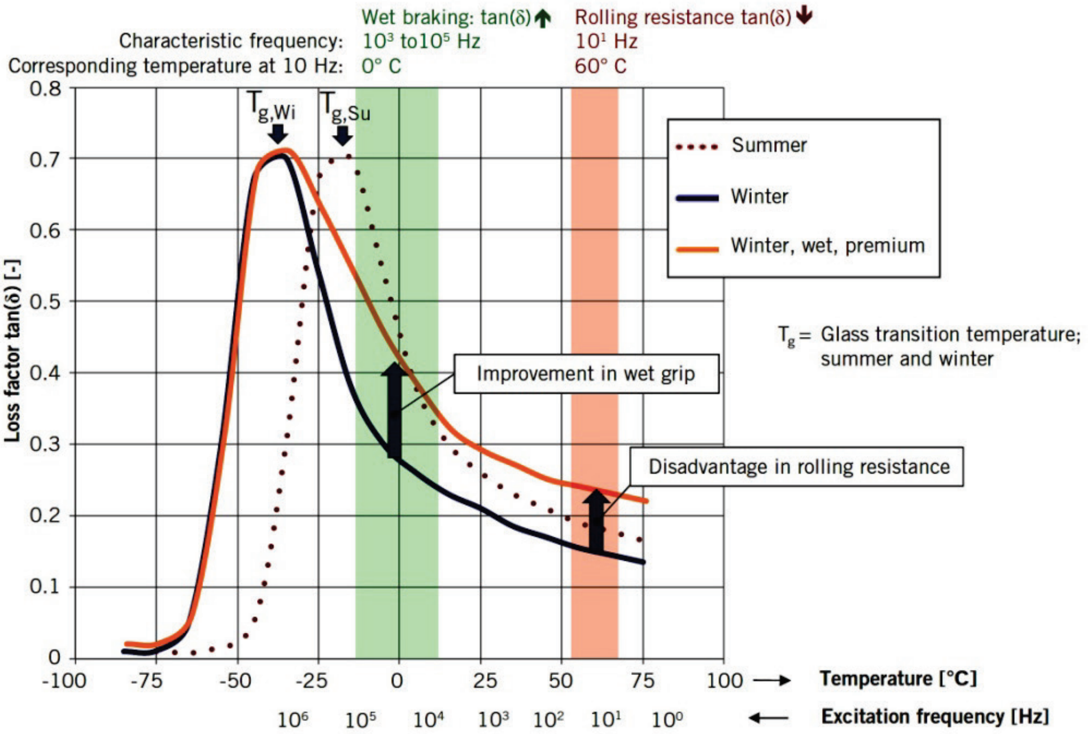


Fig. 6. Curve of the rubber loss factor tan(δ) versus temperature and corresponding excitation frequency of a summer, winter and winter-premium tread compound [13]

Rubber loss factor $tg(\delta)$ expresses the ratio of the energy distributed per cycle of the deformation to the energy stored during the deformation process and it is a measure of internal friction. The course of changes in the value of the loss factor depending on the temperature of the rubber (Fig. 6) allows to determine the qualitative effect of the rubber mixture on the tyre performance characteristics, namely the wet grip and the rolling resistance of the tyre (hysteresis loss). In this figure, marked area (including the direction of change) in which the value of the $tg(\delta)$ determines the mentioned properties of tyres (also Fig. 7). Clearly, for most of the tested rubber compounds, there is a range of temperature values in which the rubber provides good adhesion. In addition to this area, both the increase and the decrease of the temperature value, a sharp decrease in the adhesive properties of the rubber is observed. In the first case (temperature rise), this changes results in a reduction in strength and sometimes even a degradation of the rubber chain, in the second case (lowering the temperature) reducing the hysteresis of the rubber in the less susceptible to deformation. Obviously, depending on rubber composition, the change in the value of rubber loss factor as a function of temperature is different (e.g. rubber of summer and winter tyre).

