Tyre-road Interaction: a holistic approach to noise and rolling resistance

Tiago Vieira

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KTH Royal Institute of Technology
School of Architecture and the Built Environment
Department of Civil and Architectural Engineering
Division of Building Materials
SE-100 44, Stockholm, Sweden

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Abstract

Energy dissipation, fuel consumption, real-estate property prices and health issues are some of the aspects related to the tyre/pavement interaction and its functional properties of rolling resistance and noise. The first two aspects are affected by the tyre/road interaction as energy is dissipated mostly by hysteretic losses as the tyre is subjected to dynamic deformations when contacting the pavement surface, revealing the relevance of rolling resistance as a result of this interaction. The other effect of this contact system that is analysed in this thesis is noise. Excessive noise exposure leads to a decrease in real-estate property values and even health issues such as increased blood pressure, sleep disturbance, cognitive impairment in children, among others.

To mitigate such issues, a good understanding of the underlying causes is crucial and therefore a holistic approach was used to analyse the contact interaction in a more comprehensive way, encompassing the pavement, tyre, environmental and contact media (such as water, snow and contaminations). This leads to the importance of considering variables such as temperature or tyre rubber hardness when analysing the results presented here. Both noise and rolling resistance were analysed after subjecting the contact system to controlled interventions in one variable while maintaining the other variables constant and then comparing to a reference condition. In the first part of the investigative work, different tyres were tested while maintaining other variables such as pavement, environment and contact media constant or to reference values. This

allowed an evaluation of the impact of winter tyres on noise and rolling resistance. In the second part of the investigation, an intervention in the pavement surface was applied while maintaining the other variables to constant or reference values. This allowed an evaluation of the impact of surface grinding as a technique to optimize the pavement surface, reducing noise and rolling resistance.

Results from the first part quantified how noisier studded tyres are in comparison to non-studded tyres, yet no substantial difference in rolling resistance was found between the two tyre groups. The second part of the study revealed the potential of the horizontal grinding technique as means to reduce noise and rolling resistance, having a limitation, however, on the duration of such effects, especially for Swedish roads where studded tyres are used.

Keywords
Pavement, surface, texture, noise, rolling resistance, tyre

Sammanfattning

Energiförluster, bränsleförbrukning, fastighetspriser och hälsoproblem är några av de effekter som följer av däckens interaktion med vägytan och som relaterar till de funktionella egenskaperna för rullmotstånd och buller. De första två effekterna uppkommer av väg- och däckinteraktionen eftersom energi förbrukas mestadels genom hysteresförluster när däcken utsätts för dynamiska deformationer vid kontakt med vägytan, vilket innebär att denna interaktion har stor betydelse för energiförbrukningen och därmed eventuella avgasutsläpp. Den andra effekten av däck/vägkontakten som analyseras i avhandlingen är bulleremission. Alltför hög bullerexponering intill boendemiljöer leder till minskning av fastighetspriser och även till hälsoproblem såsom ökat blodtryck, sömnstörning, kognitiv försämring hos barn, med mera.

För att mildra sådana problem, är det avgörande att ha en god förståelse av de bakomliggande orsakerna, och därför används här ett helhetsgrepp för att genomföra en mer omfattande analys av interaktionen. Analysen inkluderar egenskaper hos vägytan, däcken, omgivande miljö samt kontaktmedier (vatten, is och förorenande skikt). Dessutom innebär det att det är viktigt att inkludera till exempel temperatur och däckgummis hårdhet i analysen. Både bulleremission och rullmotstånd har analyserats efter att på ett kontrollerat sätt ha varierat en viss variabel medan de andra variablerna hållits konstanta, och sedan jämföra resultaten med referensförhållandet. I den första delen av denna undersökning provades flera olika däck medan andra variabler såsom vägytan, miljö- och kontaktmedier hölls konstanta eller varierade på ett kontrollerat sätt. Detta möjliggjorde i detta fall en utvärdering av effekterna av olika vinterdäck på rullmotstånd och bulleremission. I den andra delen av avhandlingen beskrivs effekter av en förändring av vägytan, utförd genom att slipa bort topparna i vägtexturen, medan de andra

variablerna hålls konstanta. Detta möjliggjorde en utvärdering av effekterna på bulleremission och rullmotstånd av slipning av vägytan.

Resultaten av första delen kvantifierar bullerökningen vid användning av dubbade vinterdäck i jämförelse med odubbade vinterdäck. Några betydande skillnader i rullmotstånd hittades däremot inte mellan de två däckgrupperna. Den andra delen av texten visar på potentialen av horisontell slipning för att minska buller och rullmotstånd, dock är varaktigheten av sådana effekter mycket begränsad; särskilt för svenska vägar där dubbade vinterdäck används.

Nyckelord
Vägbeläggning, vägyta, textur, buller, rullmotstånd, däck

Preface

This thesis is intended to provide an overview of how tyre and pavement interact and how this interaction is related to noise and rolling resistance properties. The holistic approach proposed here is intended to provide a more comprehensive perspective on the topic that is wide and should be analysed simultaneously with other relevant tyre-pavement functional properties, such as friction and the emission of non-exhaust particles. The latter topic is analysed by my fellow PhD candidate, Joacim Lundberg. Moreover, this holistic approach is expected to contribute to procurement processes as the Swedish Transport Administration can apply the knowledge on functional performance of pavements to develop requirements on road surfaces based on functional characteristics.

This thesis contains both a literature review on the topic of tyre-road interaction with focus on noise and rolling resistance and an investigative research part. By no means, the literature review presented here is intended to be exhaustive, but rather give an overview on the topic by presenting relevant aspects to this surface interaction. The text begins with an introductory chapter, in which the background, the objectives and the method of investigation are presented. Chapter 2 consists of a brief discussion on surface interaction and is followed by chapter 3 which deals specifically with tyre-road interaction. The functional aspects of noise and rolling resistance are then discussed in chapters 4 and 5, respectively. Chapter 6 contains a discussion on some strategies to optimize noise and rolling resistance and leads to chapter 7, which contains a summary of the papers appended to this thesis. Chapter 8 finalizes this work with conclusions.

There are three appended papers in this thesis. The first two deal with the usage of winter tyres and how their performance, with respect to noise and rolling resistance, differs in comparison to other types of tyres. This is,

therefore, a relevant topic for Sweden and other cold-climate regions. The third paper deals with surface optimization and indicates the potential of using the horizontal grinding technique as means to improve noise and rolling resistance characteristics of pavement surfaces.

Linköping, February 2018
Tiago Vieira

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List of appended papers

This licentiate thesis is based on the following scientific articles:

Paper A

SANDBERG, U., MIODUSZEWSKI, P.; EJSMONT, J.; **VIEIRA, T.** (2016) Noise and rolling resistance of various types of winter tyres compared to normal car tyres. In: *45 Inter-Noise Conference*, Hamburg, pp. 1737-1746.

Tiago Vieira performed part of the analysis under the supervision of Ulf Sandberg.

Paper B

VIEIRA, T., SANDBERG, U. (2017) Acoustical performance of winter tyres on two in-service road surfaces: a frequency spectrum analysis and comparison. In: *46 Inter-Noise Conference*, Hong Kong, pp. 6825-6836.

Tiago Vieira performed the analysis under supervision of Ulf Sandberg

Paper C

VIEIRA, T., SANDBERG, U. (2018) Negative texture, positive for the environment: results of horizontal grinding of asphalt pavements. In: *97 Transportation Research Board Annual Meeting*, Washington D.C.

Tiago Vieira contributed to the analysis under supervision of Ulf Sandberg

Other relevant papers

The following papers were not appended to this thesis due to content overlapping or scope limitations.

VIEIRA, T., SANDBERG, U., MIODUSZEWSKI, P., EJSMONT, J. (2016) Noise and rolling resistance properties of various types of winter tyres compared to normal car tyres: results from measurements 2015. In *Baltic Nordic Acoustics Meeting,* Stockholm

SANDBERG, U., GOUBERT, L., **VIEIRA, T.** (accepted for publication) (2018) New measures for characterization of negative surface textures. In: Symposium on Pavement Surface Characteristics: SURF 2018, Brisbane.

Terminology

Abbreviations

ASTM	American society for testing and materials
CPB	Controlled Pass-By
CPX	Close Proximity (method)
CTM	Circular Track Meter
CTM	computer tomography
DAC	Dense Asphalt Concrete
EU	European Union
ISO	International Standardization Organization
LCA	Life-cycle analysis
MHR	Mean Hydraulic Radius
MPD	Mean Profile Depth
MTD	mean texture depth
PERS	Poroelastic road surface
PIARC	Permanent International Association of Road Congresses
RMS	root mean square
SMA	Stone Mastic Asphalt (Stone Matrix Asphalt in USA)
SPB	Statistical Pass-By (method)
SPL	Sound Pressure Level
TUG	Gdansk University of Technology
VTI	Swedish National Road and Transport Research Institute
WHO	World Health Organization

Latin Symbols

A	surface area
A_o	nominal contact area
C_a	temperature correction factor based on air temperature
C_c	temperature correction coefficient
CL	texture profile centreline
C_r	temperature correction factor based on pavement surface temperature
C_z	height-difference correlation function
D	dimension
E	Elasticity Modulus
fc	pressure in the tyre/pavement contact area
F_c	tyre/pavement contact force
F_N	normal force
F_r	rolling resistance force
F_x	horizontal reaction force at the contact patch
G	energy release rate
K_u	kurtosis of a surface profile
L	texture profile length
L_c	tyre/pavement contact length
p	pressure
P	Average texture channel perimeter
$p(z)$	amplitude density function
PFT	portable friction tester
p_I	emitted sound wave
P_{in}	Power input
$PM10$	particles with aerodynamic diameter smaller than 10 µm
P_{out}	Power output
p_R	reflected sound wave
R_a	centreline average
RR_c	rolling resistance coefficient
S_k	skewness of a surface profile

SK_u	kurtosis of a surface area
SS_k	skewness of a surface area
t	time
T	torque
$U_{elastic}$	elastic strain energy
U_{IF}	interface energy
U_{total}	Total Energy
v	linear velocity
W_{adh}	work of adhesion
x	axis parallel to the surface profile or to the surface plane
y	axis within the pavement surface plane, normal to x and z
z	axis normal to the pavement surface profile or to the surface plane

Greek Symbols

Δ_c	distance between reaction force and tyre symmetry axis
Π	potential energy
δ	viscoelastic parameter for the phase angle
θ	absolute water viscosity
λ	wavelength
μ_{adh}	Friction coefficient due to adhesion
μ_{hyst}	Friction coefficient due to hysteresis
ω	angular velocity

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1. Introduction

The pavement surface is where the vehicle interacts with the road infrastructure. It plays a key role in pavement functional properties, including, but not limited to rolling resistance and noise. This chapter provides a brief introduction on some of the relevant aspects related to tyre-pavement interaction, including energy dissipation, economic impacts, public health, environmental and social impacts.

Tyre-road noise and rolling resistance are related to energy dissipation mechanisms resulting from the tyre interaction with the road surface. To illustrate how relevant energy dissipation is for a road vehicle, consider the calculations performed by Holmberg et al. (2012) on the global energy consumption caused by friction in passenger cars. From the energy obtained from fuel, about 11.5 % is lost as rolling resistance and only 21.5 % is left to actually move the vehicle.

Pavement engineering directly affects the rolling resistance component, as it is a result of the tyre rubber dissipating energy by contacting the pavement surface asperities. Still according to the same authors, a 10 % decrease in rolling resistance corresponds to a 2 % decrease in energy consumption. To have a glimpse of how relevant optimizing the road surface is, regarding only energy savings, one may consider the following information: (i) the worldwide energy consumption to overcome friction in passenger cars, for 2009, was 208 000 million litres of fuel, including both gasoline and diesel, (ii) one of the main friction loss sources is the tyre-road contact. Therefore, optimizing the tyre-road contact interaction and reducing unwanted energy dissipation mechanisms has a significant energy saving potential.

Regarding the economic impacts of noise, one direct aspect is the property prices, that are sensitive to noise exposure. Andersson et al. (2010) modelled the property prices in relation to traffic noise levels. They used noise exposure represented by the full 24 hours equivalent noise level measured in 2004, and a database of property sales in the municipality of Lerum, in western Sweden, between 1996 and 2006. The noise values were modelled as affecting the natural logarithm of the property prices. The results indicate that a 1 dB noise increase in road noise decreases the property prices by 1.7 %.

Still addressing the economic impacts of traffic noise, Sandberg (2001) made some estimations on the costs and benefits of low noise tyres and road surfaces. The costs related to tyre-road noise within an average lifecycle of 4 years were appraised at USD 90 per year for each tyre. This value is comparable to the approximate cost of a commercial car tyre in Sweden, according to the same author. Considering property devaluation caused by road traffic noise in Sweden, the estimated cost was USD 330 million per year. In the same paper, the costs and benefits of low noise road surfaces were calculated with the Swedish monetary evaluation of noise exposure. Comparing the reference case of a SMA16 (maximum chipping size of 16 mm) to a SMA8, the calculated benefits, in USD, surpasses the costs by 106 %. Comparing the reference SMA16 pavement to a porous asphalt, the surpassing beneficial value is 167 %. The benefits of the analysis are the reduced dweller's noise exposure.

Exposure to undesirable noise levels is a relevant public health issue within the European Union (EU). When considering traffic noise only, 40% of the EU population is exposed to an equivalent sound pressure level (SPL) higher than 55 dB(A) in the daytime, and 20% is exposed to SPL levels higher than 65 dB(A) (World Health Organization, 2011). Considering the Swedish population, approximately 2 million people are exposed to average noise levels exceeding the outdoor national guideline value of 55 dB (A) (Bluhm and Eriksson, 2011). Regarding road traffic noise only, approximately 1.7 million people are exposed to noise levels exceeding the same guideline value (Eriksson et al., 2013), which corresponds to approximately 18% of the Swedish population.

After analysing large-scale epidemiological studies that linked environmental noise exposure with adverse health effects, the World Health Organization (WHO) indicated that environmental noise should be considered a public health issue (World Health Organization, 2011). The same report also indicated that there is a positive correlation between road traffic noise levels and increased risk of ischaemic heart diseases. Other health issues related to traffic noise include high blood pressure, cognitive impairment in children, sleep disturbance, among others.

The tyre also plays a fundamental role in functional outputs of the tyre-road contacting system. Even though the interaction itself and the tyre are both further discussed in the forthcoming chapters, it is important to notice the relevance of this element. Polymers, consisting of natural or synthetic rubber, are the backbone of tyre rubber compounds (Gent and Walter, 2005). Considering that the demand for new tyres is increasing, and that approximately 1.4 billion tyres are sold worldwide each year (Lo Presti, 2013), and that rubber material does not degrade on its own (Fang et al., 2001), it is possible to comprehend the relevance of an environmental impact resulting from tyre waste. Approximately 17 million tonnes of tyres reach the end of their useful life every year. A tyre that has reached its end-of-life cannot be used for its original propose (World Business Council for Sustainable Development, 2010).

Finally, regarding social impacts, the World Health Organization found reliable correlations between chronic noise exposure and children's cognition (World Health Organization, 2011). Exposure to improper noise levels leads to a negative effect on children learning process encompassing reading comprehension, memory and attention. The aforementioned report also states that improper exposure to noise could have a lifelong effect on children's cognitive development. It is also interesting to have a more comprehensive approach to noise when considering social aspects. Otsuka and Sandberg (2009) applied the concept of soundscape to describe several sound art technological devices that were designed to improve the acoustical environment. The concept of soundscape allows a wider interpretation of the acoustical environment, as, according to this approach, both wanted to sound and unwanted sound are included in the

soundscape. In this sense, it is desirable to add sounds that contribute to the social wellbeing to the increasing noise exposure levels. In addition, on social aspects, undesirable sound, *i.e.* noise, maybe become less acceptable when it is not clearly linked to obvious or urgent needs (Otsuka and Sandberg, 2010). In this sense, as technology develops further, the demands for quieter roads, quieter tyres, quieter vehicles, should grow further.

It is also interesting to note some concerns about some modern cars becoming "too quiet" and posing a risk to pedestrians. For this reason, a proposed regulation is soon coming into force, requiring the addition of sound to quiet cars so that pedestrians could be aware of them. As no clear causal relationship could be established between quiet cars and pedestrians injuries, it is suggested that reducing noise levels is a much better way to increase health and safety aspects regarding transportation (Sandberg, 2012a).

Within the Swedish context, this thesis is in line with the National Plan for the Transportation System 2018-2029 as the plan predicts noise reduction for 100 000 people, originating from the transportation system as a result of pavement- and rail-related improvements (Trafikverket, 2017).

From this introductory discussion, it can be noted that tyre-road noise and rolling resistance are relevant pavement functional aspects, which, when properly addressed, contribute to an improved environment, including energy savings, economic savings, public health improvement, environmental and social enhancements.

1.1. Objectives

This thesis has the following objectives:

- Achieve a fundamental holistic understanding of the tyre-road contact interaction with regard to noise and rolling resistance.
- Analyse how noise and rolling resistance are affected by different conditions: with the usage of studded tyres

- Study the technique of surface grinding as a mean to reduce noise and rolling resistance

Furthermore, there is also the objective that this thesis is meant to represent a stepping stone on functional performance of pavements with respect to noise and rolling resistance and how it may be incorporated in the procurement processes.

1.2. Methodology

In order to achieve the aforementioned objectives a literature review was carried out, gathering together relevant aspects of the tyre-road noise interaction with focus on noise and rolling resistance. Additionally, field measurements were carried out to evaluate noise and rolling resistance of in-service road surfaces. Unless otherwise stated the noise measurements were carried out with the Close Proximity method, using a measurement trailer. Rolling resistance was similarly measured with a measurement trailer. Additionally, the road surface texture was characterized by a laser scanner and the friction values were also measured.

1.3. Limitations

The major limitations of this licentiate thesis are related to the measurement methods used. Noise, rolling resistance and texture measurements have limited precision and those are documented in the respective standards or proceedings. Further limitations include the tested scenarios, which include variables like tested temperature and other environmental conditions.

2. Surface interaction

2.1. Some fundamental issues

When analysing surface contacts, it is important to initially define a tribological system, contacting system, or, in short, a tribo-system. A tribo-system contains three elements: (i) a pair of contacting surfaces, namely a body and a counter-body, (ii) a contact medium, also known as an interfacial medium, (iii) an environmental medium (Czichos et al., 2010). As an example, the tribo-system to evaluate tyre-pavement interaction can be defined as follows: (i) the pavement and the tyre surface are the body and counter-body, respectively, (ii) a water layer on the pavement surface prevents full contact between the two surfaces, acting as a contacting medium, (iii) the previous elements are surrounded by air at a given temperature and humidity. The formal step of defining the contacting system is crucial, as it helps to identify relevant variables. For instance, not carefully defining the system and including the environmental medium, could eventually lead to neglecting relevant temperature and humidity effects on the tyre-road interaction.

The contacting surfaces, for instance, a pavement surface contacting a tyre, have asperities in different scales, or wavelengths, which affect the surface interaction in several different ways. Two examples of pavement surfaces are presented in Figure 1, one having a so-called positive skewness and the other having a negative skewness (see definition in chapter 3). The skewness parameter has a significant effect on the resulting functional performance and will be further discussed in chapter 3. The relationship between wavelength and pavement functional variables will also be explored in chapter 3. For this discussion, it is relevant to note that the two

rough surfaces have different characteristics, and this will affect the functional performance.

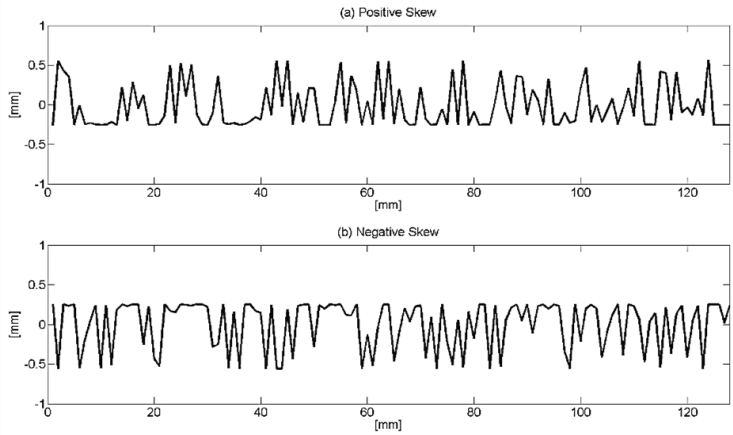

Figure 1 – Two different surface profiles indicating two different types of surfaces, one with positive skewness and another with negative skewness

The effect of this mechanical interlocking poses mechanical resistance to the relative motion between the two surfaces. This resistance, known as hysteretic friction, imposes deformations on both the body and the counter-body. In the specific case of a rubber tyre contacting the road surface, the road asperities impose mechanical deformation on the rubber. Due to the rubber viscoelastic nature, cycles of deformation result in energy dissipation, which is directly dependent on rubber viscoelastic properties, and the pavement roughness.

Another important energy dissipation mechanism that takes place when two surfaces interact with each other is the adhesive friction. This energy dissipation mechanism is related to adhesive forces which may be described, from a macroscopical point of view, as forces that provide shear resistance to the contacting asperities, also opposing relative motion between surfaces. From a microscopical point of view, adhesive forces may be described as molecular attraction forces that molecular bonds are cyclically formed and broken during the surfaces relative motion.

When rubber is cyclically deformed and indented by the pavement texture, or when adhesive bonds are cyclically broken, energy is dissipated

by noise or heat. The energy dissipation mechanisms mentioned above, *i.e.* hysteresis and adhesion, are, therefore, closely connected to noise generation mechanisms. For this reason, a brief review and formulation of these mechanisms is presented in the following subchapter.

2.2. Hysteresis as an energy dissipation mechanism

Hysteresis is an energy dissipation mechanism linked to the mechanical interlocking between surfaces. This chapter aims at providing a general view of the energy dissipation phenomena, which should still be comprehensive enough to be relevant for the complex phenomena involved in the tyre-road interaction. For this purpose, the author of this document will use Moore's formulation for elastomers and rubbers (Moore, 1975). Following this approach, when an elastomer or rubber body contacts a rough surface, this body deforms, draping or enveloping the asperity summits. With the relative motion between surfaces, the elastomer or rubber material is not able to instantly deform itself, perfectly enveloping the asperities, due to viscoelastic effects. For this reason, it accumulates on the initial flanks of the asperities and does not come into full contact to the posterior flanks. Considering that a certain amount of energy is necessary to deform the elastomer or rubber material over the asperities, and this energy is dependent on the asperity shape, it is possible to derive equation 1, which estimates the friction coefficient, μ_{hyst} due to the hysteresis effects. E and δ are the elastomer or rubber viscoelastic parameters, p is the pressure, γ is the packing factor, C and n are constants, calculated as a function of asperity shape.

$$\mu_{hyst} = 4C\gamma \left(\frac{p}{E}\right)^{n} \tan(\delta) \tag{1}$$

It is notable that the dissipated energy due to hysteresis phenomena, even with a relatively simple theory, is dependent on the elastomer or rubber material viscoelastic properties, and the surface parameters. This is in agreement with previous statements within this text, indicating the need to consider parameters from the tribological system, including surface roughness parameters and environmental medium parameters.

2.3. Adhesion as an energy dissipation mechanism

Adhesive energy losses are related, to forming and breaking bonds between surfaces. Several specific mechanisms may be responsible for adhesive forces, such as: (i) chemical, (ii) dispersive, (iii) electrostatic, and (iv) diffusive (Brach, 2006). Discussing sources of adhesive forces is not within the scope of this text, therefore, this dissipative mechanism is simply described here, without detailing which situation it might be more relevant for the tyre-road interaction. Again, Moore's formulation is presented here to fit the general purpose of this chapter (Moore, 1975). This formulation considers a stick-slip phenomenon, as indicated in Figure 2. Initially, a polymeric material is considered to be moving over a rigid surface. An adhesive bond is created in point A, the stick-phase, as the relative motion between the polymer and the rigid surface continues. The relative motion imposes a deformation on the polymer, which results in an increased stress in the junction between the two surfaces. When the junction is finally broken, a portion of the energy, which was stored as elastic deformation energy, is recovered, as point A slips over the rigid surface. The remaining energy, which could not be recovered, is lost in dissipative processes, such as heat and noise.

