Tyre and Road Surface Optimisation for Skid Resistance and Further Effects

TYROSAFE

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D10

Report on different parameters influencing skid resistance, rolling resistance and noise emissions

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Abbreviations

Abbreviation	Meaning
ABS	Antilock Braking System
BFC	Braking (force) Friction Coefficient (=LFC)
EFI	European Friction Index
IFI	International Friction Index (developed in the 1992 International PIARC Experiment to Compare and Harmonize Skid Resistance and Texture Measurements)
IRFI	International Runway Friction Index (developed in the American Joint Winter Runway Friction Measurement Program, described in ASTM E2100)
LFC	Longitudinal (force) Friction Coefficient.
MPD	Mean Profile Depth (as defined in ISO 13473-1 and ISO 13473-2)
SFC	Sideway (force) Friction Coefficient
SRI	Skid Resistance Index (=EFI)
HERMES	Harmonisation of European Routine and Research Measurement Equipment for Skid Resistance of Roads and Runways (FEHRL project)
JWRFMP	Joint Winter Runway Friction Measurement Program (led by Transport Canada and NASA)
SPENS	Sustainable Pavements for European New member States (FP6 project)
VERT	Vehicle-road-tyre interaction: fully integrated physical model for handling behaviour in potentially dangerous situations (BRITE EURAM project)
ASTM	American Society for Testing and Materials
BASt	Bundesanstalt für Strassenwesen (DE)
BRITE	Basic Research in Industrial Technologies for Europe
CEDR	Conference of European Directors of Roads
CEN	European Committee for Standardization
COST	European Cooperation in Science and Technical research
DRI	Danish Road Institute

FAA	Federal Aviation Administration (USA)
FEHRL	Forum of European National Highway Research Laboratories
ISO	International Standards Organisation
LCPC	Laboratoire Central de Ponts et Chaussées (FR)
NASA	National Aeronautics and Space Administration (USA)
PIARC	Permanent International Association of Road Congresses
RWS	Rijkswaterstaat = Department of public works and infrastructure of Ministry of transport (NL)
TRL	Transport Research Laboratory (UK)
IMAG	Instrument de Mesure Automatique de Glissance (FR)
IRV	International IRFI Reference Vehicle
PFT	Pavement Friction Tester (UK, TRL)
RoadSTAR	Road Surface Tester of Arsenal Research
ROAR	Road Analyser and Recorder of Norsemeter
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SKM	Seitenkraftmessverfahren
SRM	Stuttgarter Reibungsmesser (DE)

Definitions

Term	Definition
Adhesion	The transmission of forces by friction against tyre contact surfaces. Resulting from the interaction between tyres and pavement surface, adhesion is influenced by surface roughness, tyre characteristics, the nature and thickness of any intermediate medium such as water or mud, and speed.
Airfield operational testing	Measurement of the skid resistance of a surface on an airfield in response to an operational need and in whatever conditions exist at the time of the test, which may include contamination by ice, snow, slush or water.
Bound surface	Top layer or surface course of a road with the aggregates secured permanently in place
Braking force coefficient	Ratio between the longitudinal frictional force and the load on the test tyre, the test tyre mass and the rim mass. This coefficient is without dimension.
Calibration	Periodic adjustment of the offset, the gain and the linearity of the output of a measurement method so that all the calibrated devices of a particular type deliver the same value within a known and accepted range of uncertainty, when measuring under identical conditions within given boundaries or parameters.
Contact area	Overall area of the road surface instantaneously in contact with a tyre.
Fixed slip	Condition in which a braking system forces the test wheel to roll at a fixed reduction of its operating speed.
Fixed-slip friction	Friction between a test tyre and a road surface when the wheel is controlled to move at a fixed proportion of its natural speed.
Friction	Resistance to relative motion between two bodies in contact. The frictional force is the force which acts tangentially in the contact area.
Horizontal force (drag)	Horizontal force acting tangentially on the test wheel in line with the direction of travel.
Horizontal force (side force)	Horizontal force acting perpendicular to a freely-rotating, angled test wheel.
Longitudinal friction coefficient (LFC)	Ratio between horizontal force (drag) and vertical force (load) for a braked wheel in controlled conditions. This is normally a decimal number quoted to two significant figures.
Macrotexture	Deviation of a pavement from a true planar pavement with characteristic

	dimensions along the pavement of 0.5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands including the range 0.63 mm to 50 mm centre wavelengths.
Mean profile depth (MPD)	Descriptor of macro texture, obtained from a texture profile measurement as defined in EN ISO 13473-1 and EN ISO 13473-2.
Megatexture	Roughness elements with a horizontal length of 50 to 500 mm. Roughness of this magnitude can influence accumulations of water on the pavement surface (for instance, in unevenness).
Microtexture	Deviation of a pavement from a true planar pavement with characteristic dimensions along the pavement of less than 0.5 mm, corresponding to texture wavelengths with one-third-octave bands and up to 0.5 mm centre wavelengths.
Nearside wheel path	Wheel path that is closest to the edge of the road in the normal direction of travel. For countries that normally drive on the right, this is the right-hand side and for countries that normally drive on the left, this is the left-hand side.
Operating speed	Speed at which the device traverses the test surface.
Pedestrian slip resistance	The property of the trafficked surface to maintain the adhesion of a pedestrian shoe sole.
Push mode	When the device is pushed by a pedestrian
Repeatability r	The maximum difference expected between two measurements made by the same machine, with the same tyre, operated by the same crew on the same section of road in a short space of time, with a probability of 95 %. (This equals 2.77 times the repeatability standard deviation: $r = 2.77 * \sigma_r$)
Reproducibility R	The maximum difference expected between two measurements made by different machines with different tyres using different crews on the same section of road in a short space of time, with a probability of 95 %. (This equals 2.77 times the reproducibility standard deviation: $R = 2.77 * \sigma_R$)
Routine testing	Measurement of the skid resistance of a surface in standardised test conditions, which normally include a defined water flow rate.
Sampling length/interval	The distance over which responses of the sensors are sampled to determine a single measurement of the recorded variables.
Side force coefficient (SFC)	Ratio between the vertical force (load) and horizontal force (side force) in controlled conditions. This is normally a decimal number quoted to two significant figures.
Skid resistance	Characterisation of the friction of a road surface when measured in

	accordance with a standardised method.
Slip angle	The angle between the mid-plane of the test tyre contact surface and the direction of travel.
Slip ratio	Slip speed divided by the operating speed.
Slip speed	Relative speed between the test tyre and the travelled surface in the contact area.
Subsection	Defined length of surface for which one set of the measured variables is reported by the device.
Test section	Length of road between defined points (e.g. location references, specific features, or measured distances) comprising a number of subsections over which a continuous sequence of measurements is made.
Theoretical water film thickness	Theoretical thickness of a water film deposited on the surface in front of the measuring tyre, assuming the surface has zero texture depth.
Tow mode	When the device is towed by a vehicle
Vertical force	Force applied by the wheel assembly (the static and dynamic force on the test tyre, the test tyre weight and the rim weight) on the contact area.
Water delivery system	System for depositing a given amount of water in front of the test tyre so that it then passes between the tyre and the surface being measured.
Water flow rate	Rate (litres/second) at which water is deposited on the surface to be measured in front of the test tyre.
Wet road skid resistance	Property of a trafficked surface that limits relative movement between the surface and the part of a vehicle tyre in contact with the surface, when lubricated with a film of water.
Wheel paths	Parts of the pavement surface where the majority of vehicle wheel passes are concentrated.

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Executive Summary

The TYROSAFE Project is a Coordination and Support Action (CSA) under the Seventh EU Framework Programme. The project is examining the possibilities for developing harmonised approaches in Europe to the optimisation and management of the key safety and environmental properties of road surfaces in their interaction with tyres. The assessment of these properties – skid resistance, rolling resistance and noise – are a different stages of development generally and there is widely varying awareness of the issues and practice across Europe.

The three-year project began in July 2008 and is being carried out by a consortium comprising AIT (Austrian Institute of Technology) from Austria (formerly known as arsenal research), BASt from Germany, LCPC from France, RWS from the Netherlands, TRL from the United Kingdom and ZAG from Slovenia and FEHRL, the Forum of European Highway Research Laboratories based in Belgium. There are four technical Work Packages (WP):

- WP1 is assessing the current status of policies and approaches to management of the three key topics in the EC.
- WP2 is reviewing the technical issues and proposing strategies for the harmonisation of skid resistance test methods across Europe.
- WP3 is looking in some detail at the road surface properties that influence the three properties and their interdependencies
- WP4 will review the environmental effects of optimising the properties of surfaces and the potential impact of climatic change on a harmonised approach

The measurement and provision of skid resistance has been the subject of research for over 75 years and some individual countries now set standards for skid resistance on their road networks (or parts of them). These are typically based on measurements with specialised devices that may be local (and often unique) to these countries. However, the absence of an accepted common scale for characterizing road surfaces with respect to skid resistance properties is a serious hindrance for developing consistent policies for the provision of adequate skid resistance across Europe that would make the European road network safer.

Greater awareness of environmental aspects of roads and traffic has meant that the noise generation properties of tyres and road surfaces have become a greater focus for research in recent decades. Interest in reducing fuel consumption and vehicle emissions, especially CO_2, has led to greater attention being paid to the topic of rolling resistance, particularly by the tyre industry but, from the point of setting standards for road surfaces, work on this subject is still in its infancy. Traffic noise is a major concern within the EC but methods for assessing the noise performance pavements explicitly are not fully established.

Development of policies for these factors depends on an ability to provide road surfacings and vehicle tyres that will deliver the required performance in terms of grip and environmental impact. It is already known that some properties of roads or tyres that may be advantageous in one respect may create problems in another and so an important aspect of TYROSAFE is to assess how these properties might be optimised.

To achieve this, an understanding of the parameters that influence skid resistance, rolling resistance and noise and how they interact is needed and it is this aspect of the project that is the focus of the work in WP3. This report is the first deliverable from that work package and records the first stage of that exercise, to assess the key parameters.

All three of the topics are driven by the interaction between road surfaces and tyres travelling over them. Therefore, the parameters that govern the effects relate to the properties of the road surface, the tyre and the environmental factors that act on them.

Not surprisingly, this review has found that the greatest amount of research has been directed at understanding tyre/road friction, especially in wet conditions, and its two contributing components – road surface skid resistance and tyre wet grip. Studies of noise generation have been continuing for some 20 years or so and the basic mechanisms are reasonably well understood, as are some of the properties of road surfaces and tyres that can contribute to reduced tyre/road noise. However, the physical processes involved and the interactions between them are complex and this presents a challenge for researchers. Limitations of both measurement techniques and available of experimental data mean that there are significant areas where knowledge remains limited.

Rolling resistance research is, by comparison, still in its infancy: measurement techniques are limited, especially for studying the properties of in-service roads, and evidence supporting an intuitive understanding of how the road contributes to rolling resistance is just beginning to be obtained.

Throughout the review it has become clear that the properties of friction, rolling resistance and noise are predominantly and essentially influenced by a relatively small number of general properties of the road surface and the tyre. In short, these are:

- Road surface texture (at different scales and with different forms).
- Tyre tread (particularly compound, tread depth).

However, although the number of core parameters is relatively small, behind this rather simple summary are a great many other factors, and complex interactions, that influence them that are too numerous to include in this summary. These factors relate to the way in which road surfacings and tyres are designed, constructed and used, as well as how they respond over time to the influences of traffic and the environmental conditions to which they are exposed. Some may also contribute directly to some of the three subject areas. Less-easily quantified factors, such as driver behaviour, may also have an influence. The relative influence that the individual characteristics have and the way in which they act in relation to each of the subject areas varies, however.

Thus, characteristics of road surfacings such as the properties of the aggregate used, the constituents and design of asphalt mixtures or concrete surfaces, the shape and form of the surface texture are all of great importance. The interactions between adhesion and hysteresis in tyre rubber compounds with the micro- and macro-texture of the road surface are of great significance for friction. These properties also (albeit through different mechanisms) have an influence on noise generation and rolling resistance.

The purpose of this report was to identify the key parameters. The next steps for the TYROSAFE WP3 team are to look in greater detail at the interactions between these parameters and consider how they might be optimised, which will lead to proposals for further focussed research, to be reported in Deliverables D14 and D15.

1 Introduction

The TYROSAFE Project is a Coordination and Support Action (CSA) in the Seventh EU Framework Programme. The project is aimed at coordinating and preparing for European harmonisation and optimisation of the assessment and management of essential tyre/road interaction parameters, to increase safety and support the greening of European road transport.

This work is being carried out in six work packages (WP), as follows:

- WP1: Policies of EU countries for skid resistance / rolling resistance / noise emissions;
- WP2: Harmonisation of skid-resistance test methods and choice of reference; surfaces
- WP3: Road surfaces properties – skid resistance / rolling resistance / noise emissions;
- WP4: Environmental effects and impact of climatic change – skid resistance / rolling resistance / noise emissions;
- WP5: Dissemination and raising awareness;
- WP6: Management.

The objective of Work Package 3 is to identify and describe the different parameters of road surfaces and tyres that are relevant to skid resistance, rolling resistance and noise emission. The intention is that this should lead to a matrix which clarifies the interdependencies of the different parameters and contributes to an understanding of how they might be optimised in the construction of road surfacings in Europe. The Work Package, therefore, will make recommendations concerning the design of road surfaces with a view to improving road safety and, by identifying gaps in current knowledge, suggest approaches for further research into the optimisation of road surfaces.

To achieve this, WP3 has been split into four Tasks, described in the original project plan as:

- Task 3.1 – collecting the knowledge of parameters influencing skid resistance; road surfaces and tyres will be treated.
- Task 3.2 – collecting the knowledge of parameters influencing rolling resistance
- Task 3.3 – collecting the knowledge of parameters influencing noise emissions
- Task 3.4 – developing matrices which show the interdependencies of the different parameters, arranging the gap of knowledge and requirements for further research. This task also includes organising two workshops (one of which was held in May 2009, with the next planned for early December 2009) to obtain input from experts from different fields and countries.

Table 1.1 gives an overview of the major outcomes planned for the individual Tasks of WP 3.

Table 1.1: Overview of the major outcomes of the individual Tasks of WP 3

Task	Deliverable	Name	Month
3.1,3.2,3.3	D10	Report on different parameters influencing skid resistance, rolling resistance and noise emissions	M14
3.4	D14	Interdependencies of parameters influencing skid resistance, rolling resistance and noise emissions	M20
3.4	D15	Report on knowledge gaps and proposals for further research concerning optimisation of road surfaces and tyres for skid resistance, rolling resistance an noise emissions	M23
3.4	-	Two dedicated workshops	M10 and M21

This report is the main output from Tasks 3.1, 3.2 and 3.3 and constitutes the deliverable D10. Its main purpose is to review current knowledge about parameters for optimising skid resistance, rolling resistance and noise emissions for road surfaces and tyres. The ongoing analysis will be based on the results of both historic and current research related to these topics identified in this report and on the outcomes of the planned experts' workshop.

Chapter 2 of the report provides some general background, introducing some important concepts relating to the influence that the three main aspects (skid resistance, rolling resistance and noise emissions) have, particularly on road safety. The chapter also introduces some of the more important parameters relating to road surfaces and tyres that may need to be optimised. The individual parameters and their particular influence on skid resistance, rolling resistance and noise are discussed in more detail in Chapters 3, 4 and 5 respectively.

Chapter 6 summarises knowledge of the durability of the different parameters, but mainly concerning skid resistance. The ideas relating to interactions between the various factors will be covered later in the project, in Deliverable D14; a full analysis of knowledge gaps and proposals for further research will be covered later, in D15.

2 Background

Acting together, roads and tyres make a vital contribution to road safety but in the process they also have an impact on the environment. It is interaction between the tyre and the road surface that provides grip to allow vehicles to manoeuvre but the same process can also give rise to rolling resistance, with a potential increase in fuel consumption and CO_2 emissions. The interactions also generate noise both in vehicles and in areas close to the road. There are also safety implications for rolling resistance and noise, although these are not related to vehicle control. Vehicle emissions and noise levels have a potential influence on the health of drivers and those living or working near major roads. If road/tyre noise is very low there might be risks to vulnerable road users such as pedestrians who might not be alerted to the approach of a vehicle.

This chapter introduces the known main factors associated with road surfaces and tyres that influence these three main areas (skid resistance, rolling resistance and noise), which are the focus of the TYROSAFE project, as background, before they are discussed in greater detail in later chapters.

2.1 Tyre/road interaction – friction and skid resistance

2.1.1 The importance of adequate tyre/road friction

Clearly, the provision of adequate grip between tyres and roads is vitally important in helping drivers to be able to travel safely, a fact recognised in the earliest days of research as motor traffic began to increase. In 1936, in the first Technical Paper published by the then Road Research Laboratory (now TRL), Bird and Scott wrote:

> *"The importance of providing a road surface of a texture such that the wheels of all vehicles maintain satisfactory adhesion under diverse weather conditions does not need to be emphasized.*
>
> *The progress in motor vehicle design has resulted in engines capable of giving improved acceleration and higher speeds, but the benefits of this progress could not have been fully realised in practice had not improvements in the design of braking systems, chassis, suspensions and tyres also kept pace. The provision of adequate stopping power is very important from the point of view of safety on the roads; over-confidence in his brakes may lull a driver into a sense of false security if he fails to realise that, no matter how efficient in itself the braking system may be, the ultimate force retarding the vehicle is exerted at the areas of contact between the tyres and the road, and that if the latter does not provide the necessary adhesion the most powerful brakes are useless."* [1]

In fact, there are three particular situations in which the forces transmitted through the tyres are increased and so the adhesion provided needs to be adequate for a vehicle to be driven safely:

- Under power, when a reaction force between the tyre and the road is needed for the vehicle to accelerate or maintain speed.
- In braking, when forces are developed between the tyre and the road that react against the action of the brakes so that the vehicle slows down.
- While cornering, when reaction against side forces generated in response to steering action enables the vehicle to follow around the curve.

These forces are generated as a result of friction between the tyre and the road. In normal circumstances, the contact patch (the area of the tyre in direct contact with the road) is instantaneously stationary. However, if the forces required by the manoeuvre exceed the available friction, the contact patch will start to slide over the road surface, a condition known as “slipping”. If too much power is applied when accelerating, the powered wheels may spin freely; if the force on the brakes is too great the wheels may lock, leading to a skid; if lateral acceleration is too great when cornering, the tyre will slide sideways. If acceleration or, braking, are combined with cornering then the combined forces must be “shared” with the available friction, increasing the likelihood of grip being reduced.

Once the tyre is slipping or skidding, full control is lost. In many situations control cannot be recovered in time, if at all, and a crash of some kind is the inevitable result.

When a road surface is dry, the coefficient of friction between a tyre and the road is normally high and adequate for most vehicle manoeuvres. However when the road is wet, the tyre/road friction decreases significantly and becomes much more dependent on the properties of the road surface and the tyre. When the road is wet, friction is not only reduced but also decreases as speed increases, a phenomenon that is discussed in more detail in Chapter 3. Importantly, sliding friction on a wet road is typically much lower than the friction available just before the tyre starts to slip. It is also important to note that a damp road may also show a marked reduction in tyre/road friction even though it may no longer be raining.

2.1.2 The differences between tyre/road friction and skid resistance

This report has already made reference to two terms – “friction” and “skid resistance” (see Definitions). It is important to appreciate the differences between these two concepts since they are often used interchangeably and this can sometimes lead to confusion. The following convention, widely used in the context of road surface characteristics, is therefore used in this report to distinguish between the meanings of “friction” and “skid resistance”.

Friction, in the context of tyres and roads, represents the grip developed by a particular tyre on a particular road surface at a particular time. The coefficient of friction is a measure of this, defined as the ratio of the load (the force applied in the vertical direction) to the traction (the force resisting movement in the horizontal direction). Friction is influenced by a large number of parameters relating to the road and the tyre but it is also affected by other influences that may not be directly attributable to them, such as the vehicle suspension, ambient conditions, speed and the presence of localised contaminants (including water).

Skid resistance describes the contribution that the road makes to tyre/road friction. Essentially, it is a measurement of friction obtained under specified, standardised conditions, generally chosen to fix the values of many of the potential variable factors so that the contribution that the road provides to tyre/road friction can be isolated. Unless indicated otherwise, the term skid resistance applies to wet roads and measurements are made on a wetted surface. The principles of measuring skid resistance are not discussed specifically in this report. However, they are fully described (together with details of the many devices currently used for this purpose in Europe) in TYROSAFE Deliverable D04 [2].

In the context of a crash, or situation that might lead to one, it is the coefficient of friction available at the time and place of the incident that matters. However, for the purposes of building and maintaining roads, it is the initial designed properties of the surfacing and, subsequently, the general condition of the road surface in service that are important. This report, therefore, which is ultimately interested in optimising the design and maintenance of road surfaces, is primarily concerned with skid resistance. Clearly, properties of road surfaces that improve tyre/road friction will generally have a positive influence on skid resistance. Properties of tyres, however, will influence friction for vehicles using those tyres but not skid resistance (apart, of course, from the specialised case of test tyres on skid resistance measurement devices).

2.1.3 Principles of friction generation

Before moving on to discuss specific factors relating to roads and tyres in relation to friction, it is worth considering some general principles relating to tyre/road interaction and the generation of friction.

The mechanisms of tyre/road friction are not fully understood, but it is widely recognized that there are two main mechanisms involved: molecular *adhesion* and *hysteresis losses*, ideas proposed by Kummer in a unified theory of tyre/road friction in the 1960s [3], [4], and developed further by Moore a decade later [5]. The overall friction between tyre and road surface is the sum of these two components.

Adhesion is a surface phenomenon that occurs at the interface between the tyre tread rubber and the road, so this contribution depends on the actual contact area. Some theories have described adhesion as a thermally activated molecular stick-slip process. During sliding between a rubber and a hard surface, the separate chains on the two surfaces attempt to link together, thus forming a local bond. Sliding causes these bonds to stretch, rupture and relax before new bonds are made [5]. The contribution of adhesion to friction is the sum of the inter-facial shear tension between the tread rubber and the road surface by different islets on the overall contact area, which depend on surface roughness at the microscopic scale.

The hysteresis contribution comes from energy losses due to damping in the rubber bulk when this is deformed as it passes over the aggregate particles in the surface. The internal damping in the rubber opposes its own movement upstream of aggregates and its shape recovery downstream of aggregates, creating an asymmetric pressure distribution on aggregate surfaces. This contribution depends on roughness of the surface at the macro scale. Figure 2.1 (taken from [6]) illustrates these two concepts of adhesion and hysteresis.

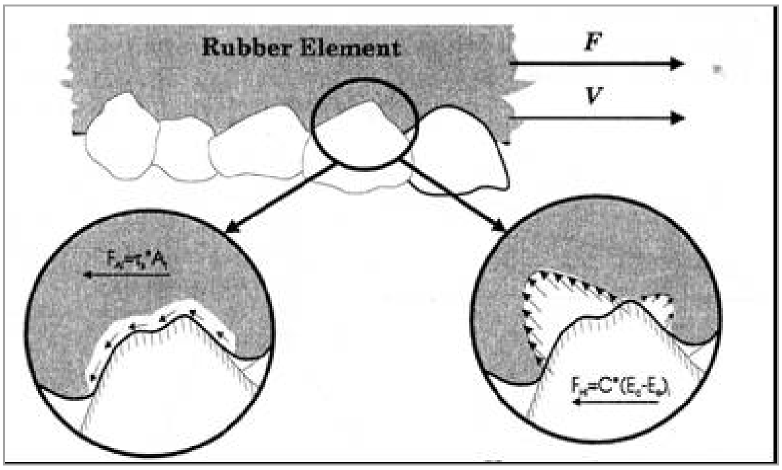


Figure 2.1: Key source mechanisms of friction between tread rubber and a rough road surface (after [6])

Adhesion depends mostly on the actual contact area and micro-level roughness of the road surface, while hysteresis depends on the macro-level roughness of the road

To be effective, the adhesion component needs close contact and thus a clean surface, while the hysteresis component needs cyclic deformation of the rubber and a rough surface. It is argued that, on rough and lubricated surfaces, the friction force derives primarily from the hysteresis contribution, whereas adhesion is dominant when rubber slips on a smooth and clean surface.

