TYRE/ROAD NOISE AND VIBRATION: UNDERSTANDING THEIR INTERACTION AND CONTRIBUTION TO VEHICLE NOISE AND FUEL CONSUMPTION

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Tyre/road noise and vibration are the main sources of road traffic noise, which is an increasingly big problem in densely populated areas. At the same time, rolling resistance, caused by the energy losses in the tyre, is a significant part of the total vehicle losses and, therefore, directly affects fuel consumption and CO2 emissions. In order to reduce both noise emissions and energy consumption a good understanding of tyre/road interaction and of the influence of tyre and road properties is needed. In this paper the main tyre and road parameters that influence tyre/road noise and rolling resistance are discussed. Special emphasis is placed on tyre/road contact, since the contact forces between tyre and road are the key to a reliable prediction of tyre/road noise, rolling resistance and wear. Although tyre/road models are widely applied to the prediction of tyre/road noise and low-noise road design, the potential of these models for low-rolling resistance road design is not yet fully exploited.

1. Introduction

Road traffic noise is becoming an increasingly big problem in densely populated areas. This noise consists mainly of tyre/road noise and engine noise. In the past engine noise has been the dominating noise source at most constant driving speeds, but in the past decades this balance has shifted towards tyre/road noise. At the moment tyre/road noise is the dominating noise source for constant driving speeds of 40 km/h and higher [1]. On the other hand, 18% of the total CO2 emission in Europe originates from road transport. Aerodynamic resistance, inertial forces, climbing forces and rolling resistance contribute to the total force a vehicle has to overcome to maintain constant speed. Rolling resistance is an important factor in this respect since, depending on the driving speed, it accounts for approximately 20-30% to the energy consumption of a typical passenger car. Therefore, in order to reduce both noise emissions and energy consumption a good understanding of tyre/road interaction and of the influence of tyre and road properties is needed.

This paper discusses tyre/road interaction and the main tyre and road parameters that influence tyre vibrations and, hence, noise and rolling resistance. These parameters are texture/tread pattern, material properties and dynamic response. Although the acoustic properties of the road are not dis-
cussed here, one should keep in mind that they are of critical importance for the noise generation at mid-high frequencies (above 1000 Hz)[1]. This paper focusses on the low-mid frequency range noise and rolling resistance. It is shown that although tyre/road models are widely applied to the prediction of tyre/road noise and low-noise road design, the potential of these models for low-rolling resistance road design is not yet fully exploited.

2. Tyre/road contact interaction

The contact forces between tyre and road are the key to an accurate prediction of tyre vibrations and, thus, tyre/road noise, rolling resistance and wear. Particularly understanding and modeling the dependence of the contact forces on the road texture is of great importance. A detailed solution of the contact problem including all texture length scales of interest using a FE model is unfeasible in rolling conditions which has lead to a numerous works on simplified contact models that are fast enough to be used in a time domain simulation and still capture the main aspects of the tyre/road interaction [2, 3, 4]. Most of the work on tyre/road contact modelling for noise and rolling resistance predictions focusses on the vertical contact forces. Although plenty of work on tyre/road friction forces can be found in the literature on handling [5, 6, 7], there is still little work on how to develop simplified models that include the effect of texture on the friction forces.

3. Main parameters that influence noise and rolling resistance

The main parameters that influence low to mid frequency noise and rolling resistance are surface texture and the dynamic and material properties of tyre and road.

3.1 Surface texture

The surface texture of both tyre and road is the main parameter that influences the frequency content of the contact forces. When talking about the tyre, we speak about the tread pattern, rather than surface texture. The tread pattern determines the main spectral content of the excitation forces on the tyre and, hence, of the tyre vibrations and noise. Obviously a very uniform tread pattern (regular spacing and size of tread blocks) leads to a tonal spectrum with distinct harmonic peaks. This is avoided by designing treads with randomized tread-block shapes and spacings, leading to a

![Figure 1. Overview of texture length-scales.](image-url)
spread of the energy in broader frequency bands with a lower amplitude per frequency. The result is a significant reduction in tyre vibrations and noise.

The road surface texture, also called roughness, is usually separated in several length-scales from very long wavelengths (unevenness) to very short wavelengths (micro-texture) as shown in Figs. 1 and 2.