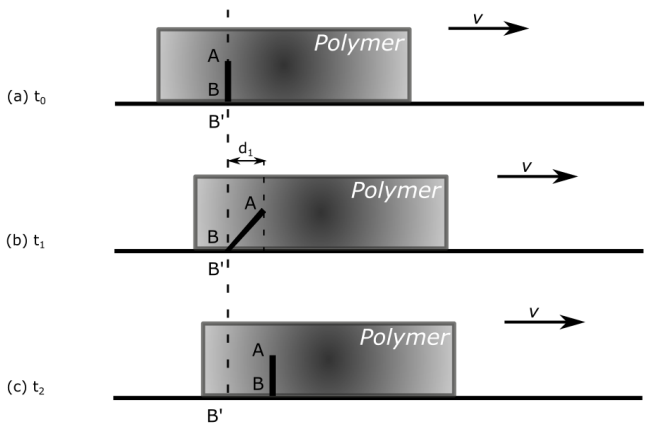

Figure 2 - Adhesion, (a) the adhesion junction is formed, (b) the shear strength holds the adhesive junction imposing a deformation on the rubber material, (c) adhesive junction broken (based on MOORE, 1975)

By modelling the polymer or rubber material with a Voigt viscoelastic model, the energy loss due to adhesive forces may be estimated by the adhesive coefficient of friction on equation 2, where r and B are proportionality constants, p is the contact pressure, E and $\tan(\delta)$ are viscoelastic parameters, and Φ' is defined as the ability to generate adhesion.

$$\mu_{adh} = B\Phi' \frac{E}{p^r} \tan(\delta) \tag{2}$$

It is noteworthy that adhesive effects are also dependent on the material viscoelastic parameters, yet, in opposition to the hysteretic losses, the adhesive losses are directly proportional to the material modulus. The dependence on the rigid surface, which represents the pavement surface, in this case, is included in the parameter Φ', which is the ability to generate adhesion. The later parameter is dependent also on the existence of a contacting medium which may suppress adhesive forces, on the surface texture, which may increase.

Another interesting approach for the adhesive effects is to calculate the energy balance for an asperity junction bound by adhesion. The energy balance presented here is based on the work of Maugis and Barquins (1978). For this calculation, three energy portions are considered: (i) elastic strain energy, $U_{elastic}$, (ii) the potential energy, Π, and (iii) the interface energy, U_{IF}. The resulting energy balance is presented in equation 3.

$$U_{total} = U_{elastic} + \Pi + U_{IF} \tag{3}$$

By modelling the separation between surfaces as a crack propagation in mode 1, the resulting equilibrium condition is presented in equation 4. G is the energy release rate, which is the energy dissipated for a unitary area created by fracture, or, in this case, surface separation. $W_{adh\ 1\ 2}$ is the work of adhesion between surfaces 1 and 2. Work of adhesion is the work that should be done in order to separate two unit area surfaces bond by adhesive forces (Deladi, 2006).

$$G = W_{adh\ 1-2} \tag{4}$$

When an energy-unbalance occurs, changes in the contacting area take place in order to resolve the unbalanced term ($G-W_{adh\ 1-2)}$. The energy required to create a new infinitesimal surface is calculated by $W_{adh\ 1-2}dA$, and the energy released by bonding two infinitesimal surfaces together is GdA. When the condition of bonding two surfaces together is energetically more favourable, $G<W_{adh}$, the contact area is increased. These changes in the contact area may be interpreted as one possible reason for rubber micro-displacements when contacting the road, and thus, may be connected to noise generation mechanisms, such as the noise generation mechanism of stick-slip.

In this chapter, some of the relevant parameters for surface interaction were presented. Even with a brief formulation of dissipation mechanisms, it is possible to demonstrate de relevance of a systematic approach to tyre-road interaction. This means that one should consider surfaces parameters, such as roughness, material parameters, such as modulus and phase angle, temperature, among others.

3. Tyre-road contact interaction

A tyre contacts the pavement surface in different conditions, like free rolling, breaking, accelerating or cornering. The rubber portion that is contacting the pavement surface, within the contact patch, has a complex behaviour, which, even on a free rolling tyre in dry conditions, includes slipping, relatively to the road surface. The contact patch also has the key role of transferring the vehicle load to the pavement infrastructure. To illustrate and characterize the contact patch, consider a tyre rolling on a pavement surface in dry conditions, i.e. no water film or interfacial medium between the tyre and the pavement surface. Under the described condition, according to Moore (1975), the portion near the leading edge will have no relative slip to the pavement surface, whereas the portion near the trailing edge will have slip relative to the pavement surface.

Figure 3 shows a tyre rolling with angular velocity ω, linear velocity v, subjected to a normal load F_N. The pressure in the contact area is denoted by *fc* which is distributed along the contact patch L_c, and the resulting force in the vertical direction is F_c, which is located at a distance Δ_c from the tyre symmetry axis and thus from the normal force. Note that the pressure distribution in the contact patch is not constant. The pressure is higher near the leading edge and decreases as it approaches the trailing edge. Such asymmetrical pressure distribution was described by Moore (1975).

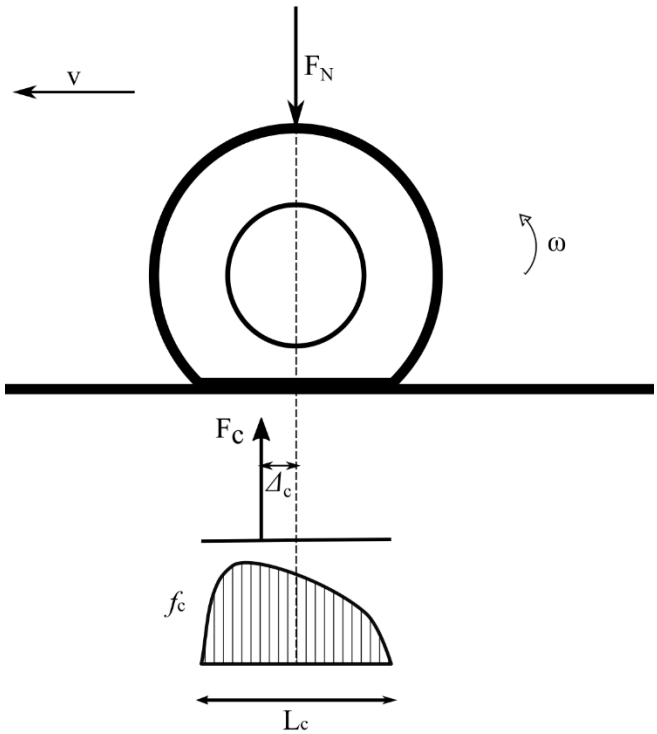

Figure 3 - Tyre/pavement contact under dry conditions

Consider now the case of a water film acting as a contacting medium, preventing the tyre to fully contact the pavement surface. This case is illustrated in Figure 4, which indicates distinct regions in the tyre/pavement contact patch. Before describing each region in the contact patch for wet conditions, it is important to distinguish two different interaction cases: (i) thin water film, (ii) thick water film. On a thin water film condition, the contact between the pavement surface and the tyre is lost if water fully invades the contact patch, resulting in the so-called viscous-hydroplaning. In the second case, when a thick water film is present, the impact region between the tyre and the pavement, generates an upward thrust, which is represented in Figure 4. This upward thrust is a result of the tyre impact, compressing the thick water film, generating a

lifting force, which prevents contact between the tyre and the pavement. This lifting force reduces the contact area between the pavement and the tyre, and in a limiting case, generates the so-called dynamic hydroplaning (Claeys et al., 2001).

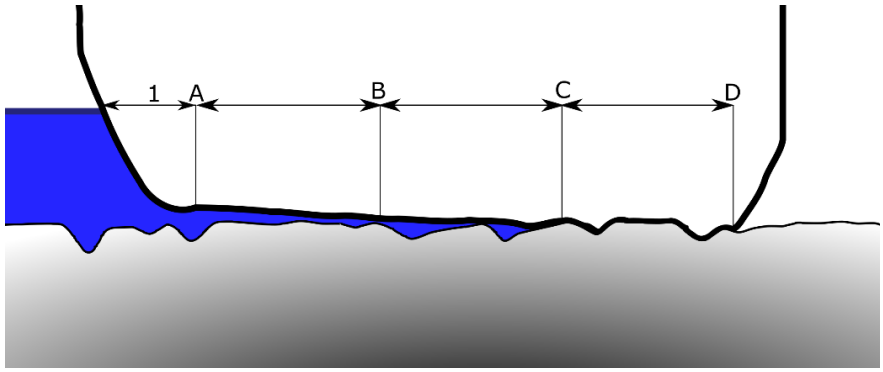

Figure 4 - Tyre/pavement contact under wet conditions according to Moore (1975), zone 1 is subjected to the upward thrust zone, segment A-B corresponds to the squeeze film zone, segment B-C to the draping zone and C-D to the traction zone.

A rolling tyre, not subjected to aquaplaning, has the following 3 distinct contact zones: (i) squeeze film, in zone 1, (ii) draping, in segment A-B, and (iii) traction, in segment C-D. The upward thrust region is not considered here as an interaction zone as, in a thick film condition, the tyre is interacting with the water film, not with the pavement surface properly. The first contacting region, the squeeze film zone, is characterized by a thin water film separating the tyre and the pavement. This film is thin enough to have only lubricating properties, but not to generate an upward thrust. Increasing speed on thin water film condition leads to an increased length of the squeezed film zone, resulting, in a limit case, in viscous aquaplaning, as the squeeze film zone reaches most of the contact patch.

After the squeeze film zone, tyre and pavement surface interact in the draping zone. In this zone, the tyre treads contact the highest and sharpest surface asperities, while other asperities remain covered by the water film. Rubber viscoelastic properties play a relevant role in this region, affecting the rubber capacity to drape over the pavement asperities. The remaining contact zone is the traction zone. In this region the water is removed from

the contact area and the rubber contacts the pavement surface generating traction.

After this brief description of the tyre/pavement contact in wet conditions, the different and important roles of pavement texture become clear: (i) to provide a good surface drainage, limiting the squeeze film zone by allowing water to leave the contact patch; (ii) to have sharp enough surface asperities that can break through the water film and provide initial contact with the tyre in the draping zone, (iii) provide proper friction levels in the traction zone. This approach may also be connected to the forthcoming Figure 6, as the macrotexture is related to surface drainage, therefore connected to the squeeze film zone, and microtexture is associated to the draping zone, as the pavement microtexture should break through the water film and provide initial draping contact with the tyre.

A remark should be made here regarding the previously described energy dissipation mechanisms. In section 2, the two energy dissipation mechanisms presented were adhesion and hysteresis. Even though a third mechanism may be considered as rubber particles or pavement surface wear particles may be worn off the surface and roll between the tyre and the pavement, which also dissipates energy, the main dissipation mechanisms considered here are adhesion and hysteresis.

A final remark should be made in this section, regarding the temperature effects on the tyre-pavement contact. Given the rubber viscoelastic properties, its interaction with the road surface is directly dependent on these properties. Therefore, the temperature is a relevant parameter that should be taken into consideration. It will affect, for instance, the rubber modulus, which directly affects energy dissipation mechanisms, by equations 1 and 2. In addition, given the viscoelastic behaviour of rubber, the pavement interaction is directly dependent on the vehicle speed. The vehicle speed affects the frequency at which the rubber is indented by the pavement texture. The indentation speed also affects the rubber viscoelastic properties. Wang et al. (2014) reviewed some correction models, including the Penn State model, which is an exponential decay function of speed for locked-wheel friction tests. The temperature-frequency dependency of the tyre/pavement interaction may be accounted for with the master curve concept, for viscoelastic materials (Moore, 1975).

The concept is that a change in temperature, for a constant speed or frequency, corresponds to a change in speed or frequency, for a constant temperature. Consequently, the importance of considering temperature and speed or frequency effects when investigating the tyre/pavement interaction, including tyre/pavement noise generation and amplification mechanisms.

3.1. Pavement stresses imposed by the tyre

The pavement top layer receives a dynamic load from the wheel. This dynamic load can be expressed, in a simplified model, by a moving sinusoidal point load, the results obtained by Yoo et al. (2006) exemplify this as they performed simulations with different loading conditions.

The surface layer of a pavement should attain good functional properties, including noise and rolling resistance, but should not compromise durability. Considering a porous pavement, for instance, an increased air voids content would increase the noise reduction properties of a given pavement surface. The limiting case, on the other hand, is when the void content is too high and will limit the pavement durability. Therefore, structural aspects may not be neglected when considering functional aspects.

3.2. Pavement

The pavement surface texture has previously been described in chapter 2 as a relevant parameter for pavement functional properties. Properly understanding and characterizing surface irregularities is a crucial step in optimizing tyre/pavement interaction.

The pavement texture is defined by the ISO (International Standardization Organization) as the deviation of the pavement surface from a true planar surface, within the wavelengths categories (International Organization for Standardization, 1997b). These definitions of road surface texture ranges are a refinement of an earlier proposed classification by PIARC (Permanent International Association of Road Congresses) (PIARC, 1987). This earlier classification was proposed as a

way to convert pavement surface qualities related to phenomena that affect road users into geometric characteristics of pavement surfaces. The texture ranges are presented in Table 1. An illustrative representation of the same surface texture categories is presented in Figure 5.

Table 1 - Texture Categories as defined by ISO 13473 - 1

Texture Category	Wavelength		Amplitude	
	Minimum	Maximum	Minimum	Maximum
Microtexture	-	0.5 mm	0.001 mm	0.5 mm
Macrotexture	0.5 mm	50 mm	0.1 mm	20 mm
Megatexture	50 mm	500 mm	0.1 mm	50 mm
Uneveness	500 mm	50 000	-	-

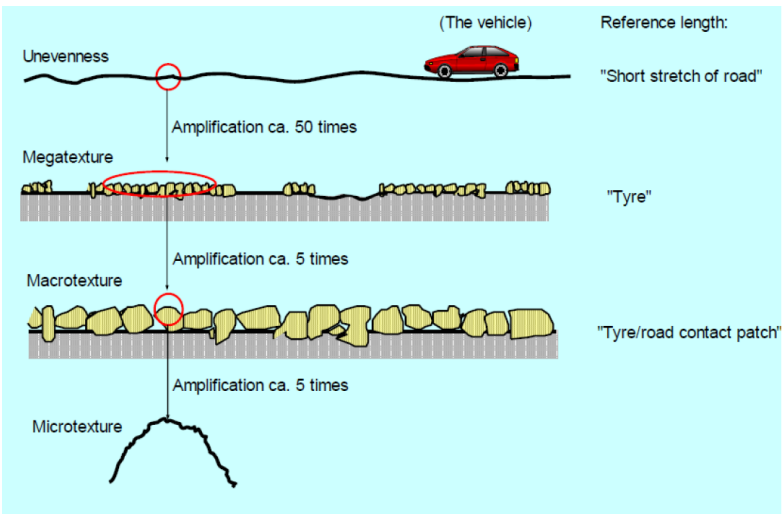

Figure 5- Simplified illustration of texture ranges (Sandberg and Ejsmont, 2002)

As the texture categories were initially proposed by PIARC in a connection to their respective phenomena that affect road user, not surprisingly, each texture category will affect specific pavement functional properties. For instance, microtexture influences on wet skid-resistance at

all speeds and high-frequency tyre/pavement noise. Macrotexture influences on wet skid-resistance at medium to high speeds, low and high frequency of tyre/pavement noise, and rolling resistance. Megatexutre affects rolling resistance, tyre and vehicle deterioration (PIARC, 1987). A simplified illustration of how pavement surface categories affect functional properties is presented in Figure 6.

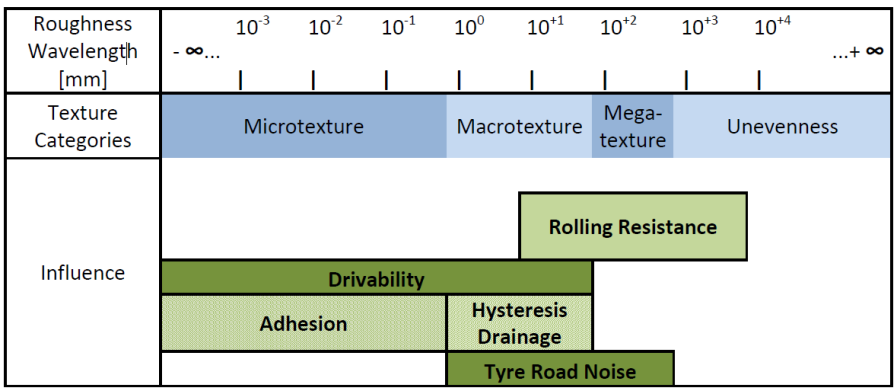

Figure 6 - Pavement functional properties affected by each surface category adapted from PIARC (1987)

Even though the pavement functional properties may be directly connected to the surface categories previously presented, optimizing a pavement surface is neither a simple nor a straightforward process. It is rather a tradeoff between the several functional pavement properties and the various operating conditions. Some functional aspects are related to more than one texture category. It should also be considered that, within a given texture category, several texture characteristics are relevant to describe a surface, therefore, solely knowing a mean roughness value within a texture category is clearly not sufficient to predict its performance. This sustains the need for several other surface indicators, other than simply the mean texture roughness. Some surface texture indicators will be presented in the following section.

It is noteworthy that, even though by some characterization methods, and by some surface texture indicators, only a two-dimensional surface profile is considered, the tyre/pavement interaction is a three-dimensional

phenomenon, it takes place in the tyre contact patch and its vicinities. Therefore, one intrinsic underlying hypothesis when using a two-dimensional measuring method or surface indicator is that the surface is isotropic (PIARC, 1987) and that the measured surface profile is representative for the surface three-dimensional roughness.

3.2.1. Surface Descriptors

In this section, three different surface description approaches are described, which are: (i) the use of statistical indicators, (ii) spectral analysis, (iii) fractals, which will be presented in this same order.

To present some surface descriptors with the first approach, using statistical indicators, initially consider a rough surface like the one schematically presented in Figure 7, and a pair of orthogonal axes, x and z. The mean profile height, or centerline average, CL in the figure, is defined by calculating the mean arithmetic height value along the profile, the root mean square, or simply RMS, evaluates the mean profile deviation from the centerline by calculating the squared difference between each point along the centerline and the corresponding point on the surface profile. The centerline average, R_a, and the root mean square, RMS, can be formally defined by equations 5 and 6, respectively, in which L is the profile length. The definitions presented in this chapter are in accordance with ISO-13473-2 (International Organization for Standardization, 2002b).

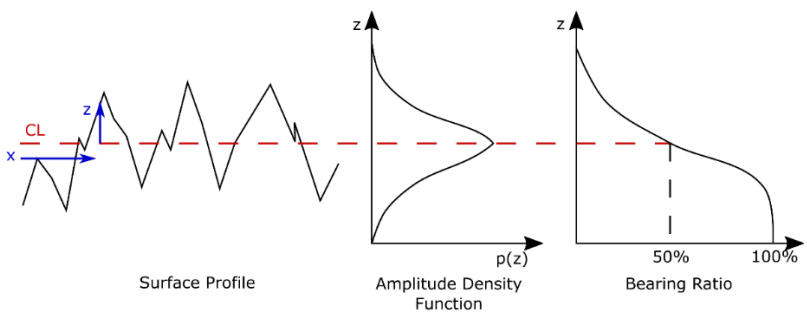

Figure 7 - Schematic representation of a surface profile, the centreline average (CL), the Amplitude Density Function and the Bearing Ratio curve.

$$R_a = \frac{1}{L}\int_0^L |z(x)|dx \tag{5}$$

$$RMS = \sqrt{\frac{1}{L}\int_0^L z^2(x)dx} \tag{6}$$

The amplitude density function, p(z), describes the distribution of asperity heights for a given profile. This function returns the probability of finding a surface point at a given deviation from the profile centerline, z. The amplitude density function is similar to the concept of probability density function for continuum variables, as defined, for instance, by Montgomery and Runger (2010). The cumulative probability density function also has its similar indicator in surface engineering, the bearing ratio curve. A schematic representation of a surface profile, with its amplitude density function and its bearing ratio curve, were presented in Figure 8.

Several indicators may be calculated with surface profiles and the concepts of amplitude density function and bearing ratio curve, as it contains relevant information on the surface profile. Two of those indicators will be presented in this section, the skewness and the kurtosis. The skewness, or 3rd moment of the amplitude density function, indicates a profile asymmetry. A kurtosis, or 4th moment of the amplitude density function, indicates how sharp the surface asperities are. Skewness and kurtosis may be calculated for surface profiles according to equations 7 and 8, respectively. Figure 8 and Figure 9 shows a schematic representation of the effect of skewness and kurtosis on artificially generated surface profiles.

$$Sk = \frac{1}{RMS^3}\int_0^L z^3(x)dx \tag{7}$$

$$Ku = \frac{1}{RMS^4}\int_0^L z^4(x)dx \tag{8}$$

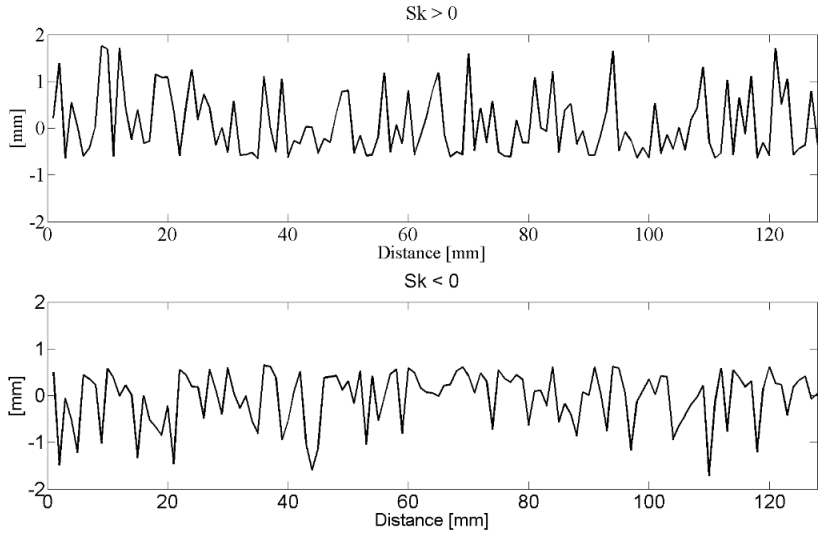

Figure 8 - Two surface profiles, the one on the top with positive skewness and the one in the bottom with negative skewness

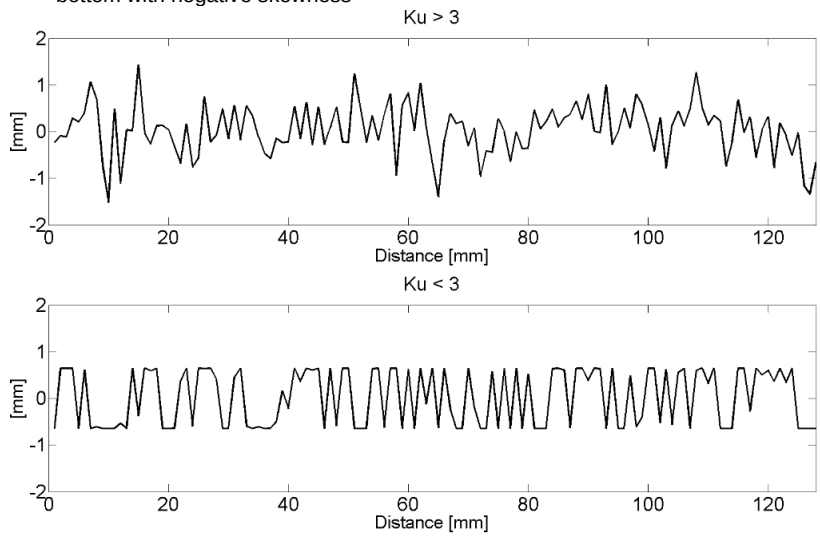

Figure 9 - Two surface profiles, the one on the top with kurtosis higher than 3 and the one in the bottom with kurtosis smaller than 3

The tyre/pavement contact takes place within the contact area, rather than along a profile, therefore, when proper data is available, a more comprehensive approach is to characterize a surface area, rather than a

surface profile. For this reason, it is relevant to extend the skewness and kurtosis definitions, in equations 7 and 8, from a two-dimensional calculation to a three-dimensional calculation. The surface skewness and surface kurtosis are presented in equations 9 and 10, respectively. SRMS, similar to SSk and SKu is a surface generalization of the RMS indicator.

$$SSk = \frac{1}{SRMS^3}\left[\frac{1}{A}\iint_A z^3(x,y)dxdy\right] \quad (9)$$

$$SKu = \frac{1}{SRMS^4}\left[\frac{1}{A}\iint_A z^4(x,y)dxdy\right] \quad (10)$$

The surface descriptors previously presented in this section evaluate surface roughness with a statistical approach. As previously stated other approaches are possible, one of them being a spectral analysis. For this approach, the surface profile is considered as a stationary[1] random function of distance along the profile or surface. With a Fourier analysis, the data series can be expressed, mathematically, as a series of sinusoidal components, each of which has a specific frequency, amplitude and initial phase (Sandberg and Ejsmont, 2002). ISO 13473-2 indicates that a spectral analysis of pavement surfaces is useful for characterizing the surface, and should preferably be done in one-third-octave bands. The proposed spectrum will indicate the texture profile level versus the spatial frequency. Praticò and Vaiana (2013) evaluated how the compaction process affects the surface texture and applied a spectral analysis to evaluate the surface irregularities using gyratory compacted specimens and roller compacted specimens. They concluded that the resulting spectrum depends on the sample thickness at a given compaction level, for the tested methods. Anfosso-Lédée and Do (2002) also applied a spectral analysis to evaluate road surface textures and compared it to noise levels obtained with the controlled pass-by method. Good correlations were found with a spectral analysis of road surfaces and the resulting noise spectrum.

