Alma Mater Studiorum – Università di Bologna

DOTTORATO DI RICERCA IN

INGEGNERIA CIVILE E AMBIENTALE

Ciclo XXVI

Settore Concorsuale di afferenza: 08/A3

Settore Scientifico disciplinare: ICAR/04

CONTEXT-SENSITIVE DESIGN IN TRANSPORTATION INFRASTRUCTURE: RELATING TIRE/PAVEMENT NOISE WITH WEARING COURSE CHARACTERISTICS

Presentata da: Federico Irali

Coordinatore Dottorato:

Prof. Ing. Alberto Lamberti

Relatori:

Dott. Ing. Cesare Sangiorgi

Prof. Ing. Andrea Simone

Esame finale anno 2014

Keywords:

Context-sensitive design

Tire/pavement noise

Traffic noise

Quiet pavements

Wearing course characteristics

ABSTRACT

A design can be defined as context-sensitive when it achieves effective technical and functional transportation solutions, while preserving and enhancing natural environments and minimizing impacts on local communities.

Traffic noise is one of the most critical environmental impacts of transportation infrastructure and it affects both humans and ecosystems.

Tire/pavement noise is caused by a set of interactions at the contact patch and it is the predominant source of road noise at the regular traffic speeds.

Wearing course characteristics affect tire/pavement noise through various mechanisms. Furthermore, acoustic performance of road pavements varies over time and it is influenced by both aging and temperature.

Three experimentations have been carried out to evaluate wearing course characteristics effects on tire/pavement noise. The first study involves the evaluation of skid resistance, surface texture and tire/pavement noise of an innovative application of multipurpose cold-laid microsurfacing. The second one involves the evaluation of the surface and acoustic characteristics of the different pavement sections of the test track of the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo. In the third study, a set of highway sections have been selected in Southern Ontario with various types of pavements. Noise measurements were carried out by means of the Statistical Pass-by (SPB) method in the first case study, whereas in the second and in the third one, Close-proximity (CPX) and the On-Board Sound Intensity (OBSI) methods have been performed in parallel.

Test results have contributed to understand the effects of pavement materials, temperature and aging on tire/pavement noise. Negligible correlation was found between surface texture and roughness with noise. As a general trend, aged and stiffer materials have shown to provide higher noise levels than newer and less stiff ones. Noise levels were also observed to be higher with temperature increase.

ACKNOLEDGEMENTS

The kind support of my Ph.D. supervisors, Dr. Cesare Sangiorgi and Dr. Andrea Simone, enabled me to undertake my doctoral study and research with proficiency and satisfaction. I would first like to express my deepest gratitude to Dr. Sangiorgi for believing in me, mentoring me in these years and, mostly, for encouraging me to address my personality and character into my work, taking the best advantage of them. I would also like to thank Dr. Simone for his support, for being always available to teach me and transfer his knowledge.

I would like to express my special appreciation and thanks to my international Ph.D. supervisor, Dr. Susan L. Tighe, for accepting me as a Visiting Research Scholar, for her guide and her endless teachings during my stay at the Centre for Pavement and Transportation Technology (CPATT). Under her tutelage I could live unique experiences and grow both as a person and as an engineer.

My sincere appreciation and gratitude are for Prof. Giulio Dondi, for the quality of his teachings, for his advice and for investing in me as one of his collaborators and teaching assistants.

My special thanks are also extended to Dr. Valeria Vignali and Prof. Ettore Volta, as well as to the other current and former post-doctorate and post-graduate fellows and PhD students of my Department, especially Dr. Claudio Lantieri, Dr. Matteo Pettinari Dr. Francesco Petretto, Dr. Giulia Manganelli, Dr. Pierpaolo Viola, Dr. Giampaolo Dezi, Luca Noferini, Francesco Mazzotta, Riccardo Lamperti and Piergiorgio Tataranni. My sincere thanks also to our faculty's technical staff, especially Ettore Cappellari and Elio Pinardi. I thank all of them for their assistance, their friendship and their support in my work.

I wish to express my most sincere thanks to the entire research group, faculty's technician and administrative staff of the Centre for Pavement and Transportation Technology (CPATT) and of the University of Waterloo, especially to Doubra Ambaiowei, Laura Bland, Mohab El-Hakim, Marcelo Gonzales, Amin Hamdi, Mohammad Hegazi, Gulfam Jannat, Vivek Kant, Aleks Kivi, Andrew Northmore, Aleli Osorio, Daniel Pickel, Sonia Rahman, Maria Josè Rodriguez, Md. Safiuddin, Xiomara Sanchez, Magdy Shaheen and Cheng Zhang. I would like to thank all of them for welcoming me into their group, for their help and their collaboration in my research activities, and for all the priceless experiences I could share with them during my stay in Waterloo.

I would gratefully acknowledge the financial support of my research of the Department of Civil, Chemicals, Environmental and Materials Engineering (DICAM) at the University of Bologna and of the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo.

Finally, I would like to express my gratitude to my family and my friends, both in Italy and in Canada, for their encouragement, their support and for being there when I needed to. The satisfaction I could gain from my research activities is also due to the fact that I have been surrounded by wonderful people.

DEDICATION

I wish to dedicate my thesis to my mother, Cinzia Beneventi, and to my father, Zeffirino Irali.

INDEX

INTRODUCTION

Background

Context-sensitive Design is a collaborative, interdisciplinary, holistic approach to transportation decision-making and design that takes into consideration the communities and natural areas through which transportation infrastructures pass. Those communities and natural areas are, therefore, the context. A design can be defined as context-sensitive when it achieves effective technical and functional transportation solutions, while preserving and enhancing community and natural environments [1]. The concept of sustainability in transportation infrastructure is therefore optimized with the context-sensitive design.

Major environmental impacts of road infrastructure include: air pollution, water pollution, landscape and habitat fragmentation, visual pollution, traffic vibration and noise. A context-sensitive design is aimed not only to mitigate those impacts, but to minimize them. This approach can provide technical solutions to the concepts studied by Road Ecology. Road Ecology, in fact, is a relatively new subdiscipline of ecology that focuses on understanding the interactions between road systems and the natural environment [2].

Traffic noise is one of the most critical impacts of transportation infrastructure and one of the main focuses of context-sensitive solution: in fact, it involves impacts both on communities and on the ecosystems. Social surveys have indicated that noise is probably the type of environmental pollution that affects more people than any other type of pollution [3]. In fact, approximately 20% of the population in the European Union is exposed to noise levels, which are usually considered to be intolerable, and 60% to levels that are usually considered undesirable [4].

In addition to annoyance, noise may lead to effects on health both with instantaneous and long-term exposure. Many wildlife responses parallel our responses to disturbance [5] and they can modify their behaviour to try to adapt to disturbance: human-made noise, in fact, alerts the behaviour of animals or interferes with their normal functioning [2].

Traffic noise is the main cause of environmental noise. During its operation, vehicles generate noise from various sources, which can be divided into three main categories: power unit noise, wind turbulence and tire/road noise. Heavy vehicles may also have additional noise sources constituted by auxiliary and special equipment. Tire/pavement noise starts to dominate over power unit noise over some “crossover” speed, which for cars is about 30-35 km/h in case of cruising and 45-50 km/h in case of accelerating vehicle. Wind turbulence can be negligible at average speed, i. e. below 120 km/h [3]. Therefore, tire/pavement noise is usually predominant on other road noise sources at regular traffic speeds.

Engineering strategies and solutions to reduce and mitigate noise exposure varies on the type of transportation infrastructure. They can include a strategic location of the infrastructure to prevent noise exposure of communities and highly natural areas, as well as use of specific materials and devices to reduce noise at the source or to screen sensitive areas. For traffic noise control, common strategies can be classified into two categories: active control, aimed to reduce noise at the source, and passive control, including interventions to control noise propagation from sources to receivers. In the case of road noise, noise barriers can be considered passive control strategies, whereas possible active control solutions consists of tires with specific tread patterns and quite pavements.

The concept of quiet pavements consists of operating directly at the tire/pavement interface to reduce noise generation and amplification mechanisms. A low noise road surface, in fact, is defined as “a road surface which, when interacting with a rolling tire, influences vehicle noise in such a way as to cause at least 3dB(A) (half power) lower vehicle noise than that obtained on conventional and most common road surfaces” [3].

Optimizing pavement characteristics to reduce tire/pavement noise mainly entails selecting proper pavement material, mix design and surface texture. To date, some previous studies attested that the absolute noise levels of cement concrete pavements are usually higher than the levels measured in asphalt concrete pavements; surface texture modifications and finishing techniques in concrete pavement, though, can provide large reductions in tire/pavement noise and be considered a suitable solution to reduce traffic noise [6] [7].

Some characteristics of pavement wearing courses are known or believed to affect tire/road noise in different ways. Unevenness is considered to provide a minor influence on tire/pavement noise, whereas surface texture performs a low-moderate to high-very high influence. Porosity also affects noise with a high influence, as well as layer thickness for porous surfaces. Adhesion and friction are believed to perform a low-moderate influence, whereas layer stiffness plays a role that is still uncertain. For some authors, though, its degree of influence may be moderate [3].

Acoustic characteristics of pavements are known to evolve with time: age, presence of distresses and surface texture modifications are believed to contribute increasing the overall road noise levels [8]. Furthermore, as the pavement gets older, noise levels from asphalt pavements usually increase even before significant pavement deterioration begins to occur [9].

It was realized in the 1980's that tire/pavement noise is influenced by temperature [3]. Many factors can cause differences in noise measurements on similar pavement types, and they can be due to a combination of environmental, tire, loading and vehicle/operator variables [10]. Previous studies in AC pavements have shown decreased noise levels at the tire/pavement interface with increasing temperature, whereas mixed results were found in PCC pavements [11].

Since aging and climate can contribute the acoustic characteristics of a road pavement to evolve, continue monitoring and repeated noise measurements are necessary over the lifetime of pavements in order to get true and valid results on their acoustic performance [12]. Research is still in progress on these topics.

Research Objective and Scope

Two are the main objectives of this research. The first is to provide an updated literature review on pavement engineering solutions to reduce and mitigate tire/pavement noise, as part of context-sensitive design and solutions. Secondly, research projects have carried out aimed to provide a contribution to the international on-going research on the effects of wearing course characteristics on acoustic characteristics of road pavements by analysing three case studies with different pavement type, materials and age.

The scope of the literature review update is to analyse major latest studies involving tire/pavement noise in the areas of interest of context-sensitive design in transportation infrastructure, from the points of view both of humans and ecosystems. For this purpose, latest results in the field of acoustic performance of road pavements and their susceptibility to wearing course characteristics and environmental effects.

The scope of the case history reports is to analyse the testing results of three, different research projects. The first was carried out in the Province of Bologna, Italy, in 2011, related to surface texture and acoustic characteristics of multipurpose cold-laid microsurfacings, constructed on the same year. The second was carried out in 2013 at the test track of the Centre for Pavement and Transportation Technology (CPATT) in the University of Waterloo, Ontario, Canada, related to the wearing course and acoustic characteristics of different flexible and rigid pavements, which had been constructed years before and subjected to the harsh, Canadian weather and heavy dynamic loads. The third one was carried out in 2013, also at the CPATT, and it involved acoustic measurements at different temperatures of flexible and rigid pavements of different age and of various highway road sections, located in Southern Ontario, Canada.

Insight of test results and data analysis of the three research projects was focused on comparing the collected results to data present in literature, as well as to provide a contribution to on-going international researches in these topics.

Thesis organisation

An introduction has been provided in this Chapter accommodating the background, as well as the objectives and scope of the research. The thesis outline is hereby described to better define the thesis structure and the sequence by which the topics have been presented and analysed.

Chapter 1 is aimed to provide an overview of the key elements of Context-Sensitive Design in Transportation Infrastructure. Major environmental impacts of transportation infrastructure, especially road infrastructure, are outlined in this Chapter, with a specific focus on the effects on humans and ecosystems.

Chapter 2 follows and it is focused on the fundamentals of noise and the mechanisms involved in tire/pavement noise.

Chapter 3 involves an overview of the state of art of the wearing course characteristics known or believed to affect tire/pavement noise. An overview of the pavement types and surfaces which, to date, are considered quiet pavement and low noise surfaces are also outlined in this chapter.

In Chapter 4, 5 and 6, three case histories are reported of studies involved in tire/pavement noise pavement types with different materials, age, location and environmental conditions. Data analysis and discussions of the test results are also included in these chapters.

A final chapter presents the overall conclusions drawn from this research, including recommendations and possible suggestions for researches to come.

The thesis ends with a list of references, provided with the same order they are referred to in the thesis.

1 CONTEXT-SENSITIVE DESIGN IN TRANSPORTATION INFRASTRUCTURE

Introduction

Many transportation agencies are recognizing the importance of sustainability, in terms of concern for the environment, community health and vitality, and economic development, now and into the future. The fundamental principles of sustainability in Transportation Infrastructure entails meeting human needs for the present and future, while preserving and restoring environmental and ecological systems, fostering community health and vitality, promoting economic development and prosperity, and ensuring equity between and among population groups and over generations [17].

A context-sensitive approach combines sustainability with functional and technical requirements. It guides the designer to evaluate multiple alternatives and select the one that minimizes environmental impacts in all phases.

This chapter provides an overview of Context-Sensitive Design (CSD) and Context-Sensitive Solutions (CSS) with respect to major environmental impacts of transportation infrastructure.

1.1 Context-sensitive design and Context-sensitive solutions

1.1.1 Historical background of Context-sensitive design and solutions

Road construction can be dated to the time of the Romans [14], when roads provided means for the overland movement of armies, officials and civilians, as well as the inland transport of trade goods and communications [15]. The beginning of modern highway construction did not begin before the late 19th and early 20th century [14].

The first set of criteria for geometric design of roads and highways was released by the American Association of State Highway Officials (AASHO), now known as the American Association of State Highway and Transportation Officials (AASHTO), after the end of World War II. In 1956, the Federal-Aid Highway Act authorized funding to construct a system of access-controlled highways based on uniform geometric design criteria [16].

Since state and federal highway engineers in the United States had complete control over freeway route locations and, until the mid-1960s, in many cities, new highways ripped through neighbourhoods, parks, historic districts, and environmentally sensitive areas [18]. As a result, citizen movements and highway revolts began to arise. These revolts took place in response to plans for the construction of new freeways, due to the disruption or displacement of neighbourhoods and the environmental effects of the proposed freeways. They mainly took place in the United States, in Canada and in the United Kingdom during 1960s and 1970s and, later in the 1970s, in Australia [19]. As a consequence, many of those projects were abandoned or significantly scaled back.