Yandell offers a slightly different interpretation, which is based on the assumption that adhesion does not play a significant part in tyre-road friction, rather that the observed effects can be entirely explained in terms of hysteresis [5], [7]. In this theory, the texture of the road surface is separated into components with different scales, ranging from microscopic to 1-2 cm. Hysteresis is generated on each of these scales and the total friction is obtained from the sum of the individual contributions. In the second of these two papers, Yandell and his colleagues showed that predictions based on this analysis, together with measurements of the damping factor of the tread rubber, agree well with locked wheel and sideways force measurements on concrete and bituminous surfaces[1].

2.1.4 The influence of water

In either of the theoretical models, the presence of water or other contaminants within the tyre-road interface prevents the intimate interaction between the tyre and road surfaces that is necessary for friction to be generated. In the Kummer model the molecular interaction between the rubber and road surface that generates the adhesive forces is prevented,

[1] In this terminology, “concrete” refers to surfaces constructed with Portland cement concrete, whereas “bituminous” refers to any bitumen-bound material, i.e. asphalt concrete.

whereas, in the Yandell model, the presence of water progressively masks texture on different scales, starting with the smallest scale.

Irrespective of the mechanism of friction generation, the wet tyre-road interface has been characterised in terms of three regions [8], illustrated in Figure 2.2.

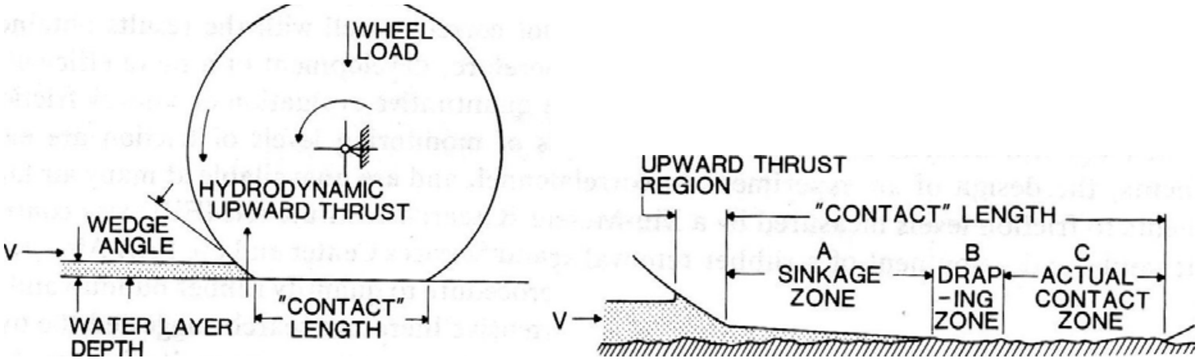


Figure 2.2: Three zones in the tyre/road contact patch [8]

In the sinkage, or "squeeze-film" zone at the forward edge of the tyre-road contact area, the tyre does not make contact with the road, but floats on a thin wedge of water. The depth of water reduces progressively towards the rear of this area, as the water film is squeezed out of the interface by the tyre. In the "draping zone", the tyre makes partial contact with the asperities of the road surface, the water film having been mainly removed by the squeezing action. Finally, at the rear of the contact area, there is an area of actual contact, where most of the friction is generated. The friction generated depends on the relative areas of these three regions, which are determined by the depth of water, the vehicle speed and the rate at which water can be dispersed from the contact area. A description with more details of these three zones in the tyre/road contact patch is included in Section 3.3.1.

2.1.5 The role of anti-lock braking and traction control systems

Although not directly linked to the aims of this report, before moving on to consider the influence of tyre/road interaction on rolling resistance and noise, brief mention should be made of the roles of anti-lock braking systems (ABS) and traction control systems (sometimes referred to as an electronic stability program, or ESP) available on many modern vehicles.

These have potentially significant safety benefits in that they detect the onset of the tyre slipping, either during braking or during acceleration and (usually low-speed) cornering. By detecting the slipping condition and then momentarily releasing and re-applying the brakes (or reducing and gradually re-applying power) they can make greater use of the higher friction level available before sliding sets in. This provides the driver with a much greater level of control and reduces the risk of skidding. However, these systems can only utilise the friction that the road provides and if the road surface is slippery, stopping distances will still be extended and the systems may not be able to cope with high cornering speeds.

2.2 Tyre/road interaction – rolling resistance and noise

2.2.1 Interactions giving rise to rolling resistance

Unlike skid resistance, which has been a major focus of research for over 75 years, the study of rolling resistance in relation to both roads and tyres has only been going on for a relatively short time. Measurement techniques for assessing the behaviour of in-service pavements are not yet fully developed, although assessments of specially-prepared samples of road surfacings can be made in large drum machines such as the vehicle/pavement interaction test facility at BASt in Germany, illustrated in Figure 2.3. Tests on tyres can be made on drum machines, on specially-designed trailers (although these are not yet standardised) or through coast-down tests, which are not suitable for use in traffic.

Figure 2.3: Vehicle/Pavement interaction test facility at BASt

Rolling resistance essentially occurs because tyres are deformed as they rotate under the action of the load of the vehicle that they carry and as they shape themselves to the road surface. Work has to be done to do this and consequently energy is used.

Hans Bendtsen from the Danish Road Institute (DRI) [9] identifies three main mechanisms through which the energy is lost:

- Losses due to the bending/deformation of the tyre sidewalls
- Losses due to micro-deformation of the tyre tread in the contact area
- Losses due to slippage friction in the contact area between the tyre and the surface

Thus, it can be seen that road characteristics such as unevenness can induce reactions in the tyre that will add to rolling resistance. At a smaller scale, the adhesion and hysteresis effects that contribute to friction when the tyre is sliding (see 2.1.3) can also be relevant when the tyre is rolling since the tread blocks will still experience some deformation; energy lost in this process will contribute to rolling resistance.

It has been estimated that road surfaces can be responsible for roughly doubling the rolling resistance of a vehicle's tyres and therefore roughly increasing the vehicle's fuel consumption about 10% [9].

2.2.2 Interactions giving rise to noise

Noise emission of road vehicles is attributed to three main sources: propulsion noise (including engine, power train, exhaust and intake systems), tyre-road interaction noise and aerodynamic noise. Engine noise is the dominant source at low speed, i.e. below 30 km/h for passenger cars and 50 km/h for trucks, especially in the acceleration phase. Above this speed, tyre-road noise becomes the dominant source for vehicles [10]. Aerodynamic noise increases with speed but it is assumed to be dominated by tyre-road noise at least at speeds below 130 km/h. In this context, it is obvious that tyre-road noise is the principal mechanism of noise generation to be mitigated in many urban conditions and in most suburban and extra-urban situations.

Tyre road noise is generated through four general processes:

- Impact of the tyre tread blocks as they strike the surface
- Vibrations generated as tread blocks, which are deformed as the contact patch rolls over the road, spring back into shape when they are released.
- Vibrations generated by the release of air that has been compressed into voids in the texture of the road surface as the tyre passes over it (sometimes called "air pumping").
- Vibrations in the tyre carcass induced by its deformation and recovery as it follow and react to the shape of the road surface.

The mechanisms involved can be divided into two groups: vibration-related (including tread impact and adhesion) and aerodynamically-related (involving air displacement). The different mechanisms in these two groups are identified and illustrated in the next two Figures (taken from Sandberg and Ejsmont [11]): Figure 2.4 shows the vibration-related mechanisms; Figure 2.5 illustrates the aerodynamically-related mechanisms.

These different mechanisms are discussed in greater detail in chapter 5.

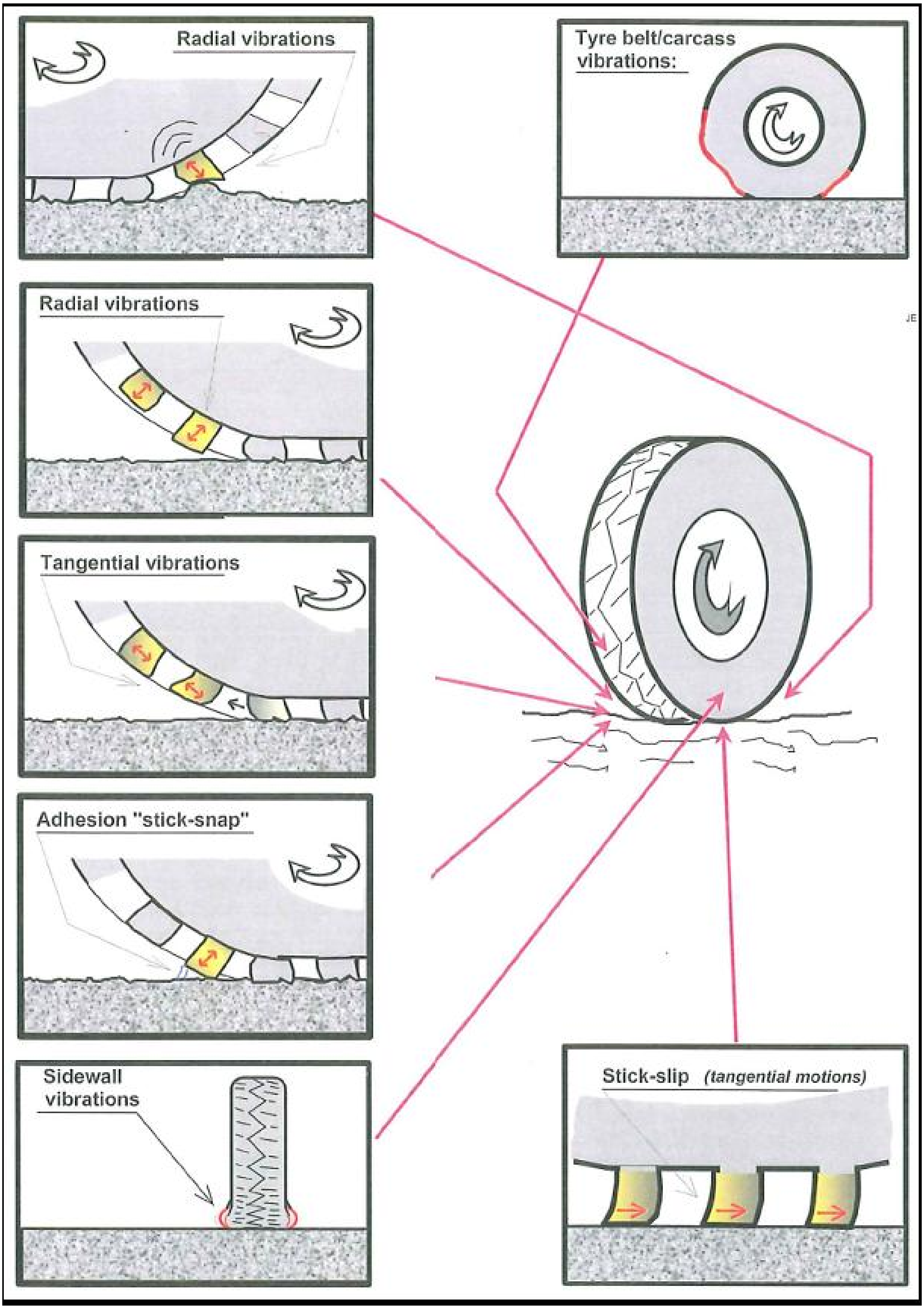


Figure 2.4: Vibration-related mechanisms of tyre/road noise generation [11]

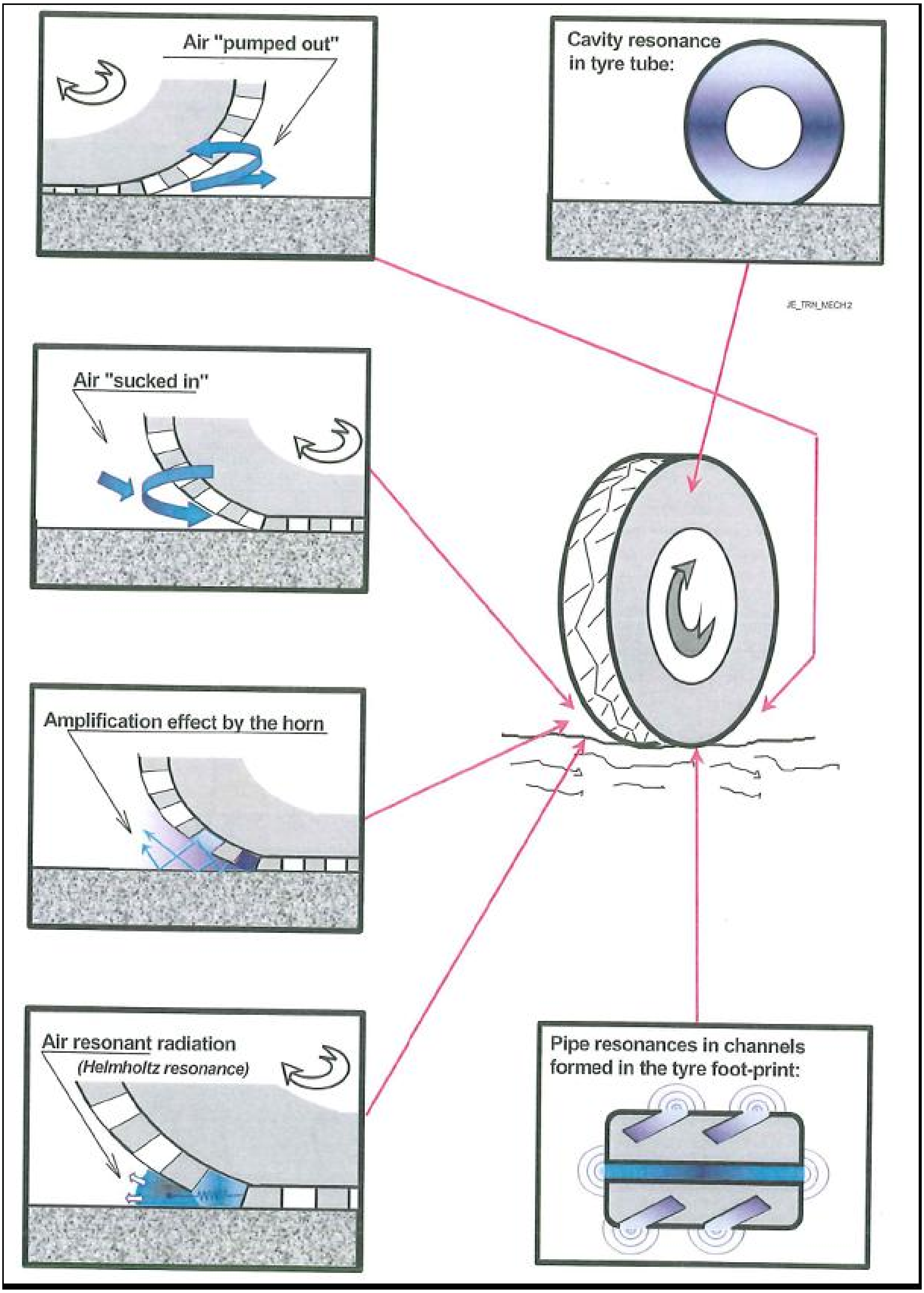


Figure 2.5: Aerodynamically-related mechanisms of tyre/road noise generation [11]

2.3 Important parameters for road surfaces

As we have seen, the interactions between the tyre and the road that affect the three main topic areas of skid resistance, rolling resistance and noise emission all derive from the way in which different parts of the tyre deform to make intimate contact with the road, and then are released again as the tyre rotates further or moves on.

The surface profile of a road with which tyres interact is often described in terms of its "surface texture". In order to describe the components of texture (the overall irregularities from a true planar surface) in relation to the factors that they influence, the profile is divided into different texture scales, based on wavelength ranges. Figure 2.6 illustrates the "irregularity ranges" that are typically used to describe these texture scales and the different factors, including skid resistance, rolling resistance and noise that are influenced by them.

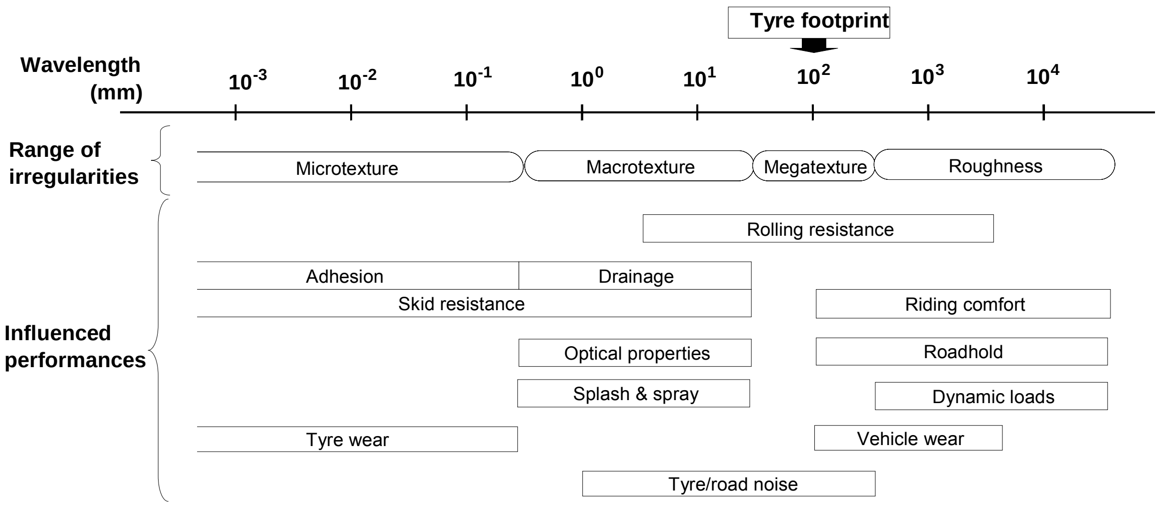


Figure 2.6: Texture wavelength influence on tyre/road interactions (after [12])

Although their influence varies, it can be seen that essentially there are just three main parameters relating to the road surface that affect the three main factors in this study. They are:

- *Microtexture,* which is formed by the microscopic asperities on the surface of aggregate particles and fine grains in the road surfacing material.
- *Macrotexture*, which is formed by the shape of and spaces between the larger aggregate particles (or grooves formed in concrete) at the surface of the road.
- *Megatexture*, which arises from variations in the surface profile on a larger scale.

These three parameters (which are formally defined in the Definitions) and the effects that each of them has, together with other important factors that influence how they are formed and maintained, are discussed in more detail in the contexts of the three main subject areas in Chapters 3.1, 4.1 and 5.2.

2.4 Important parameters for tyres

This section gives a short introduction to tyres, their components and the parts which influence the three main topics (skid resistance, rolling resistance and noise emissions). At the outset, the comment should be made that skid resistance and noise emissions might not be the correct terms to use when discussing these matters from the tyres' point of view.

In particular, skid resistance is described as the "Characterisation of the friction of a road surface when measured in accordance with a standardised method" and does not therefore relate to the contribution that different tyre types or properties make to road/tyre friction. The ability of a tyre not to skid on a surface is sometimes referred to as "wet traction" or "wet grip".

Tyres are a rotationally symmetric composite that consists of a complex rubber compound with about 200 constituent parts which is reinforced by different layers of textile or steel fabric. Tyres have to support wheel loads but, as explained in section 2.1.1, they also transfer torques that enable the vehicle to accelerate and decelerate and transfer lateral forces in order to steer.

There are different types of tyre design but the predominant type for cars and many trucks is the radial tyre. Radial tyres are built on a carcass of steel cords running radially from bead to bead. A stabilizing belt of crossed steel cords surrounds the carcass. The rubber tread, which is the part of the tyre that is contact with the road surface, is bonded to the belt and sculpted with a tread pattern [13]. Figure 2.7 shows a cross-section of a typical tyre for passenger cars. The process of building a tyre is very complex and is not described in detail within this report.

The two parts of the tyre that have the main influences on skid resistance, rolling resistance and noise are the carcass and the tread. The design of the carcass, its inflation pressure and aspect ratio all have an influence on the way in which the tyre rolls over the surface and responds to changes in surface characteristics such as megatexture, or changes in driving pattern such as braking or cornering.

In the case of the tread, which is the part of the tyre through which frictional forces are transmitted and which is distorted by the road surface, there are a number of particular aspects that influence our main topics in different ways. In particular:

- The tread pattern.
- The tread depth.
- The tread compound (including factors such as the resilience and hardness of the rubber).

As with road surfaces, although there is a common general set of characteristics, their influences on the three main topics and the mechanisms involved are different. These are explained in more detail, together with other parameters that contribute, in the separate contexts of skid resistance, rolling resistance and noise in Chapters 3.2, 4.2 and 5.3.

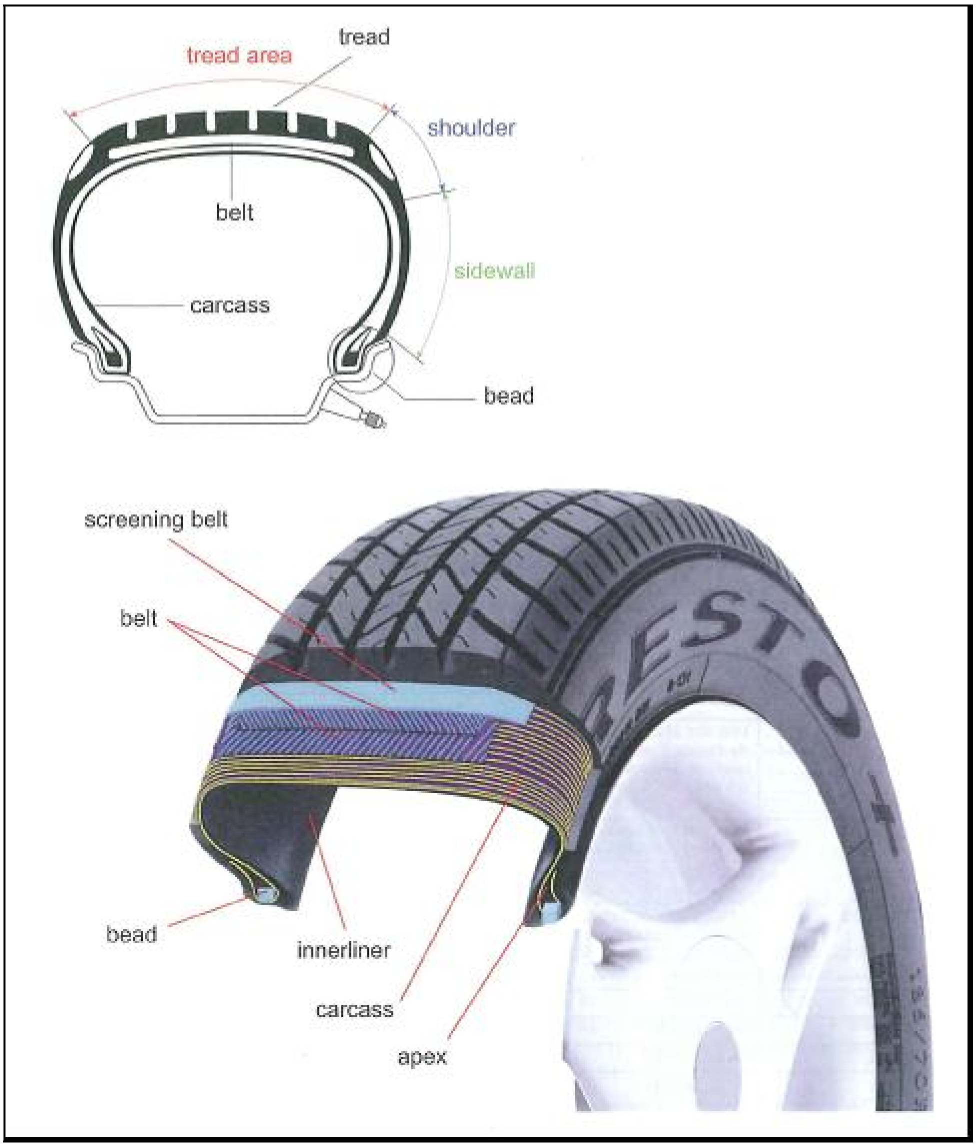


Figure 2.7: Cross-section through a modern radial tyre for passenger cars [11]

2.5 External environmental influences

The earlier sections of this Chapter have discussed the principles involved in tyre/road interaction in relation to skid resistance, rolling resistance and noise, together with the main factors relating to the road and the tyre that influence them. As well as these factors, there are external environmental factors that also have an influence in the real world of in-service roads and tyres travelling on them. This section introduces the most important of these external influences.