[1] A data series may be considered stationary when properties such as mean, standard deviation and autocorrelation do not change along the series.

In addition to the two previously presented approaches to characterize surface roughness, i.e. statistical indicators and spectral analysis, a third approach is possible, which is the fractal approach. To provide a brief description of a fractal approach, consider a rough pavement surface. The surface may be described as “protuberances upon protuberances upon protuberances…”, such as the one presented in Figure 10. This description was proposed by Archard, which is the description of a fractal surface, 20 years before this term was mathematically coined (Greenwood and Wu, 2001). Non-fractal shapes may be classified by a composition of regular geometric shapes, such as lines, curves, and spheres. Fractal surfaces, such as road surfaces, may be characterized by their fractal dimension, which is a measure of how smooth the surfaces are. An extremely smooth surface has a fractal dimension approaching 2, whereas an extremely rough surface has a fractal dimension approaching 3. When considering a surface profile, an extremely smooth one would result in a fractal dimension approaching 1, whereas an extremely rough one would have a fractal dimension approaching 2. Furthermore, classical roughness parameters, like RMS, may be modelled as a function of the fractal dimension and a cut-off frequency. A direct implication of this is that classical roughness parameters, such as RMS, are not intrinsic properties of a rough surface. On the other hand, the fractal dimension may be interpreted as an intrinsic surface property; it does not change with the scale of measurement or measurement frequency (Militký and Bajzík, 2001).

Techniques for evaluating pavement surface texture with a fractal approach have been developed, for instance by Yuan et al. (2009), by using digital image processing. They were able to correlate the mean texture depth to the fractal dimension. Measuring surface characteristics by fractals has been used in more recent developments of friction and contact theories. As indicated by Gal et al. (2005), pavement surface roughness can be properly characterized by fractal descriptors, as they may be considered self-affine surfaces. When magnified, a self–affine surface profile holds the same fractal characteristics as the unmagnified profile (Persson, 2006). Self-affine surface roughness may be quantitatively characterized by their fractal dimension, D. A fractal surface characterization may be obtained, for instance, with a surface roughness profile. The height-difference

correlation function, $C_z(\lambda)$, which represents mean squared horizontal fluctuations for a given length scale λ. Persson (2006) points out that asphalt and concrete pavement surfaces are nearly perfect self-affine fractals, with a typical dimension of $D \cong 2.2$. Self-affine fractal surfaces result in a characteristic power-law height-difference correlation function, below a certain length scale, $\lambda < \xi_{\parallel}$, which may be described by equation 11.

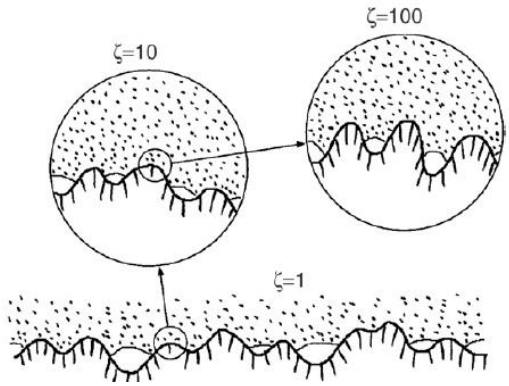

Figure 10 - Pavement surface with a fractal approach, "asperities upon asperities, upon asperities...". The surface profile is presented in 3 different increasing magnifications, ζ = 1,ζ = 10, ζ = 100, respectively (Persson, 2006)

$$C_z(\lambda) = (\xi_{\perp})^2 \left(\frac{\lambda}{\xi_{\parallel}}\right)^{(6-2D)} \tag{11}$$

Self-affinity is fulfilled only for length scale values below $\xi_{\parallel}$, after which, the plateau value, $\xi_{\perp}{}^2$ is reached. A physical interpretation of $\xi_{\parallel}$ and $\xi_{\perp}$ is possible, as they represent the maximum roughness scale, parallel and perpendicular to the measured profile, which hold self-affinity properties. This limit is related to the maximum aggregate size in pavement surfaces, according to Persson (2006). A typical height-correlation function for self-affine surfaces, like pavement surfaces, is presented on Figure 11. Note that the height-correlation function reaches a plateau, with a value of $\xi_{\perp}{}^{2,}$ when the length reaches a given value of $\xi_{\parallel}$. The fractal dimension may be calculated by the slope, *sl*, of the height-correlation function, before it

reaches the plateau, as indicated by equation 12. Note that this equation is only valid in the region where self-affinity holds and not in the plateau region.

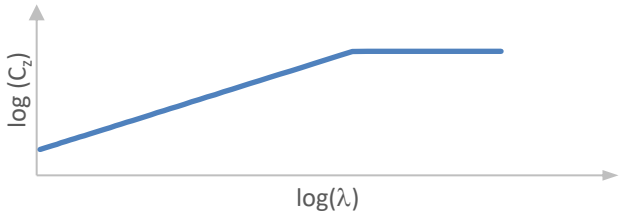

Figure 11 - Typical height-difference correlation function for pavement surfaces following equation 11.

$$D = 3 - \frac{sl}{2} \tag{12}$$

The fractal approach allowed the development of contact theories that are better fitted for the tyre/pavement contact. One notable limitation of previous contact theories, like the Greenwood-Williamson theory (Greenwood and Williamson, 1966), in a more general case, the Greenwood-Tripp theory (Greenwood and Tripp, 1970), or even the Bush, Gibson and Thomas theory (Bush et al., 1975), is that they were developed for relatively low squeezing forces, when the real contact area, A, is significantly smaller than the nominal contact area, A_o. Persson's contact theory (Persson, 2006) allows more accurate results when the real contact area is not significantly smaller than the nominal contact area, which is a better assumption when analysing the tyre/pavement interaction.

3.2.2. Experiments to evaluate pavement surface texture

This section presents some methods applied to characterize the pavement surface. Techniques to access surface roughness may be classified into two categories: contacting and non-contacting (Hutchings, 1992). While contacting techniques require some sort of physical contact between a measurement equipment and the measured surface, non-

contacting techniques do not require physical contact, which is usually an advantage.

Contacting methods use, for instance, a stylus profilometer that sweeps the surface. The vertical displacement is recorded as the measuring stylus moves over the surface asperities, resulting in two-dimensional surface profiles. Contacting methods have a limitation related to the physical contact, a stylus has a finite tip size, and may only penetrate on some of the pavement texture valleys. The finite physical contact may also smooth the resulting surface profile as the stylus shape may not allow it to properly describe sharp texture asperities. The use of stylus techniques to analyse pavement texture was reported, for instance, in the United States, by Rose (1971), already pointing that such devices were difficult to operate and had a poor to average repeatability. A similar approach, using a pointer attached to a probe that records pavement surface roughness on a chart, is the MERLIN, designed for use especially in developing countries (Cundill, 1991). Non-contacting methods have some advantages over the previously mentioned methods due to the non-required physical contact between the measuring device and the pavement surface. No-contacting methods are further classified into direct and indirect (Gullón, 2003). Direct methods evaluate texture by primarily measuring distances, for instance, measuring the time-gap required for a laser beam to reach the surface and to be reflected in a sensor. Indirect methods evaluate texture by analysing light intensity images of the surface. The resulting measuring methods classification is presented in Figure 12. Non-contacting methods have been used to evaluate pavement surface texture due to their advantages of describing pavement asperities, which may have sharp edges, narrow and possibly occlusive valleys (McQuaid et al., 2014), which would be more difficult to evaluate with direct measurements. Some measurement techniques to evaluate pavement surface texture will be more deeply described in the following sections.

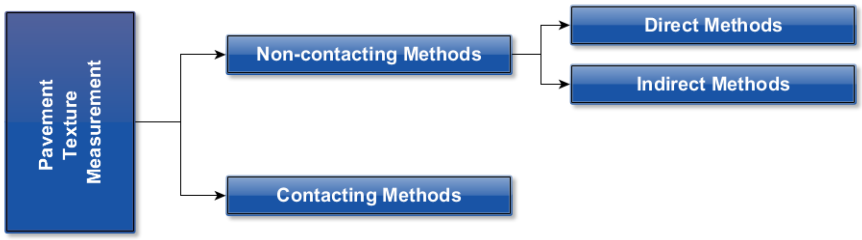

Figure 12 - Pavement texture measurement methods

3.2.2.1. Volumetric Patch

The volumetric test consists of spreading a known volume of material over the pavement surface until the major texture summits are visible. This allows an estimation of the mean texture depth, MTD, by dividing the know material volume, by the resulting covered area. If the material is spread approximately in a circle shape, the covered area may be easily estimated by measuring the circle diameter. It is also possible to use photometric techniques to evaluate the covered area (Vieira, 2014). This test considered a contacting method to evaluate the surface texture, as it relies on the physical contact between the glass spheres and the test surface. It holds, therefore, some of the characteristic limitations of contacting tests, such as precision limited by the finite size and shape of the glass spheres.

The volumetric patch for pavement surfaces, standardized by ASTM (ASTM International, 2015) and ISO (International Organization for Standardization, 2014) consists of spreading solid glass spheres, having a controlled roundness and size gradation on the pavement surface. The spread should be executed in circular movements with a flat disk, resulting in a circular patch. According to the ASTM standard, the resulting covered area diameter should be measured 4 times, and the resulting value should be used to determine the MTD value. The volumetric patch with glass spheres is presented in Figure 13. The volumetric patch is a crude method (International Organization for Standardization, 1997b), significantly operator-influenced (Rose, 1971), and requires partial or full traffic closure prior to its execution. According to the standardized procedure, the test surface should be dry, homogeneous, without cracks or joints. It should

also be clean of debris or loosely bonded aggregate particles. This method is not recommended for grooved or porous surfaces.

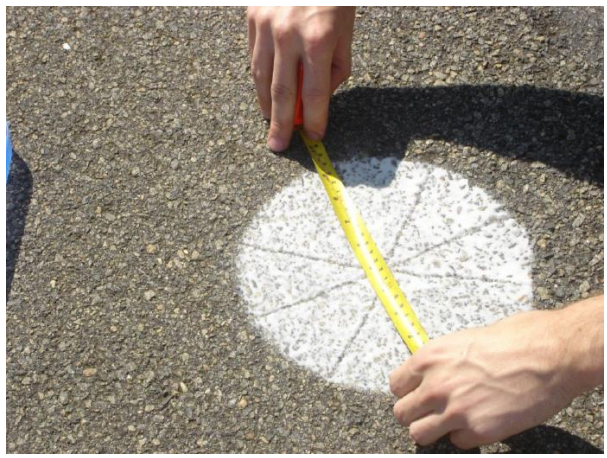

Figure 13 - Volumetric patch with glass spheres

The previously described volumetric patch was initially executed with sand particles and only later glass sphere particles were adopted to increase the test repeatability and accuracy.

The volumetric patch provides mean texture depth information from the tested surface area. It may be related to laser measurements and indicators, such as the Mean Profile Depth (MPD), which will be further discussed in section 3.1.2.2, yet one interesting advantage of this method is that it samples a surface area, rather than a profile.

3.2.2.2. Outflow

The outflow method to evaluate pavement texture, similarly to the volumetric patch, is used to determine mean texture characteristics. It consists of a contacting method, as it relies on water flowing on the pavement surface. This method provides information on the pavement macrotexture, which is, as previously stated in this chapter, related to surface drainage, removing water away from the tyre pavement contact. The measurement consists of placing a cylinder on the pavement surface and filling it with water. The bottom side of the cylinder contacts the

pavement surface with a rubber ring. As a known volume of water flows through a circular hole in the bottom of the cylinder, and thru open gaps between the rubber ring and the pavement texture, the outflow time is measured. The method was originally proposed by Moore (1966) and is standardized by ASTM International (2005), British Standards Institution (2002), among others, with slight differences on the outflow equipment and measurement procedures. The relationship between texture parameters and the outflow time, which is the time taken for a known water volume to flow out of the cylinder, is presented in equations 13 and 14. The measurement depends on the outflow time, t, the absolute water viscosity, ϑ, an instrument constant, K_{ofm}, the average texture channel perimeter, P, and the number of asperities per unitary length on the surface, $\sqrt{N'}$ (Moore, 1975).

$$MHR = K_{ofm}\left(\frac{\vartheta}{t\sqrt{N'}}\right)^{1/4} \tag{13}$$

$$MTD = MHR\sqrt{(N')}P \tag{14}$$

An increased outflow time, t, results in an increased MTD, by analysing equations 13 and 14. It is noteworthy that the test results depend on the rubber hardness, which will affect how it will be indented by the pavement texture, and that this harness may change over time. It is also noteworthy that the test is not suited for porous surfaces, as a significant amount of water would flow into the pavement pores, instead of only flowing thru the gaps between the texture and the rubber ring. The resulting MTD values estimate consistently smaller spacing than the volumetric patch method, as a result of the draping effect of Figure 14.

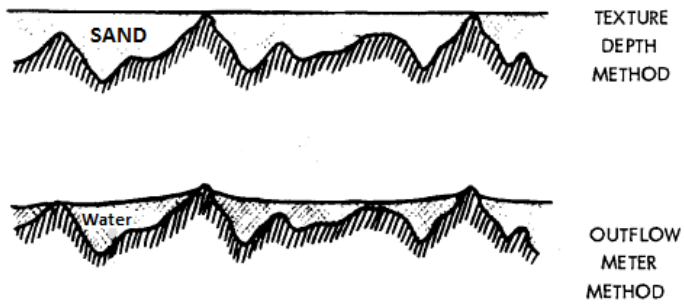

Figure 14 - Rubber ring draping over pavement surface asperities, adapted from Moore (1975).

Even though it may be difficult to relate MTD obtained by the volumetric patch and by the outflow meter (van Es and Giesbert, 2003), following specific procedures like saturating the pavement pores with water and correctly observing the measurement instrument limitations, it is possible to obtain good statistical relations between the volumetric patch results and the outflow meter values (Kuchiishi et al., 2014).

3.2.2.3. Laser Profilometry

The evaluation of pavement surface texture with laser profilometers is commonly used to evaluate pavement macrotexture and is usually applied to evaluate parameters such as the Mean Profile Depth, MPD. This is a non-contacting, direct technique, which measures the time required for a laser beam to be reflected into a sensor, and with this information, it is possible to estimate the surface texture. With the obtained surface profile, it is possible to filter the data into the macrotexture wavelength limits of Table 1. It is also possible to use the obtained profiles to calculate surface indicators presented earlier in this chapter, perform spectral analysis and fractal analysis if a proper resolution is obtained. It is also possible to sweep a surface area with laser sensors, obtaining a more comprehensive representation of the surface texture. A mobile measurement is presented in Figure 15 with VTI's RST.

Figure 15 - Laser sensors attached to a vehicle for road surface texture measurements (Edvardsson et al., 2015).

One commonly used surface parameter obtained from laser profilometers is the Mean Profile Depth (MPD), among other profile characteristics, which are standardized by ASTM International (2009b) and International Organization for Standardization (1997b). The latter states that laser measurements is a safer and more economical technique when compared to the volumetric patch method. The MPD value is calculated after filtering the profile and segmenting it into 100 mm parts, removing a possible slope with a linear regression, and then splitting each 100 mm part into two 50 mm halves. For a 50 mm segment, the distance between the maximum peak in this segment and the profile average level is calculated. The same procedure is applied for the other 50 mm segment. The mean value between the two halves is then averaged resulting in the Mean Segment Depth for a given 100 mm segment. This procedure is repeated the other 100 mm segments and then averaged, resulting in the MTD. The procedure is illustrated in Figure 16.

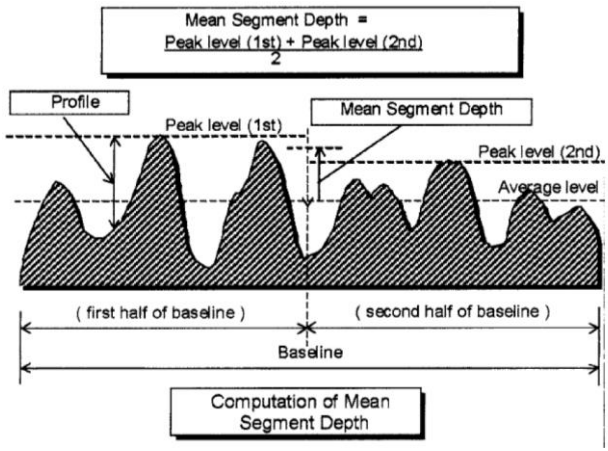

Figure 16 - Mean Segment Depth calculation (ASTM International, 2009b).

It is important to acknowledge possible operational limitations when measuring pavement surface profiles with mobile equipment. Fisco (2009) indicated that pavement MPD value obtained by some equipment are significantly affected by the measuring speed. For increasing measuring speeds, the obtained MPD value decreased. Praticò and Vaiana (2015) found a non-linear relationship between MPD and MTD values, evaluating dens-graded friction courses, SMA surfaces, open-graded friction courses and porous mixes. The divergence from linearity is explained by the authors as MPD and MTD indicators are related to different surface properties, therefore, a more complex relation was expected.

3.2.2.4. Circular Track Meter

Similar to the previously described Laser Profilometry equipment, the Circular Track Meter (CTM or CTMeter) evaluates the surface texture with laser sensors. The major aspect that differs the CTM method is that the laser sensors are attached to a rotating arm, which measures a circular track with a diameter of 284 mm. This method is also considered a non-contacting, direct measurement and is standardized by ASTM (ASTM International, 2009a).

The resulting profile, measured along the total circumference of 892 mm, is equally divided into 8 segments of 111.5 mm, and the Mean Profile Depth (MPD) is calculated for each segment. The resulting MPD value is reported as the average of the eight measured MPD values. Hanson and Prowell (2004) indicated that CTM measurements are comparable to the volumetric patch measurements, with nonsignificant offset when excluding the tested open-graded mixtures. Abe et al. (2001) found relevant correlations between CTM measurements, volumetric patch and outflow measurements. They also indicated that the correlations are not well fitted for porous surfaces.

3.2.2.5. Photometry

The photometric technique is a non-contacting intensity method, which uses specific algorithms to evaluate surface texture from photographs taken in know and controlled conditions. Different algorithms and procedures are possible and will result in different levels of accuracy. Two different techniques to obtain surface information with photometry are the stereo photometry and the photometric stereo technique (Szeliski, 2010). Other techniques are available even though they are not discussed in this text. The first requires a set of images taken from slightly different and known positions to generate a three-dimensional representation of the surface texture. The latter requires a set of images to be taken from the same, known position, yet with different and controlled lighting conditions. One of the main advantages of the latter technique is that it does not require to take images from different points of view, correspondence between points in each image (Woodham, 1980). Properly selecting the algorithms allows one to produce a more comprehensive three-dimensional representation of a pavement surface texture, including sharp asperities and narrow valleys. An illustrative image is provided in Figure 17. Even though this technique requires several controlled conditions, such as lightning positioning and sufficient light intensity, it may provide a comprehensive three-dimensional representation of the pavement surface texture if those conditions are fulfilled.

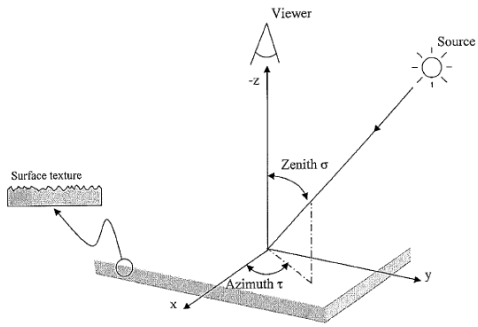

Figure 17 - Pavement surface obtained by a photometric stereo technique, a light source in a known position illuminates the pavement surface, and the camera (viewer) registers the reflected light. Several images with different source positions are required to generate the surface (Shalaby and Gendy, 2011)

3.2.2.6. Interferometry

Another non-contacting, indirect method to evaluate surface texture is the Interferometry, which relies on measuring the phase shift between two light beams. The equipment emits a light beam at a given frequency, which is then split in two beams by a beam splitter. One of the resulting beams is directed to a reference mirror. The other is directed to the test surface. After being reflected by the reference mirror or the test surface, the two beams then reach a detector. The equipment analyses the coherence between the two beams, which evaluates the correlation between two given light wave positions, separated by a given delay. With the coherence measurement, the equipment adjusts the distance between the test surface and the light source in order to maximize the coherence for a specific point in the surface. The resulting interference pattern between the two light beams, *i.e.* fringe, is used to calculate the texture height. This procedure is then repeated for each surface point, resulting in a three dimensional representation of the pavement surface (Leach et al., 2008). Figure 18 presents a schematic representation of an interferometer equipment used to evaluate surface texture. Nguyen (2002) developed a prototype interferometer to measure pavement surface characteristics, including, but not limited to macrotexture and microtexture.

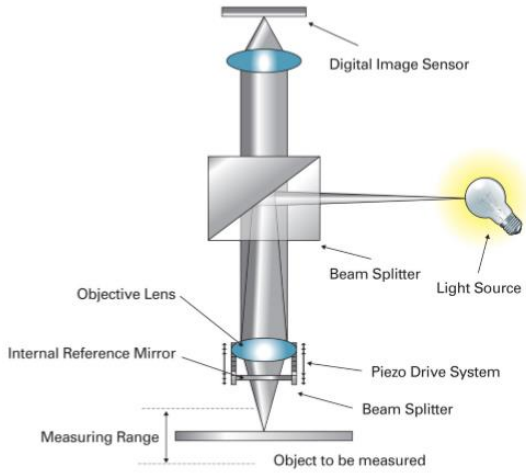

Figure 18 - Schematic representation of an interferometer (Leach et al., 2008)

3.2.2.7. Closure remarks for pavement surface texture evaluation

The previous sections presented briefly some possibilities to evaluate the pavement surface texture. It was not an exhaustive presentation, yet the most relevant and commonly used methods have been disclosed, including their procedures, basic principles and limitations. It is noteworthy that a three-dimensional surface evaluation is generally more comprehensive then a two-dimensional one, and that several surface aspects influence the resulting surface performance. Therefore, one single texture indicator, such as the MPD, the MTD or even the RMS, is not sufficient to fully characterize the surface texture (Flitsch et al., 2012). A wider selection of texture parameters should be made, including, for instance the surface skewness, kurtosis, or the fractal parameters.