One of the first acts attesting a growing environmental awareness was the Clean Air Act, issued in 1963 in the United States to control air pollution on a national level. Congress designed the Clean Air Act to protect public health and welfare from different types of air pollution caused by a diverse array of pollution sources [20]. It required the Environmental Protection Agency (EPA) to develop and reinforce regulations to protect communities from airborne contaminants, known to be hazardous to human health. A second act was the Wilderness Act of 1964, which created the legal definition of wilderness in the United States and established a National Wilderness Protection System for preservation and protection of designated lands in their natural condition [21].

A milestone in the history of Context-sensitive design and Context-sensitive solutions was the National Environmental Policy Act (NEPA), enacted in 1969 by the 91st United States Congress [22]. The Act required transportation agencies to consider adverse impacts of road projects on the environment and it came to existence after growing concerns in the United States about the environment and ecological and wildlife well-being.

In 1972, the Clean Water Act passed in the United States, governing water pollution and aimed to restore and maintain the chemical, physical, and biological integrity of the national waters [23].

In the 1990s, two additional pieces of the federal legislation in the United States of America reshaped the relationships between transportation agencies and the public. Proactive public involvement became fundamental and American states were delegated more responsibility and discretion in design criteria and requirements. The Federal Highway Administration (FHWA), in fact, was authorized to develop design criteria that consider the constructed and natural environment of the area and the environmental, scenic, aesthetic, historic, community, and preservation impacts of the activity. Therefore, Context-sensitive design (CSD) was born as a way of “thinking beyond the pavement”: it is a process through which the objectives of safety, mobility, the natural environment, and community values are pursued and balanced [17]. Context sensitive solutions (CSS) can be defined a collaborative, interdisciplinary approach that involves all stakeholders in providing a transportation facility that fits its setting. It is an approach that leads to preserving and enhancing scenic, aesthetic, historic, community, and environmental resources, while improving or maintaining safety, mobility, and infrastructure conditions [24]. Therefore, the terms Context Sensitive Design and Context Sensitive Solutions refer to an approach or process as much as they do an outcome [1].

The diffusion of CSD/CSS practices was further incentivized in 2003, when FHWA’s Performance Plan identified Environmental Stewardship and Streamlining as a Vital Few Goal [22]. Environmental Streamlining is aimed to improve project delivery without compromising environmental protection, whereas Environmental Stewardship contributes demonstrating the natural and human environment awareness, while addressing mobility and safety needs of the public. Within this goal, is an objective to incorporate context sensitive solutions into planning and project development in all 50 states by 2007 [25].

In 2009, the National Cooperative Highway Research Program (NCHRP) report 642 presents guidelines for quantifying the benefits of applying the principles of Context Sensitive Solutions (CSS) to transportation projects. The report attested that as more organizations apply CSS principles, evidence continues to grow that measurable benefits result from this approach to all phases of transportation decision-making [26].

1.2 Road Ecology and Context-sensitive design/solutions

Road ecology is a relatively new subdiscipline of ecology that focuses on understanding the interactions between road systems and the natural environment [27] [2]. The term derives from the combination of “road” and “ecology”, where road can refer to an open way for the passage of vehicles [28] and ecology is the study of interactions between organisms and the environment [29]. Road ecology is an applied science and much of the work within this field endeavours to find ways to minimize the detrimental effects of road systems ecosystems, air and water quality, and human communities [27].

The main aspects of Road ecology involve all the various types of road infrastructures: a road segment, in fact, slices through an heterogeneous landscape, so that the pair of adjoining local ecosystems or land uses on opposite sides of the road keeps changing along the segment [2]. Road systems intersect almost all areas of ecology [30]: road ecology involves water and water flows, microclimate, wind, atmospheric effects, vegetation and biodiversity, populations and wildlife, landscape ecology and habitat fragmentation [2].

Road Ecology can be related with Context-sensitive design/solutions in highway planning, since a CSD solution can be potentially beneficial in developing measures to reduce and mitigate the expected environmental damages of highway projects [31].

1.2.1 Historical background of Road Ecology

The first clues of road ecology stem from the work of European scientists and transportation ministries, especially in the Netherlands, Germany, and France [28].

A milestone in the history of Road Ecology is the UN Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992. The Convention on Biological Diversity, drawn up at the conference, aims to develop and strengthen strategic policies for the protection of species, ecosystems and gene stocks both within different countries and across continents [32].

In the same year, in Europe The Habitats Directive was issued, together with the Birds Directive, to form the cornerstone of Europe's nature conservation policy. The directive can be considered a further milestone in Road Ecology and it is built around two pillars: the Natura 2000 network of protected sites, which is the centrepiece of EU nature and biodiversity policy, and the strict system of species protection [33].

Furthermore, in the late 1990s and early 2000s important international conferences on road ecology were held in The Netherlands, in Florida, Montana and Colorado, as well as symposia at annual meetings of the Ecological Society of America and the American Geophysical Union, and collections of articles in scientific journals [2]. A unique line of research by Australian scientists focused on the potential for road rights-of-way to serve as a linear network of conservation lands [27].

In Europe, the Europe-wide organization Infra Eco Network Europe (IENE) was created in 1996. IENE is “a network of experts working with various aspects of transportation, infrastructure and ecology to provide an independent, international and interdisciplinary arena for the exchange and development of expert knowledge” and aimed “to promote a safe and ecologically sustainable pan-European transport infrastructure” [34].

A fundamental moment in the modern road ecology was the publication in 2003 of the multi-authored volume “Road Ecology: Science and Solutions, which summarizes the state of the science and elaborates a call for this new field of study [27] [2].

1.2.2 Characteristics of a CSD/CSS design

Context sensitive design attempts to raise several criteria to the primary level, such as minimizing cost, maximizing throughput, maximizing safety, protection and preservation of historic elements, achieving visual aesthetics, minimizing environmental impacts, maximizing positive benefit on local and regional economies, and incorporating local community values [22].

Therefore, transportation and public works agencies that apply the principles of context-sensitive design, may encounter the prospect of including design features that do not meet relevant criteria [16]. One way to incorporate CSD/CSS into transportation planning and design is widen the community involvement and incorporate stakeholders' inputs into design decisions [22].

Therefore, in a context-sensitive design process, decisions become collaborative rather than authority- based [16]. CSD/CSS calls for the interdisciplinary collaboration of technical professionals, local community interest groups, landowners, facility users, the general public, and stakeholders living and working near the road or who use it [18]. The prospect of including diverse perspectives and persons in the design process, influencing the final decision, is believed to provide an incentive for stakeholders to participate [16].

The intent of this policy is to provide guidance to the designer, as well as allowing sufficient flexibility to encourage independent designs tailored to particular situations [22]. Although CSS discussions commonly involve design exceptions [16], several case studies avoid design exceptions by lowering the design speed [36].

Flexibility is a key factor [36] and if a design exception is to be made, documentation is required to protect the agency from liabilities [22]. The AASHTO "A Guide for Achieving Flexibility in Highway Design" shows highway designers how to think flexibly and how to recognize, among all the options available, the best solution for the particular situation or context [1]. Flexible thinking, in fact, entails making informed choices and cautioned that a simplistic, rote application of values within a design range without explicit consideration of context might not best meet a project's objectives [35]. Design flexibility is frequently misunderstood to mean an increase in the use of design exceptions: only 20% of the State Department of Transportations in the United States, though, indicated that the advent of context sensitive design had increased the number of design exceptions they prepare [35] [36]. The NCHRP report 480, "A Guide to Best Practices for Achieving Context-Sensitive Solutions", in fact, asserts that "Design exceptions are not viewed as essential to successful CSD/CSS. Creativity or flexibility in design should not be equated with ignoring design criteria or an agency's accepted design practices" [35]. Moreover, most of the DOT representative says their agencies view design exceptions as a value-adding process [36]. CSD/CSS principles, in fact, are highly compatible with assessing all the aspects of transportation projects, including safety concerns. CSD/CSS principles can assist agencies by providing additional information about the specific users and conditions, as well as allow better analysis of the risk factors and their potential consequences [36].

Full application of the CSD/CSS design processes, in fact, supports risk management, as it entails the application of the following aspects: Consider Multiple Alternatives, Evaluate and Document Design Decisions, Maintain Control Over Design Decision Making, Demonstrate a Commitment to Mitigate Safety Concerns, Monitor Design Exceptions to Improve Decision Making [35].

Successful CSD leads to safe and feasible transportation solutions. Above all else, stakeholders value safety and expect that transportation agencies will only implement solutions that provide an acceptable level of safety. By implementing CSS principles, agencies can better communicate the data to non-engineering stakeholders and the public, so that collaborative decisions can be made [36] [35].

1.3 Context-sensitive design, Sustainability and Road Ecology in Highway Planning

1.3.1 Highway planning and development in the CSD/CSS approach

Highway development is composed of the planning, the project development, the final design, the right-of-way and the construction phases. It is during the first three phases that designers and stakeholders can work together to define the final design characteristics of the project [22].

1.3.1.1 Planning stage

At the planning stage, the needs and objectives of the project are defined and this is the key time to get the public involved to provide inputs into the decision-making process. The problems identified usually involve a structure repair, an increase in capacity, an enhancement of safety, an increment of accesses. Obtaining a community consensus on the problem requires proactive public involvement and if a consensus cannot be reached at the beginning, it is unlikely to expect a consensus on the final design [37].

1.3.1.2 Project development

At the project development phase, the environmental analysis intensifies and it varies, depending on the scale and impact of the project. Multilayer efforts to prepare Environmental Assessments (EA) and/or Statements (EIS), or minor environmental reviews can be required in this stage [37].

An Environmental Assessment is a concise public document aimed to provide sufficient evidences and analysis to determine whether an EIS is required, to aid agency's compliance with NEPA when no EIS is necessary, e.g. by helping identify alternatives and mitigation measures, and to facilitate the preparation of an EIS when necessary.

An Environmental Impact Statement, instead, is a detailed analysis aimed to insure that the policies and goals defined in NEPA are included in on-going programs and actions of the federal agency: an EIS is usually required for projects with significant prospective environmental impacts [38].

Regardless of the level of detail or duration, though, project development processes generally require a description of the location and major design features of the project, while continually trying to avoid, minimize, and mitigate environmental impact [37]. The basis steps in this stage include:

- refinement of purpose and need;
- development of a range of alternatives, including the "no-build" and Traffic Management System (TMS) options;
- evaluation of alternatives and their impact on the natural and built environments;
- development of appropriate mitigation measures [37].

In this stage the designer must consider the context and the physical location of the project to better assess the character of the area.

1.3.1.3 Final Design

In this stage a complete set of plans, specifications, and estimates (PS&Es) are provided of required quantities of materials ready for the solicitation of construction bids and subsequent construction. This process may take from a few months to several years [37].

The final design involves the developing of the project concept, which involves a number of separate, interrelated design decisions. The definition of elements, to achieve a common goal or concept, helps the designer in making design decisions [22]. Examples of elements defined in this phase can be related to geometric design, e.g. lanes and shoulders, traffic barriers, overpasses and bridges [37]. A multidisciplinary team can assist in establishing the "theme" of the road design or determining some existing functions need to be maintained [37]. The contribution of landscape architects, architects, planners, urban designers, and others will be enhanced when involved from the beginning [22].

This phase also requires an attention to the different scales by which the road is perceived by road users. Trying to accommodate road users with different design scales can be a difficult task for designers, who are required to prioritize the safety of pedestrian and non-vehicular traffic in the first place, along with the safety of motorists. For instance, a context-sensitive approach enables perceiving that widening a roadway that once allowed pedestrian access to the two sides of the street can turn the roadway into a barrier and change the way pedestrians use the road and its edges [37].

The design element with the greatest effect on the roadway scale is its width, or cross section. The wider the overall roadway, the larger its scale is. Some design techniques that can help reduce the perceived width and scale of a roadway can be:

- limiting the width of pavement width;
- designing a grass or planted median in the centre in four-lane highways;
- use of grass shoulders to limit the perceived width of the roadway and provide a breakdown area for motorists;
- use of green space between sidewalks or non-motorized vehicle paths and the travel [37].

Elements, or a lack of elements, along the roadside can contribute to the perceived width and affect the speed at which motorists travel. With all else being equal, in fact, the wider the road is perceived, the faster motorists will travel. Along with horizontal and vertical alignment, cross-section elements, vegetation along the roadway, buildings close to the road, on-street parking, and noise barriers may contribute to reducing the perceived width and speed of the road [37]. Considering these elements is important to achieve a design that can be defined as context-sensitive.

Because of their visibility, the treatment of details is a critical element in the final stage of a good design. The project details are often the most recognizable aspect to the public. For instance, a special type of tree used as part of the landscape plan, antique lighting, brick sidewalks, and ornamental traffic barriers are all elements of a roadway that are easily recognizable and leave an impression [37]. Traffic barriers, bridge rails, and the treatment of overpasses, medians, and landscape development should be integral parts of a context-sensitive design process.

1.3.1.4 Right-of-way, Construction and Maintenance

Once the final designs have been prepared and the right-of-way is purchased, construction bid packages are made available and a contractor is selected: the construction stage is, thus, initiated. During the right-of-way acquisition and construction phases, minor adjustments in the design may be necessary: therefore, continuous involvement of the design team throughout these stages is needed [37].

Once construction has been completed, the facility achieves the operation and maintenance stages. A plan for maintenance interventions is fundamental to guarantee that the character of the road remains unaltered. In fact, maintenance personnel may not be aware of the use of special design elements to define the "character" of the highway. When special design treatments are used, on-going operation and maintenance procedures acknowledging these unusual needs should be developed [37].

1.3.2 Sustainability in Transportation Planning, Design and Operation

Sustainability in transportation can be applied to every stage of decision-making: planning, design, and implementation of projects and infrastructure, as well as to operations and maintenance [13]. Transportation decisions usually include long-range planning, programming, environmental review, project design, construction, maintenance, and operations. Each step of project development and infrastructure management affects sustainability [13].

In long-range transportation planning (LRTP), sustainability performance can be referred to in terms of desired sustainability outcomes and broad performance goals established, driving subsequent investment patterns.

Transportation plans can vary from broad policy statements to specific and detailed preferred investment strategies. The LRTP can also reflect the state and local sustainability objectives, policies, and programs [13].

In Short-range transportation programming (SRTP), sustainability established in long-range planning can be translated into explicit targets, associated with implementation of a specific set of projects [13].

In Project-level planning, sustainability performance measures may be used to inform project-level planning decisions. Planning efforts are most extensive for major projects with potential for significant environmental impacts. Minor projects, such as guardrail replacement, acquisition of new buses, or roadway resurfacing, may involve little or no planning activity. The planning phase helps agencies to identify project needs, community concerns, and potential solutions. In many states, early consideration of environmental issues before an environmental document is prepared is an increasingly common part of project planning [13].