<table>
<thead>
<tr>
<th>Texture wavelength</th>
<th>Rolling Resistance</th>
<th>Tyre / road friction</th>
<th>Tyre wear</th>
<th>Tyre / road noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 m</td>
<td>5 m</td>
<td>0.5 m</td>
<td>50 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

**Figure 2.** Relationship between texture length-scales and noise, rolling resistance and wear.

It is generally acknowledged that the long wavelengths, from 5 to 0.05 m, are responsible for rolling resistance, whereas tyre/road noise is originated by smaller wavelengths between 0.5 m and 0.5 mm. The surface texture wavelength is related to the temporal frequency through the traveling velocity of the vehicle. As an example, at 80 km/h, the frequency range of tyre vibrations influencing rolling resistance and noise is approximately 4-400 Hz and 40-4000 Hz respectively. In order to reduce the excitation due to the road surface texture small stone sizes are used on the top layer of the asphalt, leading to a smoother road surface.

### 3.2 Dynamic properties

The dynamic properties of the tyre have an influence on both the contact forces and, of course, on the tyre vibrations and generated noise. At low frequencies the point mobility of the tyre shows distinct peaks corresponding to the first vibration modes of the tyre, but as the frequency (modal density) increases the mobility tends to be rather independent of frequency, as it is for an infinite plate. This shows that the tyre curvature has no influence at higher frequencies, above approximately 400 Hz.

Regarding the dynamic properties of the road, it is still unclear how the road impedance affects noise and rolling resistance generation. There is experimental evidence that rubberized road surfaces, which have a significantly lower impedance than normal asphalt, lead to lower noise levels but, in some (not all) cases, higher rolling resistance values [8]. Further research is needed to understand how the road impedance affects contact force generation.

### 3.3 Material properties

A tyre is a complex structure made of wire, cloth and rubber. An average tyre can contain several rubber compounds on the different parts of the tyre, all optimized to give the required performance. The rubber properties are the key to the contact force generation between tyre and road, since they
determine the size of the contact area, the amount of damping in the tyre, the friction forces between tyre and road, etc. A complicating factor is that rubber is a visco-elastic material, with properties change with temperature, with frequency and with time leading to a varying performance depending on climate, travelling velocity and age of the tyre. These are all factors to consider when trying to understand and predict tyre/road noise and rolling resistance.

Interestingly, the mortar used as ‘glue’ between the stones in asphalt is also a visco-elastic material and has the same kind of properties as rubber: frequency dependent, temperature dependent and aging. A better understanding of how the mortar properties influence the road impedance and noise and rolling resistance generation could lead to an optimized road design for both noise and rolling resistance.

4. Tyre/road models

4.1 Overview

Accurate and efficient models of the tyre dynamic behavior and of the tyre/road contact interaction are needed in order to better understand how tyre vibrations contribute to the interior and exterior noise and to the energy losses through rolling resistance.

In the literature over tyre/road noise it is generally accepted that, due to the non-linear character of the interaction, the tyre/road contact problem must be solved in the time-domain [9, 10]. However, the dynamic response of the tyre itself is often described by linear theory, linearising the equations of motion around the undeformed state and formulating the dynamic response in terms of unit impulse response functions or Green’s functions [9, 10, 11, 12]. This implies that non-linear effects which occur when the tyre is loaded, due to the large deformations of the tyre belt and the hyperelastic rubber material properties, are not included.

Furthermore, these models consider a stationary (non-rotating) tyre and a contact zone which is rotating around the tyre. In other words, the contact forces and tyre dynamic response are found in the Lagrangian (tyre-fixed) reference system. In order to determine the vibration transmission to the vehicle interior or the tyre sound radiation, a description of the hub forces and the tyre vibration field in the Eulerian (vehicle-fixed) reference system is needed. This can be done by transforming the tyre response from the Lagrangian to the Eulerian frame taking into account the shift in frequencies due to the rotational velocity [13, 14]. However, it has been shown that this approach does not predict the effect of rotation on a loaded tyre correctly, since the change of the tyre eigenfrequencies due to rotational velocity cannot be described with a simple shift [15].

An alternative is to use a fully non-linear FE model and apply the Arbitrary Lagrangian Eulerian (ALE) formulation to obtain the dynamic tyre response in the Eulerian reference frame [16]. In this way both the non-linear effects due to large deformations and the influence of rotational velocity are included in the tyre response, but at a high computational cost.