3.3. Tyre

This subchapter discusses the tyre, including its structure, properties, the processes of wear and ageing, and some features of different types of tyres.

3.3.1. Tyre structure

The four basic functions of a pneumatic tyre, according to Potts (2009) are: (i) support the moving load, (ii) generate steering forces, (iii) generate driving and braking forces, (iv) provide isolation from road irregularities. Today's tyres are made of a variety of cord fabrics, according to the same author, including polyester, glass, rayon, nylon, Kevlar and steel. Tyres have three basic construction methods, which are presented in Figure 19. The diagonal bias method has body ply cords laid at angles smaller than 90° to the tread centreline and extended from bead to bead. This construction method leads to shear stresses between the plies, which generates heat as the tyres roll over a surface. The belted bias tyres have body plies in diagonal angle and belts in the tread region, which will limit the tyre deflection. Consequently, this construction method will lead to improved wear and handling, but the ply structure will still generate heat. Finally, the radial tyres, which have body ply cords laid radially, extending from bead to bead. The ply cords are usually laid at a nominal angle of 90° from the tread centreline. Belts are laid diagonally to add strength, similarly to the belted tyres. The radial ply cords will generate less shearing stress under load, reducing the heat production, and therefore, being more efficient regarding rolling resistance, wear and handling. This more complex construction method, though, will result in increased production costs.

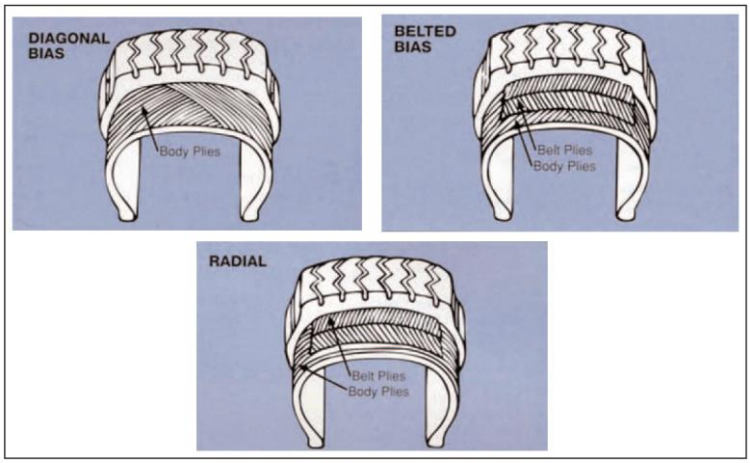

Figure 19 - Tyre construction methods (Gent and Walter, 2005)

The tyre structure is constituted of several different materials, including different rubber compounds and reinforcement materials. The rubber compounds may be summarized in 5 groups (Gent and Walter, 2005): (i) polymers, which are the major component of tyres, being of either synthetic or natural types, (ii) fillers, most commonly carbon black and silica are used, it provides reinforcement for the structure, (iii) softeners, which aids the processing of the material, (iv) antidegradents, which improves the material resistance to deterioration by ozone, oxygen and heat, (v) curatives, which help to achieve proper vulcanization of the rubber. The reinforcement materials provide strength and stability to the tyre structure and include the tyre cords and bead wire[2].

A radial tyre usually contains several different layers that are presented in a typical radial tyre structure of Figure 20. Some of these layers will be briefly described here, for a complete description, please refer to Gent and Walter (2005). The presented tyre structure has an innerliner, which is a compound specifically formulated to decrease air permeability through the tyre. Body plies provide strength and resistance to impact. The sidewall

[2] Bead wire is a steel wire coated with bronze. It is placed on each side of the tyre, in various configurations to anchor the inflated tyre to the rim GENT, A. N. & WALTER, J. D. 2005. The pneumatic tire. Washington DC, USA: NHTSA..

rubber protects the body plies from abrasion, impact and flex fatigue. Steel belts restrict the expansion of the body ply cords, stabilize the tread area and provide impact resistance. The shoulder inserts contribute to maintain a smooth belt contour and insulate the body plies from the belt edges. The tyre tread will directly contact the pavement surface, with resulting values of grip, traction, braking, cornering, wear, among other functional properties. The tread pattern in moulded into the tread during the tyre vulcanization and is designed to fulfil the tyre performance requirements. The subtread, if used, is a lower hysteresis component placed under the tread compound to improve rolling resistance performance and fine-tune riding quality, noise and handling. The undertread boosts adhesion between the tread/subtread and the stabilizer plies during assembly.

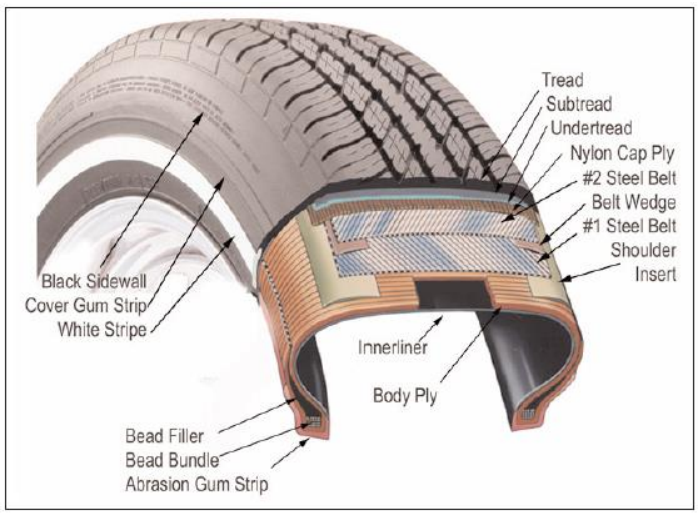

Figure 20 - Typical radial tyre structure (Gent and Walter, 2005)

As previously mentioned the tread design will have a major effect on noise and rolling resistance. An increase of the tread thickness and decrease of the hardness of the bead filler may reduce coarse road noise, yet it increases rolling resistance (Gent and Walter, 2005). This illustrates that the tread design should be balanced among the several functional tyre properties.

3.3.2. Tyre properties

Rubber is a viscoelastic material, therefore its mechanical properties, such as elastic modulus, are temperature and frequency dependent. Thus, to properly describe its mechanical behaviour, one should know the real and complex modulus, for instance, G' and G" at a given temperature and load frequency. Figure 21 shows the viscoelastic properties as a function of the indentation frequency.

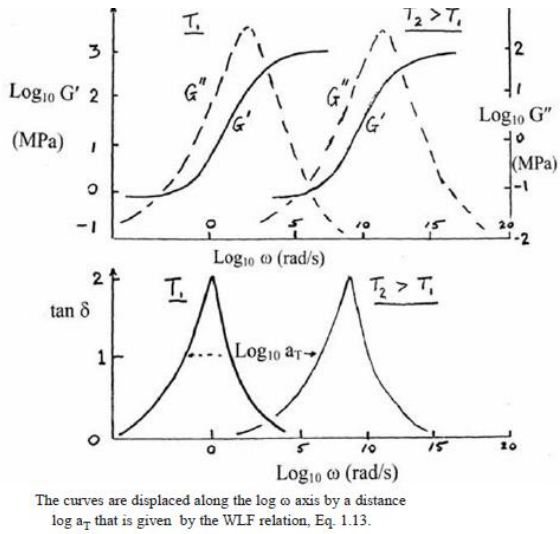

Figure 21 - Schematic representation of the viscoelastic properties of rubber materials as a function of the frequency(Gent and Walter, 2005)

The addition of filler to the rubber, for instance, carbon black results in a more complex mechanical behaviour, as the material has a more inelastic behaviour. The resulting filled rubber is softened by straining and has an increased softening the greater the pre-strain level is. This effect of strain history is named Mollins effect and is illustrated in Figure 22.

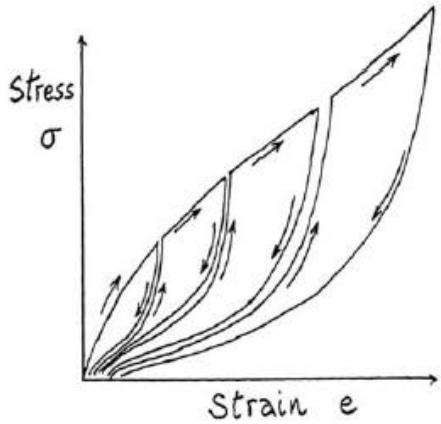

Figure 22 - Mullins effect on filled rubber (Gent and Walter, 2005)

The Mullins effect is a phenomenon that encompasses the rubber softening at higher strains, according to Gent and Walter (2005). A similar effect takes place in smaller strains, approximately 0,1% strain, and also results in a softening effect of the material. This phenomenon is named Payne effect.

The temperature-frequency superposition principle applies to filled rubber, as the filler does not significantly affect the molecular mobility of the elastomer, as well as the glass transition temperature (Gent and Walter, 2005). Therefore, it is possible to use mastercurves to characterize the behaviour of filled rubber compounds.

ofThe friction mechanisms previously discussed in chapter 2, namely hysteresis and adhesion take place in a rolling rubber tyre. More interestingly, the mastercurve concept may also be applied to the friction coefficient of rubber sliding over a rough surface. Using the Williams Landel Farry equation, Grosch (1963) constructed a mastercurves for the friction coefficient. By comparing the results of friction on rough and smooth surfaces, the author concluded that both adhesional and hysteretic components of friction were dissipating energy. Even though the tests performed by Grosch are within limited conditions, it revealed the importance of considering both adhesion and hysteresis mechanisms taking place at the same time (Gent and Walter, 2005). Given this viscoelastic behaviour, a rubber compound engineer may adjust the

viscoelastic properties to achieve the desired performance at a given indentation frequencies and temperature, therefore resulting in tyres optimized for certain temperature and road conditions.

Also under limited conditions, it is possible to relate abrasive wear to temperature and frequency, in this case of non-filled rubber, also indicating a relevant effect of the viscoelastic properties. Considering tyre tread rubber compounds, there is still temperature and frequency dependency, even though it is weaker and not so well described by the Williams Landel Farry equation (Gent and Walter, 2005).

3.3.3. Tyre wear and ageing

A rubber sample contacting a rough surface commonly has a pattern on its surface, with ridges normal to the relative sliding direction. Those are the so-called Schallamach waves, or Schallamach pattern of wear and were observed by Adolf Schallamach (1971). Even though properly describing the formation of the Schallamach Waves and the underlying mechanisms is not within the scope of this text, it is noteworthy that there are different approaches available in the literature. For instance, Fukahori et al. (2010) described the pattern formation as a surface instability phenomenon related to stick-slip processes. Other approaches considering localized changes in rubber modulus are also available. This pattern is found in rubber tyres (Barquins, 1985), even though, due to the presence of filler, it may be less pronounced and the waves more closely spaced. In rubber compounds with lower contents of carbon black, the pattern will be more pronounced and not so closely spaced (Gent and Walter, 2005). Figure 23 shows the wear pattern on a tyre tread rubber compound after being worn on a rough surface at +20 °C. Figure 24 shows a British Pendulum rubber test pad worn down after several tests on pavement surfaces in controlled conditions, also presenting a wear pattern.

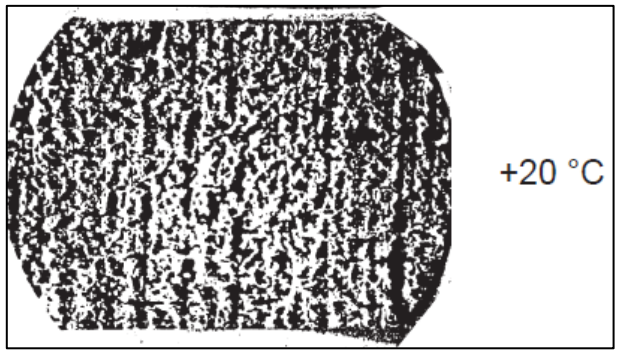

Figure 23 - Wear pattern on tyre tread rubber compound after being worn on a rough surface at +20 °C (Gent and Walter, 2005)

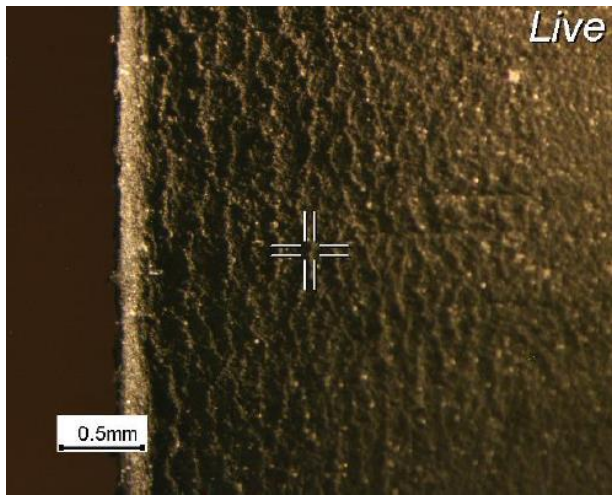

Figure 24 - Wear pattern on a British Pendulum rubber test pad, resulting from several tests under controlled conditions (Vieira, 2014)

The wear mechanisms in rubber tyres are also affected by chemical processes, such as oxidation and thermal decomposition. As Gent and Walter (2005) point out, a highly degraded rubber becomes sticky and may be pulled off the tyre by adhesive forces acting within the tyre/road contact area. In addition, the temperature effect should not be neglected in the wear process, the energy dissipated in the process will also increase the interface temperature and affect the subsequent wear process.

The tyre deterioration caused by its interaction with the road surface, resulting in loss of material is usually referred to as mechanical wear. Another type of ageing effect is also relevant for tyres and is named chemical ageing (Sandberg and Glaeser, 2008). The later does not require any mechanical action and affects even tyres that are in storage conditions. The exposure to oxygen and ozone are the two primary contributing factors for the ageing process of rubber tyres. Other relevant contributing factors are heat, light and humidity. The ageing process will lead to a deterioration of the tyre, *i.e.* loss of its mechanical properties.

According to Gent and Walter (2005), the ozone attack is an important deterioration mechanism as ozone reacts with the unsaturated elastomers commonly found in rubber tyre composites. If there is no tensile strength in the surface, the ozone reaction will be limited to a thin layer of approximately 20 μm depth, not affecting the inner rubber material. If there is a tensile strain of approximately 10 % in the rubber surface, the ozone deterioration reaction will lead to characteristic cracks starting in the rubber surface and propagate inwards, continuously exposing new material to the ozone reaction. As the authors point out, the cracks may become as deep as 1 mm after only 2 weeks after exposure to a normal outdoor air with an ozone concentration of approximately 5 parts per hundred million. The ozone degradation is critical mostly in tyre sidewalls, which are subjected to tensile stresses both in storage and in use.

The other type of chemical deterioration, still according to Gent and Walter (2005), is the oxidation. This process is slower than the ozone attack, but it penetrates deeper into the rubber material. The hydrocarbon elastomers will, after reacting with oxygen, form new crosslinks by interacting with neighbouring molecules. The oxidized rubber, therefore, becomes harder and often brittle. As a result, the material is more likely to crack under stress.

Two other ageing mechanisms are mentioned by Gent and Walter (2005): additional vulcanization and weathering. Additional vulcanization is the continuation of the vulcanization process that began during tyre manufacturing and will continue at much lower rates afterwards. A result of additional vulcanization, if the tyre is stored or used at higher temperatures, is that more crosslinks will be formed, increasing the rubber

hardness. Existing crosslinks may also be decomposed, by a phenomenon called termed reversion, resulting in rubber softening. Weathering is another mechanism that seems to be connected to UV and sunlight radiation, but as the authors point out, this mechanism is still ill-defined.

Rubber hardness changes due to ageing and usage significantly affect the CPX measured values. Bühlmann et al. (2013) evaluated the ageing effect of the CPX reference tyres during the 2012 measurement season, concluding that the ageing processes resulted in approximately 1 dB (A) increase in measured noise levels, and therefore should not be neglected. Regarding rolling resistance, the effect of tyre ageing is also unneglectable. Sandberg and Glaeser (2008) evaluated the effect of ageing and wearing of tyres and concluded that those have a dramatic effect on rolling resistance and also noise generation on rough-textured surfaces.

To mitigate the ageing process on tyres, several recommendations were proposed by Sandberg and Ejsmont (2009), such as storing tyres in dark, dry and cold rooms, in an as ozone free as possible atmosphere, and in a condition that does not impose deformations to the tyre. For the usage of reference tyres, to prevent ageing it was recommended to inflate tyres with nitrogen instead of air.

3.3.4. Features of different types of tyres

As previously exposed tyres may be optimized to different operating conditions, balancing different performance aspects. For instance, in older winter tyres, which were optimized for friction in winter conditions, the tread was designed with high air voids, relatively large tread blocks, and wide channels between them. This is not the case for more recent winter tyres, which employ more advanced and softer rubber compounds, with smaller tread blocks that are cut by sipes, resulting in narrow ridges (Sandberg and Hjort, 2013). Another example of different tread design is found on the CPX reference tyre Avon AV4, which has larger tread blocks and therefore behaves more similar to heavy vehicles tyres regarding to its noise performance (Morgan et al., 2009).

The aforementioned examples indicate how different optimization techniques, involving both material properties and tread geometries, may be used to design tyres to a given operational condition. The mechanics of

the tyre contact patch will significantly affect the tyre performance, as different tread designs directly affect the tyre performance. These mechanisms are complex and not within the scope of this text, even though, a brief discussion will follow.

The contact patch is a moving boundary that will dynamically impose deformations on the tyre structure. When contacting the road surface, the tread elements will be subjected to stresses and will slip while contacting the road surface. For instance, within the contact patch, the loads will relax on the belt at the centre of the contact, resulting in shear stresses in the outward direction with respect to the centre of the contact patch. A rolling tyre will also have higher normal and lateral stresses near its shoulders regions than in the centre of the contact patch.

The presence of contaminants in the contact patch leads to the necessity of designing proper tread patterns. The contact patch stresses may be evaluated, for instance with a stress measurement pad coupled to a rough textured surface, such as used by De Beer and Fisher (2013).

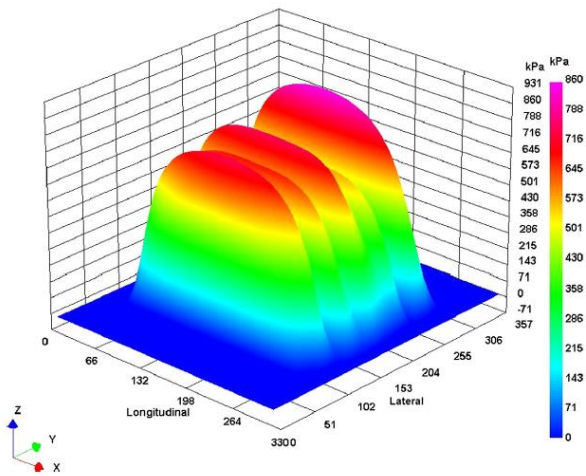

Figure 25 - Contact patch vertical stresses of a tyre with a 25 kN of load and 520 kPa of inflation pressure (De Beer and Fisher, 2013)

This chapter presented a brief description of the tyre structure, some of its relevant physical properties and characteristics. Several other aspects are relevant for noise and rolling resistance, such as an in-depth analysis of the tyre stresses and the contact patch mechanics, among others. For more detailed information, the reader is encouraged to refer to the

references used within the chapter, most importantly, Gent and Walter (2005), which was the basic literature reference for this section and also the basic reference for the Tyre Mechanics course, by the University of Akron, which this author attended in 2016.

3.4. Enveloped Surface

Given the viscoelastic behaviour of the tyre structure and the roughness of the road surface, the tyre will not be able to establish direct contact with narrow valleys or follow steep gradients on the pavement surface. The previous discussion indicated that there are several parameters affecting how a tyre will deflect and contact the pavement surface. Providing a precise estimate of how the tyre will deform around the road surface asperities is, therefore, a complex problem. However, it is desirable to provide an approximation that does not necessarily require a significant extent of computational effort but still allows an approximate assessment of how the tyre surface will interact with the road surface. For this purpose, one can rely on the so-called enveloped texture, instead of the original texture. The enveloped texture is the texture portion to which the tyre is able to establish direct contact. The different methods to calculate the enveloped profile will have different precision levels, therefore the envelopment method should be selected depending on the desired application.

Goubert and Sandberg (2018) presented a discussion on enveloped surface and on different algorithms available to calculate it. Among the methods discussed by the authors are the von Meier method, which is a mathematical/empirical model that calculates the enveloped surface starting from the original pavement surface and applying limitations to the second-order derivate, smoothing the original surface. Other models can be found in the literature, like the static model described by Hamet and Klein (2000) that models the tyre using its Green Function and solves the tread displacement in the time-domain, or the dynamic model, presented by the same authors, which calculates the tread displacements in dynamic conditions. In both cases, the resulting envelope surface is dependent on the stiffness of the tyre.

Another enveloping algorithm available is the so-called *Indentor* method that was developed within the European project ROSANNE (Goubert and Sandberg, 2018). It relies on the assumption that, for a two-dimensional profile, the area indented by the tyre is constant. The method was later used in the analysis of rolling resistance test results from the IFSTTAR test track. The enveloped surface resulted in an improved correlation with the results in comparison to other surface indicators, like MPD.

The enveloped surface is, therefore, an interesting tool that can be used to analyse the tyre/pavement interaction and its functional aspects, like noise or rolling resistance. Different methods to calculate the enveloped surface are available and should be selected in accordance with the desired application and analysis' complexity. Noise

4. Noise

According to its traditional definition, is an unwanted sound (Sandberg and Ejsmont, 2002). From this definition, and according to the authors, it is required that a human or even an animal is disturbed by the sound generated by the tyre/pavement interaction in order to consider it noise. The European Parliament and Council (2002) on the Environmental Noise Directive defined environmental noise as *"unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic, rail traffic, air traffic…"*. This definition clearly relates to this report, as it explicitly includes road traffic noise. The United Nations, on its Glossary of Environment Statistics (United Nations Statistical Division, 1997), explicitly include the term traffic noise on its definition of environmental noise: *"noise is an audible sound from traffic, construction and so on that may generate unpleasant and harmful effects…"*.The several health, economic, environmental and social impacts were previously discussed in chapter 1 of this report. This chapter will focus on tyre/pavement generation and amplification mechanisms, followed by a description of the available methods to measure and evaluate noise resulting from the tyre/pavement interaction.

4.1. Tyre/road noise generation and amplification mechanisms

Noise generated by the tyre/pavement interaction is the result of several mechanisms and phenomena. The relative importance of each mechanism is a function of several system variables, including tyre characteristics, pavement surface characteristics, environmental and interfacial characteristics. Whereas the relative contribution of each mechanism is debated among experts, the existence of such mechanisms is

generally an agreement among them (Sandberg and Ejsmont, 2002). This entire section is based on Sandberg and Ejsmont (2002), for this reason, when more comprehensive information is desired, the reader is encouraged to look for this reference.

There are 16 tyre/road noise mechanisms, which are initially divided into 9 generation mechanisms and 7 amplification mechanisms. The 9 generation mechanisms are further divided into 5 vibrational/structure-borne mechanisms and 4 aerodynamical/air-borne mechanisms. Figure 26 shows the 9 generation and 7 amplification mechanisms, which will be more detailed exposed in the following subsections. See Figure 26.