Generally, transportation infrastructure projects that receive federal support must follow an elaborate environmental review process to ensure that the impacts of federal actions on the environment are considered before the project goes forward. As in planning, project-level sustainability performance measures may be used to inform project-level environmental decisions [13].

Most design work of a transportation infrastructure can include environmental mitigation, compensation or enhancement features. Sustainability may also be included within design and right-of-way determination related to such components as aesthetics, compatibility, multimodal accommodations, construction requirements, and materials and equipment selection [13].

Major sustainability considerations are part of construction, maintenance, and operations stages, as much as planning and design ones. Construction and staging footprints can affect the amount of land affected by construction and they can reasonably be described as environmental costs. Sustainability also influences selection of materials and methods and frequency of maintenance. Construction, maintenance, and operations work can be therefore designed to support an agency' s sustainability goals [13]. These goals and considerations can all be successfully included within a context-sensitive approach to transportation design and are perfectly compatible with public involvement and participation in all phases of decision-making processes.

1.3.3 Major environmental impacts in highway planning and design

There is a growing awareness in the latest decades that road development has major environmental impacts [39]. Although there are numerous benefits in having roads and access, most of these benefits are social or economic rather than environmental [40]. Roads, in fact, impact on the environment in many different ways and this applies from the initial construction to maintenance, upgrading and usage [41]. Environmental effects of roads include spatial and temporal dimensions, as well as biotic and abiotic components: these effects can be local, i.e. along the road segment, or extensive, i.e. related to a large road network [40].

In CSD/CSS, it is essential that road agencies and stakeholders be able to recognize potential environmental concerns, especially because researches and studies on environmental matters are increasing and they include a broad range of topics [40]. Major environmental impacts involve impacts on soils, on water resources, on air quality, on habitat and ecosystems, on human communities and their economic activity, from land acquisition and resettlement, on indigenous people, on cultural heritage, on aesthetics and landscape, on human health and safety, and on the noise environment [40]. Both human and wildlife populations, and ecosystems in general, are subject to these impacts.

1.3.3.1 Impacts on soils

Road development causes the elimination of the soil portion covered by roads and its productive capacity. Usually, the best sites for road location also tend to be ideal for agriculture [39]. The total area of land removed from production becomes significant, when the road width is multiplied for its length:

the removal of productive soil from the local economy can have socio economic and habitat implications, discussed subsequently.

A consequence of soil alterations due to road construction is erosion, which may appear both on roadside areas or in cumulative impacts far beyond the road itself, affecting slopes, streams, rivers, and dams even at some distance from the initial impact [39].

The construction of road cuts and embankment can also cause problems of slope stability and lead to problems in the management of tipped materials, when the soil amount removed and re-used in site is unbalanced. Additional erosion problems can be due to embankment and cuts construction and diversion of natural water flows [39].

Another serious issue is soil contamination. It can arise from daily traffic operation, typically in roads with over 20,000 vehicles per day [39]. It is due to metals such as chromium, lead, and zinc, which remain in the soil for hundreds of years and whose extent of movement within the soil is related to the surface chemistry of the soil itself and to the specific properties of the metal [42].

Pollutants settling in roadside soil can impair the growth of vegetation and the success of soil organisms, thus in creasing the likelihood of erosion. These effects are usually very localized, affecting only a narrow band on either side of the road [39].

In colder climates, salting of roads can also contribute to soil contamination and subsequent decreases in fertility [39]. Pollution risks also arise from transportation of hazardous products during road construction and traffic operations [39]. Cumulative impacts involving soil damage may affect many other aspects of the environment.

1.3.3.2 Impacts on water resources and road runoff

The effect of roads on water quality is a concern to water resource management, highway departments, and other agencies involved with environmental conditions [2] [43].

Roads can modify the movement of water, the material transporter by water and the chemistry of the stream [2]. Changes in water flow can contribute to flooding, soil erosion, pavement erosion, unpaved road erosion, channel modification, siltation of streams, even well beyond the immediate vicinity of the road, road pavement deterioration through freeze-thaw cycles in some climates, discharging groundwater which can saturate soils and roadbeds [2] [39].

Road drainage and excavation can lower water tables in surrounding areas, while embankments and structures can raise them by restricting flow: potential effects include deterioration of vegetation, increased susceptibility to erosion, loss of drinking water, and habitat modifications [39].

Roads also contribute polluting rain water. As water comes into contact with waterproof surfaces of the urban areas and washes off a part of that material, which has built up during the dry period before rainfall [22]. Eventually, water reaches the sewage system, either mixed or separated, where the sediment previously collected can come back into suspension.

Stormwater pollution is due to the build up phenomenon in dry period and wash-off during rainfall. The magnitude of these phenomena is due both to the intensity and the length in time of the rainfall, and to the type of surface. The more important the road is, in terms of traffic, the greater the pollutant amount becomes [22]. Chronic pollution of surface runoff from exhaust emissions, pavement and tire wear, petroleum product drippage, and corrosion of metals can easily occur in high-traffic roads. Salting of roads for winter maintenance and during periods of low stream flow enhance seasonal pollution [39].

The ecological effects of chemicals added by roads and vehicles are little known [2]. Numerous studies focused on lead accumulation in vegetation, observing that lead concentrations vary not only by distance from road but also by type of vegetation, time of year and wind [44]. Chemical pollution from vehicle exhaust, though, may change plant species composition radically along highways [45] [2]. Some of them, such as nitrogen, stimulates the growth and dominance of a few species at the expense of many others, thus altering certain natural plant communities [2].

Regarding animal species, their response to heavy metal concentrations vary and depend mainly upon differences in metabolism, type of diet, amount of food consumed, home range and life span [2].

Most ecological studies on heavy metal were focused on lead, whereas the results provided little insight into ecological effects of other heavy metals. For instance, copper, zinc, cadmium, nickel, mercury and chromium, usually present in road runoff, cause different effects in living organisms and each is highly toxic to humans, laboratory animals, aquatic organisms and plants [2].

Context-sensitive design/solutions can provide effective solutions for management and treatment of road runoff, thus reducing pollution of water resources. Some solutions can include basins to store first-flush rainwater, especially for major highways, or green Best Management Practice which use specific vegetation species and plants [22].

1.3.3.3 Impacts on air quality

The emission of pollutants by vehicles has a great contribution to the total anthropogenic atmospheric pollution: therefore, air pollution from road traffic should be considered in any road project [39]. At concentrations seen in the late 1970s, adverse health effects of air pollutants were regarded as unlikely. In the two decades since then, however, air pollution has re-emerged as a major environmental health issue. Whereas air pollution from fossil fuel combustion is now present in much lower concentrations than 50 years ago, other components have increased [46].

The main products of the motor fuel combustion are carbon dioxide and water, but inefficiencies and high temperatures inherent in engine operation encourage the production of other pollutants. They can be nitrogen, oxides, hydrocarbons, carbon monoxide, sulphur dioxide, particulates, lead, aldehydes and secondary pollutants [39]

In the latest decades, research studies confirmed that outdoor air pollution contributes to morbidity and mortality. Some effects may be related to short-term exposure, others to long-term exposure [47].

Research has suggested that long-term exposure of humans to particulate matter air pollution is associated with increased mortality from respiratory and cardiovascular disease and from lung cancer. [48] As a major source of both primary PM emissions and precursors of secondary particulate matter, traffic substantially contributes to the overall impact of outdoor air pollution This high contribution is also because the emission densities of traffic are, on average, highest in highly populated areas [47].

Regarding ecosystems, air pollution can affect both vegetation and animals. Plants, in fact, are affected both physically and chemically by air pollutants and some fauna health problems have also been connected to air pollution: as in humans, the problems are mostly respiratory in nature.

Context-sensitive design/solutions to reduce air pollutant in road infrastructure can be related to the choice of pavement materials with a lower carbon footprint and producing less fumes at the production and paving stages, as well as photocatalytic materials, capable of activating oxidation-reduction reactions on air pollutants and converting them into harmless compound [22].

1.3.3.4 Impacts on landscape and habitat fragmentation

The environmental impacts of roads in terms of landscape and habitat fragmentation must be considered in the larger context of biodiversity conservation. In fact, biodiversity refers to the wealth of species and ecosystems and of genetic information within populations in a given area. Preservation of biodiversity is of global concern, but the causes of loss are very often at a local scale [39].

Landscape fragmentation is the result of transforming large habitat patches into smaller, more isolated fragments of habitat [49]. The causes of habitat fragmentation can be related to the development of linear transportation infrastructure and to the destruction of natural habitats due to land use change [22]. This process is most evident in urbanised and intensively used regions, where landscape and habitat fragmentation are the products of the linkage of built-up areas via linear infrastructure [49].

Direct impacts of roads and highways can be classified into two categories: direct impacts and indirect impacts. Direct impacts can be related to habitat loss, habitat and landscape fragmentation, landscape connectivity and corridor restrictions, and disturbance of biogeochemical cycle. Indirect impacts, sometimes even more damaging than direct ones, can be related to the fact that roads provide access to areas which were previously relatively untouched b humans: this increased accessibility can cause disturbance, ecological disequilibrium and contamination of ecosystems. [39].

Major effects on wildlife are related to the so-called barrier-effect. Traffic flow and roadside elements, such as fences in highways and railways, cause restrictions to animal movement as they limit accessibility to humans. This process effectively creates smaller patches of habitats and restricts movement across those habitats. The end result is a decrease in both the number and the abundance of the species that once inhabited the landscape [2].

Road mortality is probably the best-known impact of traffic on wildlife and it contributes to decreasing abundance of species. Whereas traffic mortality is considered responsible for just 1-4% of the total mortality of common species, for more sensitive species it can be a significant factor in local population survival [50].

Landscape fragmentation also affects vegetation, since the abundance of non-native species in roadsides is important as a potential source of invasives that may damage surrounding vegetative species. The expansion of non-native plants in a landscape is a concern, since introduced plants may modify the ways landscape functions, by altering water use, fire danger and soil nutrients to a distance up to 120 m [2].

Road development continues to play a major role in the overall reduction of biodiversity [39], and proper CSD/CSS planning at the project level can provide a valuable contribution in limiting the phenomenon, while still serving the transport need. Context-sensitive design/solutions to reduce landscape and habitat fragmentation can operate at various levels.

At the planning stage, the correct selection of the infrastructure location can avoid slicing high-natural areas and preserve landscape connectivity. After the impact has been minimized, it can be further reduced by means of specific defragmentation measures and design solutions, such as fauna overpass/underpass and special devices to prevent road mortality of wildlife. Should none of these solutions be possible, a final possibility is the construction of compensation areas, aimed to restore the amount of natural areas in the landscape [22].

1.3.3.5 Impacts on human communities and their economic activity

Similarly to the aforementioned barrier effect for wildlife, roads can split communities because of faster traffic, access controls, and median barriers, which generally cut traditional lines of travel or communication [39].

Potential consequences can be discomfort for local movements, which can become sometimes substantially longer and directly affecting businesses, pedestrians, and users of non- motorized transports. In rural areas, connectivity links between villagers and their farmlands may be cut by a new road or increased traffic, potentially leading to impact on economic activity for loss of agricultural productivity or increased travel costs [39].

A CSD/CSS approach in both urban and rural areas should be aimed to facilitate the maintenance and the restoration of existing patterns of movement and connectivity. Especially for those roads, which are already difficult to cross, such simple devices as pedestrian bridges, underpasses and traffic signals are valuable options to restore and improve connectivity.

An option to be considered is the use of by-pass roads, which can reduce the immediate impacts of traffic on the community. On the other side, communities may fear a loss of business from the diversion of traffic, and some community activities may migrate to the new route, potentially changing existing land use patterns.

Another aspect that ought to be considered is the "culture shock" effect, which can potentially arise when somewhat isolated communities are exposed relatively rapidly to increased communication and traffic [39].

An additional impact is related to the gentrification effect, caused by changing in value of land in particular areas, increased by infrastructural improvements, potentially leading to a turnover in occupancy, and a replacement of tenants and residents according to their affordance to rental costs [39].

All of these factors give rise to justifiable concerns on the part of local communities about the effects of proposed road projects on their lifestyles and welfare [39]. CSD/CSS at an early stage in the road planning process is essential to involve communities and stakeholders, and adjust projects accordingly.

1.3.3.6 Impacts from land acquisition and resettlement

Road development often requires the procurement of privately owned land by the government. While it is sometimes possible to negotiate a price for voluntary sale of a property, governments sometimes have to use their rights to expropriation, i.e. compulsory acquisition of properties for public projects.

By its nature, expropriation causes economic loss, and social and psychological disruption for the affected individuals. The economic impacts of expropriation may include the loss of houses or businesses, or the loss of business income, either temporary or permanent, which can both be estimated. The social and psychological impacts and associated costs are much more complex [39].

CSD/CSS in this scenario implies that the teams conducting the assessments and implementing the land acquisition and resettlement programs must invest considerable time and effort in evaluating the specific context in which the infrastructure will be located. At the same time, public involvement is essential to minimize the impact on communities.

1.3.3.7 Impacts on indigenous people

Road development can lead to rapid economic and social change: this aspect is more evident in areas inhabited by indigenous peoples. The cultural, social, political, and economic integrity that characterizes indigenous societies renders their lives extremely vulnerable to external disruptions and contamination [39].

Therefore, when a road is planned to cross an area inhabited by indigenous peoples, it is expected to have a marked effect on their lives, providing an artificially accelerated development stream. This situation will affect social cohesion, produce physiological effects on individuals, and have a negative impact on individual perceptions of self-worth [39].

Involvement of stakeholders and communities, typical of CSD/CSS, is essential. Road planners must work closely with indigenous community representatives and sociologists to attempt to enable indigenous people to adapt at a pace and in ways that they can manage and control. Their involvement must be addressed to prevent loss of traditional sense of identity, loss of livelihoods, potential violation of traditionally-exercised land rights, potential health and social problems [39].

1.3.3.8 Impacts on cultural heritage

Cultural heritage and property refer to sites, structures, and remains of archaeological, historical, religious, cultural, or aesthetic value. This particular form of expression of human values serves to record past achievements and discoveries [39].

Road projects may impact cultural heritage by causing damages in the road construction stage, due to related works such as quarries and borrow sites, and unregulated access to cultural heritage sites. Furthermore, road construction can potentially cause aesthetic impacts on cultural monuments and archaeological sites, in spite of positive impacts arising from improved access to sites recognized for their cultural value [39].