Another possibility is to still model the tyre dynamic response as a collection of Green’s functions but use the fully non-linear FE model to determine the static deformation due to loading and linearise the equations of motion around the deformed state [17, 15, 18]. In this way, the effect of the softening due to the large deformations and the non-linear material properties on the dynamic properties of the tyre is included in the linearised dynamic response, while the low computational cost of describing the tyre as a set of Green’s functions is preserved. This approach, termed Modal Arbitrary Lagrangian-Eulerian (M-ALE) approach is further described in the following section.
4.2 Modal Arbitrary Lagrangian-Eulerian Approach (M-ALE)

4.2.1 General framework

The M-ALE approach allows to derive the dynamic equations of loaded rotating tyres directly in the vehicle-fixed (Eulerian) reference system based on a modal base extracted from an ordinary FE calculation of the loaded tyre. The M-ALE approach opens the possibility to determine the rotational velocity dependent impulse response functions of a loaded rotating tyre directly in the vehicle-fixed reference frame. In the same manner, it is straight-forward to derive the rotational velocity dependent transmissibility matrix from contact to axle forces in a vehicle fixed reference frame. This transmissibility matrix is in fact a reduced model of the wheel to be implemented in efficient routines for virtual prototyping of vehicle suspensions and the prediction of structure-borne sound transmission to the interior of road vehicles. As shown in Fig. 3, the input to the model is the road texture and a set of eigenvectors and eigenvalues obtained from a FEM calculation. The M-ALE model provides the Green’s functions of the rotating tyre to the contact model and, once the forces are calculated they can be multiplied with the receptance and the transmissibility of the rotating tyre to obtain the tyre vibrations and hub forces respectively. Furthermore, given the tyre response and the contact forces, the amount of energy dissipation and, thus, the rolling resistance can be obtained.

\[\ddot{\eta}(t) + \tilde{\mathbf{D}}(\Omega)\dot{\eta}(t) + \tilde{\mathbf{K}}(\Omega)\eta(t) = \mathbf{Φ}^T\mathbf{f}(t)\]

where \(\eta\) represent the modal coordinates and \(\Phi\) represent the eigenmodes of the tyre which are calculated with the FE tyre model. Therefore the displacement vector in cartesian coordinates is given by \(x = \Phi \eta\). The vector \(\mathbf{f}(t)\) contains the applied forces in the reference frame and \(\Omega\) is the rotating velocity of the tyre. The modified damping and stiffness matrices \(\tilde{\mathbf{D}}\) and \(\tilde{\mathbf{K}}\) are defined as

\[\tilde{\mathbf{D}} = 2\mathbf{P}(\Omega, \mathbf{M}, \Phi) + \mathbf{D}_{mod}\]

\[\tilde{\mathbf{K}} = \mathbf{S}(\Omega, \mathbf{M}, \Phi) + \mathbf{D}_{mod}\mathbf{P}(\Omega, \mathbf{M}, \Phi) + \mathbf{K}_{mod}\]

The mass matrix, \(\mathbf{M}\), is extracted from the FE tyre model. The reduced stiffness matrix \(\mathbf{K}_{mod}\) is a diagonal matrix with elements \(k_{ii} = \omega_i^2\), where \(\omega_i\) are the eigenfrequencies of the tyre. The

Figure 3. Overview of the M-ALE modelling approach.

The dynamic equations of the deformed rotating tyre in a fixed (Eulerian) reference frame is derived applying the M-ALE approach proposed in [17]. The M-ALE equation of motion reads

where \(\eta\) represent the modal coordinates and \(\Phi\) represent the eigenmodes of the tyre which are calculated with the FE tyre model. Therefore the displacement vector in cartesian coordinates is given by \(x = \Phi \eta\). The vector \(\mathbf{f}(t)\) contains the applied forces in the reference frame and \(\Omega\) is the rotating velocity of the tyre. The modified damping and stiffness matrices \(\tilde{\mathbf{D}}\) and \(\tilde{\mathbf{K}}\) are defined as

\[\tilde{\mathbf{D}} = 2\mathbf{P}(\Omega, \mathbf{M}, \Phi) + \mathbf{D}_{mod}\]

\[\tilde{\mathbf{K}} = \mathbf{S}(\Omega, \mathbf{M}, \Phi) + \mathbf{D}_{mod}\mathbf{P}(\Omega, \mathbf{M}, \Phi) + \mathbf{K}_{mod}\]

The mass matrix, \(\mathbf{M}\), is extracted from the FE tyre model. The reduced stiffness matrix \(\mathbf{K}_{mod}\) is a diagonal matrix with elements \(k_{ii} = \omega_i^2\), where \(\omega_i\) are the eigenfrequencies of the tyre. The
reduced damping matrix $\mathbf{D}_{\text{mod}}$ is the projection of the system damping matrix on the retained modes. In general $\mathbf{D}_{\text{mod}}$ can be a full matrix, since there is no fundamental assumption in the formulation that requires this matrix to be diagonal. However, as a first approximation, Rayleigh damping is assumed in [19]. Definitions of the additional stiffness and damping matrices caused by tyre rotation, $\mathbf{S}$ and $\mathbf{P}$, can be found in [15].