2.5.1 Road surface polishing and seasonal variation of skid resistance

In Section 2.3, the concept of microtexture was introduced. This is the scale of texture on the surface of the road that interacts with the tyre to provide adhesion (Section 2.1.3). On an asphalt road, this is provided by the fine texture on the particles of aggregate at the surface. On a concrete road, microtexture comes primarily from the grains of sand in the mortar, unless this has worn away to expose the coarse aggregate.

Over time, microtexture is polished by the action of the repeated passage of vehicle tyres, especially those of heavy vehicles. This leads to a gradual reduction in skid resistance as the road ages until an equilibrium value is reached. The extent to which a surface will polish, and hence the equilibrium skid resistance achieved, depends on both the level of traffic and the ability of the aggregate to resist polishing. The effect is also influenced by other stresses such as braking and cornering forces, so an aggregate may provide different levels of skid resistance depending on where it is used.

Generally, the greater the polishing resistance of the aggregate, the better the microtexture and the better the skid resistance will be. Conversely the greater the traffic level, the greater the polishing and the lower the skid resistance will be. On very lightly trafficked roads, it may take many years for the equilibrium skid resistance to be reached. On heavily trafficked roads this may happen in as short a time as six months to a year.

It has been found that, especially in temperate climates such as in much of western and central Europe, there is a marked variation in skid resistance (and consequently in road/tyre friction) throughout the year and from one year to the next. Typically, skid resistance is at its lowest in summer and higher in winter.

This cyclical effect, known as "seasonal variation", was first recorded by Bird and Scott in their seminal work on skid resistance in the 1930s. Figure 2.8, which is taken from that report [1], illustrates the effect that they observed. It can be seen, particularly in the 30 mile/h measurements (30 mile/h ≈ 50 km/h), that not only does the skid resistance decrease in summer and increase in winter, the average level in any year can also change – in 1934 and 1935 the skid resistance on this particular road in southern England was higher than it had been three or four years earlier. Such observations have been replicated in principle many times since.

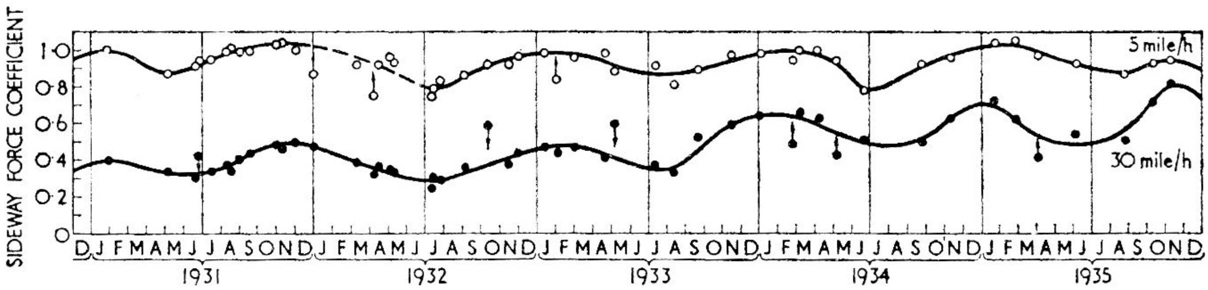


Figure 2.8: Seasonal changes in skidding resistance for a section of road [1]

The process is explained as follows. Initially, the skid resistance on a new road is high because the aggregate is unpolished. During the summer period, fine deposits on the surface act as a polishing medium, leading to a reduction in the microtexture. However, in winter, frost action and more frequent rainfall mean that the deposits are coarser and so the microtexture is roughened. Initially, the polishing process dominates and the skid resistance gradually falls to the equilibrium level. Once reached, the skid resistance will remain at this same general level but, depending on the balance between summer polishing and winter roughening, it will vary from year to year as Figure 2.8 illustrates. A change in traffic will also alter the balance of the polishing cycle and the equilibrium level may then increase (lighter traffic) or decrease (heavier traffic).

While seasonal variation is a significant phenomenon in the study of skid resistance, and must be taken into account in any standards for roads based on skid resistance measurements, it is not strictly a parameter of either the road or the tyre. Rather, it reflects in part the way in which the road responds to the effects of traffic and weather over time.

2.5.2 Winter conditions – ice and snow

The presence of ice and snow on the road surface primarily impacts on tyre/road friction. By covering the surface of the road with a slippery film, the normal frictional characteristics of road surfaces are masked and the tyre has to interact with ice. If the ice or snow has a water film on its surface then clearly it becomes very slippery indeed. However, when it is dry, for example on recently-fallen snow, reasonable levels of grip may be available.

The use of studded tyres during winter in Nordic countries can affect skid resistance or friction by roughening the surface, reducing the effects of summer polishing.

Salt or other de-icers may be spread on the road during winter maintenance operations to counteract the effects of ice formation. Some of these might have an adverse effect on skid resistance but recent research in the UK [14] suggests that the effects, if any, are negligible and preferable to an icy road.

2.5.3 Summer conditions – prolonged hot, dry weather

During long, hot, dry spells, especially in summer, deposits of dust, oil and rubber can build up on the road. When it next rains, at first these deposits create a slippery film on its surface that has a worse effect on friction than water alone. Once sufficient rain has fallen, the deposits are washed from the surface but for a short time they are potentially hazardous. This is an important factor of which drivers need to be aware but it has little directly to do with the properties of road surfaces and tyres.

2.5.4 Ambient temperature

Temperature itself does not directly influence the skid resistance of roads but high summer temperatures and frosty conditions can have an influence on the deterioration mechanisms of road surfacing materials that then affect their performance characteristics.

There are also small effects due to temperature changes that can influence tyre rubber characteristics and consequently affect friction, or skid resistance measurements.

3 Skid Resistance

3.1 Parameters of road surfaces affecting skid resistance

As explained initially in Section 2.3, the main characteristic of a road surface that influences skid resistance is its texture. Wet skid resistance decreases with increasing speed and the levels of skid resistance achieved are governed by the interaction between the various components of texture and the tyre tread. In turn, the ability of the road surface to provide the required texture is influenced by the design and laying procedure of the surfacing and by the properties of the aggregates at the surface.

3.1.1 Categories of road surface texture

Section 2.3 introduced the concepts of different scales of texture, dividing them into different categories. The two-dimensional sample of the texture is known as profile and is described using two coordinates: distance (along the surface plane) and amplitude (in the direction normal to the surface plane). The wavelength of a profile is the inverse of a spatial frequency and is physically the various lengths of periodically repeated parts of the profiles. The three main categories of texture are based on wavelength [15]:

- **Megatexture** often appears as waviness and includes wavelengths between 50 and 500 mm and peak amplitudes from 0.1 to 50 mm. These wavelengths are of the same order of size as the length of the tyre/road contact area.
- **Macrotexture** is of the same order of size as the elements of tyre treads. Its wavelength range and peak amplitudes are between 0.5 mm and 50 mm and 0.1 and 20 mm respectively.
- **Microtexture** is on a scale too small to be observed by the naked eye, but can be felt in terms of the harshness of the surface. All wavelengths less than 0.5 mm and having peak amplitude from 0.001 to 0.5 mm constitute the microtexture.

In practice, there are no boundaries between these categories; one merges into the next. Figure 3.1 illustrates the range of textures that could be encountered on roads. It is macrotexture and microtexture that have the greatest influence on skid resistance and tyre/road friction. Their contributions are analysed in more detail in the next two sections.

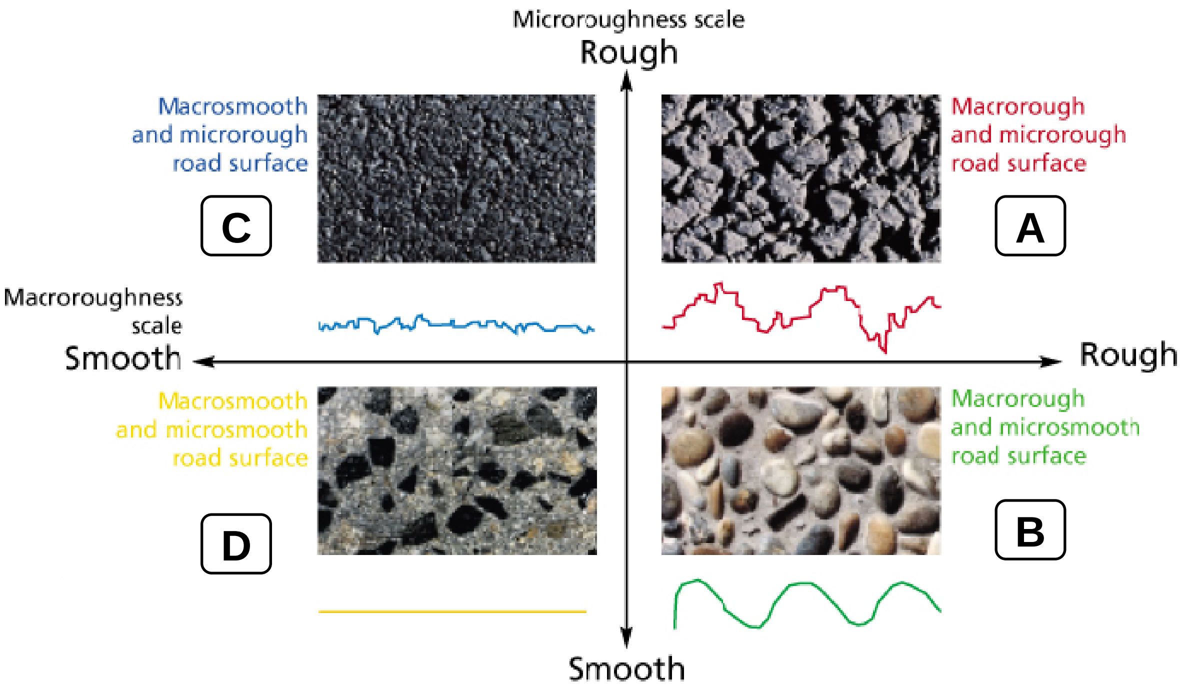


Figure 3.1: Extremes of texture likely to be encountered on roads: in practice there are no boundaries between these categories; one merges into the next (Image from MICHELIN-FRANCE)

3.1.2 Influence of texture on skid resistance

The effects of texture scales on the two basic mechanisms of tyre/road friction can be summarised as the adhesion component being highly sensitive to microtexture, whereas the hysteresis component is mostly sensitive to macrotexture. Although skid resistance is generally high on dry and clean road surfaces (brake force coefficient values in these conditions are typically around 0.8 and can reach a range of values from 1 to 1.3, whatever the levels of texture), in wet conditions road surface texture on both the micro- and macro-scales is essential.

The surface must provide sufficient macrotexture to assist effective drainage of water from the road/tyre interface and increase the zone of potential dry contact at the rear of the tyre/road contact patch (see Figure 2.2). However, drainage alone is not sufficient to provide good skid resistance; the water film can only be broken if the road surface has a good microtexture on which localized high pressures are built up.

The texture of the surface also influences how skid resistance varies with speed. Figure 3.2 shows the influence of wavelength on the variation with speed of the locked-wheel skid resistance (brake force coefficient), measured with a smooth tread tyre, [16]. The surfaces on which the measurements were made are illustrated in Figure 3.1. As is normal practice in studies of skid resistance, a standardised smooth tread tyre was used in the tests to separate the effect of road characteristics from those of the tyre, such as tread pattern and depth. A smooth tyre represents the worst case in practical terms.

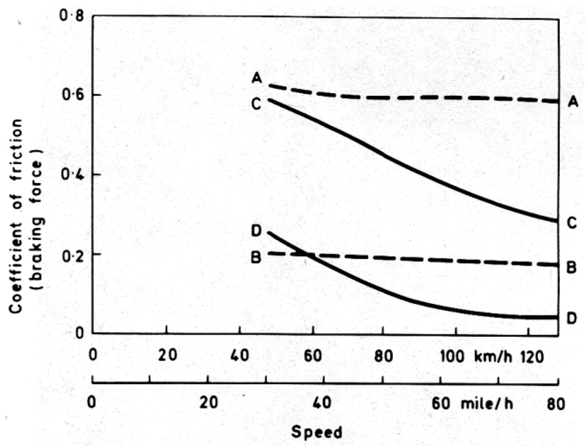


Figure 3.2: Wet road skid resistance measured with smooth tyre on four surfaces representing the extremes of micro and macrotexture as shown in Figure 3.1 (Reprinted from [16])

Figure 3.2 demonstrates that microtexture determines the level of skid resistance at low speed and that the capability of maintaining this level of friction when speed increases is provided by macrotexture.

The four surfaces used in these tests represent theoretical extremes. A similar effect, measured over a slightly wider speed range, can be seen in Figure 3.3 (derived from data reported in Roe et al, [17]). In this case, two actual road surfaces, one (Site 1 in the figure) of chipped rolled asphalt, the other (Site 2) a well-trafficked concrete surface, were measured (again using a smooth-tyre locked-wheel measurement technique). Both surfaces had harsh microtexture (as indicated by the high levels of skid resistance measured with SCRIM at low speeds) but the concrete had markedly less macrotexture as indicated by its Sensor Measured Texture Depth (SMTD). Both surfaces show a reduction in skid resistance with increasing speed but the adverse effect of low macrotexture on high-speed skid resistance can be clearly seen.

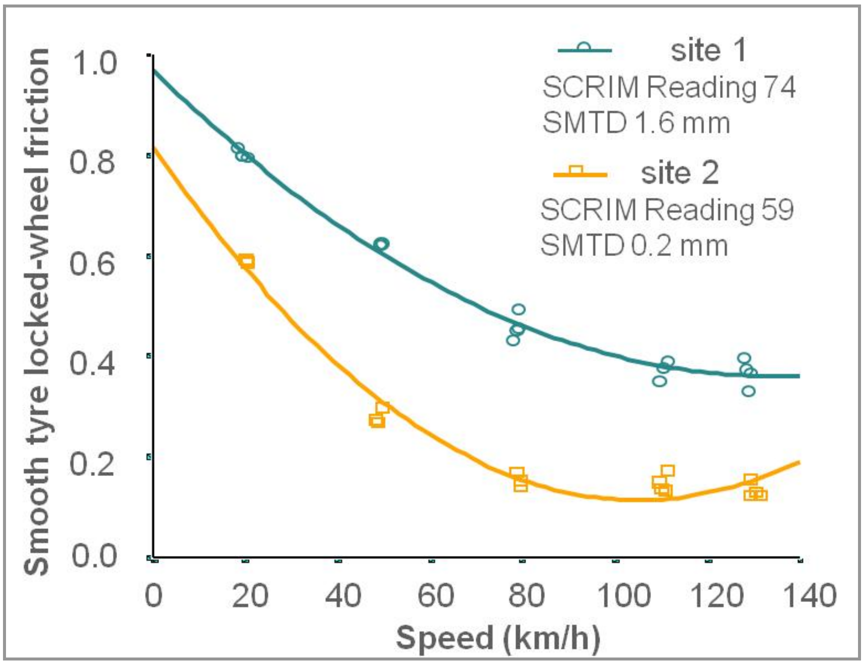


Figure 3.3: Relationship between skid resistance and speed for two in-service roads with markedly different levels of macrotexture

The curves in Figure 3.3 have been drawn using a second-order polynomial which Roe et al. found to provide the best overall fit to the data. However, Henry [18] has proposed a simple formula in exponential form to express the relation between friction and slip speed (the speed at which the contact patch slides over the road surface) and furthermore has found that the coefficients of his model are correlated to the texture scales of the road surface. This relation, as indicated by the experimental data in Figure 3.1, supposes that tyre/road friction increases linearly with microtexture and, at the same time, non-linearly with macrotexture.

$$F(S) = F_0 \exp\left(-\frac{S}{S_p}\right) \qquad 1$$

Where:

F is the friction at a given speed;

S is the slip speed;

S_p is called Speed Number and defines the relationship between a measured friction and the vehicle slip speed;

F_0 is a figure representing friction at very low speed and is intended to represent the microtexture level.

The PIARC International experiment [19] provided data regarding the influence of macrotexture on friction and these were used to propose a mathematical relation to link the Speed Number and the Mean Texture Depth (MTD) in the form:

$$S_p = a + b\,\mathrm{MTD} \qquad (2)$$

Where:

a and b are constants related to the device and method used to measure the MTD.

The HERMES experiment [20] used this model as a basis for its attempts to harmonise a range of devices for measuring skid resistance that attempted to use the model to account for the effect of texture on the measurements made at different slip ratios and slip speeds. As part of this study, different models for representing the texture depth were considered. This work, which had only limited success, is analysed in some detail in TYROSAFE Deliverable D05 [21].

More recently, using a large set of field and laboratory testing and statistic analysis, Ergun et al [22] proposed a similar exponential formula to that of Henry, but with more explicit relations for F_0 and S_p to macrotexture and microtexture:

$$F_0 = 0.37 + \frac{0.11}{\mathrm{MPD}_{mac}} + \frac{0.15}{\mathrm{La}_{mic}} \qquad (3)$$

$$S_p = \left[149 + 81\log(\mathrm{MPD}_{mac}) + 80\log(\mathrm{Rq}_{mic})\right]^{-1} \qquad (4)$$

Where:

MPD_{mac} mean profile depth at the macrotexture scale,

Rq_{mic} root-mean square at the microtexture scale,

La_{mic} is the average wavelength of the profile at the microtexture scale, estimated from Ra and Da as follows:

$$\mathrm{La} = 2\pi\frac{\mathrm{Ra}}{\mathrm{Da}} \qquad (5)$$

Where:

Ra and Da are the arithmetic mean deviation and arithmetic mean slope.

This investigation suggested that the friction at low slip speed depends not only on the average wavelength of microtexture, but also on the mean profile depth of macrotexture, and that the slope parameter, the so called “Speed Number” in the Henry formula, is related to both the mean profile depth of microtexture and the root-mean square of microtexture.

To summarise, it can be seen from the results of many studies that all texture scales have a significant effect on tyre/road friction. Both the microtexture and the macrotexture of a road surface should be high in order to increase adhesion, hysteresis and water drainage. Microtexture affects friction over the range from almost zero up to the maximum possible friction and is important at all speeds. Macrotexture has some influence on friction at low speeds, albeit to a much lesser extent than microtexture, but is the dominant factor at higher speeds on wet roads.

However, as yet there are limitations to the reliable modelling of the influence of macrotexture, partly due to the ways in which this factor is quantified and measured. Microtexture currently cannot be measured quantitatively. Work is in hand at many institutes to study this but measurements made with low-speed devices such as the pendulum tester or dynamic friction tester are often used as surrogates.

3.1.3 The influence of surfacing materials

In order to produce road surfacings with effective texture, it is necessary to know how the composition of the asphalt or concrete influences the development and maintenance of skid resistance.

Parameters of the surfacing material that will influence the texture and therefore the skid resistance include:

(1) Aggregates (shape, size, type).

(2) Bitumen (content, type).

(3) Void content.

(4) Paving and compaction of asphalt surfaces.

(5) Texturing of concrete surfaces (brushing, grooving, exposed aggregate).

(6) Asphalt/concrete – the types of surfacing.

As well as providing appropriate levels of microtexture and macrotexture when new, it is important that the surfacing can maintain appropriate levels during its service life. This will depend on various factors, including:

- The aggregates' ability to resist polishing and the associated loss of microtexture when trafficked.
- Resistance to wear that could lead to reduced macrotexture as surface aggregate particles are worn down or concrete brush-marks are worn away. Microtexture may also be affected as aggregate particles in the body of the surfacing material with less polishing resistance become exposed at the surface.
- The ability of the surface to maintain its structural integrity and hence macrotexture. This is important on modern asphalt materials in which loss of some aggregate particles from the surface can lead to a gradual degradation of the surrounding material as unsupported particles are broken away. Deformation or flushing of bitumen could lead to the embedment of surface chippings with loss of macrotexture (or even, in the extreme, the covering of microtexture).

Asphalt mortar can also influence skid resistance by the way it is distributed or exposed at the surface, as will be discussed later in relation to the influence of bitumen and filler.

(1) Aggregates

Shape

In addition to the wavelength scales of the texture, the shape of the various asperities on the road must be taken into account in order to explain the main differences in the friction performance of different types of road surfacing materials. Depending on how the surface is made, patterns of texture can vary widely, both at the micro- and macrotexture scales.

On asphalt surfaces these may range from closely-packed small particles through larger individual chippings spaced out from one another with relatively smooth asphalt mortar in the spaces between them. The aggregate particles may be orientated differently, with pyramid-like angles or, conversely, essentially flat surfaces uppermost. The natural properties of the aggregate after crushing and grading will have an influence on these factors. A high proportion of naturally-flaky particles, for instance, will tend to present flatter faces to the surface, whereas more cuboid particles are more likely to present an angled edge. On concrete surfaces the ways in which grooves and ridges are formed can create a different range of texture patterns, including repeating patterns that may be transverse or longitudinal compared with the direction of traffic movement.

In relation to microtexture and, in particular, its ability to break through a water film, it is reasonable to assume that aggregates with sharp asperity peaks produce higher localised pressures in the contact patch and that these are likely to be more efficient at breaking the last slight water film than aggregates with rounded asperities. Another advantage of sharp asperities is that the total load on a tyre could be carried on quite a small area; thus, only a small area need be cleared of water before much of the load is supported upon a dry road surface.

In relation to macrotexture, Tabor's theory (quoted by Greenwood et.al [23]) states that the hysteresis component of friction is a function of energy loss, together with a factor determined by the shape of the indenter (which, in the case of road surfacings, is an individual aggregate particle). He proposed a formula that evaluates the deformation shape factor for different indenters (see Table 3.1).

Table 3.1: Shape factors for different indenters proposed by Tabor [23]

	Spheres	Cylinders	Cones	Wedges
Shape factor S	$\frac{3}{16}\frac{a}{R}$	$\frac{2}{3\pi}\frac{a}{R}$	$\frac{\cot\theta}{\pi}$	$\frac{\cot\theta}{2}$

Figure 3.4 shows some experimental results from a study undertaken at the UK's Road Research Laboratory (now TRL) which investigated the influence of indenter shape on skid resistance. A normal force of 45 N was applied between the indenter and the surface and wetted Natural (N) and Butyl (B) rubber tracks. The deformation shape factor has been evaluated for each of different shapes used and a numerical value calculated for the

conditions used in the friction tests. The highest coefficients of friction were obtained using indenters with the highest deformation shape factor [16].

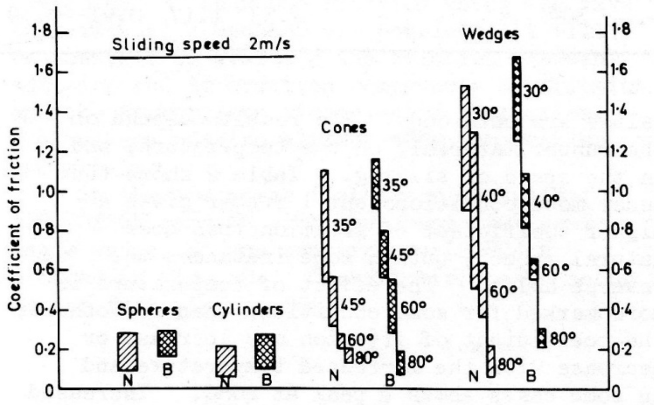


Figure 3.4: Ranges of coefficient of friction for different shaped indenters on natural and butyl rubber. Reprinted from [16]

The shape of the aggregates used can be assessed by the shape index or flakiness index. Flaky aggregates tend to lie flat during the paving process and so make a relatively small contribution to macrotexture. For this reason, it is better to use (coarse) aggregates with a low shape or flakiness index and this is often taken into account in different national regulations or specifications.

Angularity of the aggregates is only relevant for the sand (0.063 – 2 mm) within the mix, because for the coarse aggregates in surface layers crushed materials have to be used. This property of the sand is determined by the flow coefficient. Crushed sand gives a higher value of the flow coefficient and the friction coefficient increases with the crushed sand content. This is currently taken into account in different national regulations.