A CSD/CSS approach can lead to optimized solutions by involving experts and stakeholders, with the purpose of maximizing the access to cultural heritage sites, while minimizing potentially dangerous impacts at construction and operation phases.

1.3.3.9 Impacts on aesthetics and landscape, visual and landscape pollution

To be well-designed, roads should fit in well with its surrounding landscape and its design are expected to reflect the principles of regional landscape design. These principles should be applied regardless to the fact that the area is considered of special physical beauty. This principle serves to minimize the visual disturbance to the landscape, but also the disturbance to the physical functioning of the natural and human ecosystems [39].

Road construction can produce landscape modifications, as the alignment develops to comply with geometrical and functional rules imposed by the national road standards, aimed to guarantee road safety and legibility [22]. Negative aesthetic impacts, though, can express poor design principles and a result in lack of harmony between the road and various landscape characteristics [39].

A CSD/CSS approach can lead to the adoption of soil Bio- engineering techniques. They are green engineering solutions that use natural raw materials, such as vegetation, rocks, metal cables, geosinthetics, bio-nets and natural soil instead of concrete and steel. In Italy, a definition was given by G.Sauli, president of the Italian Association for Soil Bio-engineering: “the soil bio-engineering is a technical and naturalistic subject that uses autochthon live plants as construction material, together with inert materials either traditional or not” [51].

Several interventions can be designed with these techniques either for slope stabilization, retaining solutions and natural acoustic shields, providing equal efficiencies of traditional engineering solutions [22].

These are alternative techniques compared to the traditional grey engineering solutions, not antithetic, but usually compensative [22].

Road and railway infrastructure design can use soil bio-engineering techniques for re-naturalization, stabilization and reconstruction of the lateral slopes as retaining solutions, instead of cement concrete ones, and for noise shielding, in the place of noise barriers [22].

1.3.3.10 Impacts on human health and safety

In addition to the previously discussed air and water pollution issues, road projects can lead to additional serious negative consequences for the health of local populations. By encouraging direct contact between previously disparate areas, in fact, roads provide ideal corridors for the transmission of disease between humans, and from plants and animals to humans [39].

Furthermore, road safety is an issue that must be addressed as well, since road accidents result in casualties, injuries, and damages to properties. Pedestrians and non-motorized vehicles are at greater risk of being injured in accidents, since they are the most vulnerable road users.

In areas where they mix with motorized traffic, a CSD/CSS design must minimize potential risks for road safety and adopt special measures to prevent the increased mobility of motorists from undermining the safety and health of all other road users [39].

1.3.3.11 Impacts on the noise environment

Despite the effects of noise are often given lower priority than economic or other environmental impacts, there is a large amount of scientific literature dealing with the evaluation of noise effects on human beings and wildlife [3] [2].

Many humans and animals, that suffer chronic exposure to severe noise pollution, may experience a range of problems as a result of this exposure [39]. Noise nuisance, for instance, is not fatal itself, but some case histories have been reported involving people driven crazy by noise nuisance and due to lack of actions by authorities [3].

Furthermore, whereas environmental noise exposure does not normally cause noise induced hearing loss, prolonged exposure to high noise levels may cause temporary shifts in the threshold of hearing. If this occurs daily during several hours, hearing may be damaged irreparably [3].

Other extra-auditory effects can be related to physiological stress responses and, at particularly higher noise levels, in cardio-vascular reactions. For instance, some studies indicate that people living in streets with an average daytime exposure of 65dB(A) run a higher risk of myocardial infarction compared to those living in less noisy streets [52]. Also effects on mental health, blood pressure, heart rate, vasoconstriction and endocrine excretion levels and admission rates have been observed and documented [3].

Noise can cause sleep disturbance from steady state continuous noise levels above 30dB(A). However, the most important parameter for sleep disturbance is the maximum level of the exposure, i.e. impulsive noise due to the transit of noisy trucks, motorcycles and cars in residential areas at night can cause sleep disturbance. Side effects can be related to tiredness, headaches, nervous stomach and irritation [3]. High noise levels during the day can cause not only annoyance by people, but they can also affect children cognitive performance and other intellectual tasks [53].

Regarding noise effects on animals, generally, many of the aversion responses for wild animals are the same as for humans, whereas some differences exist [2]. Human-made noise, in fact, interferes with the normal behaviour of animals and can harm their health, as well as their reproduction, survivorship, habitat use, distribution, abundance or genetic composition [5]. Also, noise can be perceived by animals as a threat and as a form of discomfort [2]. Furthermore, vibrations induced by low-frequency noise are also detectable by some animals, especially birds and reptiles [5]. Many songbird population appear to be inhibited by remarkably low noise levels [54].

As a general trend, a road-avoidance zone can be observed from correlations of wildlife density with distance from roads and it is interpreted as mainly due to traffic noise [2].

Context-sensitive design/solutions can be highly beneficial to highway design and road development. It is therefore important to understand how road noise comes to exceed acceptable levels and possible strategies and solutions to prevent, mitigate, or compensate for its effects. Engineering solutions can be applied to screen sensitive receptors from noise, by means of noise barriers, as well as to design low-noise road surfaces and quiet pavement, which are designed to provide noise reduction at the source, i.e. at the tire/pavement contact.

Conclusions

Highway planning and road project development can benefit from Context-sensitive design/solutions from the early stages of the process, since CSD/CSS provide a holistic approach that enables achieving efficient technical solutions, while minimizing the impacts on human communities, wildlife and ecosystems.

In its broad acceptation, Context-sensitive design/solutions include sustainability in all the life-cycle of the infrastructure and it enables identifying possible impacts on the population and on the environment by involving experts and stakeholders from the early stage of the planning.

Flexibility is a key factor in effective CSD/CSS, since it encourages designers to tailor their projects to the particular context. CSD/CSS solutions in transportation infrastructure provide strategies and solutions to preserve the cultural, social, political, and economic integrity of surrounding communities in the first place, as well as urban and ecological connectivity of landscape. Technical solutions can include sustainable materials, strategies and devices to reduce air and water pollution, use of green materials to harmonize the infrastructure with the landscape and the context, solutions to screen communities and ecosystems from traffic noise as well use of low-noise road surfaces and quite pavements to reduce road noise at the source.

2 STATE OF THE ART IN QUIET PAVEMENTS AND LOW-NOISE ROAD SURFACES

Introduction

Noise sources generated by a vehicle during its operation are several. The main noise sources are the power unit, which is related to the engine, air inlet and exhaust, cooling fan, transmission, i.e. gearbox and rear axle, tire/road surface interaction, aerodynamic, brakes, body rattles and payload [55]. In general, sources associated with the power unit and transmission are referred to as propulsion noise. A second group is composed by the aerodynamic sources, related to the turbulent airflow around and partly through the vehicle [3]. All other sources are referred to as rolling noise [55].

Tire/pavement noise starts to dominate over power unit noise over some “crossover” speed, and the dominance increases as the speed increases. This crossover speed depends on type of vehicle, its load and its design: for cars made after 1996 is about 15-25 km/h in case of cruising and 30-45 km/h when the vehicle is accelerating. For older cars, made between 1985 and 1996, crossover speed is about 30-35 km/h in case of cruising and 45-50 for accelerating vehicles. For heavy vehicles made after 1996, crossover speeds are the same as older light vehicles, whereas for older heavy vehicles, i.e. made between 1985 and 1996, crossover speeds are a little higher: 45-50 km/h in case of cruising and 50-55 km/h when accelerating [3].

Aerodynamic sources do not play a significant role for exterior vehicle noise, as long as the speed is below 120 km/h, due to the effective aerodynamic design of vehicles [3]. Therefore, providing the vehicle and road pavement are well maintained and at the usual legal speed limits, the predominant noise source is from tyre/pavement interaction [55].

Engineering solutions to reduce tire/pavement noise are mainly focused on shielding devices, such as noise barriers, to screen sensitive receptors, as well as on low-noise road surfaces and quite pavements, obtained by operating directly at the tire/pavement interface to reduce noise generation and amplification mechanisms. This chapter provides an overview of the tire/pavement noise mechanisms and outlines the current state-of-the-art with respect to low-noise road surfaces and quiet pavements.

2.1 Fundamentals of Noise

Sound is the propagation, induced by a vibrating source, which propagates as a mechanical wave of pressure and displacements, through some elastic medium [22] [3] [56] [57]. The way the perturbation propagates is mainly related to the characteristics of elastic resistance of the medium [57]. Sound does not transfer matter, but only energy [56].

Sound propagates through fluids as longitudinal waves, producing local areas of compression and rarefaction, whose pressure is, respectively, higher or lower than the equilibrium pressure [57] [22]. In solids, sound can propagate as longitudinal waves, transverse waves and all their combinations [56].

When the perturbation is perceived by human ear, it produces an auditory perception [57]: the ear reacts to the strength, i.e. the amplitude, of the variations of pressure, as well as to their variations of speed, i.e. their frequency [3]. When this sensation is unpleasant, the sound is defined as noise [56]: therefore, noise can be considered a subjective term, since a particular sound may be noise to one person, but a pleasant sound for others [3] [22]. Sound from traffic, for instance, is considered noise, since it is perceived as annoying by most people [3].

2.1.1 Sound waves and parameters

Sound waves can be plane, spherical or cylindrical. An oscillating cylinder inside a tube, for instance, generates plane waves. Spherical or half spherical wave models are used when the sound source is a point, e.g. a single vehicle: this model can also describe every sound source at a great distance [56].

Cylindrical or half cylindrical wave models are used when the sound source is a line, e.g. a traffic flow [22].

A sound wave is a sinusoid and its main parameters are the following:

- wavelength: λ [m];
- amplitude: A [Pa];
- propagation speed [m/s];
- period: T [s];
- frequency: f [Hz=1/s].

When the medium is air, sound propagation speed is approximately equal to 340 m/s, normally denoted c [3].

A sound source in the air emits acoustic energy, which can result as a pressure variation with respect to the equilibrium pressure value P_a and it is expressed in Pascal, Pa. [58] [57]. The radiated acoustic energy can be described with the following acoustic quantities [57] [56] [22]:

- sound power: it is the energy emitted by the sound source per unit time, expressed as watts [W];
- sound intensity: it is the sound power per unit area, expressed as watts per square metre [W/m^2];
- sound density: it is the sound power per unit volume, expressed as watts per cube meter [W/m^3].

2.1.2 The Decibel scale and sound levels

Measuring a sound usually means to measure how higher a sound pressure is than the atmospheric pressure [22]. A human ear can normally perceive ranges of amplitude between 20μPa, i.e. $20 \cdot 10^{-6}$ Pa, and 20 Pa [3]. The range is so high that it is very impractical. Therefore, a logarithmic scale is preferable and the sound pressure is usually converted to a logarithmic sound pressure level [3] [57].

The unit for sound pressure levels is decibel [dB], whereas the Decibel is not a unit of measurements, but a dimensionless quantity used to represent the magnitude of physical quantities with wide ranges of values [22]. The reference value has been selected in order to obtain a sound pressure level of 0 dB at the threshold of hearing, i.e. representing an uncomfortably quiet environment, such as an anechoic room [3] [58]. Practically, sound pressure levels will range within 0 and 120 dB, where 120 dB correspond to the threshold of pain and above which human ear will experience hearing damage and pain [3].

The sound pressure level can be expressed as follows [22] [57] [3]:

$$L_p = 10 \cdot Log_{10}\left(\frac{p}{p_{ref}}\right)^2$$

where:

L_p=Sound Pressure Level;

p=mean amplitude of the sound pressure [Pa];

p_{ref}=mean amplitude of the reference sound pressure, equal to $2 \cdot 10^{-5}$ [Pa].

The sound power level can be expressed as follows [22] [57]:

$$L_W = 10 \cdot Log_{10}\left(\frac{W}{W_{ref}}\right)$$

where:

L_W=Sound Power Level;

W=mean amplitude of the sound power [W];

W_{ref}=mean amplitude of the reference sound power, equal to 10^{-12} [W].

The sound intensity level can be expressed as follows [22] [57]:

$$L_I = 10 \cdot Log_{10}\left(\frac{I}{I_{ref}}\right)$$

where:

L_I=Sound Intensity Level;

I= sound intensity [W/m^2];

I_{ref}= reference sound intensity, equal to 10^{-12} [W/m^2].

The sound density level can be expressed as follows [22] [57]:

$$L_D = 10 \cdot Log_{10}\left(\frac{D}{D_{ref}}\right)$$

where:

L_D=Sound Density Level;

D= sound density [W/m^3];

D_{ref}= reference sound density, equal to 10^{-12} [W/m^3].

Since the decibel scale is logarithmic, the logarithmic, or energetic, sum of two or more sound levels, expressed in decibels, can be generalized as follows:

$$L_{p,t} = 10 \cdot Log_{10}\left(10^{\frac{L_{p,1}}{10}} \pm 10^{\frac{L_{p,2}}{10}} \pm ... \pm 10^{\frac{L_{p,n}}{10}}\right) = 10 \cdot Log_{10}\sum_{i=1}^{n}\left(\pm 10^{\frac{L_{p,i}}{10}}\right)$$

where:

$L_{p,t}$=total sound pressure level [dB];

$L_{p,1}$=sound pressure level of the first sound source [dB];

$L_{p,2}$= sound pressure level of the second sound source [dB];

$L_{p,i}$= sound pressure level of the i_{th} sound source [dB].

It is important to observe that the sum of two independent sound sources with equal sound pressure levels results in an equivalent sound pressure level that is 3 dB greater than the sound pressure level of the individual source [56] [58]. For each doubling of the acoustic sound power, the corresponding sound level increases of 3 dB, and vice versa. When the acoustic sound power is halved, the corresponding sound level decreases of 3 dB, and vice versa [56].

2.1.3 Equivalent sound levels

When an acoustic phenomenon varies with time, the equivalent sound level results by the integration of the received acoustic energy in the time of observation [56]. The equivalent level of a sound variable in time is that sound pressure level that a constant sound would provide in the same time lapse [22].

Continuous equivalent sound pressure level can be calculated by the following equation:

$$L_{eq,T} = 10 \cdot Log_{10}\left\{\frac{1}{T}\int_0^T\left[\frac{p(t)}{p_{ref}}\right]^2 dt\right\} \quad \text{[dB]}$$

where:

$L_{eq,T}$=Equivalent sound pressure level over the T measuring time [dB];

p=mean amplitude of the sound pressure [Pa];

p_{ref}=mean amplitude of the reference sound pressure, equal to $2 \cdot 10^{-5}$ [Pa].