In the time domain, the displacement at position $i$ on the tyre as a result of an arbitrary forces at positions $j$ can be determined by the convolution of the forces $f_j$ and the Green’s functions $g_{ij}(t, \Omega)$.

$$x_i(t, \Omega) = \sum_j g_{ij}(t, \Omega) \otimes f_j(t, \Omega) \quad (4)$$

Note that in the above expression the Green’s functions, tyre displacement and contact forces are a explicit function of the rotational velocity $\Omega$, since (4) is expressed in the vehicle-fixed (Eulerian) reference system. These Green’s functions can be determined by solving

$$ij(t) + \mathbf{D}(\Omega)\dot{ij}(t) + \mathbf{K}(\Omega)ij(t) = \Phi_j^T \delta(t) \quad (5)$$

where $\Phi_j^T$ is the $j^{th}$ row of $\Phi$ and $\delta(t)$ represents the Dirac delta function. If this set of equations is solved a semi-analytical expression for the Green’s functions in the Eulerian reference frame can be obtained [18]. These Green’s functions form the boundary impedance condition for the tread layer in the tyre/road interaction model (Fig. 4).

![Figure 4. Schematic overview of the tyre/road model](image)

### 4.2.2 Application to rolling resistance prediction

In [20, 21] a new computationally efficient modeling approach for the prediction of the road texture contribution to rolling resistance is proposed. The large steady state tyre deformations and the small texture induced tyre vibrations are studied separately and the total rolling resistance is approximated as the sum of the smooth road rolling resistance and the road texture rolling resistance (as illustrated in Fig. 5). The smooth road rolling resistance is the energy dissipation due to the large cyclic deformation of the cross section of the tyre. A nonlinear steady-state rolling analysis on a FEM tyre model is used to determine this energy dissipation. The road texture rolling resistance is the additional energy dissipation resulting from road texture induced tyre vibrations. A reduced modal representation is extracted from the FEM tyre model and the M-ALE approach from [17] is used to include the tyre belt as a boundary condition in a tyre/road interaction model.

The main assumption in this approach is that the principle of superposition holds; the total deformation can be expressed as the sum of a large deformation due to the nominal load and (small) deformations due to the road texture and the total force as the sum of nominal load and force variations due to the road texture. In this paper the term road texture includes all wavelengths from micro texture ($< 0.5$ mm) to unevenness ($> 0.5$ m). This implies that the rolling resistance due to contact
area variations caused by the road unevenness is captured in the road texture rolling resistance. Although this approximation would be too coarse if the goal is to improve the tyre design for reduced rolling resistance, it might be sufficiently accurate for the design of low rolling resistance pavements. This expectation is supported by experimental results that show the same dependence of the rolling resistance coefficient for different tyres [8].

The smooth-road rolling resistance is defined as the part of the rolling resistance which is due to the energy losses induced by the large cyclic deformation of the cross-section of the tyre as it enters, travels along and exits the contact patch. This is obviously the main contribution to the total rolling resistance. The energy dissipation in a tyre which is rolling on a smooth road surface can be modeled using a steady state rolling analysis. This analysis uses an Arbitrary Lagrangian Eulerian transformation which removes the explicit time dependency from the problem so that a purely spatially dependent analysis can be performed. The (Eulerian) reference frame moves at the vehicle speed but does not spin along with the tyre. This choice of reference frame allows the finite element mesh to remain stationary so that only the part of the body in the contact zone requires fine meshing. Fig. 6 displays the finite element discretization of the tyre (175 SR14). The simplified model consists of a tyre belt with internal reinforcement bars. The rubber material in the tyre is described by a second order Prony series to model the visco-elastic modulus $E(t)$. The material parameters are condensed from data used by Fraggstedt [9] as explained in [20].

**Figure 5.** Schematic representation of the proposed modeling approach. (a) Base state (b) The smooth road rolling resistance resulting from steady state tyre deformations. (c) The road texture rolling resistance due to texture induced tyre vibrations.