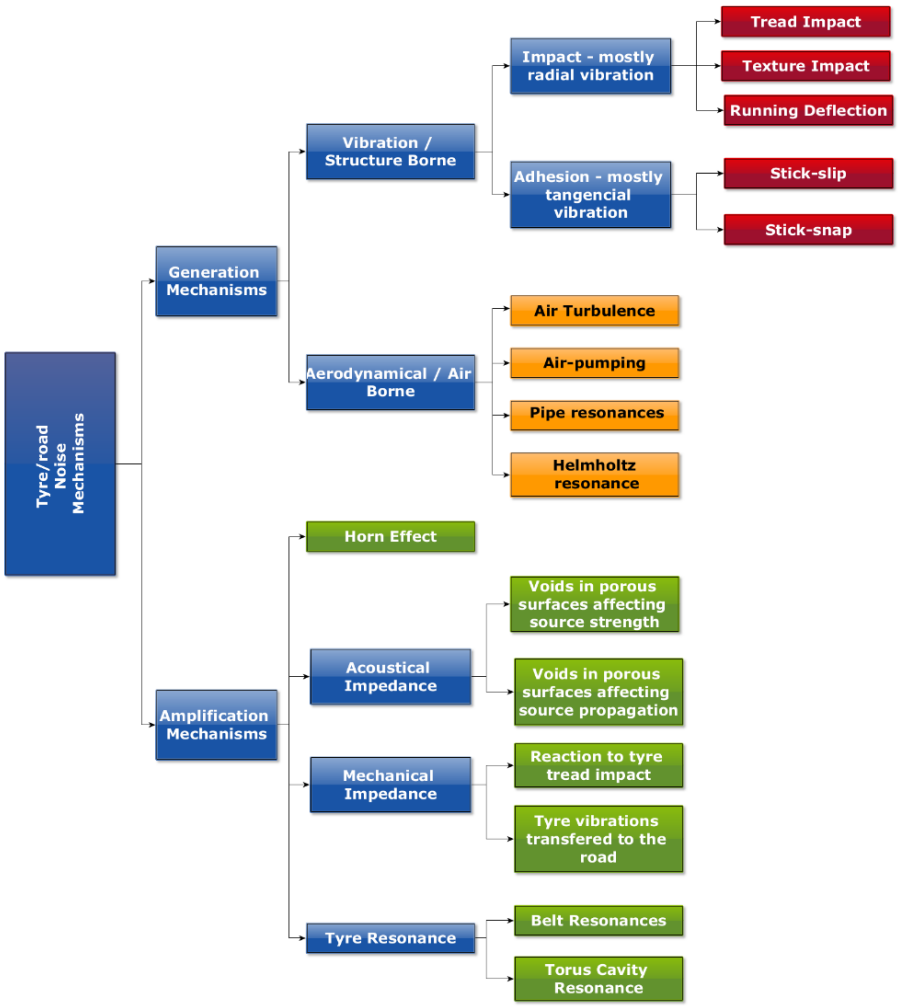

Figure 26 - Tyre/road noise mechanisms, vibrational mechanisms in salmon, aerodynamical mechanisms in yellow, and amplification mechanisms in green, based on Sandberg and Ejsmont (2002)

The different noise generation and amplification mechanisms affect the overall resulting noise in different frequencies and are affected by the pavement surface in different ways. The impact mechanisms are related to low-frequency noise, whereas the air displacement mechanisms are related to high-frequency noise (Sandberg and Ejsmont, 2002). As tyre/pavement noise is generated by several different mechanisms, not surprisingly, it is

affected by texture in different ways too. Below the so-called cross-over frequency, at which noise is mostly influenced by impact mechanisms, the noise will generally increase with texture amplitude, when considering a texture range of 10-50 mm. Above the cross-over frequency, at which noise is mostly affected by air displacement mechanisms, the noise will decrease with texture amplitude, when considering a texture range of 0.5-10 mm. The cross-over frequency is approximately 500 Hz for heavy vehicles and 1 000 Hz for automobiles, due to the significantly larger tyre treads in heavy vehicle tyres (Wayson, 1998).

4.1.1. Generation mechanisms: Vibrational

The vibration or structure-borne mechanisms are related to mechanical waves in the tyre structure. Three types of mechanical waves are relevant here: (i) type 1, membrane waves at low frequencies, and bending waves at high frequencies; (ii) type 2, longitudinal waves; (iii) shear waves. Type 1 waves at low frequency are a result of the rubber pre-stress. Type 3 waves are a result of the soft rubber on the tyre treads vibrating out of phase relatively to the stiff rubber in the steel reinforced belt. The vibrational mechanisms are further divided into impact mechanisms and adhesion mechanisms, which will be more deeply explained in the following sections.

4.1.1.1. Impact mechanisms

The three impact mechanisms are: (i) tread impact, (ii) texture impact, (iii) running deflection. The tread impact is the impact of the tyre tread blocks on the road surface, causing radial and tangential vibrations in the tyre tread and belt, and spreading to the tyre sidewalls. The texture impact is the impact of the tyre treads on the road surface texture, also causing radial and tangential vibrations in the tyre tread and belt, and spreading to the tyre sidewalls. The running deflection is a deflection of the tyre tread at the leading and trailing edges, resulting in tyre tread, belt and carcass vibrations. The resulting vibrations from impact mechanisms are presented in Figure 27 to Figure 30.

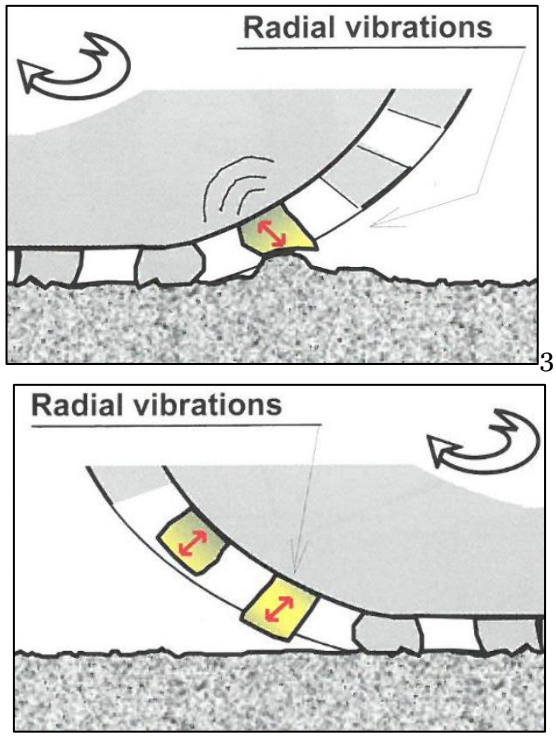

Figure 27 - Radial vibrations on tyre tread (Sandberg and Ejsmont, 2002)

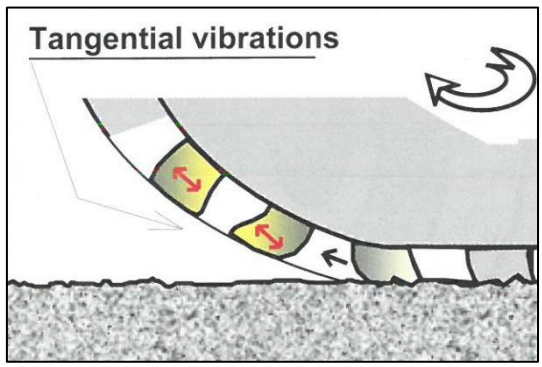

Figure 28 - Tangential vibrations on tyre treads (Sandberg and Ejsmont, 2002)

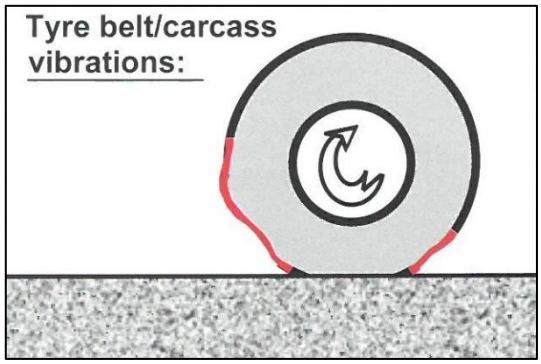

Figure 29 - Tyre belt/carcass vibrations (Sandberg and Ejsmont, 2002)

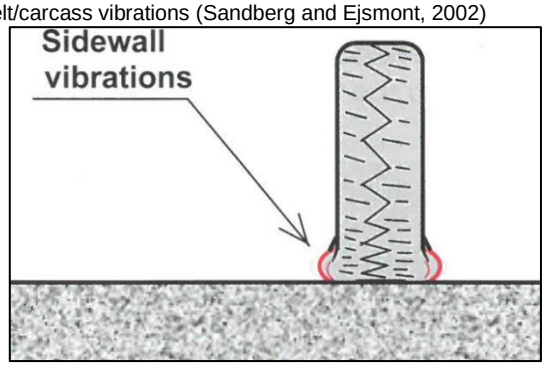

Figure 30 - Tyre sidewall vibrations (Sandberg and Ejsmont, 2002)

The tread impact takes place both at the leading and at the trailing edge of the contact patch. At the leading edge, the tyre tread is pushed inwards, towards the tyre rotational centre. At the trailing edge, the tyre tread is pushed outwards, away from the tyre rotational centre, as the contact stresses are released. In both the leading and trailing edges, the resulting vibration on the tyre tread is a noise source. Even a treadless tyre generates noise by impact as it is also subject to running deflection, which generates distortion in the tyre circumference. The resulting deflection will generate forced and free vibrations propagating in the tyre structure. These vibrations are, however quickly attenuated. The tyre is also subject to texture impacts, as the texture asperities impact the tread elements, also generating vibrations.

When the tyre contacts the pavement surface, it generates both radial and tangential vibrations, as the tyre tread elements will contact the road surface at a given attack angle, which is a function of the tyre radius, tyre tread pattern and road surface texture. Figure 31 illustrates the attack angle between tyres with different radii and a pavement surface with an exaggerated asperity. The generated noise will also be a function of speed, as an increased speed will increase the indentation frequency for a given tyre tread element.

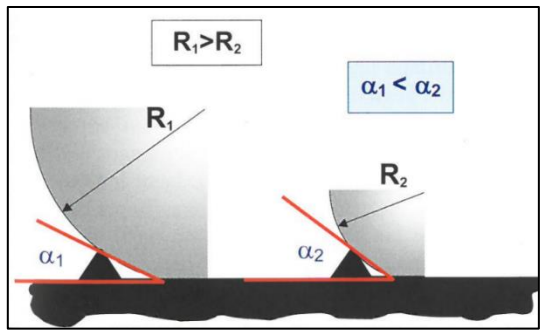

Figure 31 - Tyre attack angle with pavement surface and asperity, exaggerated proportions (Sandberg and Ejsmont, 2002)

4.1.1.2. Adhesion mechanisms

The two adhesion mechanisms are: (i) stick/slip, (ii) stick/snap. The stick/slip mechanism consists of tread elements moving tangentially to the road surface texture, causing tangential vibrations. Stick/snap mechanism consists of tyre tread snapping off the surface texture, resulting in tangential or radial vibrations. The former may provide excitations to pipe resonances and Helmholtz resonances, which will be explained in the following section. The stick/snap and stick/slip mechanisms are presented in Figure 32 and Figure 33 respectively.

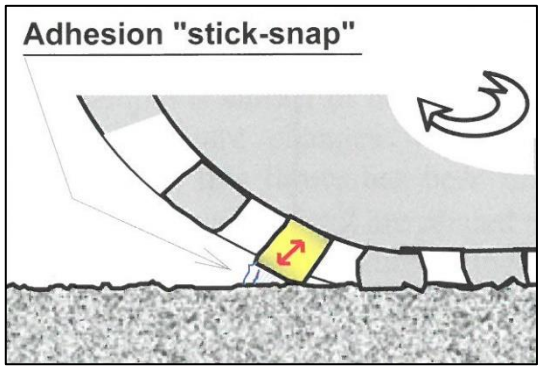

Figure 32 - Stick/snap mechanism (Sandberg and Ejsmont, 2002)

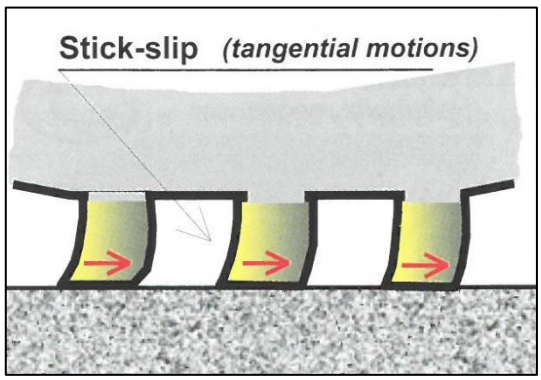

Figure 33 - Stick/slip mechanism (Sandberg and Ejsmont, 2002)

4.1.2. Generation mechanisms: Aerodynamical

The four aerodynamical mechanisms are: (i) air turbulence, (ii) air-pumping, (iii) pipe resonances, (iv) Helmholtz resonance. The air turbulence mechanism is a result of the turbulence due to the air displacements near the moving tyre. The air-pumping mechanism a result of air being displaced in and out of the cavities between the tread blocks and the pavement surface, not necessarily being in resonance. The pipe resonances are air displacements in the grooves of the tyre tread pattern, which will act as pipes, this may also be considered a special case of the air pumping mechanism. The Helmholtz resonance is generated by air displacement in connected air cavities between the tyre tread and the

pavement surface, amplified by resonances, this may also be considered as a special case of the air pumping mechanism. The aforementioned mechanisms are presented in Figure 34 to Figure 37.

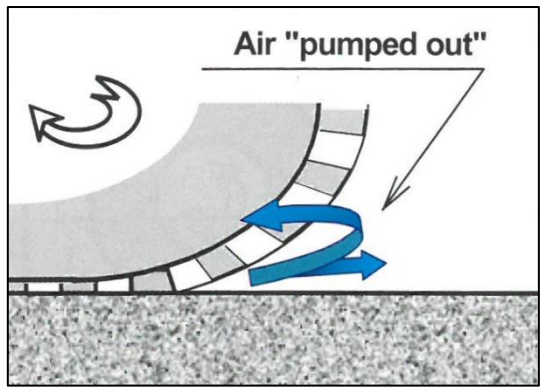

Figure 34 - Air pumping effect: air pumped out (Sandberg and Ejsmont, 2002)

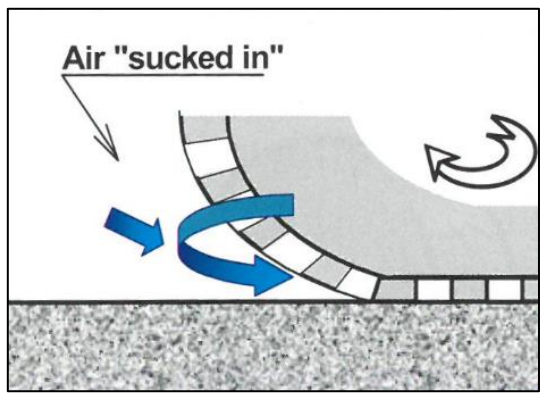

Figure 35 - Air pumping effect: air sucked in (Sandberg and Ejsmont, 2002)

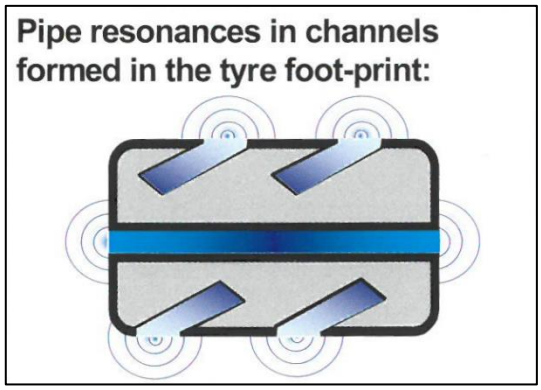

Figure 36 - Pipe resonance effect (Sandberg and Ejsmont, 2002)

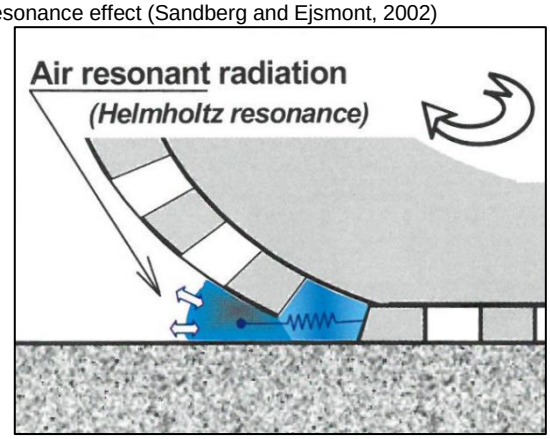

Figure 37 - Helmholtz resonance mechanism (Sandberg and Ejsmont, 2002)

4.1.3. Amplification mechanisms

The seven amplification mechanism are: (i) horn effect, acoustical impedance, (ii) voids in porous surfaces affecting the source, and (iii) far-field, (iv) road surface reaction to tyre block impacts, (v) tyre vibrations transferred to the road surface, (vi) belt resonances, and (vii) torus cavity resonance. The horn effect is generated by the curved volume between the tyre edges and the pavement surface, which has a similar shape to a horn, which is used to amplify sound, see Figure 38. The voids in porous surfaces absorb the generated noise, reducing its strength both near the source and to a far-field receiver. The road surface reaction to tyre impacts depends on the dynamic tyre/road properties and affects the noise amplification

properties. The tyre vibration may also be transferred to the road surface, which will then radiate noise. Belt resonances are resonances in the tyre belt, and torus cavity resonance is the resonance in the air volume inside the tyre cavity. The horn effect and the torus cavity resonance mechanisms are presented in Figure 38 and Figure 39, respectively.

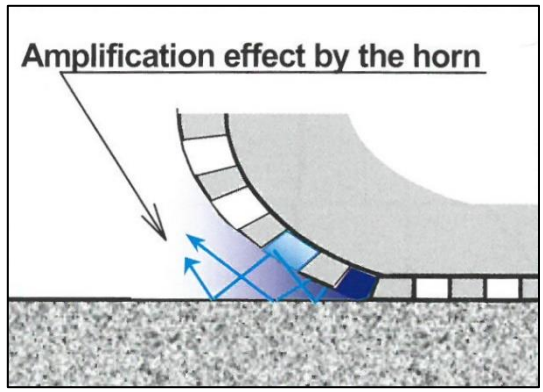

Figure 38 - Horn effect (Sandberg and Ejsmont, 2002)

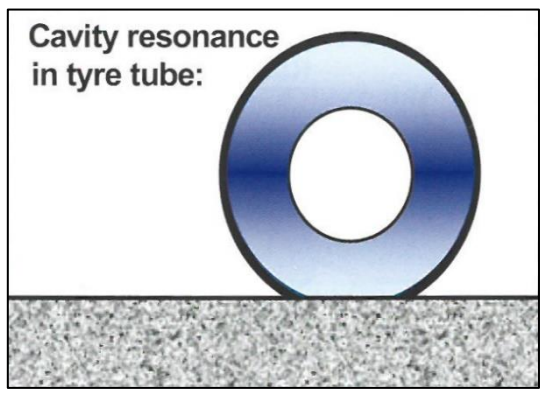

Figure 39 - Cavity resonance mechanism (Sandberg and Ejsmont, 2002)

4.2. Experiments to evaluate tyre/road noise

Considering the complexity of tyre/road noise generation and amplification phenomena, and the several variables that affect such phenomena, it is crucial to have standardized test methods to evaluate

tyre/road noise. The measurement methods are relevant not only for evaluating pavements and tyres, but for more complex studies, for instance, on noise generation and amplification mechanisms. For this section, it is important to define clearly the driving conditions that may be used in the test methods. Table 2 presents a description of the most common driving conditions.

Table 2 - Description of driving conditions (Sandberg and Ejsmont, 2002)

Driving Condition	Description
Coast-by	A vehicle passes by the test location with the engine switched off and transmission in neutral. Tyres are free-rolling
Cruise-by	A vehicle passes by the test location with the engine switched on and transmission engaged, maintaining a constant speed. Driven tyres are subjected to slight torque
Drive-by	A vehicle passes by the test location with the engine on, and transmission engaged. The vehicle is subjected to acceleration
Pass-by	Generic term which may refer to any of the above conditions

4.2.1. Acceleration Pass-By

The acceleration pass-by method is a test for measuring noise of an accelerating vehicle. This method is standardized by ISO 362. For this test procedure, the test vehicle approaches a test area at a constant speed. The test area consists of an outdoor rectangular area, with a length of 20 m parallel to the test track direction. Two microphones are placed, one at each side of the test track, 7.5 m away from the track centre line, at half the measurement length, *i.e.* 10 m away from the beginning of the rectangular measurement area. When the vehicle reaches the beginning of the test area, it is set to wide-open throttle until it crosses the end of the rectangular testing area. The initial speed is usually 50 km/h for cars and 15-50 km/h

for heavy vehicles. The maximum noise level of several runs is recorded, processed and results in the final reported value.

The power unit noise is significant considering this test speed and the extreme acceleration that the test vehicle is subjected to during the measurement. It is still possible to measure tyre/road noise if the power unit noise is lowered, for instance with encapsulation and other noise reducing measures.

4.2.2. Coast-By

The Coast-By method was developed using the acceleration pass-by method as a model, and is described in ISO 13325 (International Organization for Standardization, 2003) The major difference is that the driving condition is a coast-by one, according to Table 2. The vehicle moves in the test area by inertial forces. As there is no power unit noise, the major noise generation mechanisms are the tyre/pavement interaction mechanisms. The test speed is 80 km/h for light vehicles and 70 km/h for heavy vehicles, and it is recommended that measurement speeds should be uniformly spread in a range of +/- 10 km/h from the reference test speed.

Differing from the Accelerated Pass-by method, the coast-by method may be used to estimate tyre/pavement noise, as there is no power unit noise. This method is considered to be one of the most representative to evaluate the tyre/pavement noise levels. Positive aspects related to this test method include its simplicity, as it does not require specific equipment or measurement techniques, like power unit encapsulation, and it is a representative measurement of tyre/noise in actual traffic. One evident limitation is that the vehicle used in the tests affects the measurement.

Note that both the Coast-by and the Acceleration Pass-by are performed on a standardized pavement surface, according to ISO 10844 (International Organization for Standardization, 2014). This surface was developed to produce a relatively low level of tyre/road noise on a wide range of testing conditions and provides minor noise absorption of the power unit and related noise sources. This surface should be a Dense Asphalt Concrete (DAC) with a maximum chipping size of 8 mm (10 mm is still tolerated). The top layers should be at least 30 mm thick and the binder should be a standard penetration grade bitumen. Maximum measured

sound absorption should be 0.10 and the minimum texture depth, measured according to the volumetric patch method should be 0.4 mm. A usual SMA (Stone Matrix Asphalt or Stone Mastic Asphalt) with maximum chipping size of 8 mm will meet the requirements, even though the surface compaction (rolling) is a critical step in providing the standardized surface texture.

4.2.3. Controlled Pass-By (CPB)

This test method requires that a number of selected vehicles drive on a pavement test section, one by one, equipped with sets of market tyres. This method is standardized by NFS 31 119-2 (Association Française de Normalisation, 2000). The vehicles are driven in cruise-by mode, according to Table 2. The A-weighted noise level is recorded and the measurement is repeated on different test locations in order to obtain a representative value for the whole test area. Test speeds should be uniformly distributed within the range of 70 – 110 km/h, and the result is normalized to the speed of 90 km/h. The set of tyres should be representative of the French market, have a run-in of at least 100 km, and have at least 2/3 of the original tread depth. The test result is the arithmetic mean of the sound levels measured for each vehicle and tyres.

This test allows an effective evaluating the effect of different road surfaces, as several of the test conditions are known, including tyre properties, vehicle properties and speeds. One of the test limitations is that different vehicles and tyres may be used by different testing organizations, which may compromise a clear comparison between tests. It may also be difficult to perform this test on heavy trafficked roads, as other vehicles would disrupt the test results.

4.2.4. Statistical Pass-By (SPB)

This method consists of measuring the generated noise by an actual traffic steam, with vehicles at approximately constant speeds. This test method is standardized by ISO 11819-1 (International Organization for Standardization, 1997a). For this test, two microphones are placed near a road section, one on each side of the road, at a given distance, and they measure the resulting noise levels of the traffic stream. During the test, the

vehicle speeds, vehicle types and the respective noise are measured. After a statistical data processing, the noise values are assigned to the tested pavement, to specific vehicle types and speeds, and at a given microphone to the road distance. The test layout may differ depending on the pavement surface, for instance, two microphones may be placed at a distance of 7.5 m from the road centreline. Soft objects that may be present in the test area can affect the test result, and therefore should be covered before the measurement. Objects at the test site may interfere with the measurement, for instance, a safety barrier that may reflect sound, affecting the measurement. For this reason, it is required to have the test surroundings area free from sound reflexive objects.