2.1.4 Frequency analysis and weighting curves

While sound pressure or sound pressure levels represent the magnitude of air pressure variations, sound frequency has been introduced to describe the speed at which the air density variations or oscillations occur [3].

The whole range of frequencies is said to cover a spectrum, whereas frequency spectrum is usually referred to as a graphical illustration of sound pressure levels as a function of the frequency. Sounds oscillating with a frequency higher than 20000 Hz are referred to as ultrasounds and they are not detectable by humans. Oscillations with a frequency lower than 20 Hz are usually perceived as a kind of vibration rather than a sound: they are usually referred to as infrasound [3].

While human hearing is considered to operate within the frequency range of 20-20000 Hz, it is not equally sensitive to sound of all frequencies [3]. Human auditory response is highly non-linear and it depends both on sound frequency and amplitude [56].

Different weighting curves have been standardised to adjust the linear response of measuring instruments with the non-linear response of human auditory system, as well as to obtain a physical measurement comparable with the human sound perception [56]. Different standardised weighting curves used for sound measurements are depicted in Figure 2.1.

The filter considered to correspond the best to the human sound perception is the A filter [3], while B, C and D curves are mainly used in industrial noise measurements [22].

Measured sound pressure levels with A filter can be expressed as A-weighted sound pressure levels, with the unit dB and with the symbol L_{pA}. The scientific and engineering community usually generally uses the regular symbol L_p and, instead, writes the unit as dB(A) or dBA to specify the A-weighting [3].

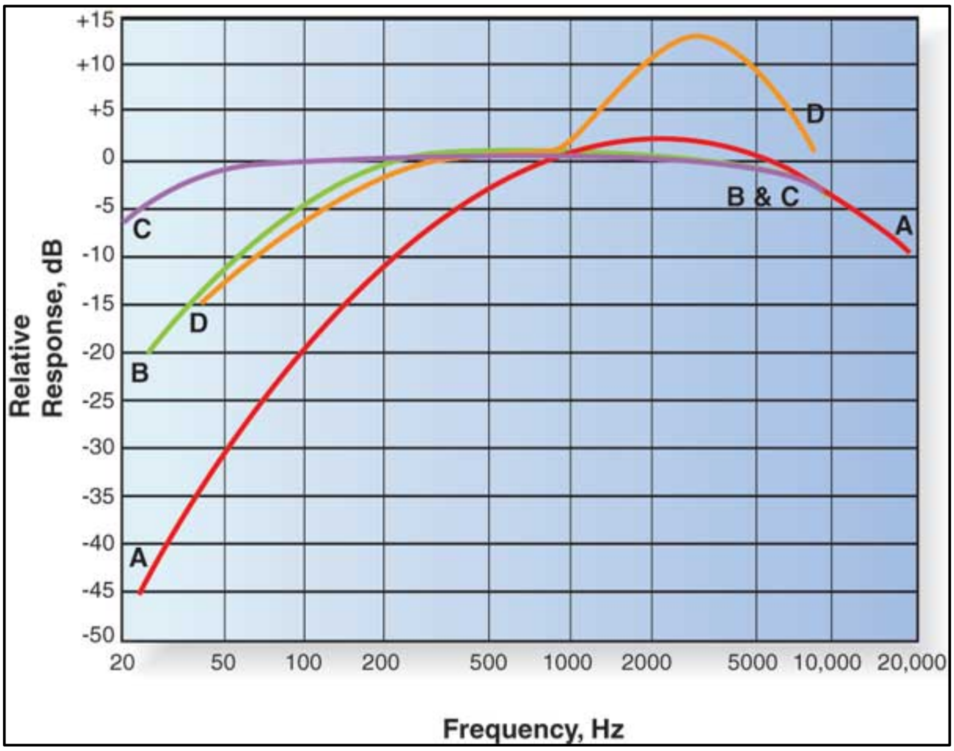

Figure 2.1: Different standardized frequency weighting curves used for sound measurements. [59]

Sound can be represented in the frequency domain by a frequency spectrum, which can be generated by a Fast Fourier Transform of its signal [57]. Octave band spectra give a general idea of the spectral characteristics and they are usually sufficient for survey purposes [3].

For detail studies of tire/pavement noise, though, octave band resolutions are too poor and third-octave band spectra are usually preferable.

They give a reasonable frequency resolution, without containing too many data, potentially difficult to evaluate [3].

2.2 Tire/Pavement Noise mechanisms

Tire/pavement noise is caused by a complex set of mechanisms between the rolling tire and the road surface [55]. They can be divided into two main groups: a first group is related to noise generation mechanisms, the second group to noise amplification mechanisms.

The former is due to mechanisms occurring at the tire/pavement interface, which create energy eventually radiated as sound. The latter is related to characteristics of the tire/pavement interface that cause energy to be converted to sound and radiated efficiently [60].

2.2.1 Tire elements affecting tire/pavement noise

Tires in use today are the result of a high level of engineering and many aspects of their construction are aimed to provide safety, durability, handling and cost-effectiveness. Noise is an additional consideration, although for tire producers this aspect is more focused on in-vehicle noise [62].

Tires are often designed for a specific engineering application: summer tires are optimized for handling and noise, whereas snow tires are optimized to move on water and improve friction. The tire tread pattern and rubber compounds typically affect most of the tire characteristics involved in tire-pavement noise mechanisms. As a general trend, the more aggressive a tire tread pattern is, the louder it will typically be; also, harder tires are also usually louder compared to softer compounds [62].

In Figure 2.2, important tire and tread characteristics are displayed, which affect tire/pavement noise mechanisms. For instance, the degree of randomness of the tread block size, influences noise mechanisms, since it will minimize tonal frequencies that most would find objectionable [62].

Furthermore, skewed blocks are used as they provide a more gradual roll in and out of each block, preventing sudden impacts that would lead to a noisier tire [62].

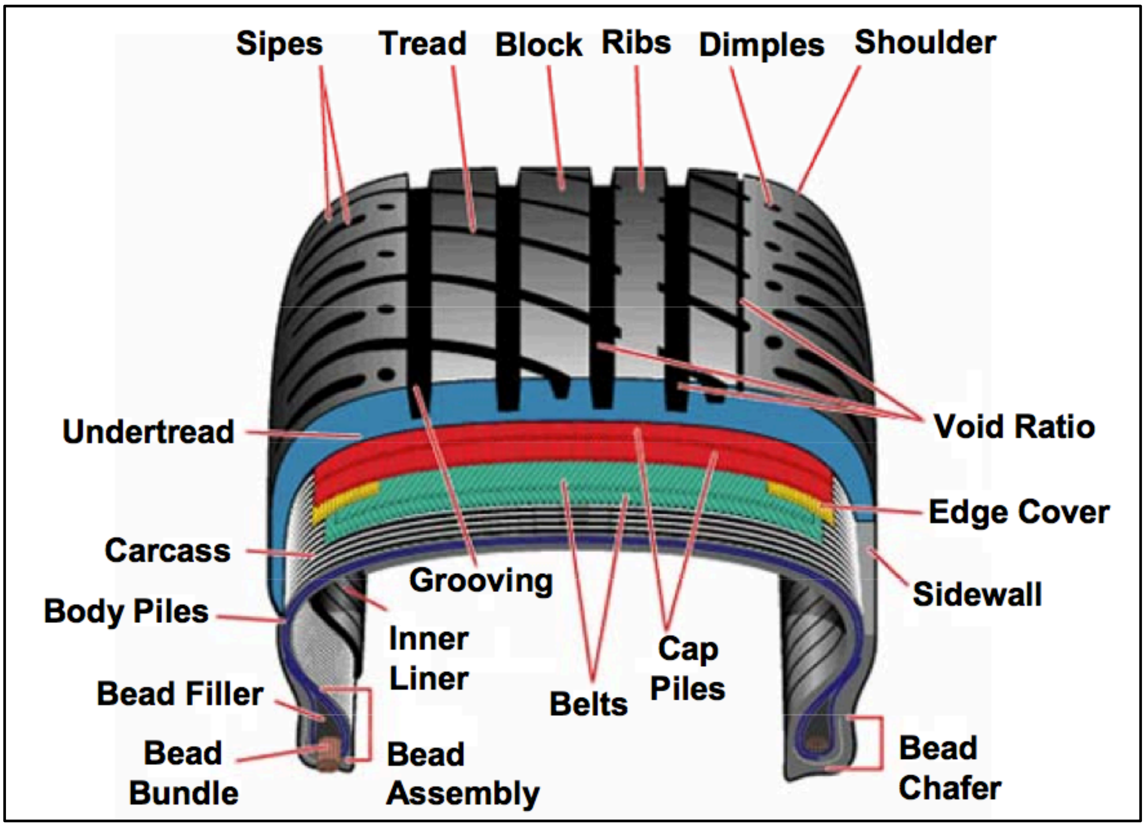

Figure 2.2: Typical tire features. [62]

2.2.2 Noise generation mechanisms

Noise generation mechanisms are due to a set of structure-borne phenomena that can cause mechanical vibrations of the tire, or to aerodynamical, air-borne phenomena [3]. The relative contribution of these two categories of phenomena may vary for different tires, road surfaces and operating conditions: therefore, it is difficult to quantify which category provides the most important contribution.

Vibrational mechanisms are mainly due to the following mechanisms [3]:

- <u>impact mechanisms</u>: they are essentially caused by the excitation of the tyre tread elements, as they impact with the road surface, by the vibrational response of the tire carcass, and the subsequent radiation of sound [61] [55]. The impact of tire treads on the road surface, as well as the impact of road surface texture on the tire treads, causes radial and tangential vibrations in the tire tread and belt, which spread to the sidewalls. Running deflections of tire treads at leading and trailing edges produce belt and carcass vibrations [3];

- adhesion mechanisms: they are related to stick/slip and stick/snap phenomena. Stick/slip phenomenon occurs as tread elements move relatively to the road surface, causing tangential tire vibrations. Stick/snap phenomenon is due to the adhesive effect between the tire rubber and the road surface, causing either tangential or radial vibrations [3].

Figure 2.3 shows an overview of the vibrational-related tire/pavement noise generation mechanisms.

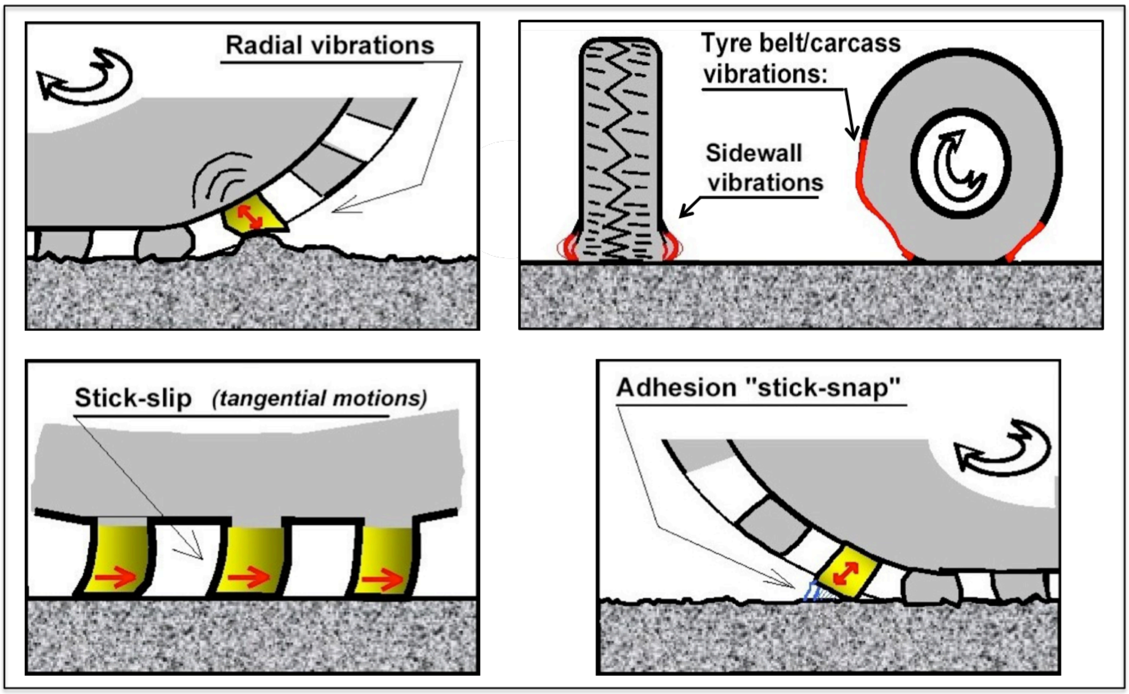

Figure 2.3: Vibrational-related tire/pavement noise generation mechanisms. [3]

Aerodynamical mechanisms are mainly due to the following air displacement mechanisms [3]:

- air turbulences: they are generated around the tire by air displacements of the tire when it is rolling on the road, as well as by air dragged around the spinning tire/rim;
- air pumping: this phenomenon is generated by air displaced into and out of cavities in or between the tire treads and the road surface;
- pipe resonances: they are caused by air displacements in grooves in the tire tread pattern, amplified by resonances;
- Helmholtz resonance: it is due to air displacement into and out of connected air cavities in the tire tread pattern and the road surface, amplified by resonances.

2.2.3 Noise amplification and reduction mechanisms

Noise generated at or near the contact patch can be enhanced or reduced by the following mechanisms [3] [55]:

- the horn effect: sound can be amplified by the curved volume between the longitudinal tire edges and the road surface, constituting a mechanisms similar to a horn;
- the acoustical impedance effect: it is due to communicating voids in porous surfaces, which act like a sound absorbing material, affecting source strength and sound propagation;
- the mechanical impedance effect: it is due to the road surface reaction to the tire block impact, depending on dynamic tire/pavement stiffness proportions. Also, some tire vibrations may be transferred to the road surface, possibly radiating and sound;
- tire resonance: it is due to the mechanical resonance of the tire belt and in the air column within the torus cavity of the tire.

Figure 2.4 shows an overview of the aerodynamical noise generation and amplification mechanisms.