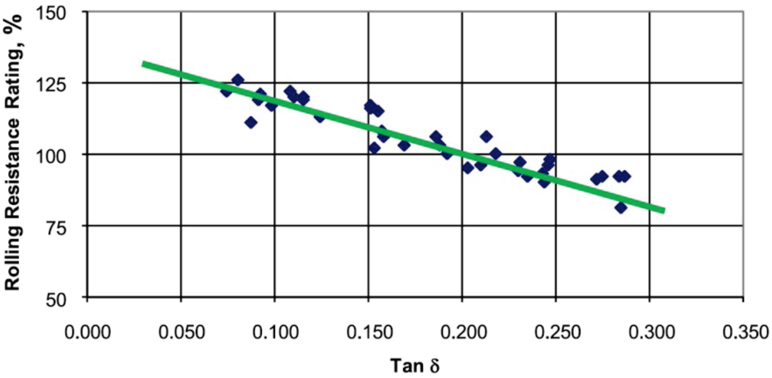


Fig. 7. Rolling resistance versus tan(δ) of tread compound at 30°C [5]

For years, the choice between grip and tyre rolling resistance was a compromise. This changed only the use of silica filler in place of carbon black. Frictional testing by using a Plint machine to obtain the coefficient of friction on silicon carbide P500 paper showed that, in both wet and dry conditions, the silica-filled ENR-25 truck tread has a greater coefficient of friction compared with the black-filled NR/BR tread compound (Fig. 8). The coefficient of friction measured for the black-filled NR/BR tread compound did not change between dry and wet runs; however, a reduction in the coefficient of friction occurs for the silica-filled tread compound where water is present. Notwithstanding this reduction in the coefficient of friction, the ENR-25 bus/truck tread still has better grip than the NR/BR tread [11]. In the case of the Michelin Energy tyres (1990's), have been able to reduce the rolling resistance by about 10-15% compared to the same tyre made by using a traditional rubber blend [18].

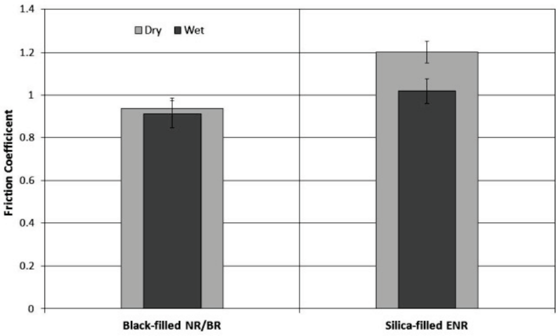


Fig. 8. Friction coefficient of rubber samples against silicon carbide paper P500 at 1 mm/s with a 10 N load applied (Plint machine) [11]

In the case of conventional rubber, local heating and energy losses are due to the aggregation of filler particles. In the latest mixes, not only new fillers are used, but also the interaction between polymers, fillers and other rubber components used in the tyre construction is controlled. The optimization is carried out at the nano dimension where the loss-generating components can be removed from the polymer by modifying the crosslinking within the chains or at the ends thereof. This leads to a significant improvement in the distribution of filler particles and reduction of internal friction [6]. The *Nedo program* may be an example of such activities [7], which is based on the compilation of tyre mixtures with three-dimensional nanohierarchical architecture. This program aims not only at reducing the rolling resistance, but also at a compromise between rolling resistance and wear. The new method of controlling three-dimensional nano-hierarchical architecture has been divided into three different ranges (Fig. 9):

- step 1: 1000 nm – mixture of polymers,
- step 2: 100 nm – filler dispersion,
- step 3: 10 nm – rubber crosslinking.

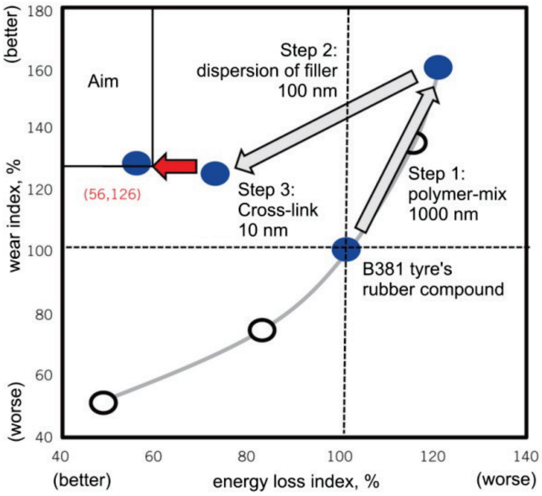


Fig. 9. The current compromise between energy loss and wear can be solve by introducing nanotechnology into the tread rubber mixes [7]