**Figure 6.** Tyre discretization

The road texture rolling resistance is defined as the additional energy dissipation resulting from
road texture induced contact force variations and tyre vibrations. Based on the M-ALE approach from [17], a tyre/road interaction model is developed to determine these contact force variations. Fig. 4 presents a schematic overview of the tyre/road interaction model.

The model consists of three layers:

- Dynamic response of the deformed rotating tyre: Green’s functions are used to represent the deformed rotating tyre [18]. These Green’s functions serve as a boundary impedance condition.
- Tread dynamics: The tread dynamics are modeled using a linear spring damper system.
- Contact mechanics: The contact mechanics between the tread blocks and the road surface are modeled using a nonlinear stiffness function which accounts for the indentation of the tread block by the road asperities [2].

The tyre is loaded with an axle load of \( N_{\text{axle}} = 4100 \) N and pressed against a rigid smooth road surface. Subsequently, a steady state rolling analysis is performed at vehicle speeds, \( v \), ranging from 20 to 100 km/h. At 80 km/h the RRC equals approximately 0.0135, which exceeds the expected values reported in literature. This result is discussed in this section and the influence of the material parameters and modeling simplifications is illustrated.

The tread layer is modeled as regularly spaced tread blocks represented by an array of spring-damper systems (Fig. 4). In a first approximation frequency independent viscous damping is used to model the tread losses, but more complex models will be developed in the future. The details of the implementation and parameter data used can be found in [20].

The contact stiffness between the tread blocks and the road surface is modeled by a nonlinear spring to account for small wavelength texture components following the approach presented in [2]. This approach uses a scan of the geometry of the road surface, the elastic properties of the tread compound and a model of a flat circular punch indenting an elastic layer. This results in an approximate stiffness function that is unique for every pair of contact elements. Although in [20] only 2D texture profiles are considered, the model can easily be extended to be used with full 3D texture data [20].

The power dissipated in the tyre due to the interaction between tyre and road texture can be determined with the following equation

\[
P_{\text{dis}} = \frac{1}{T} \sum_{i=1}^{C_n} \int_0^T F_i(t)\dot{x}_i(t) dt, \tag{6}
\]

where the time interval \( T \) represents the time of one tyre revolution in which the averaged total contact force has converged to the desired load. Furthermore, \( P_{\text{dis}} \) is the dissipated power, \( C_n \) represent the total number of contact nodes in the contact patch, \( F_i(t) \) the contact force at contact point \( i \) and \( \dot{x}_i(t) \) the velocity at the same position. The dissipated power is related to the rolling resistance through

\[
RRC = \frac{P_{\text{dis}}}{N_{\text{axle}} v}, \tag{7}
\]

with \( N_{\text{axle}} \) the axle load and \( v \) the vehicle velocity. Finally, combining (7) and (6) the contribution of road texture to the rolling resistance coefficient can be obtained.

The rolling resistance coefficient for 30 road surfaces with different texture properties from the test site at Kloosterzande (The Netherlands) is calculated with the model described above and compared to measurements performed using a trailer from the University of Gdansk, Poland. The measurements are taken at a velocity of 80 km/h and an axle load of 4100 kg. Further details on these measurements and the road texture measurements can be found in [8]. The 30 road surfaces can be divided into six road structure categories shown table 1.
Table 1. Road structure categories

<table>
<thead>
<tr>
<th>Pavement type</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>International standardized road surface</td>
<td>ISO</td>
</tr>
<tr>
<td>Stone Mastic Asphalt</td>
<td>SMA</td>
</tr>
<tr>
<td>Dense Asphalt Concrete</td>
<td>DAC</td>
</tr>
<tr>
<td>Thin Layered Asphalt</td>
<td>TLA</td>
</tr>
<tr>
<td>Single layer Porous Asphalt Concrete</td>
<td>PAC</td>
</tr>
<tr>
<td>Double layer Porous Asphalt Concrete</td>
<td>DPAC</td>
</tr>
</tbody>
</table>

In the following the root mean square (RMS) texture depth is used to quantify road texture in a single value (see [8] for a discussion on possible indicators). Fig. 7 shows the rolling resistance coefficient (RRC) as a function of the texture depth $RMS_{tex}$ for a traveling velocity of 80 km/h and a nominal load of 4100 kg. The dashed line corresponds to a linear regression fit of the calculated RRC and the solid line is the linear regression fit of the measured RRC.