Aggregate Size

As well as being affected by particle shape, macrotexture is controlled to a certain degree by the size of the aggregate particles. On surface dressings (or chipseals, as they are known in some parts of the world), and most asphalt surfacings, the macrotexture, in particular the drainage paths, is determined by the spaces between the particles at the surface (so-called “positive” texture). On porous asphalt and Stone Mastic Asphalt (SMA) thin surfacings, macrotexture is produced by voids between adjacent particles below their upper surfaces (so-called “negative texture” and is controlled by the way the particles pack together in the mix.

The size of aggregates used in surfacings influences skid resistance, with smaller sizes giving greater skid resistance. This has been observed in a number of experiments. For example, work in New Zealand [24], [25] has shown that the wet skid resistance of chipseal road surfaces is not only a function of the polishing resistance of the aggregate, but also of their size, shape and spacing. It has been shown that increasing the percentage of crushed faces increases the skid resistance [24], and is important for high-speed skid resistance while chip grade is more important at low speeds.

Coarse aggregate

For surfacings based on asphalt mixtures, in which the running surface is derived from aggregates exposed at the surface of the material rather than by spreading chippings on the surface, the skid resistance of a surface is influenced by the size of the coarse aggregates used in the mixture.

As with surface dressings, experiments have shown that using a smaller size of aggregate tends to increase skid resistance, as the quantity of sharp edges in the surface increases and, potentially, a greater area of aggregate is in direct contact with the tyre. However the use of small aggregate sizes is likely to reduce the macrotexture of the surface, with a potential negative effect on high-speed skid resistance. Using larger-sized aggregates will produce greater levels of macrotexture and provide better drainage routes to remove water from the surface/tyre contact patch.

In optimising the mix design, therefore, a balance needs to be struck so that the finished surface provides good levels of both microtexture and macrotexture. In the UK, studies are ongoing to investigate the interaction between aggregate size, macrotexture and skid resistance in thin surfacing materials across the practical speed range [26]. Figure 3.5, taken from [26] shows the effect of coarse aggregate size on locked-wheel friction at different speeds at one heavily-trafficked trial site where coarse aggregate from the same source had been used in three different sizes.

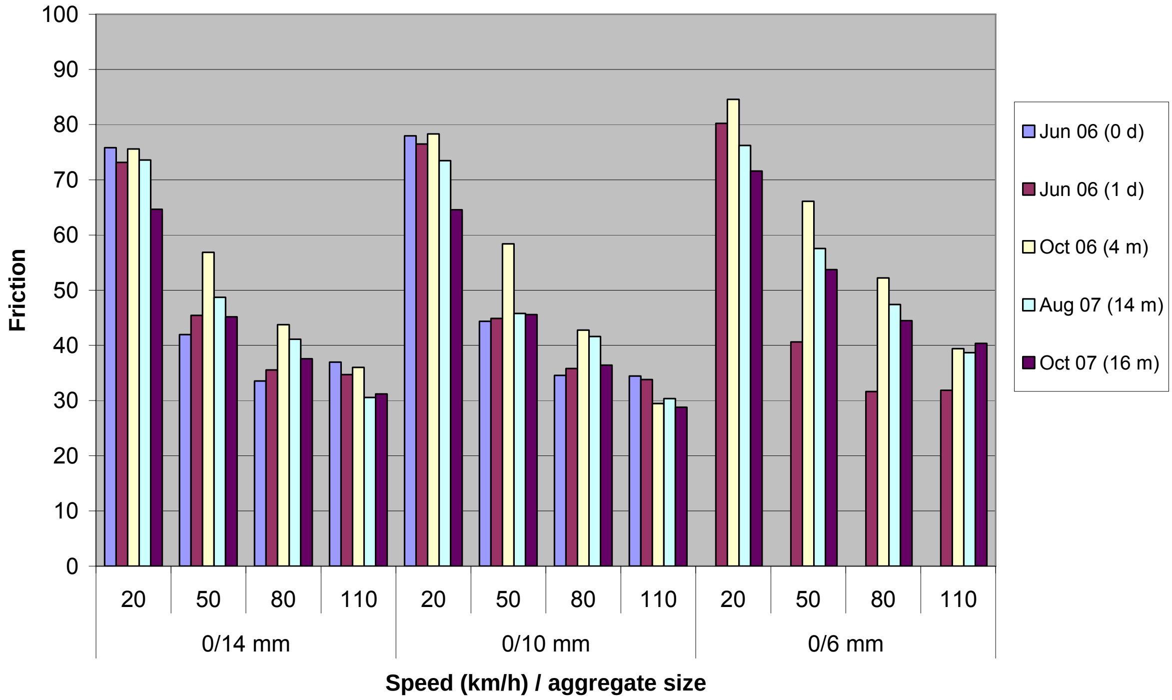


Figure 3.5: Variation of locked-wheel friction with speed and coarse aggregate size over the first 16 months of service on a trial site in the UK (taken from [26])

In this figure, measurements are shown at different ages over the first 16 months of service. In the earliest measurements the aggregates were covered, or partly-covered, in bitumen but an effect of particle size could still be seen. In the later measurements, the aggregate microtexture was largely exposed but the surfacings had yet to reach equilibrium skid resistance levels as a result of aggregate polishing. It can be seen that the 0/6mm material tends to give higher skid resistance: at the time of writing, this study is ongoing.

Fine aggregate (Sand) and filler

In a dense asphalt mix such as AC, the influence of the medium sand (0.2-0.63 mm) and the coarse sand (0.63-2 mm) on skid resistance has been found to be much greater than that of the fine sand (0.063-0.2 mm) [44]. This is probably due to the larger particles in the mortar appearing at the surface and therefore contributing to the harsher scale of the microtexture along with the surfaces of the coarse aggregate particles.

Hardly any influences of the filler (either its kind or grading) on the level of skid resistance have been detected. However, high levels of filler in rolled asphalt surfaces could reduce skid resistance as a result of raising the volume of mortar in the mix where significant areas of the mortar are exposed at the surface and form part of the tyre/road contact patch.

Grading curve (asphalt)

Steinauer reports that differences in the grading curves defining the relative proportions of sand and coarse aggregate for a type of asphalt (e.g. Asphalt Concrete) have little or no effect on the measured friction coefficient (within the limits of the precision of the measurements used) [27]. However, other studies [28] show that where finer grading curves are used, the friction coefficient tends to rise.

Aggregate type

In controlled environmental conditions, skid resistance at any time is primarily a function of the geological properties of the aggregates and the traffic loads placed upon them. The type of aggregate used will determine the microtexture of the surfacing and its ability to maintain that microtexture under loading from traffic and as a result of weathering.

Geological properties of aggregates

As discussed earlier, the microtexture of the surface aggregate is important in developing skid resistance particularly at lower speeds. However, under traffic loading high stresses are developed at the tips of the asperities which combined can cause the individual particles to polish, particularly if fine surface detritus is also present. Thus, as pointed by Smith et al. [29] and earlier by Tourenq et al [30], and earlier still by Wilson [31], the main engineering quality required from an aggregate to be used in a pavement surfacing is to be resistant to the polishing and abrasive actions of traffic. Rocks, which contained minerals of sufficiently different hardness or which were friable, consisting of grains rather insecurely cemented together, were found to give high polishing resistance [30].

The microtexture on an aggregate that is exposed in the surface of a road is affected by the: following factors [30], [32], [24]:

- Polishing.
- Differential wear.
- Weathering.

The term “polishing” describes any general smoothing of an aggregate, including rounding that takes place by abrasion. This phenomenon tends to smooth aggregates by reducing their angularity and microtexture and is caused by the action of tyre carrying detritus and grinding away material from the exposed aggregate. The severity of the abrasive action is related to the density of the traffic and the petrographic characteristics of the aggregates [33]:

- Degree of hardness and proportion of hard minerals.
- Proportion, orientation and distribution of cleaved minerals.
- Grain size
- The nature of the inter-granular bond.
- Degree of liability to chemical alteration of the mineral content.

Where aggregate particles consist of agglomerations of several minerals with different resistance to wear, rough texture can remain as the particles are worn by traffic. Some minerals remain in high relief, whilst others are worn down to a lower level [30]. This phenomenon can be expected where the minerals are of different hardness or toughness. This will tend to prevent general smoothing by recreating a microtexture [24], [32].

High hardness and less cleavability of minerals in the aggregates raise an effective resistance to levelling the former fracture surface. A directionless and bulky texture of the steric configuration of the mineral crystals has advantages for polishing resistance compared with a parallel texture. A high content of microcrystalline crystals (at a size of 0.01-0.1 mm) shows benefits regarding polishing resistance.

Also beneficial to the skid resistance properties of surfaces are the varied granularity of sedimentary rocks (such as greywacke) and the porphyritic structure of igneous rocks. These properties can offer especially beneficial coarse aggregates with minerals of different hardness and cleavability [44].

The aggregate used in a road surfacing has a progressively greater influence on skid resistance as the surfacing ages. As explained in section 2.5.1, aggregates start with good microtexture but this is lost over time and aggregates with good resistance to polishing can be expected to provide higher levels of equilibrium skid resistance. In order to help in the selection of appropriate aggregates, accelerated polishing tests have been developed that can be used in the laboratory to assess likely performance.

The most widely-used of these is the Polished Stone Value (PSV) test [35]. In this test, specimens formed from single-sized aggregate particles are subjected to a standardised polishing process. The extent of polishing is assessed using a variation of a laboratory skid resistance measurement technique utilising the portable skid resistance tester (pendulum test). It has been found that aggregates with higher PSV (high-PSV aggregates are typically regarded as those with a value over 50) generally contribute a higher level of skid resistance than low-PSV aggregates. It is important to stress that PSV is a value applicable to a particular aggregate and not to a road surface.

Some minerals are subjected to chemical and to physical changes that result from weathering. In general, this can improve skid resistance by maintaining a rough texture in a similar way to differential wear.

Influence of traffic loading

As explained previously, on opening a surface to traffic, the skid resistance can alter for the first year or two as a result of traffic action before settling to an equilibrium value around which the skid resistance will fluctuate slightly. Once equilibrium has been reached, the skid resistance at any time may vary as a result of seasonal variation and a significant change in traffic level may alter the equilibrium level.

On a new asphalt surface, the microtexture can be masked by bitumen when the surface is initially laid and for a period afterwards until the effects of trafficking and weathering remove the excess bitumen to expose the microtexture. This phenomenon, often referred to as “early life skid resistance”, has been investigated in some depth in recent years, see for example [36], [37] and is still the subject of research.

The rate at which skid resistance changes in this period depends upon the type of surfacing material [36], [38], [39], (also see Figure 3.5), [26] the trafficking and climatic conditions [37]. Particularly on more lightly-trafficked roads, the process can sometimes dominate the skid resistance performance of a surfacing throughout its life.

After the initial period, the aggregates are gradually exposed and actual polishing of the aggregate particles begins, gradually reducing skid resistance to the equilibrium level. Figure 3.6 is a generalised model of how skid resistance has been traditionally considered to vary with time [24], [40]. The different stages of the binder removal from the aggregates are presented in Figure 3.7.

Do and Kane have proposed a simple mathematical model to predict these two phases of skid-resistance variations, which incorporates the main influential phenomena such as aggregate polishing, binder removal and binder ageing due to climate. The model parameters are obtained by fitting to data provided by laboratory and field tests.

$$\mu = (1 - d)\,\mu_B + d\,\mu_G \qquad 6$$

Where:

μ friction coefficient measured at any time and trafficking.

μ_B related to the type of binder. It represents the friction coefficient provided by binder-enveloped aggregates; it is represented by friction coefficients measured on untrafficked road and is time dependent.

μ_G related to the aggregate types. It represents the friction coefficient provided by bare aggregates. Actually, aggregates also evolve over time but compared with the pavement lifetime (between 10 and 20 years), their characteristics can be assumed to remain constant. Therefore, it should depend only on the number of vehicles.

d weight factor and represents the surface fraction occupied by bare aggregates: for d = 0, there is no bare aggregate and $\mu = \mu_B$, inversely, d = 1 corresponds to a completely worn coating binder and $\mu = \mu_G$ (see fig). The authors, in this reference [38], propose a process of identification of these functions.

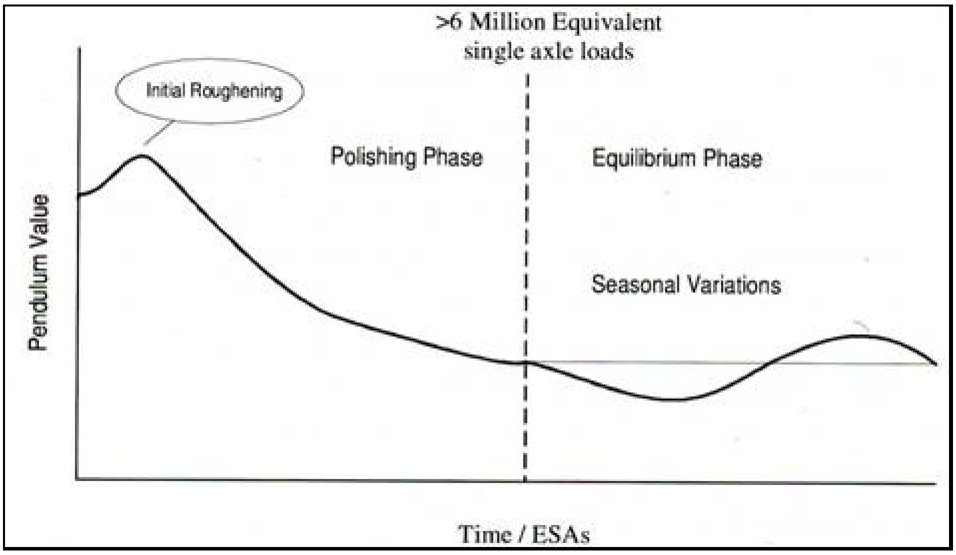


Figure 3.6: Simplified general pavement polishing model [24], [40]

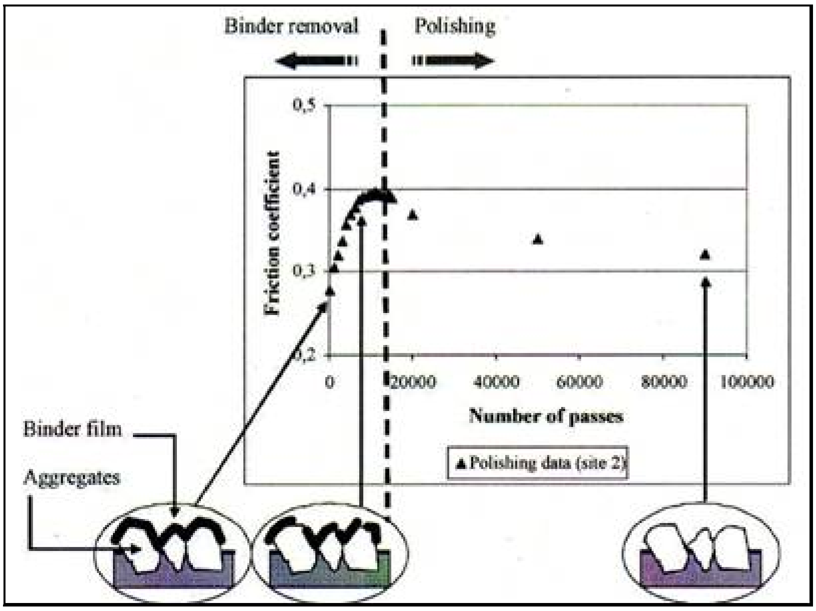


Figure 3.7: Friction coefficient versus number of passes and associated with physical mechanisms. Reprinted from [38]

The decreasing phase of the skid resistance due to the polishing effect is often accompanied by fluctuations that are widely attributed to seasonal and/or short-term environment variations [24].

There is still some debate as to what components of traffic have the greatest effect on aggregate polishing and the skid resistance achieved. It is generally considered that heavy vehicles are the main contributors but some (essentially small) contribution comes from the large numbers of light vehicles using a road, especially in situations where there is not much heavy traffic but the aggregates used are prone to polishing.

Some workers cite cumulative traffic levels whereas, particularly in the UK where a wider range of polish-resistant aggregates occur naturally, the average daily level of commercial vehicles is considered to be the main determinant of equilibrium skid resistance. Early research suggested that the increasing heavy traffic led to ever decreasing skid resistance, although it was recognised that reduced traffic (such as occurs when a route is by-passed) can lead to a recovery in skid resistance [41]. However, as traffic levels grew it became apparent there was a limit to the decrease in skid resistance that occurred as traffic increased for any particular level of PSV: the surface would eventually reach a limit in which summer polishing and winter abrasion were in balance [42].

(2) Bitumen/Binder

The amount of bitumen used in the asphalt mix can also have some influence on skid resistance. High binder contents will tend to produce a low void content, which could lead to bleeding: this may have resulting negative effects on skid resistance as a result of loss of microtexture, as the bitumen covers the aggregate, and on macrotexture as the filling of surface voids reduces macrotexture.

There is no evidence that suggests that the type of bitumen used in the asphalt mix has a noticeable effect on skid resistance. However, for carriageways with heavy traffic it is better to use bitumen with higher viscosity to ensure the durability of the surface and therefore, indirectly, its skid resistance.

Practical experience shows that the use of polymer modified bitumen (PMB) tends to produce higher levels of skid resistance compared to standard bitumen. This could be due to the higher viscosity of PMB and therefore a higher ring-and-ball softening point, resulting in a pavement that has a higher resistance to permanent deformation at high temperatures.

In contrast, however, if bitumen with higher viscosity or polymer modified bitumen is used, it may take much longer for the bitumen to be removed from the aggregate in the initial period after laying, especially if there is less traffic. This can have two influences: one is adverse, in which the bitumen blinds the microtexture and reduces skid resistance, especially as speed increases; the other is favourable because the presence of the bitumen can delay the onset of the polishing of the aggregate so better microtexture is maintained for longer.

(3) Void content

The void content and other volumetric values of the asphalt mixture are only relevant for dense rolled asphalt.

Different studies and practical experience show that, with lower ‘void content’ (V) and therefore rising ‘voids filled with bitumen’ (VFB) at the surface, the skid resistance tends to fall because of loss of micro and macro texture. A critical range of V is about 2 Vol.-% and VFB about 90%. At higher values of the VFB than 90% the kind and thus the polishing resistance of the aggregate used has little influence on the skid resistance [43], see Figure 3.8.

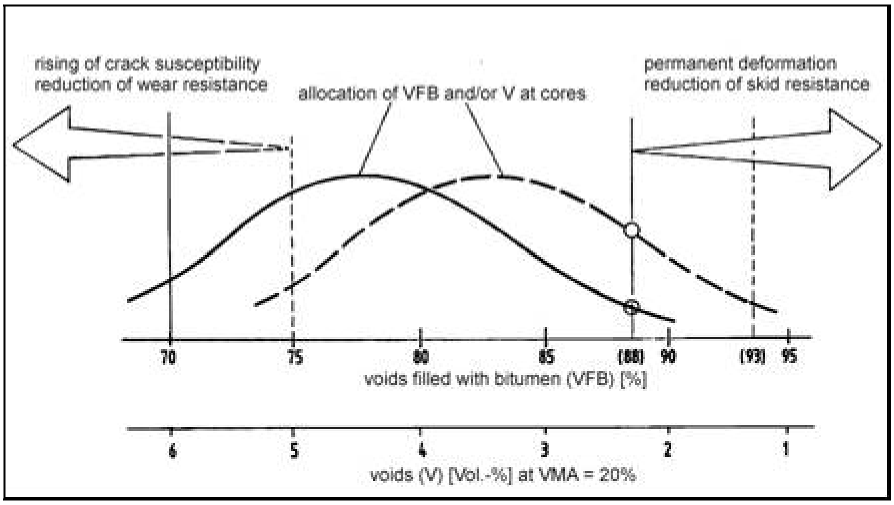


Figure 3.8: Impact of the ‘void content’ (V) and the ‘voids filled with bitumen’ (VFB) to the performance of SMA (target value of VFB during mixture design and the results on cores: - - -: VFB = 85%; ---: VFB = 80%). Reprinted from [43]

(4) Paving and compaction of asphalt surfaces

The appropriate usage of the paver and the roller compactor could avoid negative effects on skid resistance of paving and compaction to the surface. The effects are likely to vary depending on the specific material being laid, but examples found in some countries could include segregation in the horizontal direction caused by inappropriate use of the paver (e.g. extending the screed extension without extending the asphalt auger, accumulation of coarse aggregate in the paver hopper) and in the vertical direction by the selection of an inappropriate use of the roller (e.g. too long a compaction time while using vibration) [44]. Also, the temperature of the mixture can have an influence on the skid resistance achieved. For example, too high a temperature can lead to areas with high mortar content forming on the surface.

(5) Type of surface – asphalt or concrete

Asphalt

There are many different types of asphalt surfacing, as well as applied treatments such as surface dressings, used on European roads. These can have markedly different characteristics in the ways in which micro- and macro-texture are provided at the surface. Therefore, the skid resistance that a road will provide is affected by the type of surfacing.

The finished surface will have different proportions of coarse and fine aggregate exposed at the surface to interact with tyres through which the skid resistance forces are transmitted. Studies have shown that for asphalt mixtures with a high proportion of fines in the contact area (such as some Asphalt Concrete materials) the fines themselves contribute to microtexture, and hence skid resistance. In surfacings in which coarse aggregate predominates in the contact area, high-PSV aggregate (typically, PSV > 50) is needed to provide and maintain microtexture.

In some countries (the UK, for example) that generally use surfacings with a high proportion of coarse aggregate at the surface, different levels of PSV are used to deliver different levels of skid resistance depending on expected traffic levels. Nevertheless, in surfaces which are not gap-graded, it is necessary to use coarse aggregate with adequate PSV since both coarse and fine materials contribute to microtexture. There is also some experience that suggests that using fine aggregates that polish easily (such as limestone) may lead to lower than desired skid resistance even in conjunction with high-PSV coarse aggregate.

A recent study [45] has shown similar tendencies relating to the roles of micro- and macrotexture in different types of asphalt surfacing. Figure 3.9 is taken from a paper relating to a collaborative study of vehicle/tyre/road interaction (the VERT project). It illustrates three surfaces with different characteristics that were used to make comparisons of the relationship between skid resistance and speed with different combinations of micro- and macrotexture. The values indicated in Figure 3.9 for low-speed skid resistance (measured as SFC with SCRIM) and texture depth (measured as ETD) for the three surfaces show that the AC had a noticeably lower microtexture than the SD while the macrotexture of the two surfaces were on a similar level. By contrast the HRA had a microtexture level between these two but with a much greater level of macrotexture.

Figure 3.10: compares the relationships between skid resistance (measured as locked-wheel BFC) and speed for these three different test surfaces with two different water depths.