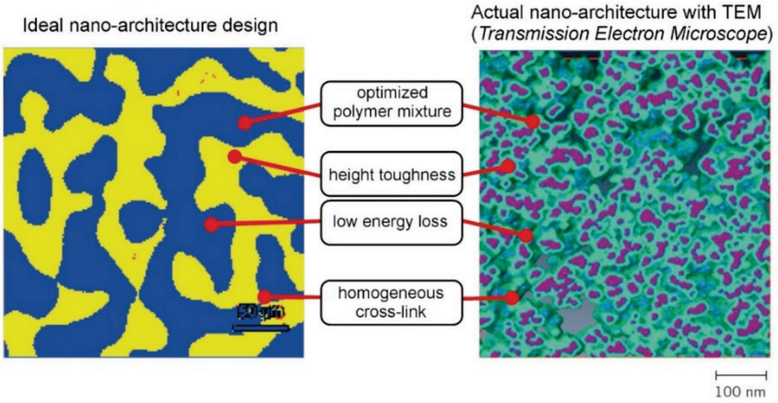


Fig. 10. Comparison of the ideal nanohierarchical architecture derived from the computational science (left) and the actual target image of the mixture, recorded by 3-D-TEM (right) [7]

Optimization of the polymer mixture has improved wear in the first stage; improved filler of dispersion reduces the energy loss in the second stage. In the third stage, the optimization of the crosslinking results in an improvement to restrict the additional energy loss. As a result, the mixture optimized in the nanotechnology architecture could achieve intended performance for the energy consumption and loss. The nanoscale transmission (3-D-TEM) and atomic force microscopy (AFM) were used to identify nanoarchitectures. These techniques have been modified to reach the nanohierarchic identification requirements of a 3-D image and the distribution of mechanical properties of nanoscale. These measures combined with the finite element analysis to simulate the mechanical behaviour (an example of the optimization of stress distribution calculated by finite element analysis and scanning image is shown in Figure 10).

The method of preparing the tread rubber has allowed reducing dependent on the tyre design the tyre weight (up to 9%), the rolling resistance (from 14% to 20%) and the tread wear (up to 25%) [6, 7].

2.2. Tyre construction

The specific design features and the features of future electric vehicles designate new requirements for tyre development. Goodyear and Continental are good examples. New tyres have a narrow cross section and an increased outer diameter, for example instead 205/55R16, a 155/70R19 tyre is proposed. Its free radius is 30 mm bigger than conventional tyre. In addition, tyres are inflated to a higher pressure (240 kPa-280 kPa). Applying this change results in lower rolling and air resistance, and the volume of material that is subject to deformation are reduced (Fig. 11). Tyres (for electric vehicles) that have very low rolling resistance are rather insensitive to inflation pressure changes, while tyres having bigger rolling resistance are very sensitive. In addition, the results indicate that behaviour of tyres is very much dependant on the road surface texture. Another advantage of a larger diameter is the smaller number of wheel's rotations needed to overcome the same distance and tyres are less susceptible to aquaplaning (Fig. 12) [22].

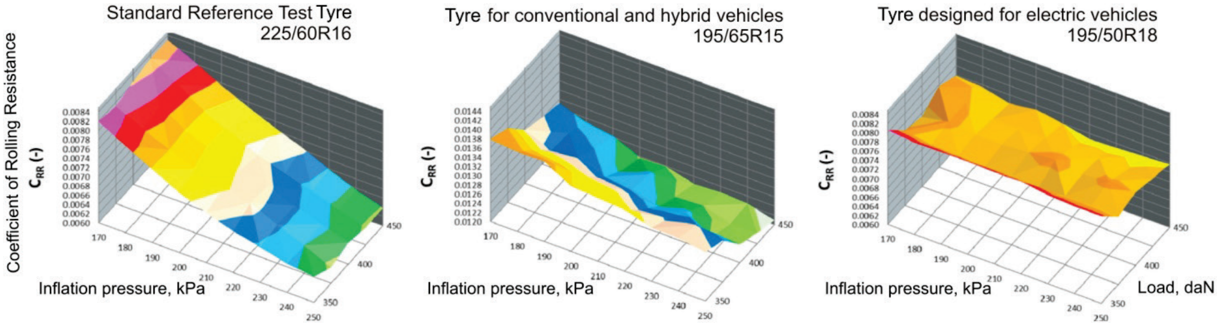


Fig. 11. Combined influence of load and inflation for different tyre rolling on road surface replica (speed 80 km/h) [4]