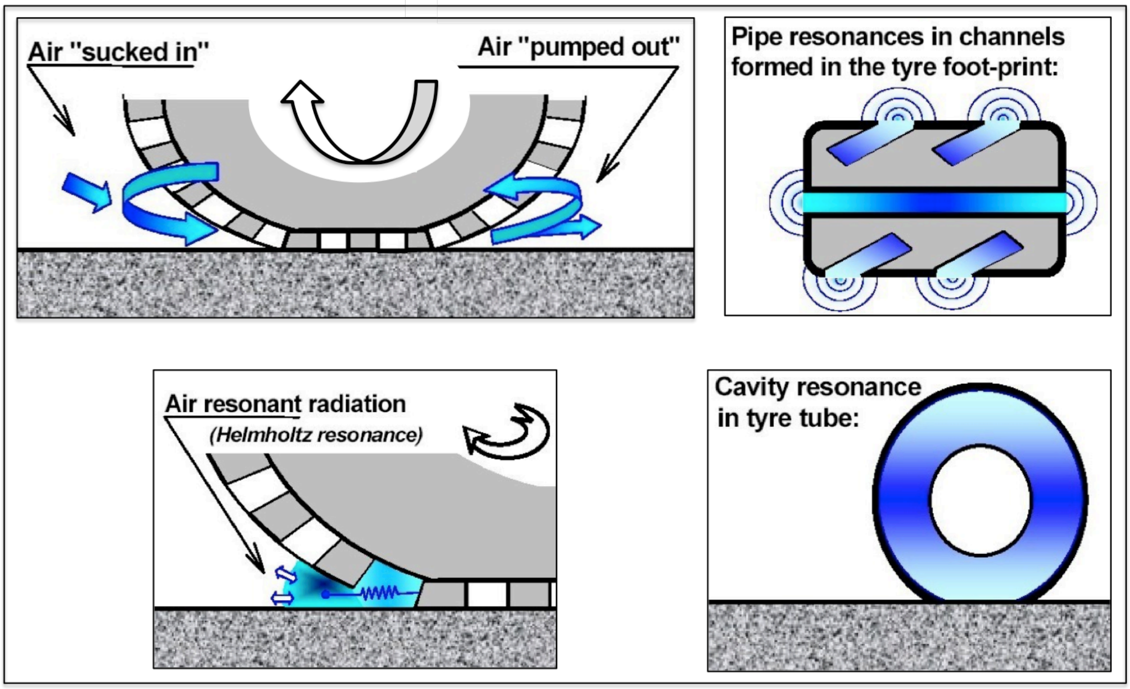

Figure 2.4: Aerodynamical-related tire/road noise generation and amplification mechanisms. [3]

The process involved in the tire/pavement interaction can be therefore summarized. As the tread block impacts with the road surface, shocks are sent through the blocks, generating vibrations, while air caught between individual tread blocks is compressed. This air compressed and decompressed as the tyre passes over the road surface, causing the air pumping, while organ pipe resonance occurs in the longitudinal tyre grooves and friction forces at the tire/pavement interface cause the “slip-stick” effect. As the tread block leaves the contact patch, compressed air in the tread cavity is expelled rapidly, causing additional air pumping effect. The tread block leaves the compressed state in the contact patch, causing a snap-out effect. Noise generated at the contact patch is amplified by the horn effect, occurring at the curved volume between the tyre and the road surface. As the tire continues rotating, the tread block returns to its steady state [55]. This process can be visualized in Figure 2.5.

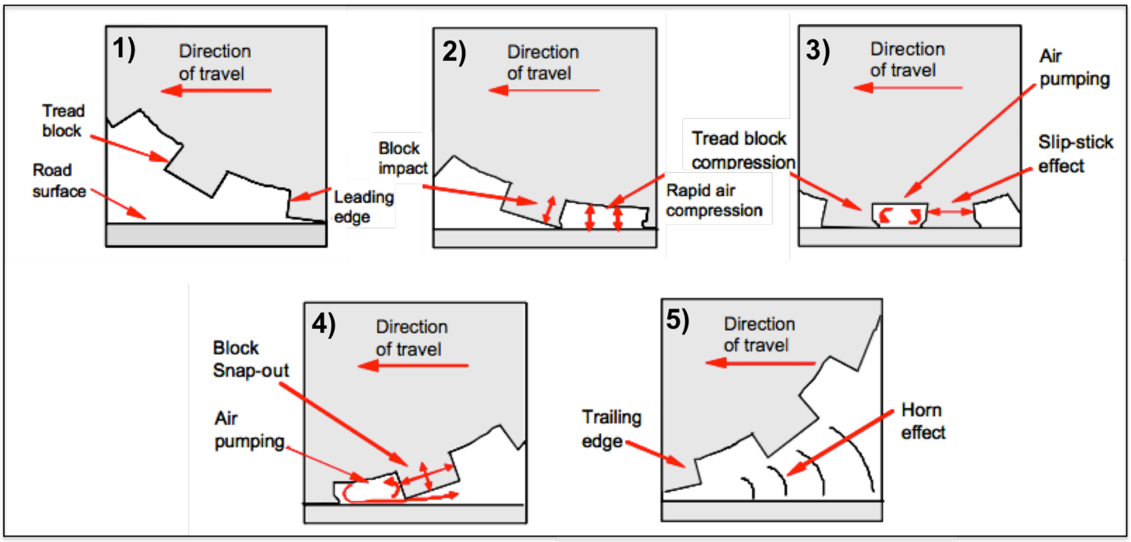

Figure 2.5: Overview of tire/pavement noise mechanisms. [55]

2.2.4 Tire/pavement noise propagation mechanisms

Noise radiating from a sound source into a free space attenuates with distance from the source [55]. At a certain distance, road vehicles can be described as single point sound sources [56].

When a source and a receiver are located above a flat surface, reflections from the ground plane occur. When the surface is perfectly reflective, the reflected acoustic ray can be considered to come from an image source, located below the surface of the ground. When the surface layer is porous, sound penetrates within the pavement and is reflected from the sub-base. [55]

For low porosity surfaces, interference occurs at relatively high frequencies and can be neglected for most practical applications. When the surface layer is porous, interference occurs at lower frequencies, typically affecting the range between 250 and 1000 Hz. The frequencies and amplitudes of these interference effects depend on the acoustical properties of the surface layer and the angle of incidence of the reflected wave [55].

Mechanisms involved in tire/pavement noise propagation mechanisms are displayed in Figure 2.6.

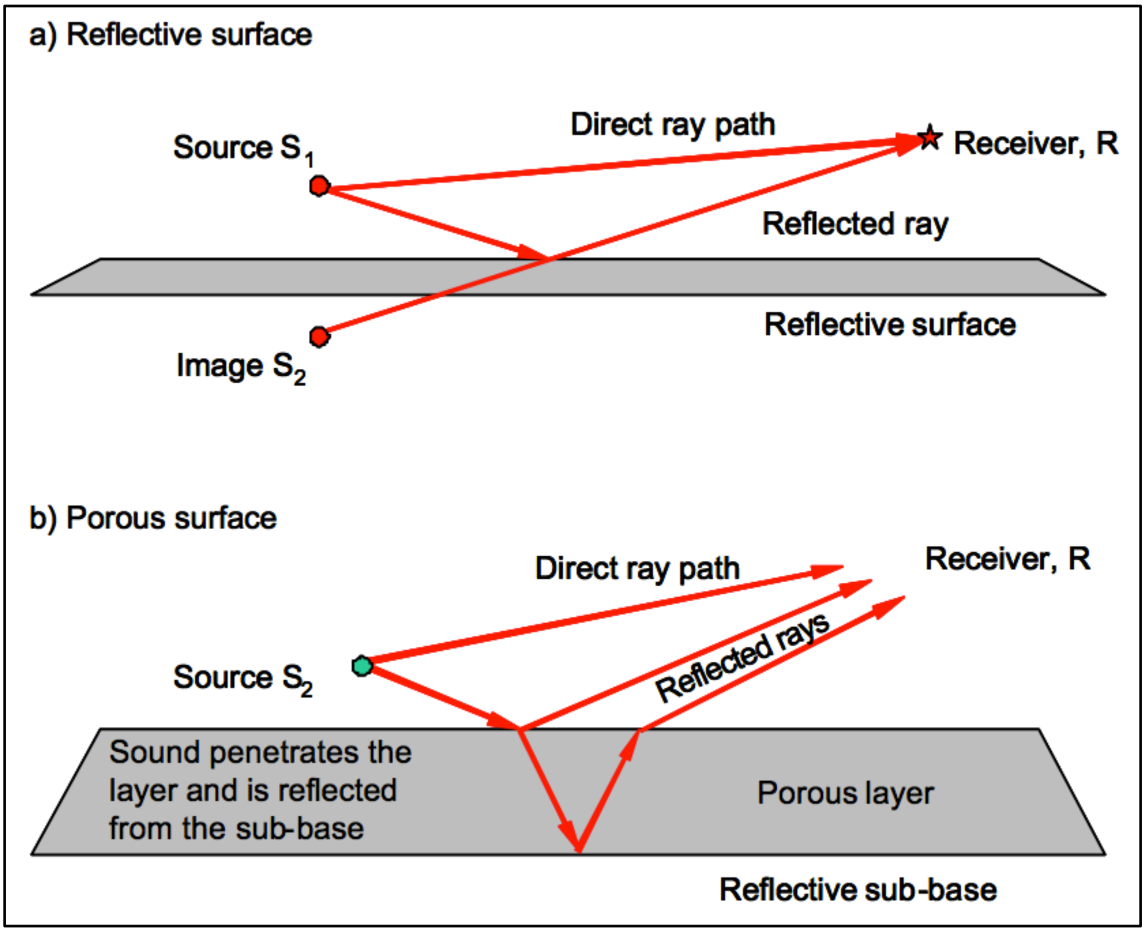

Figure 2.6: Outline of tire/pavement noise propagation mechanisms. [55]

2.3 Overview of low-noise road surfaces and quiet pavements

A low-noise road surface can be defined as "a road surface which, when interacting with a rolling tire, influences vehicle noise in such a way as to cause at least 3 dB(A) (half power) lower vehicle noise than that obtained on conventional and most common road surfaces" [3].

There are both asphalt concrete (AC) and cement concrete (CC) alternatives for quiet pavements [62]. In fact, whereas some previous studies attested cement concrete pavements usually provide higher sound levels than the levels measured in asphalt concrete pavements, surface texture modifications and finishing techniques can provide large reductions in cement concrete tire/pavement noise, so that they can also be considered a legitimate solution to reduce traffic noise [6] [7].

2.3.1 Asphalt concrete alternatives for quiet pavements

2.3.1.1 Single-layer open graded friction courses (OGFC)

Open Graded Friction Courses (OGFC) are open-graded layers, containing little or no fine material or mastic [63]. They are porous pavements with a hot-mix design, which, after compaction, provide four or five times interconnected air voids than conventional wearing courses [64]. As a result, these mixes are permeable and allow for quick removal of surface water, reducing the potential of hydroplaning and water spray, increase friction characteristics and provide lower tire-pavement noise [63] [64].

Since the mixture contains so many voids, “drain down” of the binder during placement can be a concern: therefore, polymers and/or fibres are used in the mixture to minimize this risk. Furthermore, while the additional porosity is beneficial in producing a quieter pavement, it is also the source of potential durability issues due to freeze-thaw cycles, rapid oxidation, ravelling, clogging, increased construction costs up to 70%, and/or fatigue cracking [62] [64].

Mix designs with high percentage of interconnected air voids is aimed to obtain wearing courses with high-drainage characteristics, tire/pavement noise absorption and reduction, as well as the capacity of holding pollutants. According to the particular gradation curve, conventional single-layer OGFC and microdrainage friction courses can be distinguished, as represented in Figure 2.7: the right image represents a structural scheme of the mix design, while the left image displays typical gradation curves [64].

This high-void percentage is achieved by using aggregate mixes with a discontinuous gradation curve: since the mix is poor of sand, high-quality aggregates and modified binders are recommended. With regular maintenance, the service life is about 10-12 years [64].

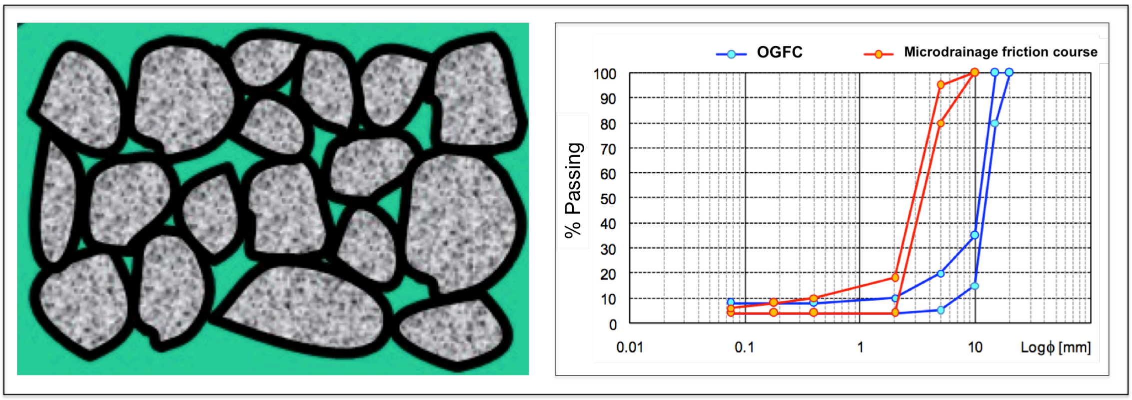

Figure 2.7 structural scheme of the OGFC mix design (left) and typical gradation curves (right). [64]

2.3.1.2 Double layered porous asphalt

Double-layered porous asphalt is designed to improve the decay of the acoustic characteristics with time of single-layer OGFC. They are usually constructed with an upper microdrainage layer, with high-void percentage, up to 20%, which works as a filter with respect to the lower layer, which consists of a drainage layer. The lower layer does not come in contact with tires: therefore, aggregate quality is lower than that of the upper layer [64].

This pavement type provides good drainage capacity and sound absorbing characteristics. Acoustic performance is also more stable in time. Peaks in sound absorption occur at lower frequencies than the single layer's ones, i.e. around 600 Hz: this is an advantage with respect to tire/pavement noise of heavy vehicles [64]. A porous asphalt schematic and related front-view picture can be observed in Figure 2.8.

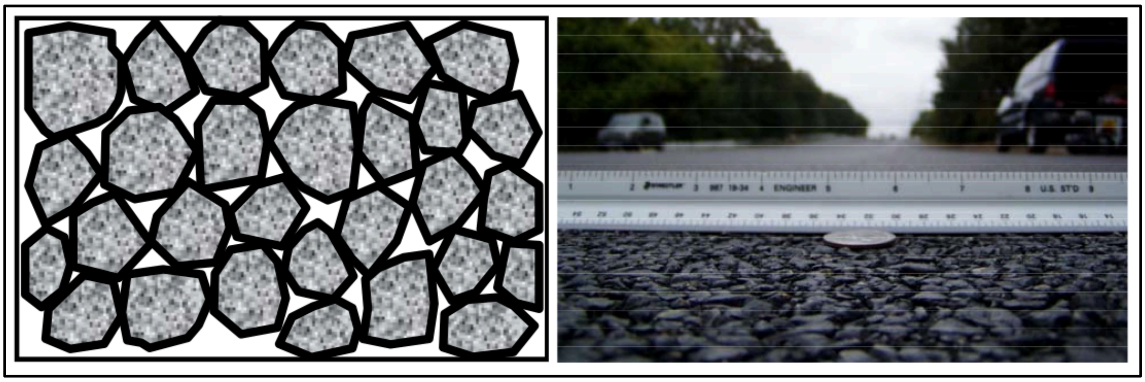

Figure 2.8 Porous asphalt schematic and front-view picture. [62]

Maintenance techniques include flushing methods, while milling and resurfacing of the sole upper layer restores almost all the acoustic and drainage performance of the pavement [64].