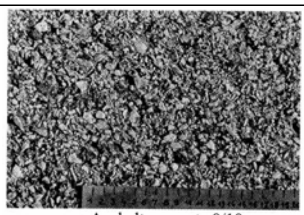
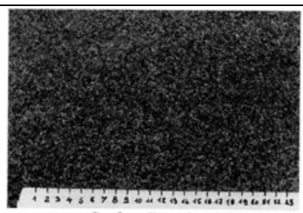
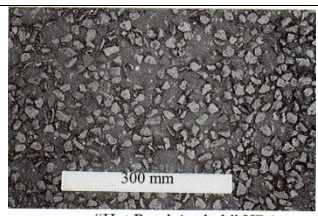
	Asphalt Concrete AC 0/10	Surface Dressing SD 0.8/1.5	Hot Rolled Asphalt HRA0/20
	 Asphalt concrete 0/10	 Surface Dressing 0,8/1,5	 “Hot Road Asphalt” HRA
ETD	0.68	0.72	1,96
SCRIM	0.67	0.94	0.77

Figure 3.9: Illustration of three surfaces used for comparative tests with different levels of micro- and macrotexture as part of the VERT project [45] (used for the results in Figure 3.10)

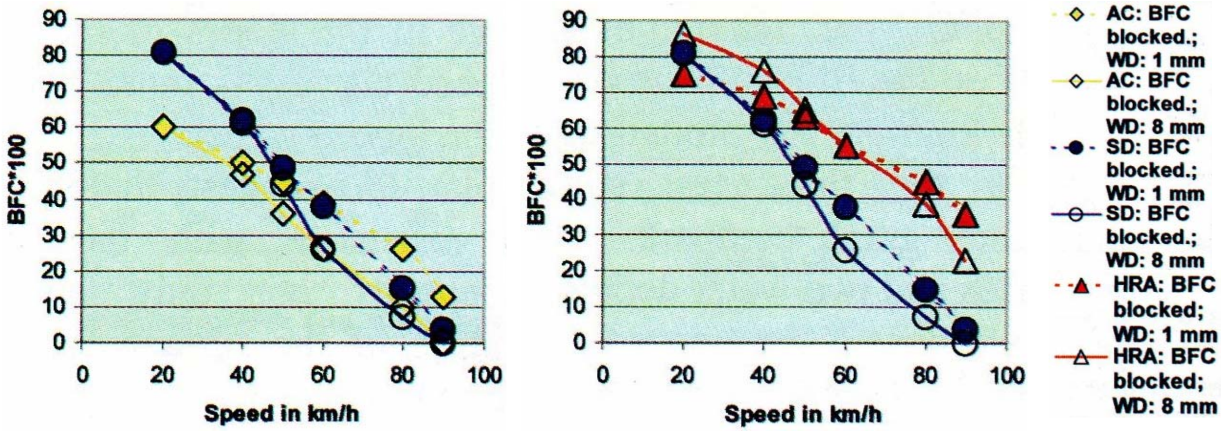


Figure 3.10: Locked-wheel BFC versus speed relationships on the three test surfaces shown on Figure 3.9. Each graph compares two of the surfaces at two water depths (1 mm and 8 mm). Reprinted from [45]

It can be seen that:

- Low-speed (20 km/h) BFC values were comparable with the SFC values, which is to be expected since the measurements are made at similar slip speeds (the results were consistent with studies elsewhere, for example [17]). Assuming that this is an indication of microtexture than a comparison of the AC and SD surfaces shows that the higher microtexture values provided the better low-speed BFC.
- The two surfaces with low macrotexture gave very low BFC levels at higher speeds whereas the high-texture HRA performed rather better, even with the deeper water level.

This study was consistent with many others (see Figure 3.3 for example) in demonstrating that microtexture governs the level of skid resistance at low speed, however wet the surface. For a saturated surface (water depth above 1 mm) and smooth (or, as will be discussed later, nearly-smooth) tyres, the importance of macrotexture is very clear at higher speeds.

In summary, asphalt surfacing materials provides the microtexture and macrotexture needed for skid resistance largely by means of the coarse aggregate used in the surface with, for surfacings with a high proportion of fines, some contribution from the asphalt mortar and its constituents. These various components have an influence on skid resistance from the outset of the life of the surfacing, with their relative contributions changing as the surfacing ages.

Concrete

Portland cement concrete surfaces behave differently from asphalt surfaces in the way in which microtexture and macrotexture, and hence skid resistance are developed initially and how this changes over time. The actual composition of the concrete has a relatively small impact on skid resistance at first because the running surface is created by the mortar (laitence) on the surface and the way in which that has been formed to provide texture. However, as the surfacing wears over time, this initial texture can change. In the worst cases, the internal structure may be exposed at the surface and consequently influences skid resistance.

The microtexture of a concrete surface is provided initially by the sand grains in the mortar. These are naturally at the microtexture scale and the polishing resistance can be important, especially if crushed-rock fines are used. Some sands are naturally hard and retain their shape, resisting polishing, or are broken out of the surface to expose fresh angular sand grains, rather as can happen with some natural aggregates. Over time, the upper surface can wear away to expose the coarse aggregate in the bulk of the material and the polishing resistance of the aggregate then becomes of great significance in terms of skid resistance, especially if this is associated with a naturally-low texture depth.

The macrotexture of concrete roads is determined by their structure, which can be broadly divided into two categories:

- *Isotropic*, in which the macrotexture is formed by aggregate particles deliberately exposed at the surface (e.g. exposed aggregate concrete, porous concrete) and
- *Anisotropic,* where the macrotexture is formed by ridges or grooves applied to the surface, either while the cement is still wet or plastic (e.g. burlap drag, brushing or plastic grooving) or after it has hardened (diamond grooving and grinding).

The anisotropic form is usually transverse (from side to side across the road, perpendicular to the direction of traffic) but (typically in an attempt to reduce tyre/road noise) the texturing may be longitudinal.

Nearly all kinds of structures have a positive effect on skid resistance provided that microtexture and macrotexture are maintained. However, excessive brushing or grooving may lead to unacceptably harsh texture (and a noisy surface) with little benefit in terms of high-speed skid resistance. The surface form created by a burlap drag in the longitudinal direction can have negative effects on low-speed skid resistance and macrotexture [47].

Exposed aggregate concrete surfaces behave in a manner analogous to asphalt surfaces in terms of skid resistance and so the polishing resistance of the exposed coarse aggregate and the macrotexture that it provides are relevant from the outset of the life of the surfacing, not just as it gets old and worn [47].

In Germany, where the composition of cement concrete surfaces can vary more than elsewhere in Europe, it has been found that using a higher stability concrete does not necessarily lead to greater durability of the texture produced [48]. Furthermore, a loss of texture geometry does not have to lead to a loss of skid resistance, provided that the mortar layer contains a high proportion of fine aggregate and is of suitable thickness, perhaps 0.5 to 1.0 mm. However it has also been found that as well as the composition of the mortar, its consistency can also have an impact on measured skid resistance [48].

3.2 Parameters of tyres influencing tyre/road friction

The key factor for road safety is tyre/road friction – the combined effect of the road and tyre in contact with one another at any instant. As has already been explained (in sections 2.1.2, 2.3 and 2.4), the road surface contributes “skid resistance” and the tyre contributes “wet grip” properties. In this part of the report, the parameters that influence the tyre’s contribution to tyre/road friction are discussed in more detail.

3.2.1 General principles

Fundamentally, the main influence on the ability of a tyre to produce grip on a surface is the fact that it is mainly built of rubber and steel. When driving on a road surface, even at constant speed, slippage occurs in the contact area. The tyre continuously has to overcome different resistance forces, the main ones being:

- Air-drag.
- Downgrade-forces.
- Forces produced because of unevenness of the road.
- Rolling resistance.

All these forces tend to slow the vehicle down and therefore a constant drive torque is needed to maintain speed. However, while these may add in a small way to deceleration, for braking, cornering or acceleration, the important factor is the tyre’s grip on the road, produced in the contact patch which, as outlined in 2.1.3, derives from the mechanisms of adhesion and hysteresis.

In the contact area, the tyre is flattened and the blocks of the tread pattern are laid down onto the road and lifted up again with further movement of the vehicle. This flattening of the tyre produces a microscopic movement of the tread blocks in the contact area and this leads to slippage between the tyre and road surfaces. This slippage is responsible for the molecular adhesion between the rubber compound with the road surface (without slippage molecular adhesion will not take place) and the indentation.

Molecular adhesion is a result of the interaction of the rubber with the road surface, also known as Van der Waals bonding effect. These bonding effects can only occur if the distance between rubber and ground is less than 10^{-6} mm (i.e. on a clean and dry road surface).

Indentation contributes to friction through the hysteresis of the rubber of the tyre. Road surfaces usually have a certain amount of roughness (the macrotexture). When the tyre strikes against a rough spot, it deforms. Due to the hysteresis of the rubber material, the tread block does not return to its original shape immediately after rolling over the rough spot. This asymmetric behaviour produces a force that is opposed to the direction of skidding.

Figure 2.1 showed a simple illustration of these two ideas: Figure 3.11. provides a more detailed illustration of both adhesion and hysteresis.

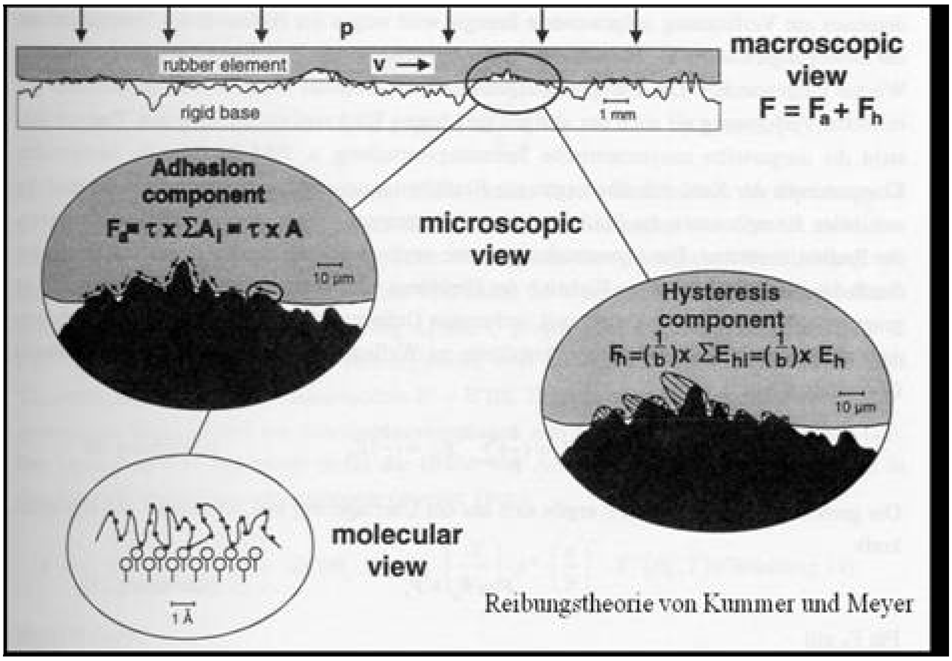


Figure 3.11: Schematic scheme of the molecular adhesion and the indentation effect [49]

As outlined in section 2.1.3, Kummer [3], [4] argues that both adhesion and hysteresis properties can be predicted from the damping properties of the tyre rubber, which are frequency and temperature dependent. The frequency at which maximum damping occurs (at a given temperature) can be used to predict the sliding speed at which the maximum adhesion and hysteresis losses will be observed, by considering the spacing of the surface atoms or molecules and the spacing of surface asperities, respectively. In this way, the maximum adhesion is predicted to occur at sliding speeds below 1 mph (1.6 km/h) and maximum hysteresis at sliding speeds above 100 mph (~160 km/h).

Summing these contributions give a predicted friction-speed curve with maxima at very high and low speeds and dropping to lower values at intermediate speeds, which are more typical of road traffic, as Figure 3.12 shows[2].

[2] It is of interest to note that the small relative increase in friction at speeds above 120 km/h recorded in locked-wheel skid resistance tests on some road surfaces – see [17] and Figure 3.3, for example – may be due in some part to this process.

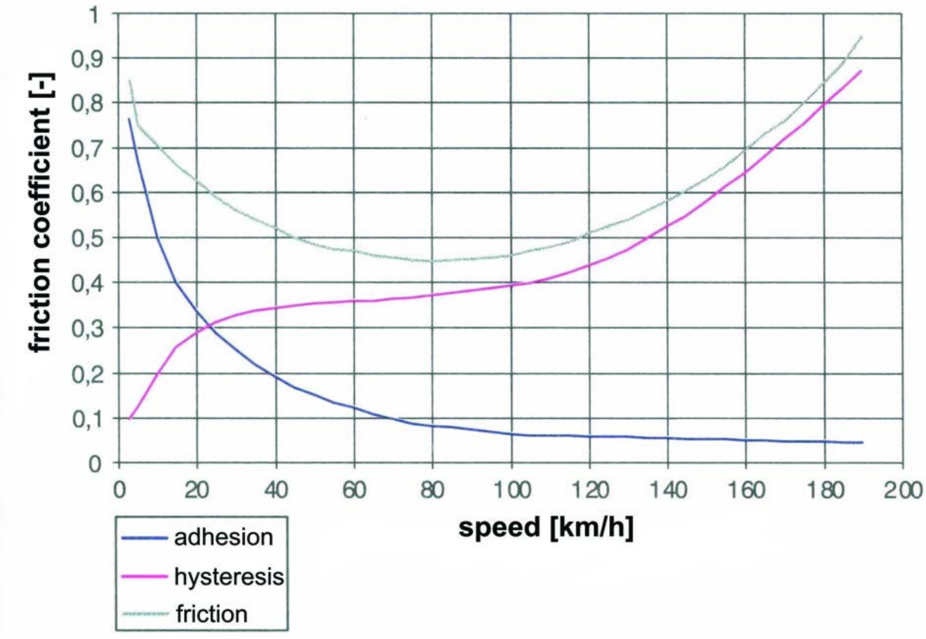


Figure 3.12: The combination of adhesion and hysteresis in developing road/tyre friction (after [49])

The following sections describe in more detail the influences that the different parts of the tyre (e.g. tread pattern, tread depth, dimensions) have on wet grip.

3.2.2 Tread pattern

We have seen that a major contribution that road surface macrotexture makes to road/tyre friction is removal of water from the contact area. The tyre also contributes to this through its tread pattern. This provides channels for water to escape, with the aim of establishing some localised dry contact between the tread and road surfaces. The role of the tread pattern is extremely important on surfaces that have low drainage capacity, i.e. low macrotexture. Sabey [16] demonstrated the influence of tyre tread pattern and surface texture on the locked wheel friction at a range of water depths, Figure 3.13. It can be seen from Figure 3.13 that at higher speeds, around 120 km/h, on the low textured concrete surface the smooth tyre has lost all its grip when the water depth exceeds 2-3 mm, while the treaded tyre still provides a braking force coefficient of about 0.15. The rougher surface texture shows a further improvement in friction of about 0.2 for the treaded tyre. The value of skid resistance obtainable at 2 mm water depth rises from around zero for the smooth tyre and smooth surface, to 0.35 for the patterned tyre on a rough textured surface. In general, in this work all tread patterns retained much of their effectiveness on smooth surfaces as long as the patterns were wholly visible on the tyre.

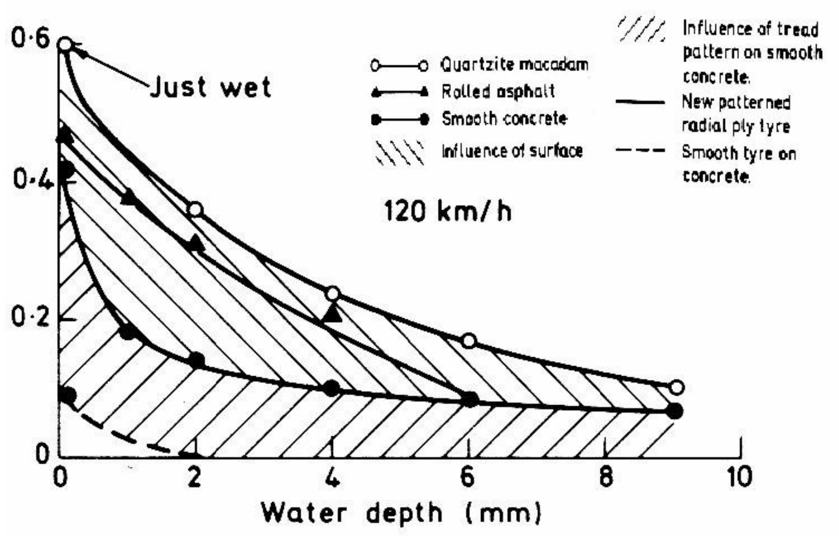
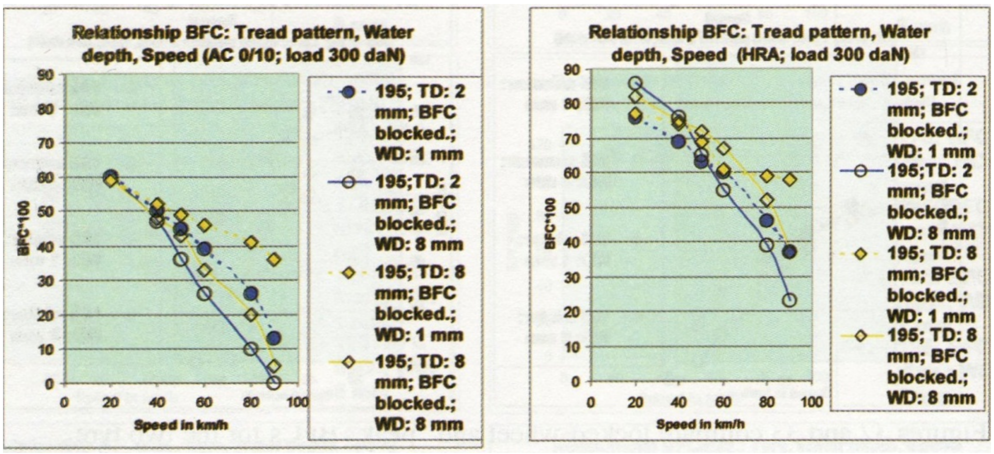


Figure 3.13: Effect of tread pattern, water depth and surface on locked wheel braking force coefficient. Reprinted from [16]

Today, there are many different designs of tread pattern but most consist of circumferential and zigzag rib patterns. Investigations were undertaken in the 1960s to determine whether particular tread patterns produce better performance on wet surfaces [50], but at that time no one pattern design seemed to show significantly better performance than others.

3.2.3 Tread depth

The effect of tread depths on skid resistance has also been studied [45] and some results are presented in Figure 3.14. The HRA, which is a surface with a high macrotexture (see Figure 3.9), and the AC 0/10, which is a surface with a low macrotexture were used for the tests along with two tread depths, 2mm and 8mm.



TD: tread depth; WD: Water depth

Figure 3.14: Effect of tread depths on locked wheel braking force coefficient. Left: AC, Right: HRA. Reprinted from [45]

On the well-textured HRA surface, the depth of tread does not appear to have a significant effect on the measured skid resistance for the 2 mm water depth, but does provide benefits at the higher water depth of 8 mm. This effect is more noticeable on the low-textured AC surface. This suggests that the surface texture and tread depth may be interchangeable to some extent. More recent studies at TRL (a report is in preparation at the time of writing) have shown similar results.

From these various studies, it appears that on surfaces with relatively high macrotexture, the influence of tread depth on the tyre is less important until water depths become high. Studies ([17], for example) have demonstrated clearly that macrotexture is important but that increasing it markedly beyond a certain level – about 1.2 mm TD (patch) has been suggested – gives no additional benefit. Therefore, on road surfaces that are already above this level in macrotexture terms, the contribution of tyre tread is small in terms of increased grip. However, on surfaces with inherently low texture depth, the contribution made by the tyre tread becomes a much more significant component of the tyre/road friction process, especially at higher speeds with greater water depth.

Another study [46] made a comparison of the “peak” friction (friction maximum) developed by tyres with different tread depths and inflation pressures on wet and dry asphalt surfaces. The results showed (see Figure 3.15), that on dry surfaces increasing the tread depth led to a decrease in friction (albeit from a very high level). However, on wet surfaces, an increase in tread depth resulted in higher friction values.

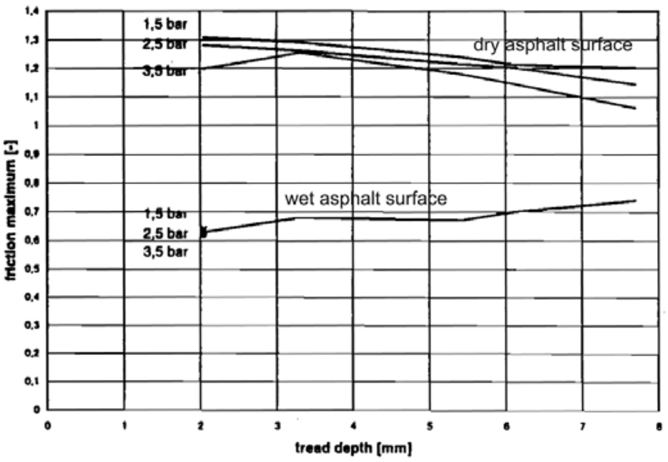


Figure 3.15: Friction maximum vs. tread depth for different tyre pressures on dry and wet asphalt

3.2.4 Rubber resilience

Tread rubber is a viscoelastic material. The term viscoelasticity is applied to materials which are neither ideal elastic solids nor viscous liquids but posses characteristics which are typical of both. On a stress against strain curve, the loading and unloading parts of a cycle have different slopes that are due to energy loss in rubber with changes in the storage and loss modulus of the rubber (this is what gives rise to the hysteresis effect). It is established that a large part of friction between rubbers sliding over a rough lubricated surface comes from energy losses in the rubber and that the lower the rubber resilience is, the greater the tyre wet grip is.

The effects of changes in the frequency of loading and unloading and the temperature are interchangeable using the empirical equation proposed by William et al and known as William-Landel-Ferry or WLF [51]. Therefore, increased temperature leads to a corresponding decrease in friction due to the changes in hysteresis losses (see discussion on the effects of external factors such as temperature in sections 2.5.4 and 3.3).

3.2.5 Inflation pressure

It is clear that changes in loading and inflation pressure will alter the dimensions and shape of the contact area. This is potentially important since this will determine the duration of the contact between each element of the tyre and the road, and so will have an effect on the water film variation. However, tests carried out in normal conditions (patterned tyre and textured surface) at RRL in the 1960s [50] – (see Figure 3.16) showed that relatively large changes in inflation pressure had hardly any effect on tyre/road friction; its effect was low compared with road macrotexture and tyre tread depth.

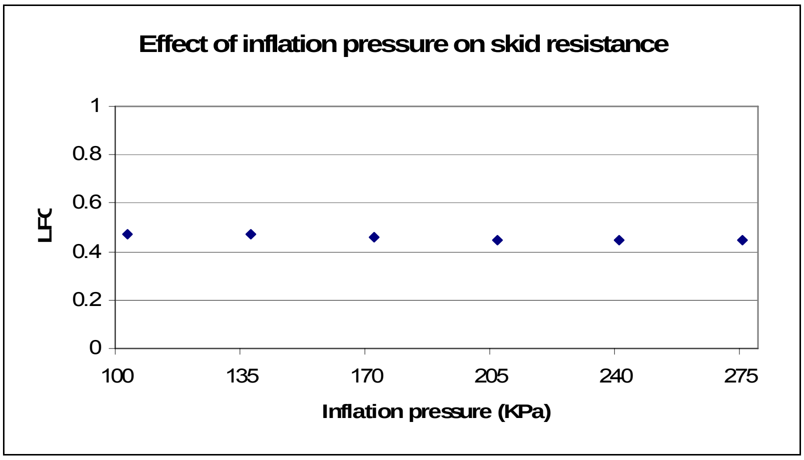


Figure 3.16: Effect of inflation pressure on locked wheel braking force coefficient [50]

Other investigations ([46], for example) have shown the same for wet surfaces, where the inflation pressure has no effect on friction value, even if the tread depth increases (see Figure 3.15). However, on dry surfaces the friction value rises, when the inflation pressure decreases, even with an increase in the tread depth (see Figure 3.15). This reduction in friction value can be explained by the reduced contact area that results from a higher inflation pressure, which leads to higher contact pressure. This, in turn, leads to lower friction values according to the following formula.

$$F_a = \tau \sum_{1}^{N} A_i = \tau \cdot A_{act} \qquad 7$$

Where:

F_a adhesion force

τ shear stress in the interface

N number of roughness elements

A_i contact area of each element

A_{act} contact area

On wet surfaces, however, it seems that the influence of the changes of the inflation pressure and therefore the inhomogeneous contact pressure are in balance. This may occur because on wet surfaces the dry area (see 2.1.3) through which the contact pressure acts to develop adhesion is already a relatively small part of the tyre contact patch and so is less sensitive to the overall change in contact area as a result of inflation pressure changes.

3.2.6 Tyre dimensions

The effect of tyre dimension was also investigated in the VERT project [45]. Three different dimensions of tyre were used (but with similar rubber compound, tread depths and pattern) to study friction and speed at two water depths on two surfaces with contrasting levels of macrotexture; HRA and AC 0/10 (Figure 3.9). Figure 3.17 reproduces some of the results obtained.

On the HRA (with high macrotexture), there is hardly any difference between tyres of all three sizes whatever the speed. The only difference seems to come from the water depth at high speeds. However, on the flooded AC surface (with low macrotexture), a very slight improvement in skid resistance seems to appear with the lower-sized tyre at speeds above 60 km/h. This finding suggests that wide tyres are more sensitive to water depth, which might be expected since it will take more for water to be expelled from a wider contact area.