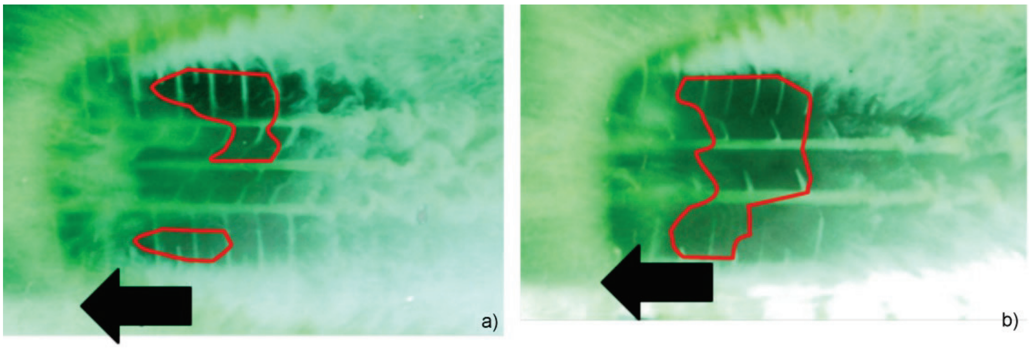


Fig. 12. Test results at Bridgestone's Tochigi Proving Ground (Japan) in 2011 a) tyre size 155/55R19; b) against 175/65R15 [22]

According to the analysis presented in [2], the tread rubber's and its pattern's contribution to the tyre's losses is more than 60%. Limitation of energy consumption can be achieved by reducing the deformation of the tread region of the tyre (in the area with belt ply) [20]. Major changes include the use of 3-D technology in shaping the treads. At the same time, due to the reduced wear intensity of the tread rubber, the depth of the tread pattern is reduced. The stiffness of the tread blocks, which determines energy losses in tyre/road contact area (Fig. 14) are shaped by self-locking lamella, grooves. Tread blocks also incorporate 3D Multi-Wave Sipes that improve both wet traction and tread wear. 3D Multi-Wave Sipes are small cuts in a tread block that are cut into interlocking angles that help to prevent tread flex and reduce the chance of irregular wear (Fig. 15) Traditional straight cut sipes can flex more and increase the chance of irregular wear or/and noise.

Introduced simplification in shaping the tread pattern is reducing the volume of material used to build the tyre has adversely affected the generated noise. Figure 16 shows the results of tyre tests on a 1.7 m diameter drum covered with special road surfaces [3]. It is clearly apparent that tyres specially designed for electric vehicle are not particularly quiet. At best, they emit tyre/road noise of "average" level. However, when such tyres are running on poroelastic road surfaces that are being developed for urban and suburban areas the noise is very low. One may speculate that there is still field for improvements. An example may be a special insert fitted inside the tyre or tread pattern designed to minimize the noise. It features circumferential grooves with dense serrations on its walls to reduce "pipe resonance noise". Circumferential grooves become a "pipe" when the tread meet with the road surface and the air in the groove is compressed and released suddenly. This phenomenon also creates the sound in a flute. The serrations on the circumferential groove walls disturb the airflow in order to help to minimize this "pipe resonance noise".