2.3.1.3 Hot-laid microsurfacings

Microsurfacing is a thin surfacing technique that uses a mixture of polymer modified asphalt emulsion, high quality frictional aggregate, mineral filler, water, and other additives that are mixed and spread over the pavement surface as a slurry [63].

Aggregate used for microsurfacing can be characterized by a gap in the gradation curve, typically in the ranges of 2/4 mm or 4/6 mm, and by a high surface roughness, partially draining and with good acoustic characteristics of sound absorption [64]. A typical gradation curve for hot-laid microsurfacing according to the Italian road pavement catalogues is represented in Figure 2.9.

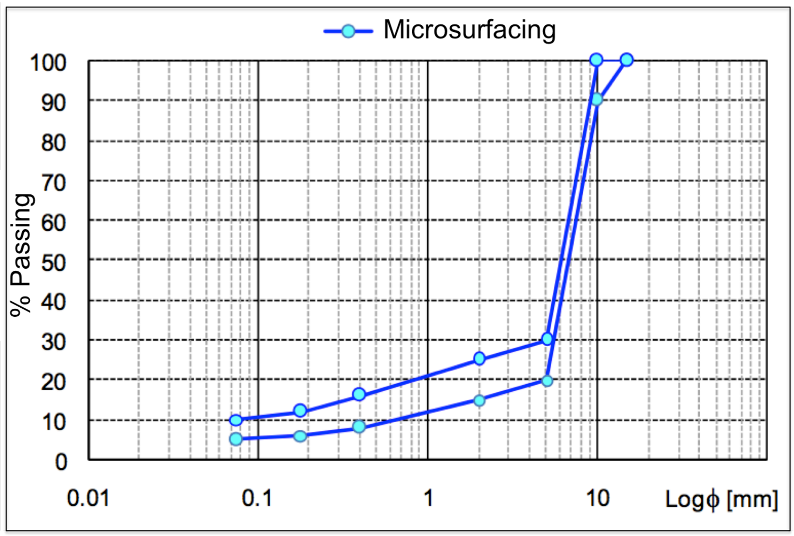

Figure 2.9 Typical gradation curve of microsurfacing [64]

2.3.1.4 Stone Mastic Asphalt (SMA)

Stone Mastic Asphalt (SMA) is a gap-graded mixture that where intermediate sized material is removed: the mixture therefore consists of the larger aggregates and mastic [62].

It typically contains 100 per cent of crushed stone materials. The addition of increased asphalt cement, mineral filler, and/or cellulose fibres to the coarse stone skeleton produces thick mastic that provides both excellent durability and increased resistance to permanent deformation [63]. SMA mixtures can also be constructed with smaller aggregates without significantly affecting durability [62]. Typical gradation curves of SMA are represented in Figure 2.10.

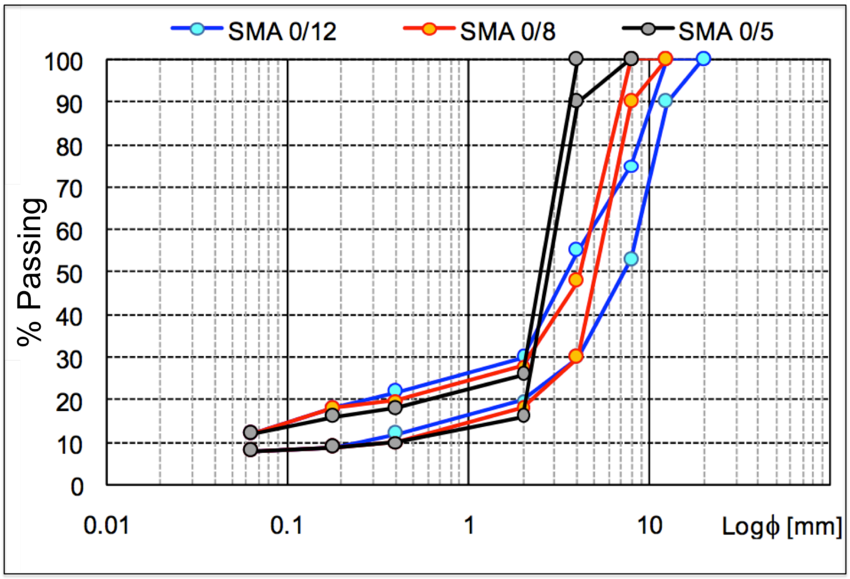

Figure 2.10 Typical gradation curve of SMA [64]

Performance characteristics of SMA are mainly related to [64]:

- stability at high operation temperatures;
- flexibility at low operation temperatures;
- high durability and resistance to aging;
- waterproofing;
- high adhesion between binder and aggregates;
- good frictional characteristics;
- drainage characteristics;
- good acoustic performance of tire/pavement noise reduction;
- good rutting resistance.

A gap graded schematic and related front-view picture can be observed in Figure 2.11.

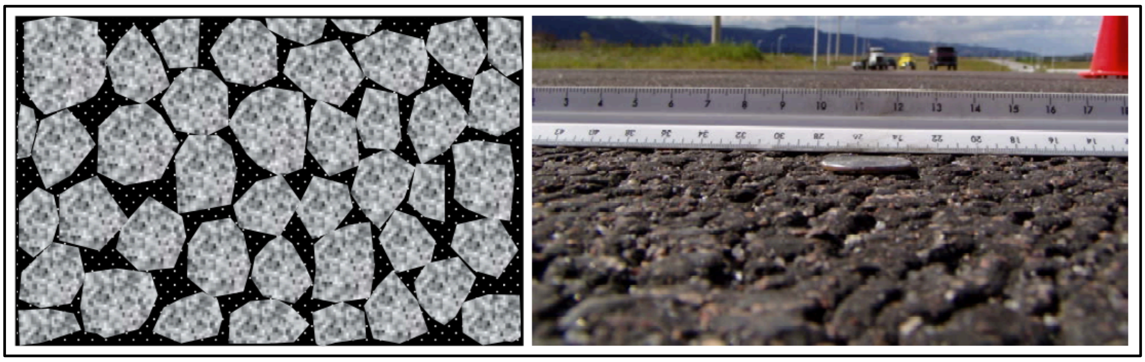

Figure 2.11 SMA schematic and front-view picture [62]

Potential limitations to SMA can be that the high SMA bituminous contents can lead to friction issues [63] and the high cost [64].

2.3.1.5 Dense-graded asphalt

Dense-graded asphalt mixtures can also perform as quiet pavements, but further research is required to identify specific mixtures and construction techniques that result in consistently quieter pavements [62]. A dense-graded schematic and related front-view picture can be observed in Figure 2.12.

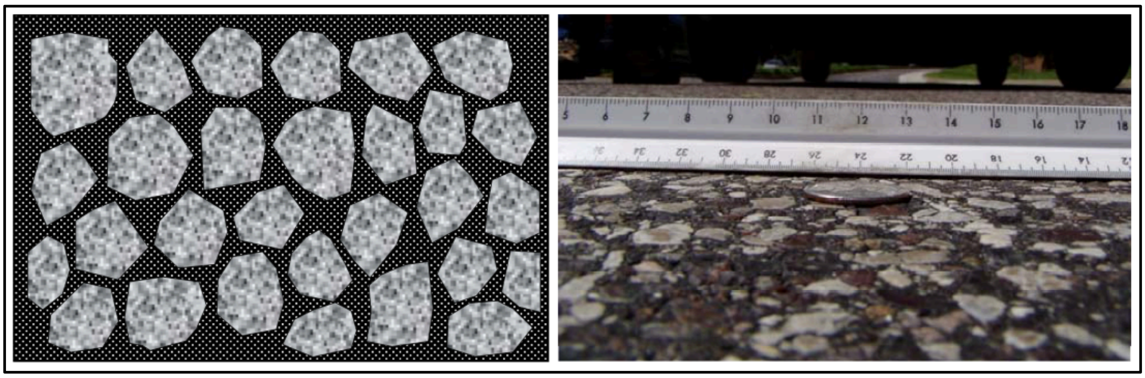

Figure 2.12 dense-grade asphalt schematic and front-view picture [62]

2.3.1.6 Wearing courses with expanded clay

Expanded clay wearing courses are conventional asphalt concrete where an aggregate portion is replaced by expanded clay. The use of this material in wearing course construction provides a dense-graded asphalt concrete with enhanced adhesion and sound absorption characteristics compared to mixes made with only natural aggregates [64].

Such improvements in terms of adhesion are due to the high surface microroughness of the expanded clay aggregates, whereas the enhanced acoustic characteristics are mainly due to a diffuse microporosity within the clay particles [64]. Typical expanded clay aggregates are represented in Figure 2.13.

Figure 2.13 Expanded clay aggregates [65] [66]

2.3.1.7 Wearing courses with optimized surface texture

Optimized surface texture wearing courses are dense-aggregate bituminous mixtures with special gradation curves, capable of, compared to conventional surfaces, tire/pavement noise. Road noise reduction is only due to the specific particle size ranges, which allow obtaining surface texture spectra so as to reduce tire/pavement noise [64].

In Figure 2.14 surface texture wavelength spectra are shown of mixture with optimized surface texture wearing courses.

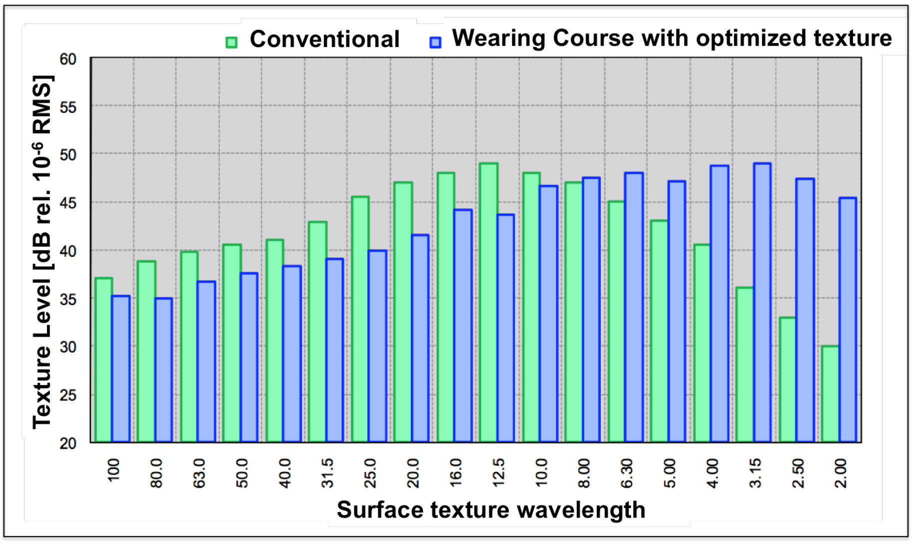

Figure 2.14 Surface texture spectrum of typical optimized surface texture wearing courses [64]

Typical gradation curves are displayed in Figure 2.15 of optimized surface texture wearing courses.

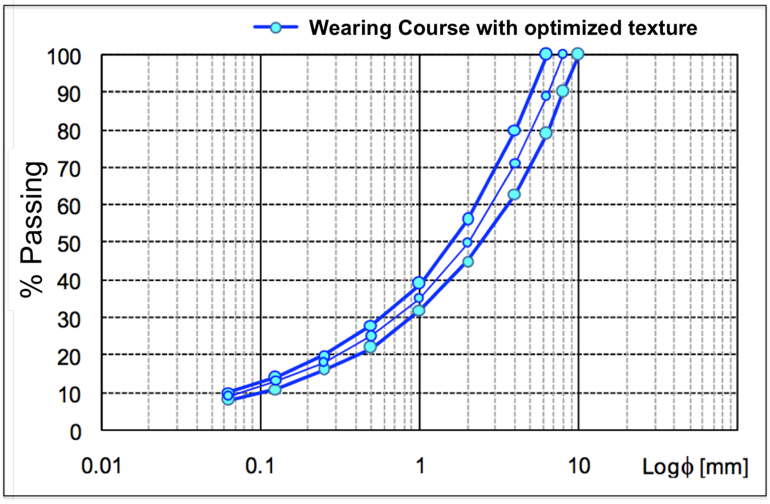

Figure 2.15 Surface texture gradation curves of typical optimized surface texture wearing courses [64]

2.3.1.8 Macro-rough asphalt concrete

Macro-rough asphalt concrete is suggested by Swiss standards as feasible solutions against tire/pavement noise, along with porous asphalt and SMA [64].

Macro-rough asphalt concrete is made of hot-mix asphalt with modified asphalt binder and additives. The mixture is characterized by a high proportion of large-size aggregates, which form a solid skeleton that provides good stability. Air voids are filled by mastic of bitumen and filler, providing high rutting resistance. This type of wearing course is typically used in road pavements designed for high-traffic [64].

2.3.1.9 Thin wearing courses

Thin wearing courses are asphalt concretes with French origin. French standards include different types of thin wearing courses: thin type BBM (Beton Bitumineux Mince), very thin type BBTM 0/6, 0/10 and 0/14 (Beton Bitumineux Très Mince) with maximum aggregate size, respectively, of 6, 10 and 14 mm, ultra thin type BBUM (Beton Bitumineux ultra Mince). BBTM and BBUM differ from each other only by the amount of mixture, less in the case of BBUM. BBTM has characteristics very similar to SMA [64].

The good acoustic performance of these types of wearing courses is due to the small maximum size of the aggregates and to the discontinuity of the gradation curve in the range of 2/4 and 2/6 mm [64].

2.3.1.10 Asphalt concrete with crumb rubber

Asphalt concrete wearing courses with crumb rubber are gap-graded or open-graded mixtures of asphalt concrete, where a certain proportion of crumb rubber has been added from scrap tires [64].