After a valid passage of at least 100 passenger cars and 80 heavy vehicles, a linear regression is fitted on the noise levels against the measured speeds, for each vehicle category. Three testing speeds are possible, as indicated by Table 3.

Table 3 - SPB speed categories

Speed category	Speed range	Description
Low	40 – 60 km/h	Urban streets
Medium	70 – 90 km/h	Collector, feeder and sub-arterial roads, some highways
High	100 – 130 km/h	High-speed highways, arterial motorways and freeways

Each speed category has a reference speed. With the previously calculated regressions, the measured noise levels are normalized to its category reference speed. The noise levels are then weighted, and the weight factor represents the share of its vehicle category in the total traffic. It means that a total traffic with predominantly passenger cars will have a higher weight for the noise levels of such vehicles, and a reduced weight for heavy vehicles. The resulting test value, the Statistical-Pass-By index

(SPBI), is the average sound level after proper weighting is calculated, according to the traffic composition.

One of the limitations of this method is that the sampled traffic during the measurement is expected to represent well the traffic at that given road, even though it is affected by the exact position and time of testing. Seasonality effects should also be considered, both on the traffic composition that may change during the year, and on the type of tyres that are used in different seasons. The latter aspect is especially relevant for cold weather climate countries, like Sweden, as the usage of winter tyres with studded is allowed and it drastically affects the resulting noise levels.

4.2.5. Close Proximity Method (CPX)

The close proximity method (CPX) consists in measuring the tyre/pavement noise levels near the pavement interface. This method currently has a standard by ISO (International Organization for Standardization, 2017a). The test trailer can encapsulate the test tyre to prevent undesired acoustical interference, for instance by other vehicles near the test trailer, wind and better encapsulation on other unexpected and unwanted noise sources. The microphones are positioned near the contact patch in accordance with the ISO specification mentioned above.

The CPX test is usually performed at one or more of the three nominal speeds: 50 km/h, 80 km/h, and 110 km/h, to determine the tyre/road sound level, L_{tr}. Those speeds are within the three speed ranges for the SPB method, previously presented in Table 3. Other testing speeds may be used if the three previously mentioned speeds are not practical. During the test, the vehicle's actual speed, and the noise level for segments of 20 m are recorded. The values are then normalized to the desired nominal speed. The resulting test value, L_{tr}, is the average noise level value registered by the two mandatory microphones, after the necessary speed corrections, for each reference speed and reference tyre. The test result, the Close Proximity Sound Index (CPXI), is the average value of the evaluated Ltr for each tested tyre. The CPX measurement trailer Tiresonic MK4, by the University of Gdańsk, is presented in Figure 40.

Figure 40 - CPX measuring trailer Tiresonic MK4 by the University of Gdańsk

One of the reference tyres, which is representative of passenger car tyres, is the Uniroyal Tigerpaw 225/60 R16, which is also used in the automotive industry as a reference test tyre. The other is the Avon Supervan AV4 195-R14C, which results in representative noise values for heavy vehicle tyres (Morgan et al., 2009). The selection of the two reference tyres is a result of an extensive program which started with 16 candidate tyres, on the different pavement, including both dense and porous surfaces. The selected tyres have good correlations to the CPX measurements with the previous reference tyres A and D, and between CPX and SPB values within a range of speeds. The SPB and CPX sound spectra were also compared, to assure that the reference tyres would have a low standard deviation considering the one-third octave band spectra. Other factors considered to select the reference tyres are the long-term availability, reproducibility within a batch, among others.

Advantageous aspects of the CPX method include that the measurement itself is quick, inexpensive, and requires little or no traffic disturbance. This test is practical if it is necessary to evaluate long pavement surfaces or several different tyres. The CPX method also does not require special care regarding reflexive objects near the road, as it evaluates noise near the source, *i.e.* the tyre/pavement contact, and it is possible to enclosure the tested tyre, to avoid unnecessary noise disturbance. The CPX may also be used to detect clogging and the

effectiveness of surface cleaning processes, surface homogeneity and compliance to surface specifications. Disadvantages include a more expensive equipment, which also requires good maintenance, and a relevant influence on the test vehicle and background noise.

One relevant limitation of this test is that, as previously mentioned, it measures noise in the near field, near the source. This is not necessarily representative of the noise perceived by a listener in the far field, which may be disturbed by the traffic noise. The test vehicle also affects the test, as the vehicle or trailer structure reflects noise, and the power unit also generates background noise. Due to the test vehicle limitations, measured noise levels below 200 Hz are questionable. The test method has a good correlation with the SPB method and the Drum method, and therefore, the mentioned tests may be used to supplement each other.

4.2.6. Drum Method

The drum method is a laboratory method in which a test tyre run on the inner or on the outer surface of a drum test equipment. Typical drum diameters are between 1.5 m and 2.5 m. The microphones are placed near the tyre, in different positions and numbers, depending on the desired test purposes (Sandberg and Ejsmont, 2009).

Care must be taken in order to prevent unwanted noise in this test, which may be generated by the equipment power unit or its bearings. Objects near the test equipment may also affect the measurement as they may reflect sound. The drum surface that interacts with the tyre must be covered by a proper surface that results in representative acoustic performance of pavement surfaces. The use of sandpaper surfaces or similar, such as “Safe Walk”, results in significantly different sound spectra, when compared to CPX measurements of actual pavement surfaces. Sandberg and Ejsmont (2002) also indicated that adhesion-related mechanism may have a more significant role in the drum test than on an actual tyre-pavement interaction. The authors relate this effect to the indoor environmental condition and to different texture roughness on the drum test. More representative results are attained when the drum is mounted with a moulded replica of road surfaces (Sandberg and Ejsmont, 2009).

Given that this is a laboratory test, a straightforward advantage is that test conditions are more easily set and controlled. Several different conditions may be tested in the drum method, which would require a significant amount of time to rely, for instance, on matching a specifically desired weather condition. It is considered to be a high precision method, well fitted for research and development purposes. It also allows testing at different speeds, and with heavy vehicle tyres. The limitations and disadvantageous aspects of this method include the previously mentioned background noise, which could significantly affect the result. The requirement of a laboratory drum facility and a proper replica of pavement surfaces. Drum test equipment radius may affect the noise measurement. Sandberg and Ejsmont (2002) indicate a drum with a minimum diameter of 1.5 m for testing passenger car tyres, and 2, or 2.5 m when testing heavy vehicle tyres (Sandberg and Ejsmont, 2002).

4.2.7. Sound Absorption Measurements

Sound absorption measurements are applied to evaluate the sound absorption coefficients of pavement surfaces, which may be carried out *in situ* or *ex-situ*, with the respective and appropriate procedure.

The *in situ* measurement is standardized by ISO 13472 (International Organization for Standardization, 2002a). It is a non-destructive technique that may be used for noise measurement, for evaluating road construction or maintenance characteristics related to sound absorption. For this method, a signal generator is connected to a loudspeaker that is positioned above the pavement surface. A microphone is placed between the loudspeaker and the pavement surface, aligned to its geometrical axis. The sound waves will travel past the microphone, to that pavement surface and be reflected back to the microphone. The detected forward sound waves, from the loudspeaker to the pavement surface, and backwards waves, from the pavement surface to the loudspeaker are analysed, in order to determine sound absorption coefficient of the pavement surface (Londhe et al., 2009). See Figure 41 for a setup example.

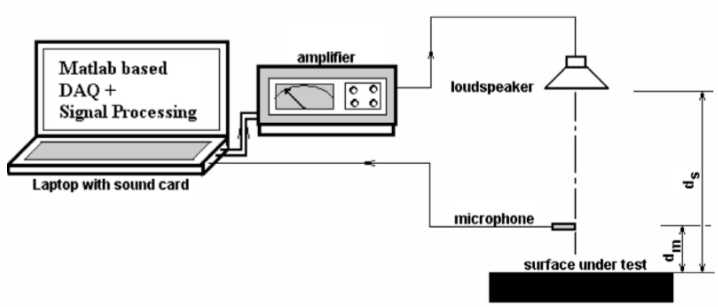

Figure 41 - Example of surface absorption measurement setup according to ISO 13472-1 (Londhe et al., 2009)

The *ex situ* method is standardized by ISO 10534 (International Organization for Standardization, 1998). For this method, a cylindrical pavement sample is placed inside a tube, at one of its extremities. At the other extremity, there is a loudspeaker, which will be connected to a sound generator. A possible test setup with two microphones is presented in Figure 42. The generated sound wave, p_I leaves the loudspeaker and is reflected back, as p_R. With a digital frequency analysis, it is possible to determine the sample sound absorption coefficient.

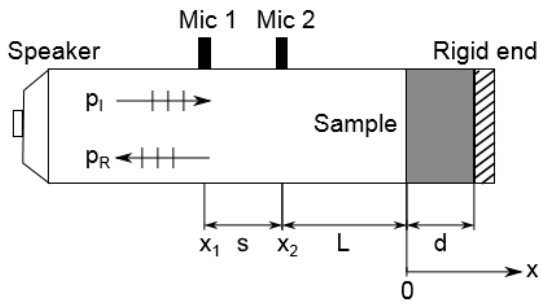

Figure 42 - Impedance tube setup according to ISO 10534 (Wolkesson, 2012)

Yamaguchi et al. (1999) used the impedance tube to evaluate sound absorption mechanisms in porous pavements, concluding that the peak in sound absorption coefficient occurs in a given frequency which is influenced by the thickness and the internal void structure. Crocker et al. (2004) also applied the impedance tube measurements, both *in situ* and

ex-situ to evaluate different porous pavements, finding experimental evidence of a correlation between sound absorption values measured by the Impedance Tube and the tyre/road noise measured by the CPX method.

4.3. Speed and temperature influence

Considering the viscoelastic nature of rubber tyres, the tyre/pavement noise generation and amplification mechanisms, that are influenced by viscoelastic parameters, it is not surprising that the tyre/noise measurements are also affected by temperature and speed. Temperature and speed corrections are necessary, from the standardization point of view, as they significantly affect the measured values. Were these two parameters not considered, the reproducibility repeatability of tyre/pavement test methods would be compromised. Proper tyre/pavement noise emission legislation also requires accurate methods, which are not significantly affected by environmental testing conditions.

An initial approximation to the temperature effect is that it affects the tyre/pavement noise at a rate of -0.1 dB/ºC, which means that a 30 ºC difference between testing temperatures results in a 3 dB noise difference, which is equivalent to switching between completely different tyre tread patterns (Sandberg and Ejsmont, 2002). It should also be considered that the tyre/pavement interaction, with a systematic approach, is potentially affected by three different temperatures: (i) the environment temperature, (ii) the tyre temperature, (iii) the pavement surface temperature. It is, thus, necessary to evaluate which temperature parameters are most relevant, should be measured, and will provide the best correlations to tyre/road noise. Sandberg and Ejsmont (2002) indicated that the best correlations for tyre/pavement noise are experimentally found for air temperature and pavement surface temperature.

The effect of temperature on tyre/pavement noise is also frequency dependent, given that temperature affects different noise generation and amplification mechanisms, and those mechanisms are frequency dependent. The most prominent temperature effect occurs in a range of 1 kHz to 4 kHz. Pavement surfaces that have low noise levels in such

frequency range will require a less significant temperature correction. The frequency that is less affected by temperature is the one related to tread block impacts and is connected to the spectral peak (Sandberg and Ejsmont, 2002).

Previous research from Bridgestone Corporation resulted in a preliminary model for temperature correction of tyre/pavement noise levels as a function of tyre parameters. The temperature correction was based on the rubber tread elastic modulus, E'. Another possibility is a temperature correction as a function of the rubber tread shore hardness, even though more studies are required for this type of temperature correction with tyre material parameters (Sandberg and Ejsmont, 2002).

A temperature correction procedure for the CPX method is available in the ISO TS 13471-1 (International Organization for Standardization, 2017b). The procedure takes into account the two reference tyres and three different surfaces: (i) dense asphaltic surfaces, (ii) cement concrete surfaces and (iii) porous asphalt surfaces. The test speed is also considered in the calculations. The proposed temperature corrections are more significant for dense asphaltic surfaces, decreasing for the case of cement concrete surfaces, and decreasing further for the case of porous asphaltic surfaces. A correction parameter is then calculated and is to be added to the measured value in order to normalize it to a reference temperature of 20 ºC. According to this technical specification it is not recommended to make CPX measurements with temperatures above 35 ºC, as adhesion effects become more significant, and the noise might increase with temperature, instead of decreasing.

Another tyre/pavement noise test and is widely applied is the Drum test, previously described in this text. Mioduszewski et al. (2015) studied the temperature effect on the drum test device. They indicate that, even though tyre temperature might be the most realistic temperature reference, it is the most difficult to be measured as well, therefore they also decided to measure environmental air temperature for the tests. They used a composite temperature correction, which is based both on air and on pavement temperatures. The resulting composite temperature correction coefficient, C_c, is a function of the temperature correction factor based on

air temperature, C_a, and the correction factor based on pavement surface temperature, C_r, as indicated by equation 15.

$$C_c = \frac{C_a + 1.8 * C_r}{2} \tag{15}$$

5. Rolling Resistance

Rolling resistance is the effort required to keep a tyre rolling at a given speed. It is a result of mechanical energy converted into heat for a rolling tyre moving in a given pavement length (Gent and Walter, 2005). Another possible definition found in the literature is that rolling resistance is the force required to keep a tyre rolling (Jackson et al., 2011). With the first definition, based on energy and by performing an energy analysis on a rolling tyre, a definition of rolling resistance based on the net power input received by the tyre as shown in equation 16.

$$F_R = \frac{(P_{in} - P_{out})}{v} = \frac{T\omega}{v} - F_x \tag{16}$$

Where F_R is the rolling resistance force, P_{in} is the power input, P_{out} is the power output, v is the linear velocity that a tyre moves with respect to the pavement surface, T is the torque applied to the wheel spindle and F_x is the horizontal reaction force at the contact patch, opposing the tyre roll, according to Gent and Walter (2005).

Energy loss occurs as the tyre is subjected to cyclic loading as the tyre surface conforms itself to form the contact patch. This leads to bending of the crown, sidewalls and bead areas, compression of the tread and shearing of the tread and sidewalls (Gent and Walter, 2005). The crown region contains the belt which behaves as an inextensible and incompressible layer. It also contains viscoelastic layers, like the tread and the liner. When the crown is subjected to bending deformations, the inner and outer layers that surround the belt will be subjected to tension and compression cycles, which substantially contributes to rolling resistance losses. Additional energy losses take place in the sidewall and bead region that combined account for approximately 30% of energetic losses during rolling. This generates a travelling wave which will also dissipate energy. When a tyre is

loaded and the crown is flattened to form the contact patch, this imposes deformations in the sidewall and bead regions. This bending deformation results in tension and compression for the inner and outer layers, similar to the mechanism described in the crown. For a more comprehensive discussion on footprint mechanics refer to Gent and Walter (2005).

Defining rolling resistance by energy dissipation results in practical difficulties when it comes to measurements on actual road surfaces. Therefore, considering the practical aspects and limitations, the force definition is preferable when measuring rolling resistance in actual road surfaces. From the force approach, the rolling resistance coefficient, RR_c, is defined by equation 16 as the ratio between rolling resistance force, F_R, and the normal force, F_N. Note that, in equation 16, the rolling resistance coefficient is calculated by dividing the force magnitudes, resulting in a dimensionless coefficient, it is a scalar and not a vector definition. The rolling resistance force is dependent on the applied load, and previous studies have found a linear relationship between the normal load and the rolling resistance. For this reason, the rolling resistance coefficient, as defined by equation 16, provides a more practical and comparable parameter. It may be used to compare different tyres and pavements (Sandberg et al., 2011a).

$$RR_c = \frac{F_R}{F_N} \tag{17}$$

Note that even though the rolling resistance has an approximately linear relationship to load, increasing load causes the energy dissipation to increase and leads to an increase in the tyre temperature which reduces the rolling resistance coefficient in some cases. A reduction in tyre pressure will affect tyre deformations in a similar way to an increase in load. An increase in tyre pressure usually leads to a decrease in rolling resistance (Gent and Walter, 2005).

The speed will also affect the energy dissipation in tyres, resulting in a higher indentation frequency, which leads to increased viscoelastic losses with an increased *tan(δ)*. On the other hand, it also causes the tyre temperature to increase which leads to a reduction of *tan(δ)* and thus a

reduction in rolling resistance. The typical net result is an increase of rolling resistance with speed, depending on the tyre viscoelastic behaviour. As previously discussed the tyre temperature has an important role as it affects rolling resistance directly. Therefore, keeping in mind that a rolling tyre may take more than 30 minutes to reach a steady-state operating temperature is crucial (Schallamach, 1971).

The non-linear behaviour of the tyre structure, which includes the Mullins and Payne effects, previously discussed in this text, are also relevant when assessing the tyre pavement interaction with regard to rolling resistance.

Rolling resistance is a relevant pavement functional property, given that one of the major challenges for European road networks now is to provide efficient transportation with proper safety levels, considering public health and environmental impacts (Haider et al., 2014). One of the major difficulties when analysing rolling resistance is that there is no recognized measurement method available. Rolling resistance measurement will be further discussed in this chapter. On the following subsection, the rolling resistance phenomenon will be discussed in the context of the vehicle's energy consumption.

5.1. Rolling Resistance and Energy Consumption

Rolling resistance affects fuel consumption and therefore is a relevant factor when evaluating different policies and strategies regarding transportation infrastructure. An analysis of the cost-effectiveness of reducing rolling resistance by selecting different pavement maintenance strategies was presented by Carlson et al. (2016). The analysis included a decision-making procedure based on cost ratio comparison. Different alternatives were compared considering not only maintenance cost but also the respective energy-related cost, which originates from fuel consumption and energy used in maintenance. Different scenarios were simulated under different conditions and with the respective uncertainty related to both energy and maintenance costs included. The results indicated that by using the decision making criterium that takes rolling resistance into account when selecting maintenance strategies, one can

reduce fuel consumption in the order of 1 %. It was also concluded that the presence of water or snow on the pavement surface leads to higher rolling resistance.

The relationship between fuel economy and rolling resistance can be evaluated by the so-called return factor, which is defined as the ratio of the relative improvement in fuel economy that results from a percentage reduction in rolling resistance. The result is usually expressed as 1:x, meaning that takes x % improvement in rolling resistance in order to result in a 1 % improvement in fuel economy (Gent and Walter, 2005). Typical values for the return factor are between 8 % and 20 % for passenger vehicles, while a loaded truck has a return factor of approximately 33 % (Gent and Walter, 2005).

Different energy dissipation phenomena are relevant to the vehicle/tyre interaction context. Other factors such as air resistance, inertial resistance, side force and wind should be taken into consideration. An example of how such different terms can be modelled and how they contribute to the total energy dissipation is found in (Hammarström et al., 2009).

The systemic approach becomes important in analysing rolling resistance again. This means that not only pavement and tyre should be examined, but also the environmental effects and the separation medium. The environment will affect rolling resistance by the environment temperature and wind. The separation medium may include water or snow and both affect rolling resistance in different ways. Water will require energy to be removed from the contact patch so that the tyre may establish contact with the road surface, otherwise hydroplaning would take place. This energy related to the presence of water will be affected, among other variables, by the tyre speed and width (Mitschke and Wallentowitz, 2004). Another effect is that water will affect the tyre temperature, which leads to an effect on rolling resistance, given the tyre viscoelastic behaviour. Snow will also affect rolling resistance as it will be compressed by the tyres during rolling. Snow may have different densities, from 50 kg/m3 for new now and about 700 kg/m3 for compact snow. A review on how water and snow affect rolling resistance will soon be published by VTI (Carlson and Vieira, 2018).

It is important to define which dissipation mechanisms are not encompassed by the term rolling resistance in this text. For this purpose, consider the terminology presented in Figure 43 based on Sandberg et al. (2011a).

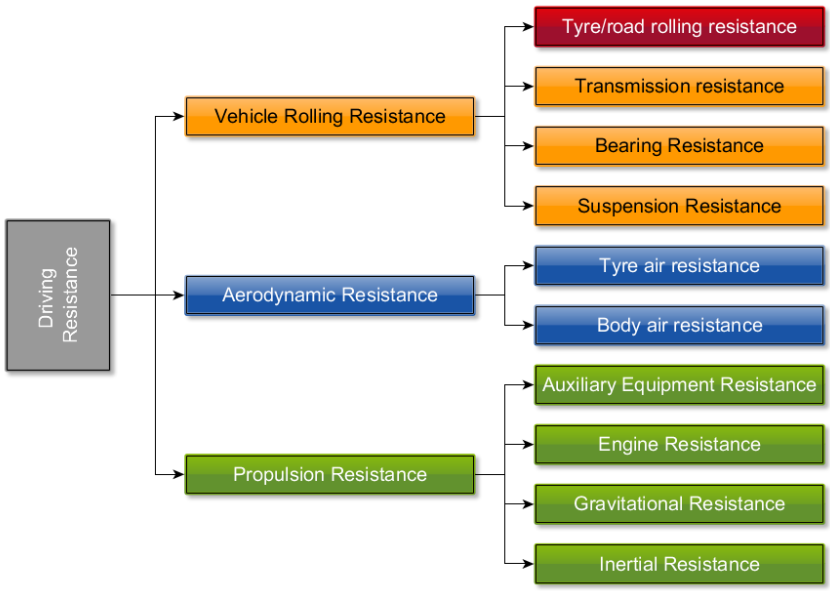

Figure 43 - Rolling resistance, driving resistance mechanisms and sources.

Note that even though tyre/road rolling resistance is separated from other mechanisms, such as tyre air resistance, such components will affect some measurement techniques and should, therefore, be taken into consideration. For instance, ISO 28580 (International Organization for Standardization, 2009), defines parasitic losses, which are not a result of the tyre/pavement interaction itself, but attributable to aerodynamic losses, bearing friction and other sources, which are intrinsic to the measurement method.

Rolling resistance was described as the result of the pavement interaction, which leads to tyre deflection, deformation and the imposed hysteretic losses due to the rolling movement. When the pavement is substantially flexible and deforms significantly under the tyre load, energy is also dissipated in the pavement top layer. Bituminous pavements

deflections under the wheel load are not negligible and affect the tyre deformation and the contact patch, directly affecting the energy dissipation. The pavement deformation is increased in the region anterior to the contact patch than it is in the region posterior to the contact patch. The pavement unevenness will also affect rolling resistance, as it will dynamically change the load on each tyre, therefore changing the contact patch deformation and all the energy dissipation mechanisms associated to it (Sandberg et al., 2011a). Pavement texture in shorter wavelengths, *i.e.* macrotexture and microtexture, will also create local stresses and shear forces in the tyre tread, again dissipating energy.

After the description of energy dissipation mechanisms that are relevant for pavement rolling resistance, it is also important to consider the parasitic losses. Bearing resistance is included in this category, as, depending on the bearing conditions, such friction is also not negligible. Transmission resistance is also relevant as part of the energy is dissipated before being transmitted to the tyre, by the clutch and other components of the transmission system. The suspension system may also result in significant energy losses which take place in the shock absorbers and other suspension components.

Aerodynamic losses may also be relevant depending on the speed, which are related both to the test vehicle and to the tyre specifically. Inertial resistance is related to the vehicle inertia, which opposes accelerations. Gravitational resistance includes the effort to overcome driving in inclined surfaces because of gravitational forces. Engine resistance includes the energy dissipated by engine components. Finally, auxiliary equipment resistance includes the energy required by other vehicle components, such as air conditioning, sound system, fans and so on.

As a final remark in this section, it is noteworthy that the energy dissipation when a tyre contacts the road surface is not limited to the contact patch area only, a substantial amount of energy is dissipated in the belt edge and sidewall regions (Padovan, 2016).

5.2. Rolling Resistance measurement methods

The measurement of rolling resistance presents major challenges, for instance, a typical rolling resistance coefficient for a passenger car would be 1 %. With a typical gross weight of 1400 kg, each tyre will have a load of 3,5 kN, and therefore the rolling resistance force will be of 3,5 N, which is a significantly lower magnitude when compared to the tyre load. For this reason, the measurement of rolling resistance requires advanced equipment, methodology, skilled and experienced staff (Zöller and Haider, 2014).