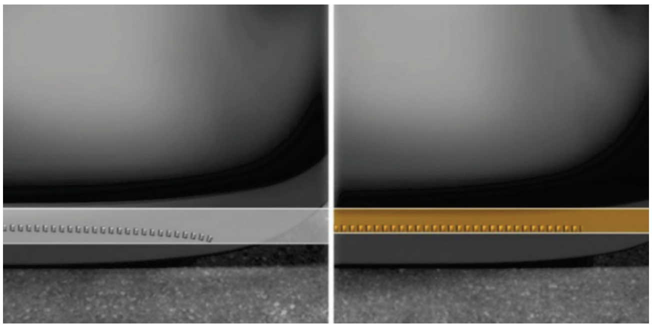


Fig. 13. Reduction of the deformation of the tyre treads area (marked in the drawing) after the arrangement of inner layer (belt ply) has been changed [20]

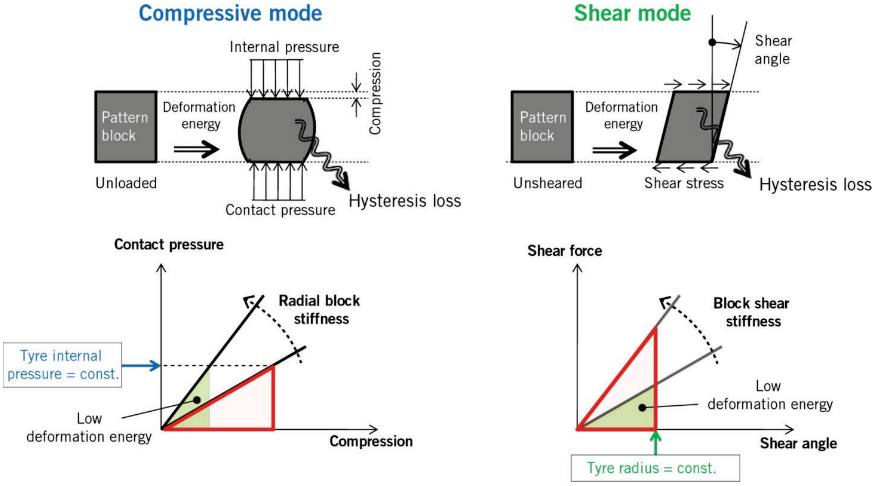


Fig. 14. Influence of block stiffness on deformation energy [13]

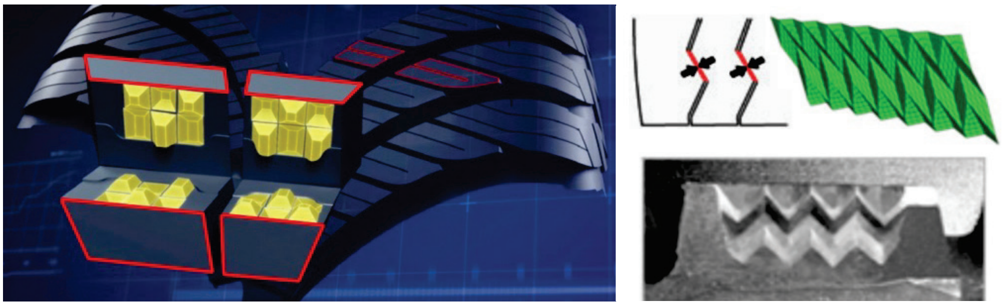


Fig. 15. 3D-sipes on tyre Goodyear Vector 4 Seasons and Polyhedral 3D-sipes Yokohama Ice Guard iG55 [18, 23]