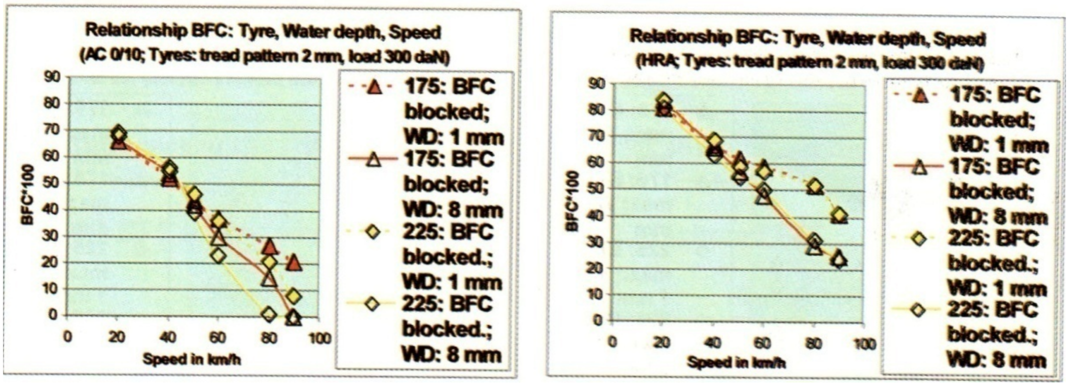


Figure 3.17: Effect of tyre dimension on locked wheel braking force coefficient. Left: AC, Right: HRA. Reprinted from [45]

3.2.7 Tyre type

Tyres are essentially of two general types – heavy goods vehicle (HGV) tyres and passenger car tyres. Car tyres can also be divided into summer and winter tyres, with different rubber compounds and tread patterns chosen to reflect the different conditions. Winter tyres are not always used in countries that do not experience great extremes between summer and winter conditions or in which the extreme conditions are not over prolonged periods.

Heavy vehicles use different tyres on different axles according to their purpose. Tyres on the drive axles usually have a traction profile to give grip for power transmission, whereas tyres on the steering axles have a longitudinal profile (see Figure 3.18).

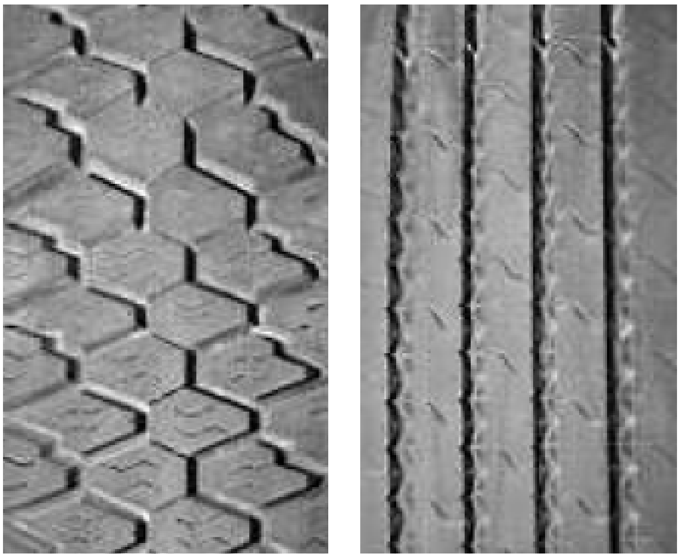


Figure 3.18: Different profiles of tyres used on HGV (left: traction profile on power transmission axles; right: longitudinal profile on steering axles) (after [67])

The different tyres on HGVs, with their various profiles, influence the braking distance of these types of vehicle. The tyres on the power transmission axles with a traction profile have approximately the same braking distance as the tyres on the steering axles with a longitudinal profile. However, the behaviour of braking distance in relation to the tyre width is inconsistent; sometimes the braking distance rises and sometimes it falls with an increase in tyre width [67].

3.3 Environmental Parameters

3.3.1 Rainfall and the influence of the water film

As has been explained in earlier chapters, when a road is clean and dry, high levels of tyre/road friction are generated whatever the vehicle operating conditions; it is water on the surface during and after rainfall that is the main factor leading to reduced friction. Various factors relating to the road and the tyre and other influences such as vehicle speed then affect the actual level of friction achieved in a particular situation.

Water acting as lubricant

The role of the water itself is primarily as a medium that separates the rubber of the tyre from the microtexture of the road by acting as a lubricant. As was explained briefly in 2.1.4 and illustrated in Figure 2.2, a wedge angle is created between the tyre and water ahead the contact area. This occurs because of the change in momentum of the water [52] as it is pushed ahead of the tyre by the rolling surface of the tyre.

This phenomenon creates a hydrodynamic pressure that increases with the square of the vehicle speed. A tread element which comes into contact with the road as the tyre is rolling must first squeeze out the film of water ahead of the contact area before it can make contact with the road surface asperities in the remainder of the contact patch. The real areas of contact between tread elements and the road occur only towards the rear of the contact patch.

Proportions of dry and wet contact areas

At any moment during the tyre movement, the tyre load is supported partly by the water trapped in the contact patch and partly by the road surface asperities that are in direct contact with the tyre tread. The greater the proportion of dry contact, the greater the tyre/road friction will be.

Section 2.1.4 explained, and Figure 2.2 illustrated, that the contact patch can be divided into three zones with different proportions that range from wet to almost dry. These zones are generally explained as follows (see Figure 2.2):

- **Squeeze-film zone (or Sinkage zone or Zone A):** Under wet conditions, the forward part of what would normally be considered the contact area under dry conditions floats on a thin film of water, the thickness of which decreases progressively as individual tread elements traverse the contact area. Since the tyre, water film, and the road surface have virtually no relative motion in the contact area, the tread elements in effect attempt to squeeze out the water.
- **Transition zone (or Draping zone or Zone B):** The transition zone begins when the tyre tread elements, having penetrated the squeeze-film, commence to drape over the major asperities of the surface and to make contact with the lesser asperities.
- **Actual contact zone (or Dry zone or Zone C):** This is the region where the tyre tread elements, after draping, have attained an equilibrium position vertically on the surface. This zone occupies the rear portion of the contact area.

The lengths of these regions depend on vehicle velocity and relate to water drainage time. At low speeds, the contact time is long, and there is ample time for water film to be expelled, thus allowing a large actual contact zone to develop with a resulting high level of friction. When speed increases, the time available for water to be expelled from the interface becomes shorter and consequently the expulsion of water is less complete, the actual contact zone is smaller and friction is lower.

Increasing speed will decrease the available drainage time so much that the squeeze-film zone is extended, ultimately to the point where it occupies the whole contact length. This situation corresponds to the viscous hydroplaning limit. At such a speed, the hydrodynamic pressure is less than the wheel load. Further increase in speed moves the situation to the point that corresponds to dynamic hydroplaning, where the hydrodynamic pressure balances the normal wheel load and the water occupies the whole contact area. In this extreme situation the tyre is effectively lifted off the road and all grip and steering control are lost.

However, normal road surface are never smooth, so the contact area is usually broken up into discontinuous areas, either by the texture of the road or by the texture of the tread pattern of the tyre. This increases the speed needed for hydroplaning to occur. Nevertheless, in practice, it is not at all necessary to have a flooded road surface for viscous hydroplaning to occur, and the slightest film of water may be sufficient to make skidding possible.

Instead of determining water drainage time, Horne and Buhlmann [53] proposed an alternative method for determining the available friction at any speed that takes the road texture directly into account. This method describes the water removal rate in the squeeze-film and transition zones. The relative drainage times from both zones are expressed in terms of pavement drainage coefficients, C_{mac} and C_{mic}. It is C_{mac} that determines the percentage of the tyre footprint in the squeeze-film zone. Since in this area the dynamic effect of water predominates, the removal rate is dependent upon bulk channel flow, which is determined by the amount of road surface macrotexture in the case of a smooth test tyre. C_{mic} determines a percentage of the tyre footprint that set the relative size of the transition zone. Unlike the squeeze-film zone in which bulk water is removed, fluid viscous forces prevail in this region. Since localized high contact pressures are required to penetrate and break this viscous film, this coefficient depends on the road surface microtexture.

$$Y_R = 1 - \left[C_{mac} \left(\frac{p_1}{p} \right)_u + C_{mic} \left(\frac{p_2}{p} \right)_u \right] \qquad 8$$

Where:

Y_R the friction rate divided by the maximum obtainable friction, p_1 and p_2 represent respectively the hydrodynamic and the viscous fluid pressure.

Lenke and Graul [10] proposed two formulas for the calculation of C_{mac} and C_{mic} as follows:

$$C_{mac} = 0.243 - 0.146\ \text{SAP} \quad \text{and} \quad C_{mic} = 0.333 - 0.144\ \text{CTT} \qquad 9$$

Where:

SAP sand patch texture depth expressed in millimetres

CTT chalk wear coefficient as measured in the transversal direction on the runway.

Water film thickness and skid resistance

According to the equation 3, the film thickness decreases rapidly with time as soon as it enters in contact with the tyre. Thus, the differences in the initial thickness of the water films are small importance. Experimental investigations [16] at the Road Research Laboratory in the UK in the late 1960s confirmed that the main skidding problem on roads is the lubricating effect of a relatively thin water film, of about 3 to 4 mm (see Figure 3.19).

Based on experimental investigations, Bohdan et al proposed a mathematical relationship between water film thickness and skid resistance with a form that responds in the same sense as the RRL results. The exponential form can approximate this relationship:

$$\mu(h) = \Delta\mu \exp(-\beta h) + \mu_F \qquad 10$$

Where:

μ friction coefficient,

h water film thickness,

Δμ magnitude of change of the coefficient of friction due to increase in water film thickness from 0 to over 0.38 mm,

β model parameter and depends to road surface texture,

μ_F friction coefficient for water film thickness greater than 0.38 mm

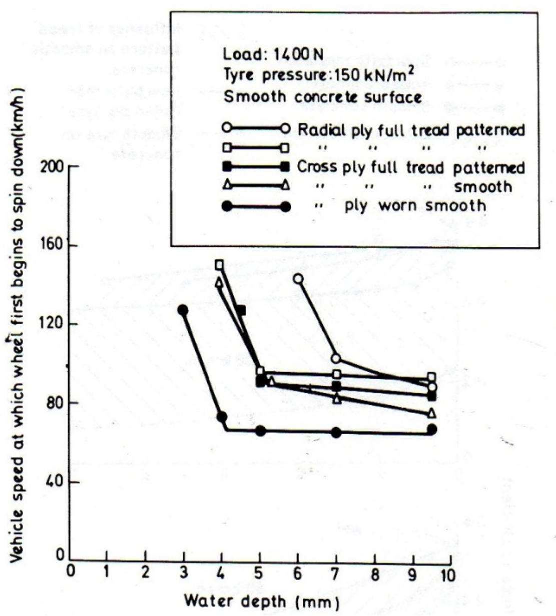


Figure 3.19: Effect of water depth on the vehicle speed at which test wheel begins to spin down. (reprinted from [16])

The effect of water thickness on skid resistance is small at low speeds but quite pronounced at higher speeds. Two studies, in France [45] and the UK [16] confirm this conclusion. Figure 3.20 and Figure 3.21 show the results of these experimental investigations on the combined effects of water depth and speed.

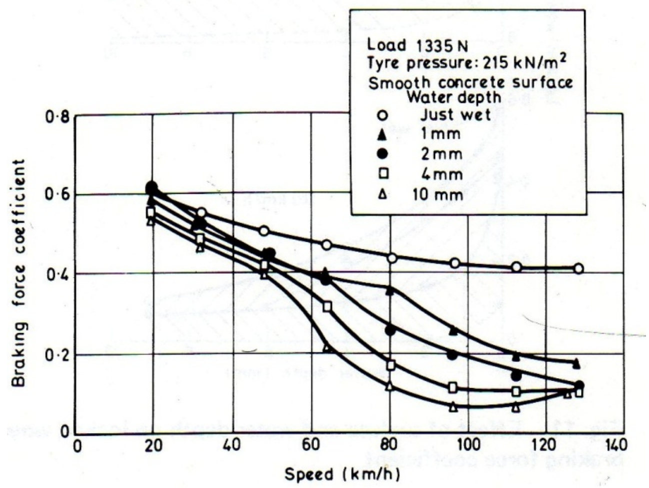
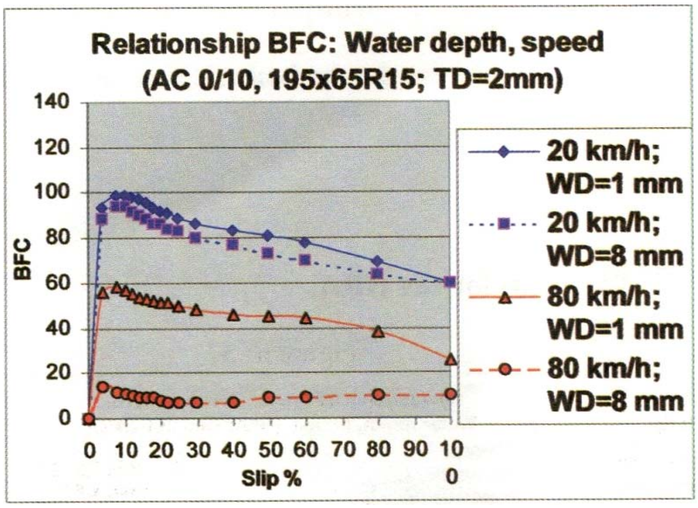


Figure 3.20: Effect of water depth on the locked wheel BFC with a radial ply tyre. Figure reprinted from [16]



TD: Tread depth; WD: Water depth

Figure 3.21: Comparison of the locked-wheel BFC versus slip ratio relationships for a tyre with 2 mm tread depth (on the AC 0/10 test surface shown in Figure 3.9), at two speeds and two water depths (1 mm and 8 mm). Reprinted from [45]

3.3.2 Temperature

Temperature follows the seasons. The effects of temperature on skid resistance are small. Both tyre rubber and bituminous materials are viscoelastic materials, so it follows that these materials are sensitive to change in temperature, particularly due to the hysteretic component of friction. Changes in temperature, may affect the skid resistance of the road [24]. Hosking [24] has listed the effects of temperature on skid resistance as follows:

- The measured coefficient of friction tends to decrease with increasing air temperature;

- Temperature change has most effect on the frictional properties of the tyre, leading to an indirect effect on skid resistance as measured by testers and the friction available to road users;
- Tyre temperature tends to be proportional to air and pavement temperature, with higher tyre temperatures leading to a decrease in measured coefficient of friction;
- Increased pavement temperatures lead to reduced coefficient of friction;
- Water temperature has only a small effect on measured coefficients of friction, but influences the tyre temperature.

3.3.3 Seasonal variation

As explained in Section 2.5.1, although so-called "seasonal variation" undoubtedly affects skid resistance, in fact the changes observed are governed by the mechanisms that bring about the fine scale change in the texture surface of individual stones [50]. The season of the year affects this process by influencing which of the mechanisms predominates. For example, the presence of dust particles in dry weather accentuates the polishing of the microtexture of the road by acting as a polishing medium. Frost action can expose fresh faces of mictrotexture. Rain can have help to increasing skid resistance by washing away the fine dust and other deposits. By acting as lubricant, it can reduce the effects of wear and consequent microtexture polishing. Also, by washing finer particles away but leaving coarser particles on the surface, it can contribute to abrasion that roughens the microtexture.

Hill et al [34] and Wilson [24] attempted to determine the parameters of seasonal variations that have an effect on skid resistance with an experimental approach. The Penn-State model (equation 10) was used as the basis relating texture, speed and friction:

$$SN_0 = SN_{OR} + SN_{OL} + SN_{OF} \qquad 11$$

Where:

SN_0 corresponds to zero speed skid number as defined above, and found to be related to the microtexture,

SN_{0L} represents the long-term variation in measured skid number and is given for asphalt surface by the following relation:

$$SN_{0L} = \Delta SN_0 \exp\left(-\frac{t}{\tau}\right) \qquad 12$$

Where:

ΔSN_0 corresponds to change in SN_0 over testing season and is a function of aggregates polish susceptibly,

t is time in days,

τ is the rate at which polishing takes place, a function of average daily traffic,

SN_{0R} short-term residual variation in measured skid number, and is given by the following relation:

$$SN_{0R} = a - b\ln(t_R + 1) - c\,T_p \qquad 13$$

Where:

a,b,c constants depending on the geographical situation,

t_R number of days since rainfall of 2.5 mm or more and upper limit of seven day,

T_p pavement temperature.

SN_{0F} measure of SN_0 that is independent of short and long-term variations.

The combined effects of polishing and seasonal variation are well illustrated in Figure 3.22 which shows comparative skid resistance measurements over a number of years on an experimental site in the South of England (from an unpublished report by P G Roe). Two sets of surfacings are compared, one an old well-established HRA, the other a newly-laid surface dressing. The materials were laid across both lanes of a dual carriageway so the effects of different traffic levels, heavy traffic in the main traffic lane (Lane 1) and lighter traffic in the overtaking lane (Lane 2) can also be seen. In both cases, the skid resistance is higher in the less-heavily trafficked lane. The effects of seasonal variation alone can be seen on the HRA which simply varies about its established equilibrium levels. The surface dressings, however, show both seasonal variation and gradual polishing – having just reached equilibrium after about three years. Both aggregates had good PSV but the aggregate used for the surface dressing had lower PSV than that which was used for the HRA chippings, hence the lower equilibrium value.

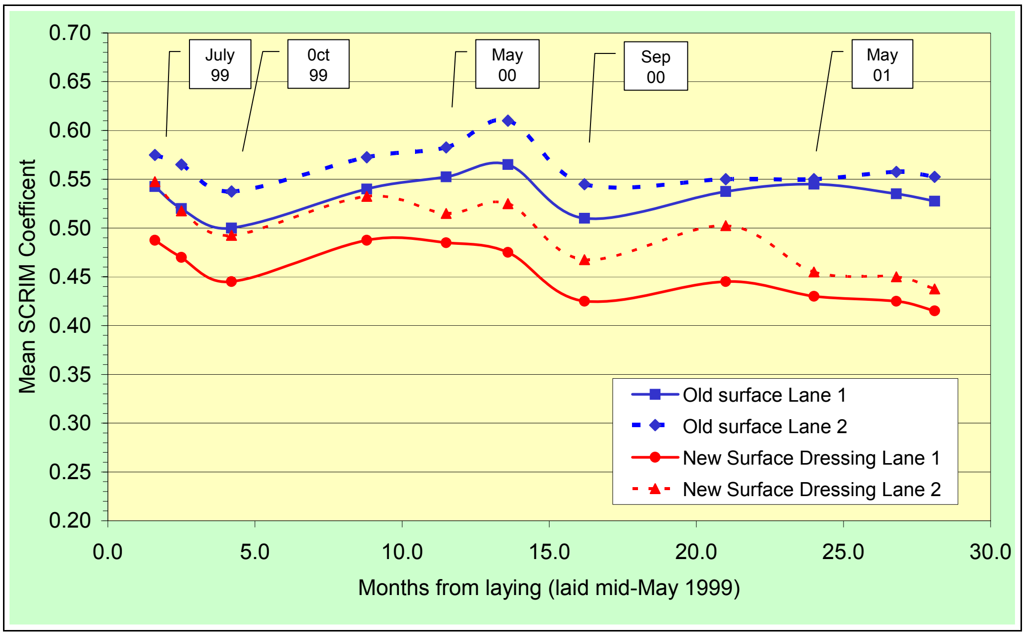


Figure 3.22: Examples of seasonal variation and polishing on an old HRA surfacing and newly-laid surface dressings

3.3.4 Deposits and contaminants

Dry roads

Dry and clean roads give generally high skid resistance whatever the vehicle speeds and whether tyre is skidding or freely rotating. However, the braking of a tyre generates heat in tyre/road contact area, especially when a high slip ratio develops, and sometimes that can lead to the removal of a thin film of rubber from the tyre or binder from the road surface. These can act as lubricant and reduce the friction during that skid. This phenomenon is more often noticed on relatively new surfacings which have thicker bitumen films on the surface

Grit on roads

The presence of grit or dust on road surface can reduce the available friction. The extent to which it reduced depends mainly on the size and shape of the particles present. Larger, rounded particles have a worse influence than small, angular materials. This needs to be borne in mind when applying grit, either for some kind of winter maintenance or as part of a laying process to reduce the any adverse influence of the bitumen film in the early life of an asphalt surfacing.

4 Rolling resistance

4.1 Parameters of road surfaces

Rolling resistance is one of the four main resistances that a vehicle has to overcome while driving on a road surface. The rolling resistance occurs due to the interaction between tyre and road. Today's air-filled tyres, which are used by most vehicles, are forced to bend as they rotate and adapt to a new shape under load in the contact patch. This mechanical deformation causes the breakaway of reinforcement fillers from the polymer chains. This chemical process emits heat. Apart from this, the aerodynamic drag of the rolling tyre can also be regarded as a part of rolling resistance.

Although deformation of the tyre is the main cause of rolling resistance, the road itself as an exciter of the tyres has an influence on rolling resistance, too.

As has been discussed in relation to skid resistance, the road surface can be classified by measuring the wavelengths spectra of the profile and defining texture classes (Figure 2.6) and four wavelengths classes are typically used:

- microtexture (< 0.5 mm)
- macrotexture (0.5 to 50 mm)
- megatexture (50 to 500 mm)
- unevenness (> 500 mm)

During the TYROSAFE project a questionnaire dealing with the influence of the road surface on the tyres' rolling resistance was sent out to experts in this field. Most of them replied that the microtexture has little or no effect on the rolling resistance.

As explained in Chapter 2, the energy loss caused by rolling resistance is a result of the deformation of the tyre rubber, mainly in the area of the contact patch, and the deformation of the sidewalls. Texture wavelengths in the macro- and megatexture ranges deform the tyre considerably. Therefore the influence of these two texture-wavelengths can be considered to be significant in relation to rolling resistance.

The rolling resistance of a tyre is influenced by the amplitude of deformation, so unevenness has a major influence on energy dissipation. Excitations with a low frequency (unevenness means texture wave-lengths greater than 500 mm) result in deformation of the tyres as well as movements in the vehicle's dampers. Energy dissipation in the vehicle's dampers is, by definition, not a part of the tyres' rolling resistance, but it can be regarded as a part of rolling resistance in the broadest sense, since the energy loss is induced in response to an influence of the road surface.

The power loss of a tyre while rolling mainly depends on deformation and deformation velocity. The tyre has to be deformed to a certain amount in order to be able to create a contact patch and to create grip between tyre and surface. Additional to this necessary deformation, the tyre gets deformed by excitation of the road surface itself. A road surface never can be ideally flat.

4.2 The influence of tyres on rolling resistance

First of all, it can be stated that one of the most effective measures to reduce the tyres' rolling resistance to a minimum is monitoring the inflation pressure and keeping the additional weight of the vehicle as low as possible.

The basis of tyres as they are available today is rubber. As discussed in Section 3.2, rubber is a visco-elastic material and this property enables the tyre to be bent and to produce micro-slippage and therefore grip while rolling on the road surface.

The visco-elastic material property is also responsible for a certain amount for the rolling resistance of the tyres. Visco-elastic materials dissipate energy when they are deformed. Unlike a spring, they do not return to their original shape immediately when they have been deformed. Rather, they behave more like the example of a spring and damper unit. The hysteresis that this shows (with more energy being required to deform the rubber than is needed for it to recover its shape) leads to the energy dissipation. This may be advantageous in a skid but for a rolling tyre the repeated deformation process contributes to rolling resistance.

The rubber compound is made of about 200 different constituent parts. Amongst them are three main ingredients that influence the tyre's rolling resistance. They are:

- *Polymers,* which are long chains of molecules. They belong to the group of hysteretic materials, which means that they dissipate energy when being bent. The positive effect of this behaviour is that tyres produce grip on the surface.
- *Reinforcing fillers,* also known as reinforcing materials, which are mainly carbon black or amorphous silica. Without these fillers the rubber compound could not be resistant against wear and a tyre would not last very long.
- *Sulphur,* which is used in the rubber compound, to create sulphur-bridges between the polymer chains during the vulcanisation process. These bridges help the tyre to keep its elasticity.