There are two possible approaches, still according to Zöller and Haider (2014), the direct and the indirect one. With the direct approach, the rolling resistance force acting on a test tyre fixed to a reference point is measured. The indirect approach will measure other physical quantities, for instance, the tyre torque or displacement angle. With the direct approach, the rolling resistance force may be measured either at the wheel spindle of a tyre mounted on a separate suspension, or by an assembly of a wheel force transducer and the test tyre, or even measured by the reaction force that an entire axle, with two or more identical wheels and the test tyre, are assembled. The indirect approach using angle measurements will require that the angle of a reference arm is measured. This arm will be deflected by the rolling resistance force, as it is assembled connected to the wheel spindle. The other possibility with an indirect approach is to measure the torque directly at the test wheel spindle. By multiplying this torque by the dynamic radius of the rolling tyre, one may obtain the driving torque of the tyre at steady speed and then evaluate rolling resistance. Figure 44 summarizes the several aforementioned rolling resistance measurement methods.

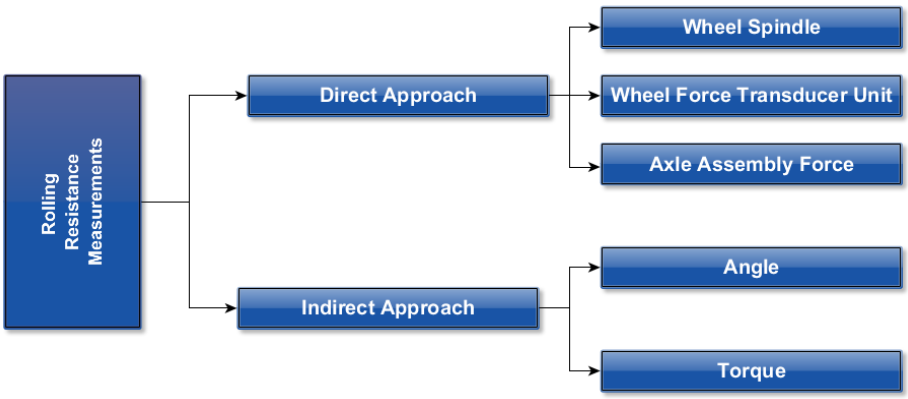

Figure 44 - Rolling Resistance measurement methods

There are several different trailer equipment to measure rolling resistance, for a more comprehensive review of several different equipments, the reader is encouraged to refer to Zöller and Haider (2014). For the purposes and scope of this document, only one trailer equipment is exposed, which is the one from the Gdańsk University of Technology in Figure 45.

Figure 45 - Rolling resistance measurement from the Gdańsk University of Technology (TUG)

The presented TUG trailer had its first measurements in 2005 and has been continuously improved afterwards. The equipment has 3 wheels,

which allows it to be easily transported and stand on its own, and a suspension system on the front wheels that will remain blocked during measurements to assure proper levelling. Details on the trailer construction are presented in Figure 46, based on the description found in Zöller and Haider (2014).

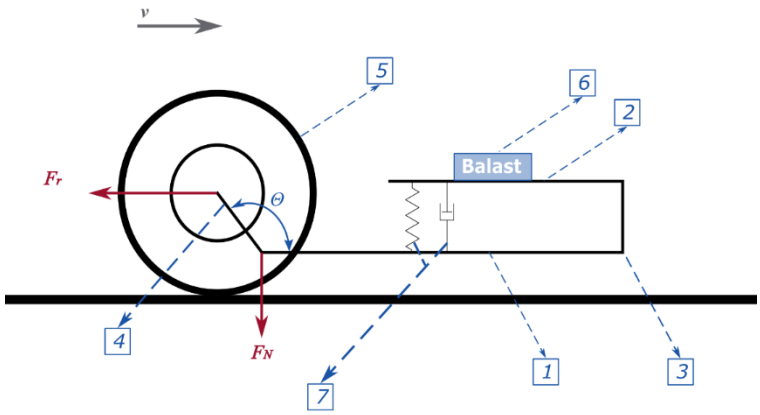

Figure 46 - TUG trailer for measurement of Rolling Resistance - construction details

In Figure 46, the horizontal arm (1) connects the front and rear suspension systems. The front wheels are positioned in (3). The load is provided by the horizontal arm (2) that has a common rotation with the horizontal arm (1). The ballast (6) will provide the normal load and is connected to the arm (2). Component (7) is a suspension element that will transfer the load between arms (2) and (1). Arm (1) is then connected to the pivoted arm (4) which is equipped with the test wheel hub. A component to reduce vibrations based on Foucault currents electromagnetic brake is also present, even though not shown in Figure 46. During measurements, the rolling resistance force will pull the pivoted arm (4). The deflection of the arm (4) is measured by a laser sensor fixed on the arm (1). The trailer systems will compensate for road inclination, longitudinal acceleration and other undesired effects. The system is protected by an enclosure which will reduce aerodynamic drag.

The equipment has a calibration procedure on a flat surface in laboratory conditions. The test tyres are warmed up before the tests for a period long enough to allow stabilization of the inflation pressure. At least two runs are performed at each speed and the measurement distance is usually 400 m.

It is also possible to measure Rolling Resistance in a laboratory environment with a drum equipment. An example of test equipment available is in the TUG and measured by the indirect approach evaluating torque in the tested tyre. The equipment presented in Figure 47 has a diameter of 1,7 m and a maximum load of 6 kN, this facility may be used for light vehicle tyres. Another drum testing facility is available at TUG which has a diameter of 2.0 m and maximum load of 35 kN, it was designed to test also heavy vehicle tyres. The rough surfaces for the drum tests were designed as replicas of flexible mouldings of existing road surfaces, namely DAC16r20 and ISOr20.

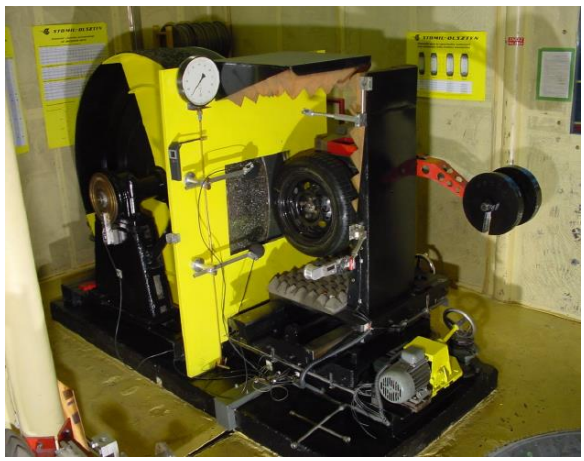

Figure 47 - Rolling Resistance measurement drum at the TUG (Ejsmont et al., 2015a)

As temperature significantly influences rolling resistance, it is also possible to control the test temperature in the drum facilities. Results from project ROSANNE indicate that a temperature increase leads to a rolling resistance decrease in the tested conditions.

Within project ROSANNE it was concluded that not only temperature should be precisely controlled, but also tyre inflation and road wetness

(Ejsmont et al., 2015b), among other variables, which must be further examined in order to propose a reliable and effective standardized method for evaluating rolling resistance.

6. Strategies to optimize functional properties of asphalt pavement concerning noise and rolling resistance

In this chapter a few different noise and rolling resistance reduction strategies are presented, the discussion in this chapter leads to the three papers appended to this thesis.

6.1. Low noise pavements

Two different strategies are discussed in this section, starting with porous road surfaces which is then followed by a discussion on thin layers.

6.1.1. Porous road surfaces

According to Sandberg and Ejsmont (2002) porous road surface is a surface with an increased number of air voids that will provide sound absorption. In order to provide such absorption though, these voids must be interconnected; therefore, a more precise term would be pervious, which describes the property of letting air and water pass through it. Even though the minimum porosity for which a pavement surface may be considered porous is not clearly established, according to the authors, a minimum of 15 % of air voids, expressed as a fraction of the total pavement volume. According to the authors also, a surface with air voids between 10 % and 15 % is considered semi-porous, and an air voids amount lower than that will refer to a dense pavement surface. Now that a more formal definition of what porous pavement surfaces was given, its noise-reducing mechanisms will be explained in the following section.

6.1.1.1. Noise reduction mechanisms in porous surfaces

Sandberg and Ejsmont (2002), the four most important properties of porous surfaces that will provide noise reduction are listed in Table 4.

Table 4 - Properties of porous surfaces for noise reduction, adapted from Sandberg and Ejsmont (2002)

Property	Description	Major consequence
Air displacement mechanisms	The increased porosity will decrease air displacements by allowing compression and expansion of the air that is entrapped in the tyre/road interface.	Reduction of air pumping and air resonance noise mechanisms.
Reduction of horn amplification	The increased porosity will decrease the horn effect amplification mechanism	Reduction of the horn effect amplification mechanism
Acoustical absorption	The increased number of pores will affect the reflection and propagation of noise. This is not limited to tyre/road noise and encompasses also power unit noise	Increased acoustic absorption
Impact mechanisms	The megatexture and macrotexture of porous surfaces will affect its acoustical properties. Therefore, the megatexture and macrotexture should be optimized to reduce noise	Reduction of impact mechanisms of noise generation

To optimize the surface texture, the authors recommended three measures: (i) use small chippings, which are not too small that would affect the surface porosity, (ii) roll the surface several times after laying, but not too much as it would reduce porosity, (iii) make it so that larger chippings are packed closer to each other.

From the discussion above it is noteworthy that a porous surface will provide a noise reduction not only at the source but also with sound propagation. Therefore, within a simplified approach, disregarding other reflections, the longer sound can propagate in a porous pavement surface, the more noise will be reduced.

6.1.1.2. Design of a noise reducing porous pavement surface

To design an effective noise reducing porous pavement, one should: (i) maximize sound absorption, (ii) minimize the airflow resistance, (iii) optimize the pavement surface. The acoustical absorption may be optimized for a given porosity. Sandberg and Ejsmont (2002) recommend that the sound absorption coefficient should be maximized for a frequency of 1 kHz for high-speed roads, and for a frequency of 600 Hz for low-speed roads.

Considering the air voids, to achieve a better noise reduction, the pavement surface should have as high air voids as possible. It should also be considered that the air voids will be subject to clogging, which will be further discussed in this text.

With regard to the second point, which is to minimize the air flow resistance, Sandberg and Ejsmont (2002) indicate that the optimum flow resistance, which will result in the widest absorption bandwidth, is in the range of 20 to 50 kNs/m^4 for high-speed roads and 12 to 30 kNs/m^4 for low-speed roads. To achieve this flow resistance range, a maximum chipping size of 10 to 11 mm is recommended.

The layer tortuosity and thickness will also affect the noise reducing properties. The tortuosity is related to the path length of the interconnected voids within a layer. This will affect mostly the maximum absorption frequency. An increased tortuosity will decrease the frequency of the absorption peak. The layer thickness will interact with both airflow and tortuosity. A thicker layer will usually contribute to noise reduction, even though it should also be adapted for the air flow resistance. A direct and more practical effect of thickness, still according to (Sandberg and Ejsmont, 2002), is clogging. A thicker layer will allow more debris deposition before the layer becomes clogged up with particulate material.

For heavy vehicles, the peak in sound absorption should be at a frequency of one or two third-octave bands lower than for light vehicles, due to the fact that heavy vehicles have an acoustic power concentrated at lower frequencies.

Durability is another parameter that should be considered when designing a porous pavement surface. An increased air voids content will significantly limit the pavement durability. Therefore, a maximum of 25% air voids is recommended (Sandberg and Ejsmont, 2002). As air voids and layer thickness interact, it is recommended to analyse those parameters together. For a low noise pavement surface, both air voids and thickness should be increased up to acceptable limits, which will still provide good durability, not compromising other functional aspects. Therefore, Sandberg and Ejsmont (2002) analysed the relationship between the product of air voids and layer thickness and the resulting noise reduction. By compiling several sources, they achieved a coefficient of determination R^2 of 74%. This could possibly be improved by considering maximum chipping size, but it also indicates that air voids and layer thickness explain a significant part of the total variation. This analysis also suggests that it is not practical to achieve a noise reduction higher than about 8 dB (A) without significantly reducing the chipping size, which would undermine the surface porosity. To achieve even further noise reduction, larger than 8 dB (A), other methods combined with porous surfaces are recommended, for instance, lower stiffness surfaces.

An alternative to improve durability, which is a conflicting aspect for increased air voids is the usage of modified bituminous binders. Sandberg and Ejsmont (2002) argue that even though there were attempts with fibres or rubber powder, no direct effect on noise was demonstrated as a result of the binder effect solely. An approximate 1 dB (A) noise reduction was obtained by using a plastic binder in an experiment in Sweden, yet it is not clear how the binder could improve noise reduction of the surface. The major aspect of bitumen might be the long-term effect though, which is connected to the pavement durability, and the speed at which a pavement layer becomes clogged up. The modified binder will also allow a better texture optimization to achieve a better noise reduction.

To balance the noise reduction aspects with the mechanical requirements, the guidelines proposed by Sandberg and Ejsmont (2002) are summarized in Table 5.

Table 5 - Guidelines regarding porosity for low noise pavement surfaces, adapted from Sandberg and Ejsmont (2002)

Parameter	Aim in order to produce a noise reducing pavement surface
Porosity	• At least 20% to be an acoustically efficient layer • High as possible without compromising durability
Optimum airflow resistance	• Maximum chipping size of 10 – 11 mm
Layer thickness	• At least 40 mm and preferably as high as possible

6.1.1.3. Some experiments and developments with low noise porous road pavements

This section will expose two examples of porous pavements applied in order to reduce noise. The first example is related to a pavement section in Huskvarna, Sweden. The second example is related the Poroelastic Road Surfaces (PERS), which was the subject of the European project PERSUADE.

Given its known noise reducing capabilities, a porous asphalt pavement was employed in the city of Huskvana, in Sweden, which is exposed by traffic noise generated by the traffic of motorway E4. To reduce the noise levels, fitting them to the limits established by a court decision, two measures were taken: (i) lower the speed limit from 110 km/h to 90 km/h, (ii) build a low noise road surface that shall reduce noise by at least 5 dB (A). As Sandberg and Mioduszewski (2014) report, the selected low noise pavement solution was a double-layer porous asphalt concrete with a thickness of 50 mm and maximum chipping size of 16 mm in the bottom

layer, and a thickness of 30 mm with a maximum chipping size of 11 mm in the top layer. CPX measurements were carried out to evaluate the pavement acoustical ageing and the decrease in its noise reduction capabilities. For comparison purposes, the authors decided to use an average SMA 16 as a reference surface to account for natural variations in the pavement condition, as well as variations in the reference tyres due to ageing and wear. In addition, according to the authors, due to research efforts, the uncertainty related to those parameters is now being reduced. The initial noise reduction obtained by this low noise porous pavement was 7 dB. The decrease in noise reduction was considered slow, accounting for 1 dB for the first 3 years. Clogging effects have been observed visually in the fourth year. The authors concluded that the bottom layer accounted for a substantial amount of the noise reduction. Another interesting result was the experiment of grinding the pavement surface to create a more negative texture. With a proper grinding equipment, approximately 1-2 mm of the top layer was ground, removing the highest surface asperity peaks, resulting in an even more negative texture. The grinding process resulted in a reduction of 1 – 2 dB (A) for CPX measurements with reference tyre SRTT, which simulates light vehicles. Considering the measured noise spectrum, there was a reduction in low and medium frequencies, yet there was an increase in high frequencies, indicating that the grinding process might have generated clogging. This process also reduced rolling resistance by 4 – 7%.

The importance of the bottom layer in a double-layer porous pavement was also examined in Sandberg and Mioduszewski (2012b) with experiments in the same pavement section in Huskvarna, Sweden. They determined that the major reason for noise reduction was sound absorption and that the sound absorbing frequency peak is proportional to the layer thickness, which is in agreement with previous experiments (Sandberg and Ejsmont, 2002).

The grinding procedure to optimize the surface texture was examined also in Sandberg and Mioduszewski (2012a). The authors mention the enveloping algorithm for porous surface texture, which will better represent the surface/tyre interaction. The portion of the rough surface which is actually contacted by the tyre is limited, as the tyre has a limited

capability of deforming over asperities and penetrate into the narrow valleys. The enveloping algorithms were previously described in chapter 3.4. With such enveloping algorithms, it is possible to evaluate the impact of negative textures contacting a tyre. The authors mention that, by analysing the frequency spectra of the double-layer section in Huskvarna, that noise was reduced mostly by a decrease in vibration excitation mechanisms due to texture impact. Grinding also had an impact in reducing rolling resistance by 4 – 7 %. Finally, the authors recommend a life cycle analysis (LCA) to evaluate when grinding should be applied to a given pavement, yet the technique has the potential of improving not only porous pavements but also other types of surfaces, like SMAs and thin asphalt layers.

6.1.1.4. Poroelastic Road Surfaces

Another approach with porous pavement is the use of PERS, Poroelastic Road Surfaces, that, according to the definition accepted in the European project PERSUADE, is a wearing course with the very high content of interconnected voids and a high content of rubber, or other elastic materials, to increase its elastic properties. The air voids content should be at least 20 % by volume and the rubber content should be at least 20 % by weight (Sandberg and Goubert, 2011b). The sound absorption will be high due to the increased porosity, which will also reduce air pumping effect. The flexibility will also be high, due to the high rubber content, which will create a surface compression and expansion cycle under each vehicle that passes over the surface. This cyclic compression and expansion will reduce clogging. The increased flexibility will also result in a surface that will soften the tyre tread impacts. Initial experiments with Poroelastic Road Surface started in Sweden, between 1975 and 1989, by Mr Nils-Åke Nilsson, by the time an acoustic consultant at IFM Akustikbyrån AB, headquartered in Stockholm. Other countries which have experimented with PERS are Norway, Japan and Holland, among others. For a proper historical review of PERS development, which is not within the scope of this document, please refer to Sandberg and Goubert (2011b).

Some of the challenges for developing an applicable PERS surface are safety and durability requirements. The European project PERSUADE had

the intention of developing a PERS into an applicable product that could be used for exceptional traffic noise reduction under specific traffic and road conditions. This project started in 2009 and was scheduled to last for 6 years. It included laboratory tests, which allowed mixture design and testing, construction of 7 test section in 5 different countries, and a follow-up phase which consisted of monitoring the constructed test sections. Some additional technical problems were faced during the project, which includes the fact that the material, with its high porosity, will retain water for a long time. This prolonged water exposure may also damage the base course. It is problematic for the material as heavy vehicles passing over the section, pass over the joint from PERS into a hard pavement surface. It is also problematic with snowploughs, which may cut into the PERS surface while passing by. Horizontal strains generated by temperature gradients may be a problem to the base course adhesion. Finally, sunshine may cause premature rubber deterioration, as previously pointed out in the tyres chapter of this document.

To overcome the base course adhesion problem, the use of epoxy glue was one interesting alternative, as indicated by Sandberg and Goubert (2011a). The selection of a proper epoxy glue should be done with care, considering that the material will be subject to thermal stresses during summer as well, when the epoxy will be stiffer, and the asphalt will be softer. This may lead to a poor load spreading capacity and eventually generate cracks in the structure. The epoxy layer may also fail due to fatigue.

Even though PERS has a high air voids content, permeability may become a problem due to two factors: (i) the pores are narrow within the PERS layer, (ii) PERS material is hydrophobic. The solution to this problem, as indicated by Sandberg and Goubert (2011a), may be adding an agent into the PERS mixture which will eliminate the hydrophobic property and use a cement base course with drains to allow a rapid water drainage.

Regarding skid resistance, the high rubber content on PERS surfaces and the resulting texture would not provide appropriate skid resistance. The solution adopted in project PERSUADE to optimize the surface microtexture was to add stone aggregates and sand to provide a better

surface macrotexture, and the usage of special binders to guarantee that durability will not be compromised.

The PERS material that was applied in Sweden and Poland, within project PERSUADE, consisted of a mixture of small stones and particles, sand, aggregates of rubber granules from recycled tyres and binder of polyurethane (Ejsmont et al., 2014). CPX measurements run in March of 2014 in the Swedish test section, which is located in Linköping, indicated that the PERS section in this location had a significant noise reducing capability. For a speed of 80 km/h, for instance, PERS was 12 dB (A) quieter than a dense asphalt concrete surface. By analysing the spectrum, it is noted that the noise reduction takes place at all frequencies above 125 Hz. It is also noteworthy, as reported by Ejsmont et al. (2014), that the PERS test section in Sweden was subjected to heavy loads of dumper tracks, heavy clogging and the Swedish winter condition, and yet it retained its favourable acoustical properties and was cleaned after rain and some heavy vehicles passing over it.

The Poroelastic Road Surface (PERS) has been briefly presented here as a localized solution to reduce tyre/pavement noise. Several challenges still need to be solved, yet the PERS solution indicated a significant noise reduction capability. As project PERSUADE came to its end, the remaining unsolved challenges should be addressed in the future development and research projects.

6.1.2. Thin layers

Another possibility to reduce the resulting tyre/pavement noise is discussed in this chapter, which is the usage of thin layers. The definition of a thin layer for this report is the one proposed by Sandberg et al. (2011b), presented in Table 6, and it is not solely a geometrical one.

Table 6 - Thin layer definition, adapted from Sandberg et al. (2011b)

Gradation	Various gradations: the layer consists of a mix of aggregate particles that follow a certain size distribution, and are bonded together by a bituminous binder, resulting in a homogeneous plant produced a mixture.
Characteristic in focus	Surface characteristics: the layer is designed with focus on functional characteristics, which means it is designed concerning the interaction between the tyre and the road surface
Typical Thickness	Between 10 and 30 mm

The first feature, regarding the layer gradation, excludes surface treatments and slurry surfaces. Note that surface treatments will be discussed further in this text, and is considered as an *in-situ* procedure rather than a homogeneous layer structure. The second feature, which establishes that the focus is on the functional aspects means that a thin layer will have specific requirements to act as an optimized interface between the road and the tyre. This means that aspects such as texture, skid and wear resistance, noise reduction, light reflection, splash and spray will be prioritized. The layer thickness, which is the third feature of thin layers, limits the layer thickness between 10 and 30 mm. The thickness could have different minimum and maximum limits depending on the timeframe and purpose of the definition (Sandberg et al., 2011b).

As one of the characteristics of thin layers is that they are designed with a focus on functional performance, a direct consequence is that the advantageous aspects of thin layers are potentially good noise reduction, decreased rolling resistance, reduced anti-spray and efficient light reflection. Other remarkable beneficial aspects of thin layers are low construction and maintenance costs coupled with a relatively high sustainability. The pavement base layer should be appropriate and its

conditions should be observed before laying the thin layer surface (Sandberg et al., 2011b).

Some of the drawbacks of using thin layers are the low wear resistance and limited durability under heavy traffic. The low wear resistance may become even more significant in countries that allow the usage of studded tyres. The limited durability under heavy traffic may also become more significant in curves or at large gradients. Further investigations concerning the thin layer's life cycle cost analysis are needed, even though that requires more data on the performance of such layers over time (Sandberg et al., 2011b).

Given the several beneficial aspects of thin layers, several proprietary thin layer products are available in Europe, mostly focused on urban community markets, such as road and street departments of medium and large-sized cities. Some product examples are Nanosoft, Microflex and Micropave (Sandberg et al., 2011b). The French product exemplified here, Nanosoft, is a hot asphalt mixture designed to provide significant noise reduction, up to 9 dB (A), when compared to a SMA16, which a common pavement surface in Sweden. The mixture has an increased proportion of small aggregates that are bound together by an elastomer modified bituminous binder (Sandberg, 2012b).

6.2. Low Rolling Resistance Pavements

The relevance of rolling resistance and some experiments related to it have already been described previously in this document. This chapter will complement the rolling resistance discussion concerning low rolling resistance pavements.