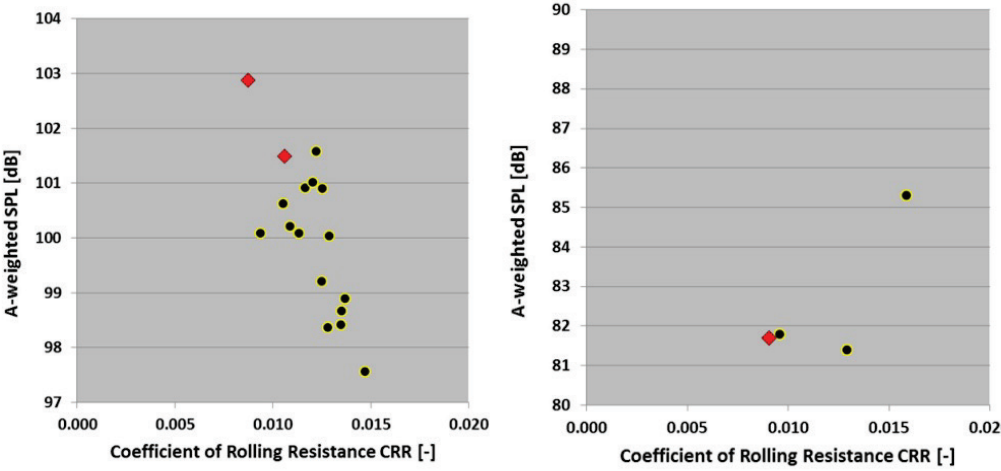


Fig. 16. Coefficients of rolling resistance and noise emission for conventional (black dots) and EV's tyres (red diamonds) measured at speed 80 km/h on replica of rough surface dressing APS-4 (left) and measured at speed 50 km/h on experimental proelastic road surface PERS-HET (right) [3]

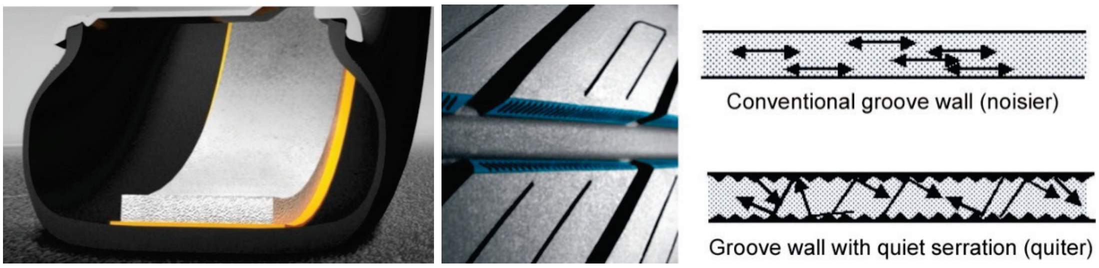


Fig. 17. ContiSilent 2 (left) and Toyo Versado LX (right) [19, 20]

Fig. 18. Dimpled design reduces air resistance (left) and data gleaned from wind-tunnel simulations helped to optimize tyre shape – tread and dimple configuration (right) [18]

The next possible way of decrease, the vehicle's energy consumption is the reduction of the air resistance. From the studies described in [14], it is beneficial to reduce the section width of the tyre, to change the shape of the shoulder area by removing the edges and sharp unevenness and to depress the inscriptions applied on the side of the tyre (Fig. 18). The outer surface of the rim should be as flat as possible. It has also been shown that the observed effects are independent of the vehicle and can contribute towards lowering the energy consumption of the conventional motor vehicle.

3. Summary

The review of theoretical considerations and research aimed at reducing energy losses during the rolling of tyres allows formulating the following conclusions:

1) The share of tyres in the balance of energy needed for car movement is currently estimated up to 50%.
2) Due to the complexity of the object, which is the tyre, the progress in improving significantly its properties is difficult to achieve and in history, it has often been revolutionary. Changes in the material and arrangement of cord plies (radial tyre) as well as the introduction of new components into the rubber mixtures are a good example.
3) Currently, as the producers themselves point out, tyres for electric vehicles (e.g. Renault zoe, BMW i3) are specially built for them. The limitation of rolling resistance is achieved by applying very simple measures such as increasing the air pressure in the tyre, increasing the diameter while reducing its width. Other changes are much more complex and more difficult to carry out. These include reducing the loss during the deformation of the tyre coating material (smaller thickness of side walls as well as reducing the depth of the tread pattern), applying advanced nanotechnology which allows even a distribution of filler particles in the rubber material. This permits a better and better combination of mutually exclusive features such as low rolling resistance; good grip and low tread wear.
4) Taking into consideration the following development of electric and autonomous cars as well as the requirements regarding the range of this type of vehicles and their equipment for safety and comfort systems, further works should be expected to reduce the energy consumption of car movement caused by tyres. However, at present it is difficult to indicate the area that will bring a breakthrough. The added value remains the fact that the developed technologies are slowly transferred to the construction tyre designed for cars with combustion and hybrid drive (mainly new rubber compounds and corrections in the shape of the tread pattern).

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