![Figure 7](image_url)

**Figure 7.** Comparison of predicted (dashed) and measured (solid) rolling resistance coefficient vs. RMS texture depth on 30 different test tracks at 80 km/h

There is a clear correlation between road texture and rolling resistance. Rolling resistance increases linearly with texture depth and a decrease in $RMS_{tex}$ of 1mm results in a decrease in rolling resistance of approximately 8%. The trends in the numerical and experimental results match despite the rough estimation of the model parameters. Due to the excessively high value of the smooth-road RRC, the predicted RRC vs. RMS texture (dashed) line is shifted upwards with respect to the experimental (solid) line. The smooth-road RRC is very sensitive to the rubber material properties used in the FE model. This is illustrated below by studying the influence of variations on the material parameters.
4.2.3 Influence of material damping on the smooth-road rolling resistance

Rubber is a visco-elastic material with frequency dependent characteristics which can be modeled by a Prony series as follows,

\[ E(t) = E_0 \left( 1 - \sum_{i=1}^{n} p_i (1 - e^{-\frac{t}{\tau_i}}) \right) \]  

(8)

where \(E_0\) is the instantaneous elastic modulus, \(\tau_i\) are relaxation times and \(p_i\) are the modulus ratios defined as 

\[ E_\infty = E_0 \left( 1 - \sum_{i=1}^{n} p_i \right) \]

with \(E_\infty\) the long-term elastic modulus.

The structure of a tyre is a complex combination of reinforcement chords and rubber, where the properties of the rubber compounds are different for different parts of the tyre cross-section. In this work a single rubber compound is used for the whole tyre. The material data is obtained from experiments performed in [9] to characterize the viscoelastic properties of a tread compound. The data from [9] is scaled to ensure that the eigenfrequencies predicted by the FE model match the experimentally determined values as shown in [15].

<table>
<thead>
<tr>
<th>(E_0)</th>
<th>(p_1)</th>
<th>(p_2)</th>
<th>(\tau_1)</th>
<th>(\tau_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3e6 [Pa]</td>
<td>0.487 [-]</td>
<td>0.137 [-]</td>
<td>9.96e-5 [s]</td>
<td>1.20e-3 [s]</td>
</tr>
</tbody>
</table>

The parameters of the second order Prony series obtained are summarized in table 2 and the resulting real and imaginary parts of the elastic modulus are plotted in Fig. 8 together with the scaled experimental data from [9] (thick solid line). In order to study the influence of the Prony series parameters on the smooth-road rolling resistance, the relaxation times \(\tau_i\) are lowered to 75% and 50% of the originally fitted values. The resulting real and imaginary of the elastic modulus are also given in Fig. 8.

![Figure 8](image_url)

**Figure 8.** Real (left) and imaginary (right) component of the shear modulus for three values of fitted relaxation times. Experimental data (dashed), Original fit (black), 0.75xOriginal fit (blue), 0.5xOriginal fit (red).

It can be seen that the shear modulus obtained when the relaxation times are 75% of the original values is in good agreement with the experimental data, so these values could as well be used in the rolling resistance calculation. When the relaxation times are 50% of the original values, the resulting frequency shift of the shear modulus is equivalent to a temperature increase of approximately 10 °C, which is a relatively small temperature change compared to the difference between the ambient
temperature and the tyre temperature in rolling conditions. In Fig. 9 the influence of the above variations of the relaxation times on the predicted rolling resistance is shown.

![Figure 9. Comparison between measured and calculated rolling resistance versus RMS texture depth for three values of the relaxation time: Original fit (black), 0.75xOriginal fit (blue), 0.5xOriginal fit (red).](image)

It can be seen that, as one would expect, the predicted rolling resistance decreases as the relaxation times decrease. When the relaxation time is 50% of the originally fitted values the predicted rolling resistance agrees almost perfectly with the measured rolling resistance. However, one should realize that this agreement is completely meaningless and it is shown to stress the fact that accurate knowledge of the rubber properties and models of the rubber behavior are essential for a reliable prediction of tyre response and rolling resistance.

5. Conclusions

Road traffic is a serious environmental problem since it originates both noise and air pollution. Understanding tyre road interaction and how to design tyres and roads to minimize noise and CO2 emissions are an urgent need. Although, plenty of work has been done to understand and predict the influence of tyre and road parameters on noise generation, there is still little understanding on how road parameters influence rolling resistance and how to design tyre/road systems to minimize both noise and rolling resistance. There is a need for simplified tyre/road interaction models that capture the key aspects of the interaction and can be used as a design tool for optimized road designs.

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Bibliography