When the rubber of the tyre is alternately deformed and released, the non-deformable carbon black particles first move closer then further away from each other. As a result of this, some polymer chains may break away from the carbon black particles. This process is called "desorption". Desorption decreases the compound rigidity and causes energy dissipation. The greater the deformation is, the greater the probability of desorption and therefore the energy dissipation. The closer the reinforced filler particles are to each other, the greater the probability of desorption. The energy dissipation and therefore the rolling resistance can be reduced by increasing the distance between the reinforcing filler particles. However, doing this has the disadvantage of decreased resistance of the rubber compound against wear. Another approach is to use low-hysteresis polymers. These polymers reduce the deformation and therefore reduce the possibility of filler particle breaking away from the polymer chains. The disadvantage of these polymers is a reduced grip performance.

The solution of this problem can be found in the replacement of carbon black by silica. On the one hand silica has a good energy dissipation a high frequencies of rubber deformation, which affects the micro-slippage of the rubber on the road surface and therefore the production of grip. On the other hand, silica allows low energy dissipation at low frequencies of rubber deformation, which causes rolling resistance.

Besides the energy loss due to the breakaway of reinforcing filler particles from polymer chains in the tread area, the mechanical deformation of the tyre's shoulder, sidewalls, together with the carcass, belt and bead cause heat emission and therefore energy loss.

The different tread profiles on HGV tyres (see Figure 3.18) also have an impact on the rolling resistance of the tyres. Tyres on the power transmission axles (with a traction profile) usually have a higher rolling resistance than the tyres on the steering axles (with a longitudinal profile). Rolling resistance increases with greater tyre width, independently of whether the tyre has a traction or a longitudinal profile [67].

4.3 Environmental Parameters and rolling resistance

Generally, unlike skid resistance, environmental factors such as changing weather conditions are not usually included in any discussion of the rolling resistance of tyres on real pavements. However, deposits on the surface (which may come from weather or the environment or the road) such as snow or wind-blown sand are indisputably significant. When rolling on sand or snow, the tyre always has a wedge of material in front of the contact patch that has to be compacted and then run over. This additional resistance can be compared to running uphill.

5 Noise emissions

5.1 Introduction

As outlined in 2.2.2, the major part of noise emitted by vehicles on roads by passenger cars and trucks in the mid- to high-speed range (above 30 km/h) is due to the noise generated by the interaction between tyres and the road surface; so-called tyre/road noise (Sandberg, Ejsmont, 2002) [11]. Tyre/road noise is generated principally when the tyre tread pattern interacts with the texture of the road surface, which generates complex tyre vibrations as well as aerodynamic effects and resonances, which are called air pumping. A typical frequency spectrum of tyre/road noise for a passenger car shows that in the low-frequency range the tyre vibrations are predominant; while in the high frequency spectrum the so-called air pumping effect becomes more relevant for noise emission.

Over the years, many measurements have been made in order to understand the most relevant parameters that influence tyre/road noise emission. Sandberg and Ejsmont have collated a large amount of data and information related to this topic in their “tyre/road noise reference book” (2002) [11]. Another relevant source of information is the SILVIA guidance manual (2006) [54], which was one of the most relevant European projects in recent years dealing with low noise road surfaces.

The tyre/road noise emission can be influenced by many different parameters. As well as those that relate to the road surface, tyres and the environment, the driver’s style, speed and acceleration can also affect noise emission.

To give approximate idea of the major influences, the most important parameters and an estimation of their influence have been listed below [11]:

- Speed → 25 dB (in a range between 30 and 130 km/h).
- Road surface → 9 dB (for conventional surfaces).
- Road surface → 17 dB (for non conventional surfaces)
- Truck and car tyre type → 8 to 10 dB
- Studs in tyre → 8 dB (compared with no studs)
- Load and tyre inflation → 5 dB (for a variation of 25%)
- Road condition (wet or dry) → 5 dB (considering heavy rain conditions)
- Temperature → 4 dB (range between 0 and 40 degrees)
- Torque on the wheel → 3 dB (considering acceleration between 0 and 3 m/s²)

These influences depend also on the kind of vehicles; for example, for cars the range of noise emission variation due to the road is greater than the variation due to tyres. Conversely, for trucks the variation due to tyres is bigger than the variation due to the roads.

5.2 Parameters of road surfaces influencing noise emission

The acoustic performance of road surfaces is influenced by a number of surface properties such as texture, porosity, flow resistance, age and wear of the surfaces, stiffness and type and dimension of the aggregates. The most important of these are discussed in some detail below. The following list gives an overview of the relevance of the most important road surface parameters influencing noise emission [11]:

- Macrotexture → very high influence
- Megatexture → high influence
- Microtexture → low – moderate influence
- Uneveness → minor influence
- Porosity → very high influence
- Thickness of layer → high influence (for porous surfaces)
- Adhesion (normal) → low – moderate influence
- Friction (tangential) → low – moderate influence
- Stiffness → uncertain, moderate

Some of these parameters have been well investigated, others need more research. The most relevant information relating to these parameters is discussed in the following sections.

5.2.1 Texture (macro- and megatexture)

Probably the most relevant road parameter influencing noise emission is the surface texture. In particular, texture wavelengths in the macrotexture and megatexture ranges (0.5 mm to 50 mm and 50 mm to 500 mm respectively) have a significant and complex influence on the generation of tyre/road noise. Different studies [57] have shown the following influences:

- *At high frequencies:* the increase of the texture amplitudes at wavelengths in the range 0.5 to 10 mm may reduce noise generation, particularly at high frequencies generally above 1 kHz. Texture wavelengths in this range accord with dimensions associated with the small asperities in the surface which are thought to have an influence on the aerodynamic mechanism of tyre/road generation, particularly air pumping.
- *At low frequencies:* the increase of the texture amplitudes at wavelengths in the range 10 to 500 mm causes an increase of noise, particularly at frequencies below 1 kHz. The tyre mechanism affected by texture amplitudes in this wavelength range is associated with tyre tread impacts with the road surface. As the texture amplitude increases, the vibration levels set up in the tyre carcass due to the tread impact increase, causing higher levels of noise emission.

- *The way in which texture is formed on the surface:* the influence of the texture amplitudes on noise in the megatexture range is different for randomly textured surfaces compared with surfaces with a transverse texture such as brushed concrete.

The results of [54] show that wavelengths of more than 200 mm have no obvious effect on noise reduction and so it is not necessary to avoid these wavelengths.

Additionally, the difference between "positive" and "negative" texture can influence the noise. Positive texture is formed by particles which protrude above the plane of the surface, while negative texture is a term often applied to materials in which the texture largely comprises voids between particles whose upper surfaces form a generally flat plane, typical of thin surfaces. Depending on the size of the chippings, positive texturing causes more vibration in the rolling tyre while negative textures contribute to the lower noise levels associated with thin surfaces [54].

Although these broad principles are evident, the parameters usually used to describe the overall texture, such as MTD and MPD, are not adequate to relate this characteristic of a surface to tyre/road noise emission. A high level of correlation between tyre/road noise and texture could be found only for smooth tyres or those with a non-aggressive tread pattern [11].

Road surface texture has various shapes and forms depending on the material used and the type of surfacing of paving. However, these different shapes are not taken into account by the normal parameters used to quantify the texture (e.g. MPD). To try and overcome this problem, the texture of surfaces can also be described by a so called "Gestaltfaktor (shape factor) (g)". The shape factor (its principle is illustrated in Figure 5.1) can divide convex and concave shapes/surfaces.

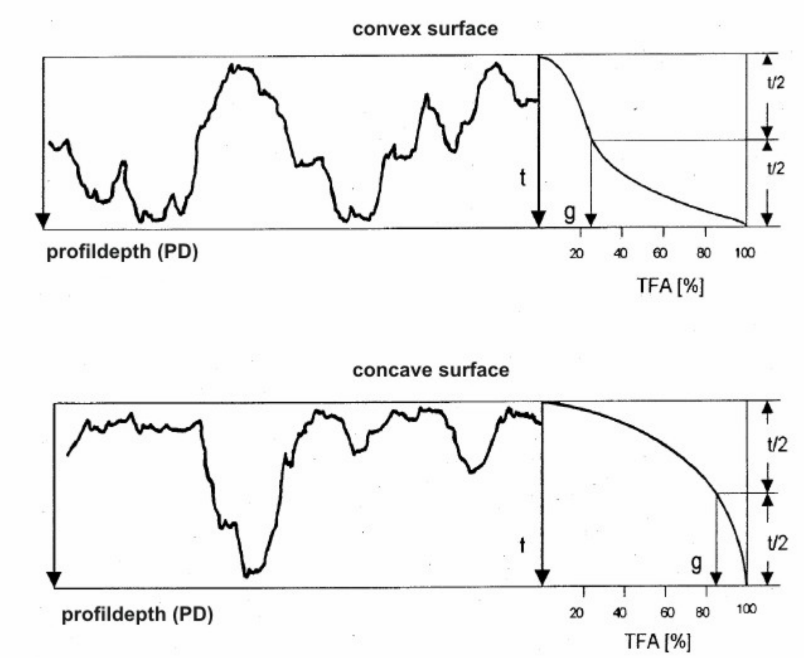


Figure 5.1: Definition of the shapefactor (Gestaltfaktor) for distinguish the different texture shapes [55]

A shape factor g which is greater than 60% represents a concave surface and a value of g < 60% represents a convex surface [55]. The concave shapes with a high value of the shape factor show advantages in relation to noise generation and therefore they are better for optimizing tyre/road noise. Normally, asphalt surfaces without applied chippings, e.g. SMA, AC, PA, show concave surfaces with so called "plateaus and canyons"; surfaces that rely on applied chippings to provide texture, e.g. MA (mastic asphalt), surface dressings and exposed aggregate concrete, have convex surfaces with "hills and valleys" [55]. However, HGV tyres are no louder on dense surfaces with chippings than on surfaces without chippings [56].

Taking into account the wavelength (λ_{max}) at the maximum of the roughness depth (R_{max}) of the spectral envelope curve (see Figure 5.2), the so called "characteristic shape length (g')" can be determined with the following formula [56]:

$$g' = \frac{g}{1\%} \cdot \lambda_{max} \quad (14)$$

Where:

g shape factor ("Gestaltfaktor") [%]

λ_{max} wavelength at the maximum of the spectral envelope curve

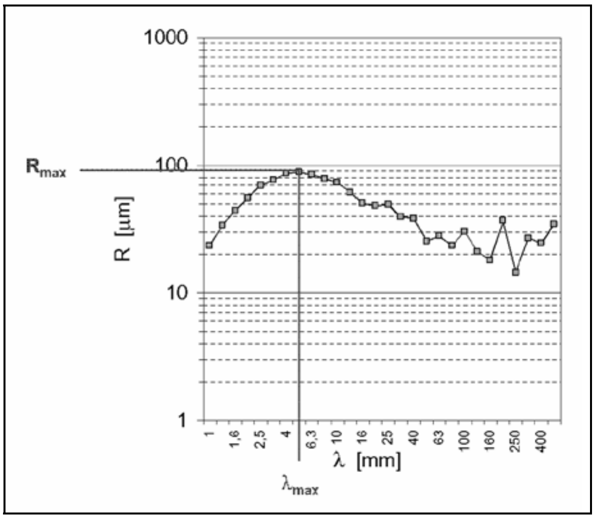


Figure 5.2: Determination of texture parameters of the texture spectrum [56]

In [56] it was established that the following texture parameters have a beneficial effect on noise emission:

- characteristic shape length (g'): 400 mm < $g' = \frac{g}{1\%} \cdot \lambda_{max}$ < 700 mm
- maximum of the spectral roughness depth: 60 µm < R_{max} < 200 µm

Provided that the values of λ_{max} and R_{max} fall within these ranges, the noise levels will decrease; conversely, outside these ranges the noise level would increase.

5.2.2 Aggregate properties

The main aspect of aggregates that affects noise generation is the size of the particles in the surface. Several studies have confirmed that noise increases as aggregate particle size increases. Generally it can be said that in order to achieve low levels of noise emission:

- The maximum chipping size should be as low as possible, for light vehicles; aggregates larger than 8 mm should be avoided (a better performance if the aggregates are 4 to 6 mm); for heavy vehicles aggregates larger than 12 mm should be avoided.
- The edges of the aggregates should be sharp, the particles should be of uniform sizes (preferably having a cubical shape) and well packed together (with little space between them).

The results of [56] show that, for dense surfaces, a maximum aggregate size of 3 mm is optimal for car tyres, whereas a maximum aggregate size of 5 mm is optimal for HGV tyres. However, to optimise the noise emission of a surface, a maximum aggregate size smaller than 3 mm should be avoided.

The use of crushed or uncrushed aggregates has no influence on noise emission, but this parameter influences the skid resistance of surfaces [56].

5.2.3 Texture orientation

Oriented textures, also called anisotropic surfaces (see the discussion relating to cement concrete in section 3.1.3) are of different types. On main roads these include transverse or longitudinal grooves, brushed surfaces, burlap drag or tined surfaces but in urban areas may also include paving stones, block pavements. Surfaces that have been ground or flailed may have anisotropic properties.

The noise emission on oriented textures can be very high, especially if the texture is transverse to the direction perpendicular to its main features. When travelling on a transverse textured surface the air-displacement mechanism will cause pipe resonances and, in addition, the impact of the tyres will be in-phase the whole width of the tyres and this will cause more tyre deflection. For these reasons the use of transversely oriented textures should be avoided if a low-noise surface is to be achieved [11].

Milling grooves in the longitudinal or diagonal direction has little or no influence on noise emission [56]. If this parameter is necessary for optimising skid resistance it can be optimised independently from the noise reducing properties. This is not the case for transverse grooves, however.

5.2.4 Porosity

After texture, porosity is the most relevant parameter in relation to the development of low-noise road surfaces. A measure of porosity can be defined as the percentage of voids that are open to the air in a given volume of total pavement mix, sometimes referred to as the residual air void content. An official definition of porous surface has yet to be established;

nevertheless in the literature, the following is commonly used [11] to distinguish between surfaces of different porosity:

- Dense surfaces → air void content under 10%
- Semi–porous surfaces → air void content between 10 -15%
- Porous surfaces → air void content over 15%

Closely related to porosity, the following parameters influence sound absorption:

- *Thickness of the porous laye*r: this parameter influences where the maximum absorption occurs in the frequency spectrum. Increasing layer thickness lowers the fundamental frequency of maximum absorption together with its harmonics.
- *Air flow resistance:* this parameter describes the air flow in the pores of the surface. A high air flow resistance is favourable to sound energy dissipation, but a too high air flow resistance prevents the acoustic waves from penetrating into the layer. The optimum range of the air flow resistance depends on the thickness of the layer. The shape of the absorption curve in the frequency domain depends on the total air flow resistance of the layer.
- *Tortuosity:* is an artificial parameter that describes how a pore is shaped. The air path through the layer will be dependent upon the shape of the interconnecting voids. The more tortuous the air path, the lower the fundamental frequency of maximum absorption. The fundamental frequency is therefore governed by both the tortuosity and the layer thickness [57].

High levels of porosity cause high levels of sound absorption and, obviously, less noise. In order to improve the sound absorption the voids should be connected. Porous surfaces play an important role in reducing the noise propagated away from the road by sound absorption. Nevertheless porous surfaces also reduce the generation of noise by several mechanisms related to the surface porosity at the source. Increasing the porosity generally increases the acoustic absorption of the surface, reduces the horn effect and the noise generated due to the impact mechanism. Furthermore, increasing the porosity of the surface reduces the compression and expansion of air trapped in the tyre tread, reducing the noise generated by aerodynamic mechanisms.

Unfortunately, providing a high level of air voids is in conflict with the mechanical strength and the durability of the pavement. Also, over time the voids become clogged with detritus that reduces the spray-reducing properties of such surfaces (one of the original reasons for developing them) and this also reduces their acoustic reduction performance. In order to avoid the clogging effect, especially in urban areas, double-layer porous surfacings have been developed.

The most useful principles to follow in order to improve the noise reduction properties of a road surface are therefore:

- From the acoustic point of view, the porosity should be as high as possible (values between 25% and 30% seems to be acceptable for mechanical stability).

- Maximise the sound absorption at the most important frequency (1000 Hz for high speed roads and at 600 Hz for low speed roads).
- Due to layer thickness and tortuosity the peak of sound absorption should be shifted to the most important frequency (for heavy vehicles one or two third-octave bands lower than for cars).
- Minimise the air flow resistance for reducing the air displacement mechanism.
- Maximise the flatness of the surfaces in order to the texture impact mechanism.

Results from a number of different sources, when combined, indicate that the noise reduction of porous surfaces is statistically highly correlated with the product of residual air voids and layer thickness. The relationship appears to hold for values of thickness < 30 mm. By taking into account the size of the aggregate, improvements in the correlation are obtained, i.e. surfaces with similar layer thickness but with smaller chippings provide greater noise reductions.

Different research studies report on the combined influence of layer thickness and air void on noise emission: experiments with super-thick porous structures (up to 700 mm) indicate a noise reduction of 7 dB instead of 4 dB for thin layers; other experiments with a 450 mm, 4-layer structure reduced noise by 6 to 11 dB; the use of a double layer instead of a single one (80 mm instead of 50 mm) will reduce noise by additional one decibel. For example, if the layer thickness is 40 mm and the air voids 25%, the noise reduction will be 3 to 5 dB [11].

The choice of the binder is also relevant for noise emission: plastic binder should improve the noise reduction by one additional decibel, and also rubber may have a positive effect on noise reduction.

The frequency response of the absorption coefficient of porous asphalt can be influenced by a number of factors, as illustrated graphically in Figure 5.3, including [55]:

- Layer thickness
- Void content
- Flow resistance

It can be seen that the thickness influences the position (frequency) of the absorption maximum, the void content affects the level of the absorption coefficient and the flow resistance has an influence on the width of the maximum [55].

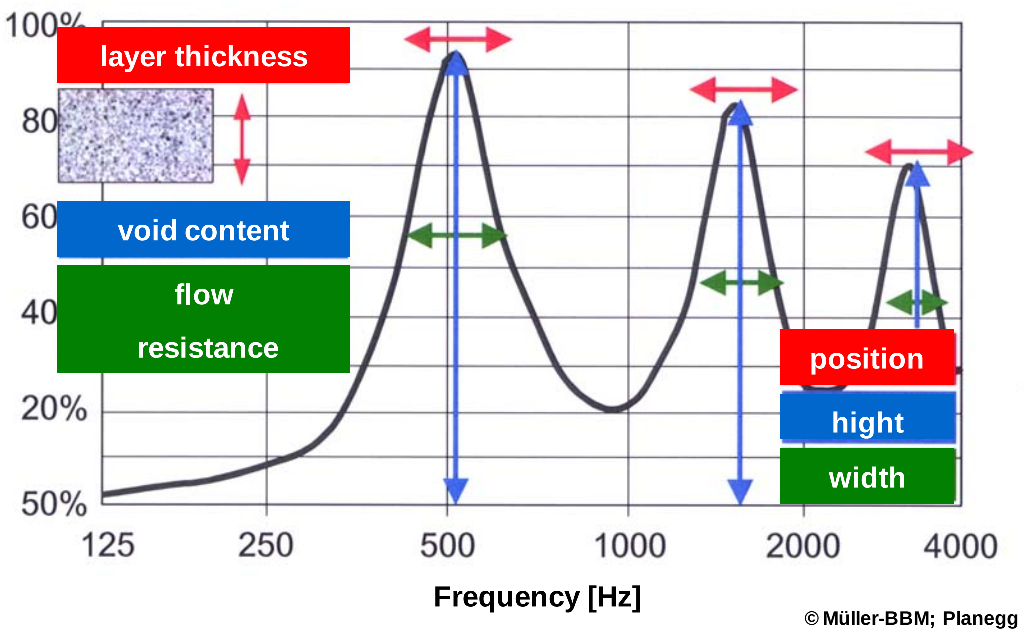


Figure 5.3: Absorption spectrum of double layer porous asphalt – influences of various parameters (after [55])

5.2.5 Friction and microtexture and noise

As discussed in Chapter 3, microtexture has a major influence on adhesion which, together with macrotexture, is important in determining the skid resistance of the surface. The relation of these properties to noise emission is rather complex and the studies reported in literature sometimes show inconsistencies and different results. In order to clarify the relationship between friction, microtexture and noise, the following list of interpretations will give a short overview of the problem:

- Two different mechanisms are responsible for the relationship between friction and noise emission: they can cause opposite influences to tyre/road noise.
- The two mechanisms are called stick-slip and stick-snap, both of which operate at the trailing edge of the contact patch. Stick-slip is a mechanism where tangential stresses are built up between road and rubber. Tangential vibrations are caused by this effect. This mechanism will increase noise when friction increases, particularly for high frequencies. Stick-snap is due to the adhesive bonds between rubber and road. This mechanism causes a combination of radial and tangential vibrations and also a transient air-flow. This effect will increase noise with an increase in the attraction force between road and rubber.
- Increase in microtexture will increase friction and increase the stick-slip effect. At the same time the adhesion will decrease and the stick-snap effect will decrease.
- The influence of friction on noise emission is actually rather low under real road conditions, but it could be more relevant for certain laboratory tests.

Summarizing this complex issue, it can be said that:

- Although a certain conflict is present between the needs of high friction and low noise, it seems to be possible to handle this incompatibility because of the weak noise-friction relation.
- For a reduced noise emission, smooth surfaces should be avoided.
- The use of hydrophobic road materials should be avoided and hydrophilic materials should be preferred in order to improve the acoustic performance of the road surfaces.

5.2.6 Stiffness

The property of the surfaces referred to as the mechanical impedance or stiffness of the surface has also been associated with noise generation relating to impact mechanisms.

Generally, the mechanical impedance of road surfaces is several orders of magnitude higher than that of the rubber in the tyre tread. Lowering the road mechanical impedance will tend to reduce the tread block impact forces transmitted into a tyre which, in turn, will reduce tyre vibration levels and hence noise generation. This seems to be the case for surfaces made of poro-elastic material which are designed to have a rubber content of at least 20% by weight. Recent results [59] indicate a decrease of 5 dB in the frequency range between 800 Hz and 1250 Hz for elastic materials referred to concrete one.

More studies are needed on this topic: currently the EU project PERSUADE (PoroElastic Road SUrface: an innovation to Avoid Damages to the Environment), which is dealing with poro-elastic surfaces, will cover also this topic.

The surface type (asphalt or concrete) can also be associated with stiffness. In [56] it was found that a dense concrete surface with chippings (e.g. 5 mm maximum stone size) created a surface which was about 2 dB(A) louder than the same chippings used on an asphalt surface. This effect derives from the higher internal damping of asphalt compared with concrete.

5.2.7 Joints on bridges and cement concrete surfaces

The effect of joints in bridges and cement concrete surfaces is very difficult to quantify. Few studies have been made on this topic, although this issue is relevant. Some observations [59] reported an increase of around 5 dB referred to the surrounding road surfaces before and after the joint.

Different studies concerning the joints between road and bridges show that the increase of noise can reach 10 dB for the overall value and even 20 db for certain frequencies. By using an improved joint design the increase of noise can be reduced to 5 dB.

5.2.8 Unevenness

Unfortunately, very few studies have been performed on the influence of road unevenness on noise emission. The results of the TINO project [60] indicate that a negative correlation is present between sound pressure level in the frequency range 200 to 1500Hz and unevenness in the 10 to 80 m wavelength range. Other authors are very sceptical on this conclusion because this should mean that making the road uneven will decrease its noise emission [11]. More data and research are surely needed on this topic, but the influence of this parameter does not seem to be great with regard to tyre/road noise emission.

5.2.9 Colour

The colour of the road surface is probably not the most relevant parameter influencing noise emission, but it can do so indirectly by influencing the temperature of the pavement. Dark surfaces absorb more solar radiation and become warmer than other bright surfaces, for example a black surface can become 10 ºC warmer than a grey surface, which could mean about 1 dB less in noise emission.

Additionally, the surface colour can act as a kind of "placebo effect" influencing the driver. Some types of surface have a negative image in the mind of the public and a colour may be associated with noisy pavements (aggressively brushed concrete, for example). In this case, a change in the colour of the pavement could create a positive effect for the driver, although no difference will occur in the real noise emission of the pavement [11].