An interesting experiment concerning rolling resistance is the project "CO2 emission reduction by exploitation of rolling resistance modelling of pavements", which was a cooperation project between the Danish Road Directorate, Roskilde University, Technical University of Denmark, and NCC Roads (Papaioannou et al., 2012). Within this project, three test sections were constructed near Vordingborg, in Denmark to evaluate how different pavement surfaces will affect the resulting rolling resistance. Particularly, there was interest in study Split SMA pavements. The three

tested surfaces were: (i) a new SMA 8, (ii) a new SMA 6, (iii) a reference SMA 8. The two new SMAs were designed specially to achieve a low rolling resistance surface by selecting different aggregates, fillers and polymer modified binders. The binder content was designed in order to result in a 4 % air voids content. This resulted in a binder content of 6 and 7,5 % for the new SMA 6 and new SMA 8, respectively. The reference SMA 8 had a binder content of 6.9%. The mixtures were designed to provide a dense and durable surface with reduced aggregate motion.

To measure rolling resistance on the test sections, the TUG trailer was used, which was already described in this document, in section 5.2. Three different tyres were used in the measurements, the two standard tyres for the CPX method, and the MCEN tyre, as, according to the authors, these tyres have been used by TUG since they started with rolling resistance (RR) measurements and was used to provide means of comparison to older RR measurements. By analysing the results, it was determined that the maximum aggregate size has a significant effect on the rolling resistance, as the reference surface had the highest value and the new SMA 6 had the lowest values

The authors concluded that it is possible to optimize a SMA pavement to provide lower rolling resistance. This includes not only optimizing the aggregates but also mastic characteristics. A smaller maximum aggregate size reduces the rolling resistance coefficient even further. It was also concluded that there is a significant effect of the tested tyre on the rolling resistance coefficient values.

6.3. Winter tyres

When discussing noise and rolling resistance in Sweden, some specific aspects should also be taken into consideration. These aspects are relevant due to harsher winter conditions when comparing, for instance, the Nordic climate to the central European one. The pavement surfaces in Sweden are subject to lower temperatures, and to the traffic of vehicles with studded tyres. The usage of studded tyres leads to rougher road surfaces and the use of larger maximum aggregate sizes in the pavement design process.

Implications to the functional performance are related not only to a rougher surface and larger aggregate particles in the pavement surface but also to the presence of the studs and different tyre designs. The studs will interact with the road surface when they enter the contact patch, affecting functional performance parameters like noise and rolling resistance. Additionally, tyres designed to operate at lower temperatures will have different rubber materials with the respective viscoelastic properties optimized for lower temperatures. This discussion leads to the investigation of the performance of winter tyres and papers A and B appended to this thesis and further summarized in the next chapter. Other consequences of the studded tyres usage are a rougher pavement surface and increased wear of the pavement surface (Angelov, 2003).

6.4. Surface treatments and surface optimization techniques to reduce noise and rolling resistance

This chapter presents some of the strategies to reduce noise and rolling resistance by optimizing the wearing course texture. Two major strategies will be discussed here: (i) surface grinding, and (ii) surface cleaning. Surface treatments are differentiated from thin layers in this text by the fact that the latter are considered the result of an *in-situ* procedure and the first is a homogeneous layer structure. For more details on the definition of thin layers, please refer to the respective chapter in this text.

The surface grinding technique described here consists of removing the highest asperities peaks with grinding tools that rotate in a horizontal plane, parallel to the road surface. This process will not only affect the macrotexture by removing some of the asperities peaks but will also affect the microtexture as a result of the coarseness of the grinding tools. This process results in a surface with a more negative skew and the now flattened asperity peaks will influence the tyre deflections in the contact patch. The effect of surface grinding is presented in Figure 48. The enveloped profile was also calculated using the von Meier algorithm as described in (Gottaut and Goubert, 2016). This shows how the ground surface affects the tyre deflections and leads to different noise levels, rolling resistance and friction. The grinding technique was explored in

paper C appended to this thesis and further summarized in the next chapter.

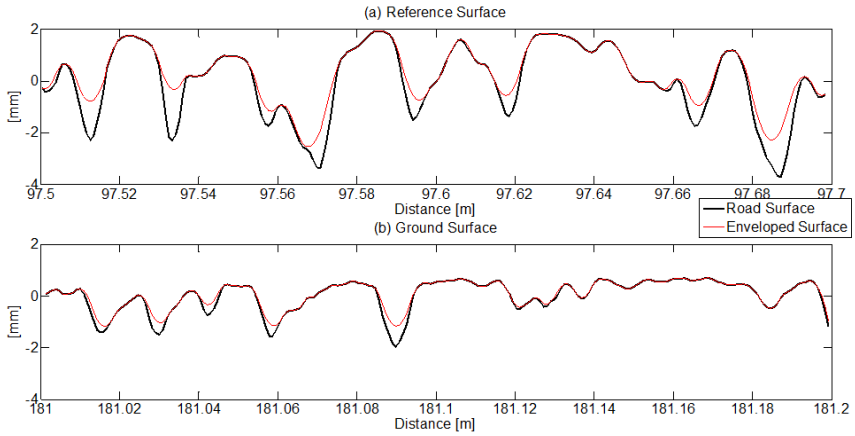

Figure 48 - A pavement texture illustrative example before (a) and after grinding (b). The respective enveloped surface is also calculated for each surface profile.

The grinding process described here, *i.e.* horizontal grinding, should not be confused with another grinding technique referred to as diamond grinding. In the latter case, the grinding tools move in the vertical plane, orthogonal to the road surface plane. While both horizontal and diamond grinding use diamond tools, the horizontal type was used in this application to reduce macrotexture by "shaving off" the top of the texture, and the diamond grinding machines aim at reducing unevenness while simultaneously creating a longitudinal texture of narrow grooves. The latter is used on cement concrete pavements, while our horizontal grinding has been used only on asphalt pavements, but can equally well be used on concrete.

Surface cleaning, which is the second major topic in this chapter, is an important strategy for maintaining the noise reducing properties of porous pavement surfaces. This is due to the fact that porous pavement surfaces lose their noise reducing properties over time mostly due to clogging of its pores (Maennel and Altreuther, 2016). The clogging of porous pavements may be restricted to the top level or extend to the bottom layer. The first prevails in conditions of low speeds or low traffic volume. This will seal the

open pores on the road surface, eventually resulting in a total loss of the noise reducing properties. The second occurs on surfaces with higher traffic loads or when an increased number of clogging particles is available, for instance near a construction site. Clogging of the bottom layer will shift the sound absorption of porous surfaces to higher frequencies by reducing the layer thickness that is acoustically relevant for noise absorption. Additionally, a homogeneous clogging may occur, depending on the available quantity of clogging particles and the pores size on the pavement surface. In this case both the top and bottom portions of the pavement will be clogged (Maennel and Altreuther, 2016).

Clogging on pavement surfaces may be investigated by sound absorption measurements, or by computed tomography (CT).

The cleaning of porous road surfaces may be performed dry or wet, even though, the optimization of cleaning processes to assure that they actually remove the clogging particles is still subject to investigation. Other approaches are also possible, for instance by using a hydrophobic polymer on the top layer with appropriate characteristics to create a coating on the surface that will prevent excessive clogging of the pavement surface (Maennel and Altreuther, 2016).

6.5. Wear and particle emissions

As it was previously mentioned in this text, the functional performance of pavement surfaces is the result of several complex phenomena that are taking place simultaneously when the tyre and the pavement interact with each other. An important output of this interaction is the particle emission, which will directly affect air quality. The particle emission discussed here is mostly a result of the tyre/pavement interactions, even though there are other sources of such particles, as it will be pointed out in this chapter. This chapter does not, therefore, include a discussion on exhaust particles that are expelled by the vehicles exhaust system.

The particulate matter concentration relevant for this discussion is regulated within the European Union by the concentration of particles with an aerodynamic diameter smaller than 10 micrometres, PM_{10}, and its regulatory limits are exceeded in nearly all European countries (Johansson

et al., 2012). The current PM_{10} limit set by the European Comission (2016) of 50 μg/m^3 for the average over 24 hours must not be exceeded more than 35 times per year.

An increased concentration of particles in the air is correlated to several health issues. For instance, Perez et al. (2009) investigated the health impacts associated with an increased level of $PM_{2,5\text{-}10}$ (particles with an aerodynamic diameter between 2,5 μm and 10 μm). The authors concluded that an increased level of those particles in the air is associated with increased cardiovascular and cerebrovascular mortality levels. For the so-called fine particles, $PM_{2,5\text{-}1}$, the authors found an association with increased respiratory mortality. Similar conclusions were also achieved by Stafoggia et al. (2013). They found a connection between cardiovascular and respiratory health issues and the admission of $PM_{2,5\text{-}10}$ and $PM_{2,5}$ in eight different Mediterranean cities.

Different estimates are also available regarding the socio-economical costs associated with an increased level of particulate matter in the air. The costs are associated with increased mortality levels, reduced life expectancy, increased costs for healthcare and reduced productivity. The social-economic costs associated with premature deaths caused by ambient particulate matter pollution (APMP) in the years of 2005 and 2010 were estimated at US$ 1 007 223 million and US$ 1 156 118 million, respectively (WHO Regional Office for Europe OECD, 2015). Considering data for Sweden only, in this same investigation, the estimated values were of US$ 3 219 million and US$ 3 641 million, for 2005 and 2010 respectively.

As previously discussed in this chapter, there are several different sources of PM_{10}, yet, as indicated by WHO (2005) and Gustafsson et al. (2011), a large part of the particle mass concentration measured in urban environments consists of wear particles. A large proportion of those particles comes from pavements, in urban areas where studded tyres are allowed. The concentrations of non-exhaust particles also have a seasonal aspect, as the particles concentration will increase on dry winter weather conditions. The concentration of PM10 particles also increases during spring, when the roads begin to dry, and the particles that were bound to

the road surface by water, snow or ice, are suspended into the air (Gustafsson et al., 2015).

7. Investigative work and summary of appended papers

In this chapter, a summary of the investigative work carried out within this thesis is presented. The chapter is structured in two parts, the first deals with the performance of winter tyres and is related to papers A and B. The second part deals with road texture optimization by horizontal grinding and is related to paper C. Using the contact-system concept previously discussed in chapter 2, Figure 49 shows how the articles appended to this thesis are related to the tyre/pavement contact system.

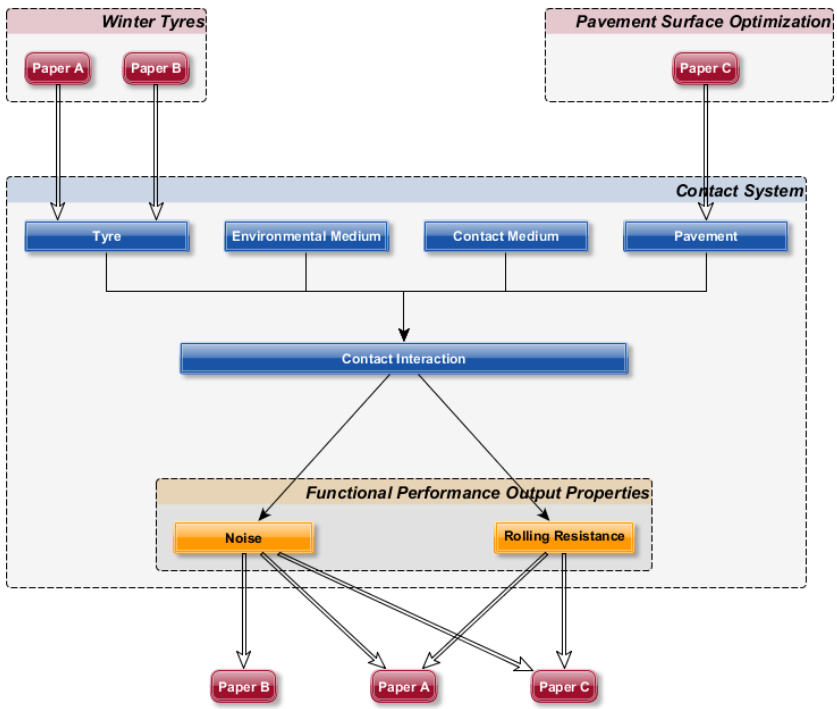

Figure 49 - Relationship between the articles contained in this thesis and how they interact with the tyre/pavement contact system

Papers A and B analysed the different contact system results obtained when winter tyres were used, including both studded and non-studded tyres. Paper A analysed the results of both noise and rolling resistance while paper B focused on noise only and developed the frequency spectra analysis. Paper C focused on the pavement and on using the grinding technique to optimize the outcomes with regard to noise and rolling resistance. Together they represent the results of different strategies to reduce noise and rolling resistance of pavements by making controlled interventions to the contact system.

7.1. Performance of winter tyres

7.1.1. Paper A

Studded winter tyres are designed to provide good friction in winter conditions, even though other functional aspects of the pavement surface may be compromised. This part of the investigative work concerned itself with measuring and analysing the performance of winter tyres. The investigation included studded and non-studded winter tyres and also summer and all-season tyres for comparison purposes. The tested winter tyres include tyres optimized for northern Europe, thus colder operational conditions, and for central Europe, thus milder operational conditions.

Measurements were carried out in two different test sections, namely an SMA 8 and a DAC 16. The first worked as a proxy for the standard surface of ISO 10844 and the second worked similar to an SMA16 surface found in Sweden. The combined results of the two surfaces are intended to be representative for the surfaces commonly found in the Swedish road network.

Noise measurements were carried out with the CPX method from the Gdańsk University of Technology (TUG) following the procedures of ISO 11812-2. The selected test speeds were 30, 50 and 80 km/h, and a minimum of two (usually four) runs were made for each test condition.

Rolling resistance measurements were performed with the trailer owned and operated by the Gdańsk University of Technology (TUG) following the method proposed in project ROSANNE (http://rosanne-

project.eu/). The selected test speeds were 50 and 80 km/h, and a minimum of three runs were made in each test condition.

Temperature normalization procedures were applied using a reference temperature of + 10 ^{o}C which is intended to be more representative to the operational conditions of winter tyres than the more commonly used temperature of +20 ^{o}C.

The results revealed that the studded winter tyres are indeed noisier than all the other tested tyre groups, however, the rolling resistance measurements indicated that studded tyres do not substantially differ from the other tested tyre groups.

A reduced sample of used tyres were both in new and used conditions. The tyres in used condition were used for two winter seasons in Sweden. Comparing the new and used conditions the results indicated that noise levels decrease in the used condition compared to the new condition. With regard to rolling resistance, there was an increase in the used condition when compared to the new condition. It is noteworthy that the tyres were not at the end of their lifetime and that the sample size was limited.

In addition to the tested studded tyres, a different type of winter tyre was tested, the so-called Green Diamond. Instead of common studs, it contains silicon carbide particles in the tyre tread. This alternative design resulted in a good performance both considering noise and rolling resistance. The tyre was one of the quietest with respect to noise measurements and had among the lowest recorded rolling resistance values.

The observed noise and rolling resistance difference between tyres are significant, which means that there is a significant potential gain in selecting quieter tyres and tyres with lower rolling resistance.

When comparing the values found on the tyre label with the values observed during the tests, no significant correlation was found. This leads to the conclusion that the EU labelling system may need to be re-examined as it is desirable that the values found in the label reflect the performance on actual road conditions.

7.1.2. Paper B

Given the significant difference in the acoustical performance of winter tyres found in paper A, a deeper investigation was carried out with the CPX results to evaluate how this different performance is expressed in the frequency spectra. This contributes to an understanding of what mechanisms are involved in the tyre/pavement interaction of such tyres that leads to such a remarkable difference found in the noise measurements already mentioned in paper A.

The noise measurements were averaged within each tyre category and for the two road surfaces. Comparing the A-weighted third-octave frequency spectra for each group, all spectra presented a peak at a frequency of approximately 800 Hz. The studded tyres have higher noise levels in all the analysed frequency spectra between 200 Hz and 10 kHz. A significant difference was found at frequencies higher than 4 kHz. The studded tyres have flat frequency spectra in contrast to the drop-off with frequency behaviour found in all other categories. It was expected that the studs would affect the noise spectra in high frequencies due to impact mechanisms and this was observed for frequencies above 4 kHz. However, the noise increase at medium and low frequencies revealed that other sound generation mechanisms are also involved. It is likely that the reaction forces in the tyre tread are influenced by the studs, increasing vibrations in the tyre structure. Such vibrations are generally considered to be more prominent at frequencies below 1 kHz.

When comparing the spectra for different speeds, no frequency shift proportional to speed was found, irrespective of tyre category. This was expected as the impact frequency between the tyre and the pavement depending on speed. This leads to the conclusion that a mechanism other than vertical vibrations gives a major contribution here. Perhaps the air pumping mechanism dominates at frequencies over 800 Hz. More research is needed to clarify this point.

From the small sample of tyres that were tested both in new and used conditions, it was observed that studded tyres are influenced by wear whereas non-studded winter tyres are not substantially influenced by it. The wear for studded tyres results in studs being worn-off, becoming displaced from their original position, and the stud protrusion above the

rubber being reduced. This effect should reduce the impact and contact forces, thus reducing low-frequency noise, which was indeed observed. Again, note that the sample size is limited and additionally the wear condition was the result of a typical use in two winter seasons only.

The alternative design of the Green Diamond tyre with the hard silicon carbide particles in the tyre tread provided the best acoustical performance of all tested tyre groups. This could also be a result of the increased number of sipes in the tyre tread and rubber materials with decreased hardness. There was, however, sign that the hard particles produce some noise at frequencies above 4 kHz, which is similar to the studs at such high frequencies.

The results indicate that more research is needed in order to better understand the generation mechanisms for studded tyres and also for the specific case of the Green Diamond tyre, given the positive results obtained for this tyre group.

7.2. Surface texture optimization by horizontal grinding

7.2.1. Paper C

The technique of horizontal grinding was explored in this paper as means of optimizing the pavement surface texture by creating a more negatively skewed texture. A total of 8 test sections were ground in Sweden using grinding machines of different sizes. The machines had between one and three heads, *i.e.* circular rotating plates with a diameter between 650 mm and 950 mm, and on each head between 3 and 4 grinding discs with diameters between 170 mm and 270 mm.

The ground pavement was compared to a non-ground reference surface adjacent to it, before or after, having, therefore, the same surface characteristics. Each test section was measured with respect to its acoustical performance, with the CPX method, and with respect to its rolling resistance performance with the trailer owned and operated by the Gdańsk University of Technology (TUG) following the method proposed in project ROSANNE. Both noise and rolling resistance were measured at 50 km/h and 80 km/h Friction measurements were carried out with the Saab Friction Tester, a car equipped with a small test tyre that rotates at

optimum slip on a wetted surface, at speeds of 50 and 80 km/h. Frictional properties were also measured with VTI's Portable Friction Tester (PFT), a device equipped with a rubber wheel that is pushed by an operator over the test surface at walking speed in order to measure wet longitudinal friction.

Temperature normalization for the CPX measurements was carried out following the procedures of ISO 13471-1 with 20 °C as a reference temperature. The measurement values were also corrected for harness and velocity fluctuations according to ISO 11819-2 and ISO/TS 118193.

The pavement texture for all the ground and reference surfaces were characterized by VTI's RST laser measurement vehicle. The 2017 measurements were an exception as they were measured by Ramboll Sverige AB yet using the same measurement technique. Texture data was collected in accordance with ISO 13483-1, megatexture in accordance to ISO 13473-5 and unevenness with the respective CEN standards.

The intent of grinding the surface texture was to have a more negatively skewed surface. Judging from the available data it seems that this objective was achieved.

With respect to the functional performance of the ground surface, the results indicate an improvement in acoustical performance with a noise reduction up to 3 dB. The noise reduction varied with tyre and pavement type. The highest effects were achieved with pavements that originally had higher macrotexture values, such as SMA 16.

The frequency spectra analysis revealed that the noise reduction took place in frequencies up to 1 kHz. This reduction is, therefore related to the texture impact on the tyre tread, according to the literature. The analysis also indicated that noise reductions were smaller for the H1 tyre, which is a proxy for heavy vehicle tyres. This result can be logically interpreted given that the pavement surface texture has a relatively small effect on such tyres.

With regard to rolling resistance, the observed reduction was up to 15 %, which is significative given that a 10 % reduction in rolling resistance is estimated to reduce the fuel consumption of vehicles and the CO_2 emissions between 1 and 2%. Again, the H1 tyre was less sensitive to the grinding operation and this result is, similarly to the noise results, interpreted as a result of heavy vehicle tyres being less sensitive to the surface texture.

Frictional properties were not compromised by the grinding procedure. Quite the opposite was observed as small increases in friction values were observed when comparing the ground and original surfaces. The reason is that the grinding operation leaves a rougher microtexture which leads to a small improvement in frictional values.

A crucial question regarding the grinding effect is how long it's beneficial aspects last. As the ground surface is subjected to traffic the beneficial aspects are progressively lost as the texture characteristics change. The surface asperities will be polished at the edges and the surface will lose its negative skew. This will increase the resulting indentation in the tyre surface, reflecting in an enveloped profile with higher deflections. This process is accelerated in Sweden by the use of studded winter tyres. The noise reduction seemed to disappear after a year while the rolling resistance reduction was diminished after the same period.

It is noteworthy that the grinding operation is not very expensive and if done on a larger scale should result in a positive cost-benefit analysis result.

8. Conclusions

In this licentiate thesis, the tyre/pavement contact interaction was analysed with a systematic approach, meaning that an interference was made in one of the four contact-system entities, while the other three were kept to constant or reference values or even normalized to reference values with correction procedures. The four contact-system entities considered here are: (i) tyre, (ii) pavement, (iii) contact medium, (iv) environmental medium. A reference scenario was also analysed, where the system entity that was subject to an intervention previously, was later analysed in a reference condition.

The first part of the investigative work in this thesis, related to papers A and B, carried out an interference in the tyre type. Several types of winter tyres were analysed and compared to non-winter tyres. The results indicated that studded winter tyres are significantly noisier than non-studded winter tyres, the measured difference is between 6 and 10 dB. However, the two tyre groups do not differ significantly in terms of rolling resistance. Comparing the differences within the different tyre categories that were evaluated, it is concluded that there is a substantial gain in selecting quieter and more energy efficient tyres as the difference in noise and rolling resistance is substantial. The frequency spectra analysis revealed that winter studded tyres differ from non-studded tyres not only in higher frequencies, as it was previously expected, but also in middle and low frequencies. The high-frequency changes are attributed to the studs impacting the road surface when entering the contact patch and then sliding against the pavement within the contact patch. The medium and low-frequency changes are attributed to the studs creating reaction forces when contacting the pavement surface and thus exciting different tyre vibration modes.

A limited sized sample of used tyres was analysed with respect to their worn condition, revealing that studded tyres are more significantly

affected by use and wear than non-studded winter tyres. This was attributed to the studs being worn and displaced and in this manner decreasing their protrusion with respect to the tyre tread.

The first part of this thesis contributed to a better understanding of noise and rolling resistance behaviour of winter tyres, indicating how their performance differs from other tyres, including non-studded winter tyres, at what frequencies these differences are expressed and to what they may be attributed.

In the second part of this thesis, related to paper C, an interference in the pavement was carried out. Surface grinding was used as a mean to optimize the pavement texture in order to improve noise and rolling resistance characteristics. The texture analysis indicated that grinding creates a more negative pavement surface texture, and this was analysed and quantified by the surface skewness and by analysing the resulting enveloped surface. The results indicated that the ground surface leads to an improved performance considering both noise and rolling resistance. Noise reductions were up to 3 dB and rolling resistance reductions were up to 15 %. The resulting ground surface did not have its frictional characteristics compromised as the grinding process results in a rougher microtexture.

The second part of this thesis contributed to a better understanding of how the pavement surface texture can be optimized by horizontal grinding and how this leads to improved acoustical and energetical performance in the tyre/pavement interaction.

8.1. Future Work

Some aspects related to this thesis that require further investigation are named in this final chapter. A further investigation motivated by the results shown here is an analysis of the noise generation mechanism related to studded tyres, to better understand the differences observed in the noise spectra. A more comprehensive study of tyre performance in used conditions which requires an increased sample size. Regarding the surface grinding technique, further investigations would be interesting on the durability of the results and how this process can be connected to road maintenance cycles in order to generate a positive cost-benefit result. Further analysis of the usage of different grinding tools and on how the ground depth affects different functional properties of pavement surfaces.

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