5.2.10 Age and wear

The problem of ageing is one of the most relevant and at the same time one of the most difficult to assess. The acoustic performance of road surfaces should not only be assessed on their initial performance but should be considered over the whole life time of the road. The lack of a sufficient quantity of measurement data for different surfaces over the whole life time of the surface is probably the biggest problem in attempting to forecast the durability (in terms of noise) of the pavements.

The ageing process due to trafficking, winter treatments and general exposure to the weather, and its effect on acoustical performance is complex. It is dependent on a number of parameters including surface type, porosity of the road surface, degree of trafficking and exposure to weathering. Generally, the trend is for the acoustic performance of surfaces to stabilize after an initial period of 1 to 2 years of trafficking. Those surfaces which provide low levels of tyre/road noise tend to increase in noise over this initial period, whereas surfaces which exhibit higher levels of tyre/road noise have shown some noise reductions [11].

For smooth- and medium-textured dense asphalt surfaces, noise levels increase during the first two years then stabilize their acoustic performance until cracks or unevenness occur in the megatexture. Asphalt surfaces like DAC and SMA show a noise increase of 1 to 2 dB during the early years at frequencies related to the air displacement mechanism [11].

Surface dressings have a rough texture initially a high level of macrotexture that is gradually worn down and this fact causes a shift of generation mechanism from texture impact to tread impact and air displacement. Due to this shift, a reduction of noise during the first years can be seen, after which the acoustic performance of the surface stabilises.

The effect of ageing can be particularly dramatic on the acoustic performance of some porous surfaces. Trafficking and weathering causes the voids in the surface to become clogged with detritus reducing acoustic absorption, resulting in increased noise levels. The use of de-clogging machines using water under high pressure to flush out the detritus has only been partially successful. Alternative designs using double-layer porous systems have proved to be more successful. The top porous layer consisting of small chippings acts as a filter, accumulating most of the detritus and leaving the lower larger aggregate size porous layer relative detritus-free. This design allows the cleaning process to be more efficient in retaining surface porosity than compared with single layer designs and can therefore extend the lifetime of its acoustic benefits. However, after a period of stabilization some surfaces can exhibit significant increases in noise, particularly as the surface reaches the end of its life.

Concrete surfaces can also exhibit similar characteristics, for example, grooved concrete where after a period of heavy trafficking causes fraying of the grooves resulting in shallow/wider spacing which can promote higher noise levels. On the other hand smooth-textured cement concrete surfaces are generally very stable with the time.

5.3 Parameters of tyres affecting noise

Tyres produce noise whenever they are rolling on road surfaces. From the tyres' point of view, it is the design of the tread pattern that is mainly responsible for this noise. Other parameters like tyre/wheel load, inflation pressure, rubber compound and the carcass influence the frequency and the amplitude of the tyre/road noise as well.

Sandberg and Ejsmont [11] split the generation mechanisms of the tyre/road noise into two different kinds of noise sources: noise generated by the tread of the tyre when having contact with the road surface and noise generated by the air.

On making contact with the road surface, the tread blocks are moved in both the radial and transverse directions of the tyre. The radial movements lead to a radial movement of the tyre's belt and this movement leads to a noise emission, caused by the vibration of the air inside the tyre.

Additional transverse vibrations of the tread blocks occur, mainly on the trailing side of the tyre due to the displacement of the tread blocks during slippage.

The aerodynamic mechanisms are generated by the tread pattern and the effect that air gets compressed in front of the tyre near the surface. The air between the tread blocks is compressed and partially pumped out again. At the rear of the contact patch, air is getting sucked in between the tread blocks (= air pumping).

Another effect is called the horn effect. The geometrical shape on the leading and the trailing edge of the tyre is shaped like a horn. As a result of this, the noise is amplified. The tread pattern itself produces noise due to fact that while moving through air and to some extent having air drag, pipe resonances are generated by the tread pattern.

For a graphical illustration of these various effects, refer back to Figure 2.4 and Figure 2.5.

5.3.1 Number of tyres

Although the different tyres of a vehicle have to be considered as uncorrelated noise sources, for our scope they will be considered as omni-directional sound sources located at the same point. On the assumption that the tyres are of the same type and size and they have to carry the same load, a simple formula can describe the influence of the number of tyres on the noise emission.

$$\Delta L = 10 \log (n / n_{ref}) \qquad 15$$

Where n is the number of tyres and n_{ref} is the number of tyres in a reference case, which is 4 for passenger cars. That means that we can easily calculate the additional noise emission due, for instance, to 6 tyred vehicles (as a light truck) with reference to passenger cars: following the formula the noise emission will increase by 1.8 dB. Considering an increase of tyres from 4 to 20, the noise emission will increase in the ideal case by 7 dB. However, in calculating this, one must take into account that car tyres and truck tyres have different noise emission behaviour.

For heavy trucks the relation has been validated with measurements and although for these vehicles tyres on the driven axles often have different from the non-driven axles, the relation gives good results. If we consider a 2-axle vehicle as a reference, an increase of 2 dB will be calculated for a 3-axle vehicle, while for a vehicle with more than 3 axles the noise emission will increase by 3.2 dB [11].

5.3.2 Tyre dimensions

The influence of tyre dimension on noise emission is very complicated to determine. The connection to other parameters like load, inflation pressure, tread pattern and speed class make the separate study of the geometrical parameters very difficult. Generally it can be said that an increase of tyre width generates an increase of noise [11] especially for passenger cars, where a noise emission increase of about 0.4 dB per 10 mm increase in width can be found. For tyres wider than 200 mm this influence tends to reduce. For a doubling of width, the increase of noise emission is around 4 dB [11].

The influence of tyre diameter on noise can be divided in two different components:

- The noise emitted by the impact mechanism decreases with greater tyre diameter.
- The noise emitted by the air displacement mechanism increases with the tyre diameter.

Regarding the difference between passenger car tyres and truck tyres, it is normally accepted to assign 6 to 10 dB more noise emission to truck tyres.

5.3.3 Inner tyre structure

It appears that a decrease of belt stiffness increases tyre/road noise [61]; other studies [62] found that an increase of carcass stiffness reduced the noise emission. More recent studies on this topic [64] concluded that in order to obtain a decrease of noise emission the increase of bending stiffness should be performed together with an increase of the belt mass.

During the sixth framework programme the project "SILENCE" was established. In this project among other things, the influence of different tyre constructions on the noise emission on real road surfaces was tested indoors, at the Vehicle/Pavement Interaction Test Facility (PFF) at BASt. Six different tyres with the same tread pattern and the same tread depth but different tyre construction were tested on eight novel road surfaces. The driven speeds were 100, 80, 50 and 30 km/h. The collection of tyres consisted of a regular tyre and tyres with different rubber compounds, different belt constructions, different beads and different liners.

The following results emerged:

- The basic tyre emitted the highest noise levels at nearly all speeds
- The most silent tyre was the one that consisted of winter-compound, a soft and heavy belt, a soft bead and a thick liner.

5.3.4 Non uniformities of tyres

The non uniformities of tyres generate an increase in noise particularly in the low frequency range. Ejsmont found out an increase of 7 dB at 80 Hz by giving a radial force variation twice as the average of the tyre. The overall levels increased by 0.5 to 1 dB. The effect of unbalance is also very relevant at low frequencies: an increase of 20 dB was found at 20-63 Hz [62]. The overall levels are not really influenced.

5.3.5 Rubber hardness

Different measurements indicate that hard tread rubber generates more noise than soft. In 1987, Watanabe [63] found a difference of 5 to 8 dB between tread rubber hardness of 40º Shore and 59º Shore. Other measurements performed by the Technical University of Gdansk confirm that supposition. The conclusion of these studies was that by using the appropriate rubber hardness it is possible to save 2 to 3 dB of noise emission. This potential could be more relevant for an aggressive tread pattern than for a smooth pattern.

5.3.6 Tread pattern

The influence of the tread pattern is relevant to noise emission. A good possibility for save noise using an improved tread pattern construction is so-called tread randomisation which is normally performed using computer simulation programs. This optimisation distributes the sound emission in a more suitable way, but influences the overall value of the sound level very slightly.

Another way to reduce noise by modifying the tread pattern structure is so-called ventilation. Cavities with narrow outlets, closed pockets and long grooves without ventilated sides will increase the noise generated by air pumping and pipe resonances. Noise emission can be reduced up to 3 dB in the frequency range between 1.6 and 4 kHz using better ventilation.

The contour of the tyre/road footprint is also very relevant for noise generation. It is important that the contour of the elements should be approximately transverse to the rolling direction.

Other measurements [64] show that the increase of groove from 9 to 12 mm decreases noise and due to randomisation a slightly decrease of noise emission is possible to reach.

5.3.7 Tyre age and wear

Although the ageing and wear of tyres is a very relevant parameter influencing noise emission, at this time only few studies have been made of the topic. The causes for the wear influence on noise are many and rather complicated; the following list will explain some of the most important:

- Decrease of thickness of the tread and decreasing of stiffness may change the load distribution and the vibration characteristics of the tyre structure.
- Decrease of the height of the tread elements causes changes in the deflection of the elements, in resonance frequencies, air flow through the grooves and vibration properties of the elements.
- Change in the tread curvature and changes in the pressure distribution in the tyre/road interface.
- Uneven wear around the tyres causes low frequency vibration and modulation of the noise emission.
- Rubber hardness increase in the sidewall and in the tread.
- The carcass could be affected by cyclic strain and change its vibration characteristics.
- In the case that the tyre has a soft rubber compound on the top and a stiffer compound lower down, the first layer could be worn away and the noise emission will change due to the different rubber mixture in contact with the road surface.

For the most part of measured cases (but not all), wear increases noise in comparison with the same tyre when new. Sometimes the noise increases with the wear and then decreases if the wear continues. Investigation on this topic is lacking at the moment and probably more research is needed in order to clarify the influence of tyre ageing on noise emission. The non-uniformity of the wear is an additional problem that should be taken into account in further research.

5.3.8 Tyre type

As explained in 3.2.7 tyres can be categorised into different types: passenger car tyres and HGV tyres, with different car tyre types being available for summer or winter use and HGV tyres having different tread profiles according to the function of the axle on which their wheels are mounted, with a longitudinal profile on steering axles and a traction profile on power transmission axles (Figure 3.18).

In [66] it is stated that the noise level of summer tyres is independent of the width of the tyre, but on winter tyres the noise level rises together with the width of the tyres. Tests under the same test conditions reported in [66] determined that summer tyres generate more noise than winter tyres. It should be pointed out that these tests were carried out in operating conditions that were optimal for summer tyres but not for winter tyres.

As a result of their various tread profiles, different HGV tyres show different behaviours in relation to noise emission. Tyres with a traction profile are about 3-4 dB louder than the tyres with longitudinal profile [67].

5.3.9 Retreaded tyres

In order to reduce tyre costs and environmental impact, if the tyre carcass is still in good condition, the worn-out tread will be replaced with a new one. The influence of the retreading process on noise emission is also an interesting question, which cannot be easily answered. Generally it can be said that if the tyres have been retreaded according to high quality standards, these tyres are no noisier than new tyres; sometimes they can be even less noisy if the retread rubber compound is softer [11].

5.3.10 Studded tyres

Winter tyres are sometimes fitted with studs. Although some summer tyres are noisier than some winter studded tyres, normally tyres with studs are noisier than tyres without them. At speeds between 70 and 90 km/h the influence of studs is as follows [11]:

- For high studs protrusion noise increases about 2 to 6 dB within 500 Hz to 5 kHz and 5 to 15 dB in the frequency range above 5 kHz.
- For low studs protrusion noise normally increases approximately 3 to 7 dB above 5 kHz.

At lower speed this influence could be even greater.

However, studded tyres are only used as winter tyres in few Nordic countries in Europe, such as Sweden, Finland and Norway. Besides the increase of noise of these tyres they also cause road wear.

5.4 Environmental Parameters affecting noise emission

Environmental parameters are normally very difficult to measure and some of these, e.g. the amount of water on the road surface, have been investigated very rarely so there is a shortage of knowledge on this topic.

5.4.1 Temperature

A lot of studies have been performed on this topic. Normally, tyre/road noise for passenger car tyres increases if the temperature decreases. For each temperature degree change, noise changes between 0.05 and 0.1 dB; this means that, for a temperature difference of 30 degrees, the difference in noise emission can be between 2 and 4 dB. The relation between temperature and noise emission can be generally written as follows:

$$L = a + b^* T \qquad 16$$

Where:

L is the sound level in dB,

T is the temperature in degree Celsius,

a and b are two constants.

The coefficient b is the slope of the curve and is also called temperature coefficient; negative values of b mean decreasing of noise for increasing temperature. Some authors use the road temperatures rather than the air temperature. It has been agreed that the reference temperature is 20 ºC (for air and road temperature). All the measurements should be normalised at this temperature. The temperature coefficient depends on the road surfaces and on the used tyre, but generally it could be useful to apply a generic temperature correction for all road/tyre combinations e.g. -0.06 dB/ºC. Especially for the ISO 10844 surface Sandberg suggested to use the following correction: -0.08 dB/ºC (Internoise, 2004) [65].

The EU directive 2001/43/EC on tyre noise adopts for example the following correction:

- For passenger car tyres the temperature correction is -0.06 dB/ºC if the temperature is lower than 20 ºC, -0.03 dB/ºC if the temperature is more than 20 ºC,
- For light truck tyres and van tyres the temperature correction is -0.02 dB/ºC
- For heavy truck tyres there is no temperature correction.

Concerning the spectral influence of the temperature it can be said that the largest effect occurs in the range between 1 and 4 kHz and at low frequencies.

5.4.2 Humidity

Humidity does not influence tyre/road noise emission. The only interesting case could be when the humidity becomes so high that water condenses on the road surface. This case is discussed in the following section.

5.4.3 Water

The influence that water on road surface has on noise is very difficult to quantify. Only few studies have been carried out on this topic. Approximately, it can be said that compared with a reference dry surface the noise emission for speeds up to 60 km/h increases from 2 to 6 dB on a wet surface. For speeds between 60 and 80 km/h the increase is from 1 to 4 dB, while for speeds higher than 80 km/h the noise emission increases up to 3 dB related to a dry surface [11]. This effect is generally higher for the frequencies above 1000 Hz. The biggest problem for the research on this topic is the lack of quantification concerning road moisture, water depth or rain intensity. No data are available on the effect of water depth on noise emission.

5.4.4 Wind

The background noise due to the air turbulence in the microphone could cause an increase of the recorded noise. For this reason it to measuring road noise at wind speeds higher than 5 m/s should be avoided. Aerodynamic noise due to the air turbulence near the vehicle and near the wheels could occur at speed around 120 km/h for cars and 90 km/h for trucks. This issue needs more research.

5.4.5 Dust

No results or information could be found in the literature or from the authors' experience concerning the quantification of the influence of dust on the tyre/road noise emission.

5.4.6 Winter maintenance

The winter time influences the road surface in many ways, some of which might affect noise but no specific results on this topic could be found.

5.5 Driver-controlled parameters

The following parameters represent the driver influence on the tyre/road noise emission. These are not easy to control because each driver can drive in a different way and with a different speed on the same road section. Nevertheless the parameters discussed are some of the most relevant concerning tyre/road noise and greater control and awareness of these will help to reduce overall tyre/road noise emissions.

5.5.1 Speed

The speed is certainly the driver-controlled parameter that has the greatest influence on noise emission. This parameter depends totally on the driver and a speed variation from 30 to 130 km/h causes a noise emission difference of 25 dB. The noise-speed relationship is characterised by a rapid increase of noise with increasing of the speed. If the speed scale is linear this relationship is logarithmic, but if the speed scale becomes logarithmic, the relation between speed and noise becomes linear. For this reason the sound levels can be quite easily calculated using the following formula:

$$L = A + B * \log (V) \qquad 17$$

Where:

L	is the sound pressure level in dB,
V	is the speed in km/h,
A and B	are two constants speed coefficients. The literature includes many different suggestions based on different measurements regarding the value of these two constants.

This relation is normally used for the calculation of tyre/road noise and in most cases this logarithmic approximation is very precise. Nevertheless measurements show that in some cases irregularities can occur in this relationship. Deviations from this relation are observed when the tyre tread pattern or the surface texture contains distinct frequencies.

Spectral levels are anyway influenced by speed in a more complicated way than the overall levels. Some components like the tread vibration generate tonal noise, which is related to the speed. Other mechanisms generate noise in particular frequencies related to the materials or to the geometry without a significant relation to the speed.

5.5.2 Tangential forces and acceleration

The tangential forces on the tyres are the second relevant parameters influencing noise emission. Concerning driving and braking forces (longitudinal slip), it is well recognised that they tend to increase the noise emission up to 12 dB. Different studies [11] show that there is a greater increase of noise for lower speed than for high speeds.

Side forces developed during cornering and curving are also very relevant to noise emission. This lateral slip can influence tyre/road noise by a 2 or 3 dB during common driving, while in severe cornering the influence can be up to 4 to 7 dB. This influence is low at low frequencies and high at medium and in the high frequency range.

5.5.3 Load and inflation pressure

Two other relevant parameters influencing noise emission are load and inflation pressure. Different studies show that by doubling of load the noise emission increases by 1 to 2 dB. The combination of load and inflation can influence up to 5 dB, but generally these influences are between – 2 dB and + 2 dB, in relation to an ideal and nominal load/inflation combination.

A large number of different mechanisms are involved by the noise generation due to the variation of load and inflation. These include: the deflection of the tyre sidewalls, the change of the tyre radial and tangential forces; changes in the local load distribution, change in the contact area, change of air channels in the tread patterns. Generally can be said that:

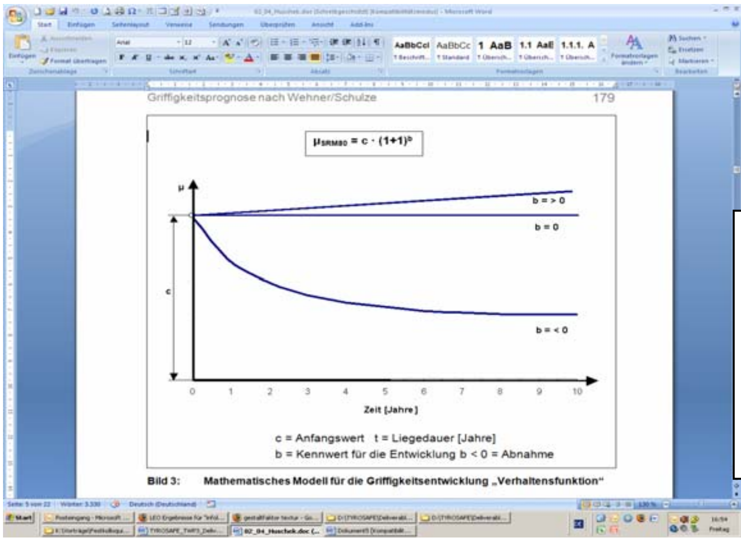
- Higher load decreases noise at low frequencies (but could increase noise at frequencies related to the torus cavity resonance)
- Higher load increases noise at medium and high frequencies up to 3-4 dB for a load variation from 50 to 100%.
- Higher inflation decreases noise in the low frequency range up to 8 dB for a 20% variation of pressure.
- Higher inflation increases noise by 2-3 dB at medium and high frequency range when running on a smooth surface.

Summarizing, the driver can influence noise by approximately 1 dB by driving with the recommended inflation pressure and by further 0.5 dB by making sure that no unnecessary loads are present on board.

6 Durability of parameters

During its lifetime the properties of a surface do not remain constant because of exposure to trafficking and different climatic conditions. The durability of performance in relation to all three of the topics covered by this report can be affected by the permanent deformation of surfaces (such as rutting). Durability of performance of the three topics is also affected by the influence of road geometry and the impact that it has on traffic acting on the surfacing, such as bends and corners (compared with straight roads) and cross-fall.

Normally, skid resistance tends to decrease due to these external influences but, apart from the influence of weather and traffic, the durability depends mostly on the type of surfacing, mixture design and the aggregates used and the texture of the surface. In some circumstances, if traffic is light (with low polishing action) skid resistance may increase as a result of weathering action (see Figure 6.1, which represents an attempt to derive a mathematical model for the evolution of skid resistance over time.



c	**–**	**starting value (measured with a blocked tyre)**
t	**–**	**laying time (years)**
b	**–**	**value, that represents the development (b < 0 – represents a lowering of the values)**

Figure 6.1: mathematical model of the skid resistance development [69], [55]

Experience in the UK has shown that, provided an appropriate aggregate is used low-speed skid resistance should not deteriorate beyond the equilibrium level targeted. However, this does require adequate resistance to abrasion and polishing (PSV) for the traffic expected and the level of skid resistance required in the particular location. However, even though low-speed skid resistance may be maintained, deterioration in texture depth over time can result in poorer high-speed performance and this may be significant in some situations. For this reason some countries specify a minimum texture depth for new surfacings that includes an allowance for deterioration to ensure that performance is maintained over a reasonable working life.

In some countries (see [27], for example) it is found that the type of asphalt mixture has more impact on friction developed than the aggregate type but this may be in part due to the types of material used (such as dense materials with a smaller proportion of polish-resistant coarse aggregate at the surface) and the lack of availability of aggregate with high polishing resistance. Surfacing types with naturally-low macrotexture are also likely to show greater deterioration in skid resistance performance over time.

Another way to predict the skid resistance value of a surface is by using the "Wehner/Schulze machine" to polish samples of actual surfacings (asphalt or concrete) or aggregates alone and measure the skid resistance after different stages of polishing. Various studies are ongoing to assess the suitability of this technique for forecasting likely skid resistance performance of aggregates or surface mixes in service.

Experience in Germany has shown that, for cement concrete surfaces, there is no evidence that the durability of the texture depends on the water/cement ratio and the content of the mortar. However, a low water/cement ratio (about 0.36) has a negative impact on the durability of microtexture in concrete surfaces. The type of fine aggregate, Different types of fine aggregates (provided that is has high enough polishing resistance) has no effect on the durability on the surface texture [48].

7 Conclusion

The purpose of this deliverable within WP3 of the TYROSAFE project has been to identify and discuss the key parameters that influence the three main topics of skid resistance, rolling resistance and noise emission. All three of these topics are driven by the interaction between road surfaces and tyres travelling over them. Therefore, the parameters that govern the effects relate to the properties of the road surface, the tyre and the environmental factors that act on them.

Not surprisingly, this review has found that the greatest amount of research has been directed at understanding tyre/road friction, especially in wet conditions, and its two contributing components – road surface skid resistance and tyre wet grip. Because it has such important implications for safety the subject has always had a high profile and work in this field has been ongoing since the 1930s.

Studies of noise generation have been continuing for some 20 years or so and the basic mechanisms are reasonably well understood, as are some of the properties of road surfaces and tyres that can contribute to reduced tyre/road noise. However, the physical processes involved and the interactions between them are complex and this presents a challenge for researchers. Limitations of both measurement techniques and available of experimental data mean that there are significant areas where knowledge remains limited.

Rolling resistance research is, by comparison, still in its infancy: measurement techniques are limited, especially for studying the properties of in-service roads, and evidence supporting an intuitive understanding of how the road contributes to rolling resistance is just beginning to be obtained.

Throughout the review it has become clear that the properties of friction, rolling resistance and noise are predominantly and essentially influenced by a relatively small number of general properties of the road surface and the tyre. In short, these are:

- Road surface texture (at different scales and with different forms).
- Tyre tread (particularly compound, tread depth).

However, although the number of core parameters is relatively small, they are influenced by a great many other factors that relate to the way in which road surfacings and tyres are designed, constructed and used, as well as how they respond over time to the influences of traffic and the environmental conditions to which they are exposed. Some may also contribute directly to some of the three subject areas. Less-easily quantified factors, such as driver behaviour, may also have an influence.

The relative influence that the individual characteristics have and the way in which they act in relation to each of the subject areas varies, however. Sometimes what is advantageous for one property may be a disadvantage for another.

The purpose of this report was to identify the key parameters. The next steps for the TYROSAFE WP3 team are to look in greater detail at the interactions between these parameters and consider how they might be optimised, which will lead to proposals for further focussed research.

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