Two methodologies are used to include crumb rubber into AC mixes: dry process and wet process. In the Dry process, crumb rubber is included within asphalt mastic to obtain a gap-graded gradation curve with high percentage of asphalt binder, where air voids are filled with mastic of binder, filler and crumb rubber [64]. In the Wet process, crumb rubber is added to modify asphalt binder: the result is called Asphalt Rubber (AR), a rubber-modified binder with enhanced performance. Asphalt binder is heated at high temperature to ensure the swelling of individual crumb rubber particles [64].

The advantage in the use of the crumb rubber for asphalt concrete mixes can be related to the pavement stiffness reduction, enhanced friction and reduced tire/pavement noise emissions [64].

To date, the international scientific community does not have a unanimous opinion on the beneficial effects produced by asphalt concrete with crumb rubber with respect to tire/pavement noise and research is still in progress on these topics [64].

2.3.1.11 Very Thin Asphalt Concrete (VTAC) and Ultra Thin Layer Asphalt Concrete(UTLAC)

Very Thin Asphalt Concrete (VTAC) are designed to provide advantageous noise properties, which, in some cases, show a magnitude close to or comparable to those registered on some conventional porous asphalt sections [67].

Compared to conventional asphalt pavements, VTAC minimum noise reduction is in the range of 3-5 dB(A), while offering easier winter maintenance, lower initial investments and easier repair than porous asphalt. The open surface texture of VTAC also provides very high skid resistance and quite stable low noise levels [67].

Ultra Thin Layer Asphalt Concrete (UTLAC) is a hot mix asphalt road surface course with a nominal thickness between 10 and 20 mm. Before the surface course is laid, a thick layer of polymer modified bitumen emulsion is spread on the existing road surface, upon which a very open graded hot mix is laid. The purpose of the unbroken bitumen emulsion is to fill the air voids of the pavement layer, leaving only the upper part of the structure open. Noise reduction is about 2-3 dB(A) compared to conventional asphalt pavements [67].

2.3.1.12 Euphonic pavements

Euphonic pavements consist of a highly porous wearing with underneath a continuously reinforced concrete slab with Helmholtz resonators of about 500 cm3, made of cavities connected to the upper layer by a thinner neck [64] [66].

Resonators are located longitudinally and transversally and are responsible for acoustic energy dissipation. The energy of the incident sound excites the air contained in the resonator's neck: the air starts vibrating and behaves as a mass-spring mechanism. The individual resonator is characterized by a resonance frequency, at which the maximum dissipation of acoustic energy occurs [64]. A cross-section of a typical euphonic pavement is represented in Figure 2.16.

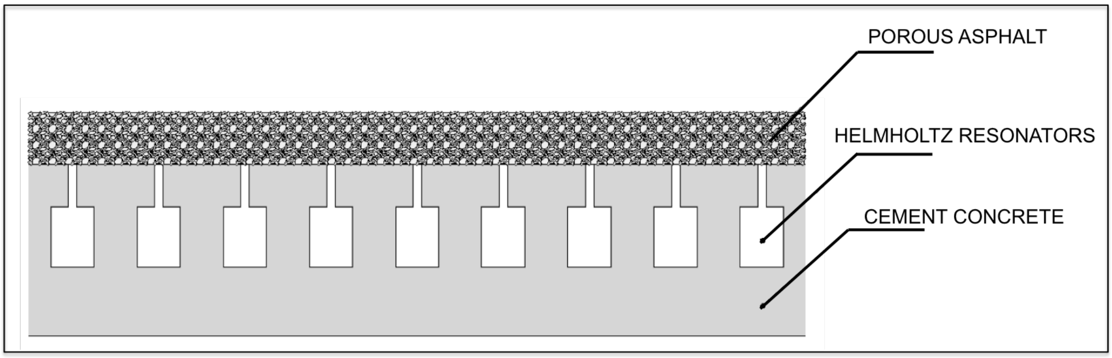

Figure 2.16 Front-section of a typical euphonic pavement [64]

Therefore, Helmholtz resonators are extremely effective only within a limited frequency range, centred on the resonance frequency. However, combining the resonators with an upper open-graded drainage layer, it is possible to realize a pavement system capable of absorbing a wide frequency range. This multilayer system is suitable not only for tire/pavement noise, but also for other vehicle noise components: this aspect makes it a suitable solution for urban areas, when road noise does not have a predominant source [64].

2.3.1.13 Poro-elastic road surface

A poro-elastic road surface (PERS) is a wearing coarse with high content of interconnected air voids, which ensure air and water drainage. They are also provided with certain elasticity by the use of rubber or any other elastic material as main aggregate [64].

PERS mixtures are usually made of natural crumb rubber, or from scrap tires, coarse and fine aggregate, all bound together by polyurethane or artificial resins. PERS can be paved directly on site or pre-cast in panels, anchored to the lower rigid support by epoxy resins. The remarkable resilience characteristics of this surface, which greatly limits the vibrations and provide for outstanding sound absorption, allows for substantial reductions in tire/pavement noise emissions, even up to 12 dB(A) [64].

Some disadvantages can be related to problems of poor anchoring to the underlying layer, poor durability, low friction in wet conditions, poor resistance to damages caused by the transit of snowploughs, high manufacturing cost and poor resistance to fire. Research and experimentation is still in progress due to the high acoustic performance of this pavement type [64].

2.3.2 Cement Concrete alternatives for quiet pavements

If an appropriate mix design is used, containing high quality aggregate, longitudinal diamond ground surfaces and drag surfaces, such as burlap and artificial turf, can be used to produce quite, safe concrete pavements. Longitudinal tining and longitudinal grooved textures can also be used to produce quiet pavements [68] [62].

In Figure 2.17, there can be observed heavy turf drag texturing and diamond ground concrete pavements.

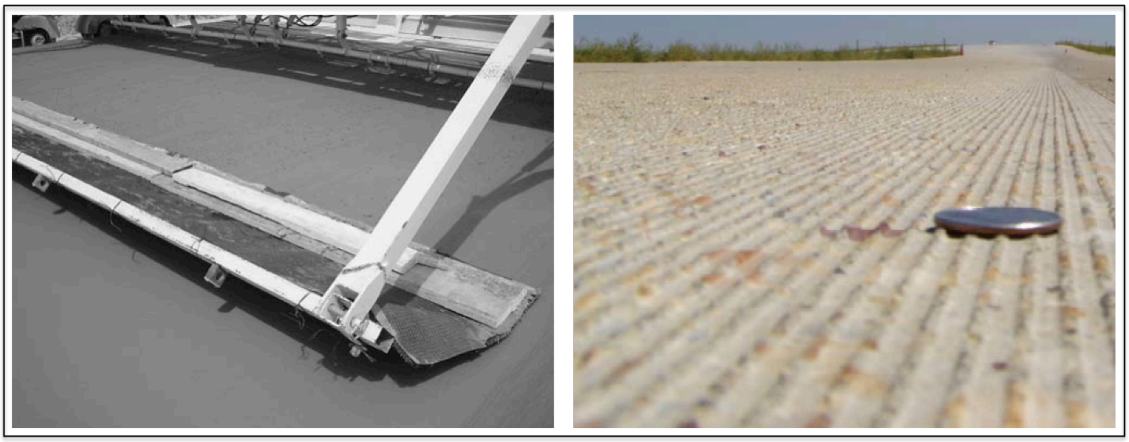

Figure 2.17 Heavy turf drag texturing (left) [68] and diamond ground concrete pavement (right) [62]

Pictures of longitudinal grooving and longitudinal tining texturing are depicted in Figure 2.18.

A high degree of quality control is required, especially when texturing, to achieve a quiet pavement. Furthermore, compatibility is required between the mix, speed of placement/texturing, and the texturing technique, which has to be selected in advance. For instance, specific techniques are recommended to minimize periodic deposits of concrete displaced by the tining process, such as minimizing vibrations of the paver and texture cart [62].

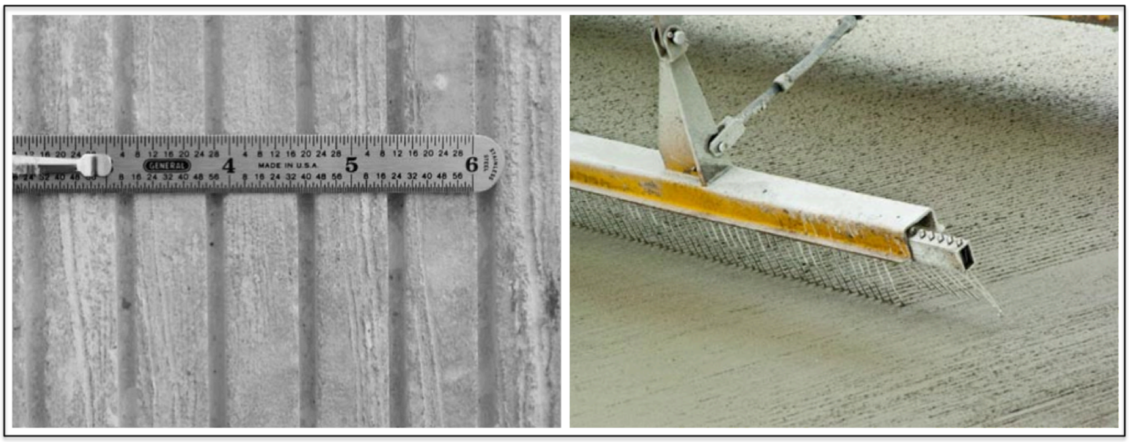

Figure 2.18 Close-up picture of longitudinal grooving (left) [68] and longitudinal tining texturing (right) [69]

Transverse tining is considered among the loudest textures, especially when tined with a uniform spacing, because they can contain a “whine” that enhances noise. Quieter transverse tined pavements are possible, but are often found to have a short spacing between the tines, e.g. nominally 12 mm or less. Furthermore, randomizing this short spacing can minimize the potential for is phenomenon.

A European technique for concrete pavement surfacing involves termed exposed aggregate and it is sometimes considered a quiet concrete pavement. Measurements on similar surfaces placed in North America, though, have provided contradictory results. Furthermore, some noise measurements found in the literature show noise results similar to conventional concrete pavement textures [62].

Porous concrete pavements have been built in trial sections: whereas they seemed to be quieter than any dense concrete, they have provided poor durability [62]. Research is still in progress on these topics.

In Figure 2.19, pictures of exposed aggregate concrete and porous concrete are displayed.

Figure 2.19 Exposed aggregate (left) and porous concrete (right) [62]

2.4 Noise testing for tire/pavement noise

Several techniques and methods are used to measure road noise and to quantify acoustic performance of road pavements. Direct methods to measure tire/pavement noise include pass-by methods, close-proximity methods and input noise measurements [22]. Pass-by methods measure roadside or wayside noise at a certain distance from the roads, while in close-proximity methods measures are taken close at the source, i.e. close to the tire/pavement contact. Input noise measurements are, instead, aimed to measure traffic noise perceived indoor by receptors: therefore, the distance between the road and the point where the measurements are taken is variable.

Indirect methods to describe acoustic characteristics of a road pavement include the measurement of the sound absorption characteristics [22]. Sound absorption, in fact, can be related in some tire/pavement noise mechanisms, such as acoustical and mechanical impedance effects: porous asphalt pavements, for example, provide good characteristics of sound absorption and they are considered as quiet pavements. Since other components are involved in noise generation and amplification mechanisms, though, some road pavements with low characteristics of sound absorption can still provide low-noise levels and be considered as quiet pavements.

2.4.1 Statistical Pass-by Method (SPB)

The Statistical Pass-by (SPB) method is regulated by the ISO 11819-1 Standard: it describes a method of comparing traffic noise on different road surfaces for various compositions of road traffic for the purpose of evaluating different road surface types [70].

The SPB method can be used essentially to classify surfaces in typical and good condition, according to their influence on traffic noise, or to evaluate the influence on traffic noise of different surfaces at particular. This latter type of application can be useful for “before” and “after” measurements, e.g. for roads where a resurfacing intervention is intended and differences in traffic noise are required before and after resurfacing [70].

The maximum A-weighted sound pressure levels of a statistically significant number of individual vehicles are measured at a specified roadside location together with their speeds.

The roadside location is different in the European and American standards: in the European standards, horizontal distance from the microphone position to the centre of the lane shall be 7,5 m, while in the American standards it is 15,0 m.

Three categories of roads are defined with respect to the range of speeds at which the traffic flows: low road speed, which relates to traffic operating at an average speed of 45-65 km/h, medium road speed, which relates to traffic operating at an average speed of 65-99 km/h, and high road speed, which relates to traffic operating at an average speed of 100 km/h or more [70].

In Figure 2.20 a picture is depicted of a typical measurement with the SPB method.

Figure 2.20 Typical SPB noise measurement [71]

Each measured vehicle is classified into one of three vehicle categories: “cars”, “dual-axle heavy vehicles” and “multi-axle heavy vehicles”, for which a nominated reference speed is given. Each individual pass-by level together with its vehicle speed is recorded of a statistically significant number of vehicles [70].

A linear regression of the maximum A-weighted sound pressure level versus the logarithm of speed is calculated for each vehicle category to obtain the statistical sound pressure level of each category at the reference speed. This allows calculating the Statistical Pass-By Index (SPBI), which is an index that can be used for comparison of road surfaces so that their influence on sound level of a mixed traffic flow can be determined [70].

2.4.2 Close-proximity method (CPX)

The Close-proximity method (CPX) is regulated by the ISO 11819-2 Standard draft: it is a method for evaluating different road surfaces with respect to their influence on traffic noise, under conditions when tire/pavement noise dominates [72].

The method has the same main objectives as the SPB method, but it is also intended for similar purposes and applications that are complimentary to it, such as noise characterisation of road surfaces at arbitrary sites, check the state of maintenance of a road segment, and check the longitudinal and possibly lateral homogeneity of a road section. The CPX method is faster, more practical and more economical than the SPB method, but it is relevant only in cases where tire/pavement noise is predominant and it cannot take heavy vehicle tyre/road noise into account as fully as the SPB method can [72].

The average A-weighted sound pressure levels emitted by two or four specified reference tires are measured over a certain road distance, together with the vehicle testing speed, by at least two microphones, located close to the tire/pavement interface. Therefore, a special test vehicle is used, either a testing self-powered vehicle or a trailer. Four reference tires are mounted on the test vehicle, either one by one, or a few at a time. Tests are performed to the tire/pavement sound pressure level at one or more of the nominated reference speeds, i.e. 50, 80 and 110 km/h [72].

In Figure 2.21 the layout of the microphone locations is represented for noise measurements with CPX method, as well as a picture of a trailer equipped with noise testing instrumentation for CPX measurements.

Tire/pavement sound levels may be averaged of the selected reference tires, to calculate a single index, which can be used for comparison of road surfaces [72].

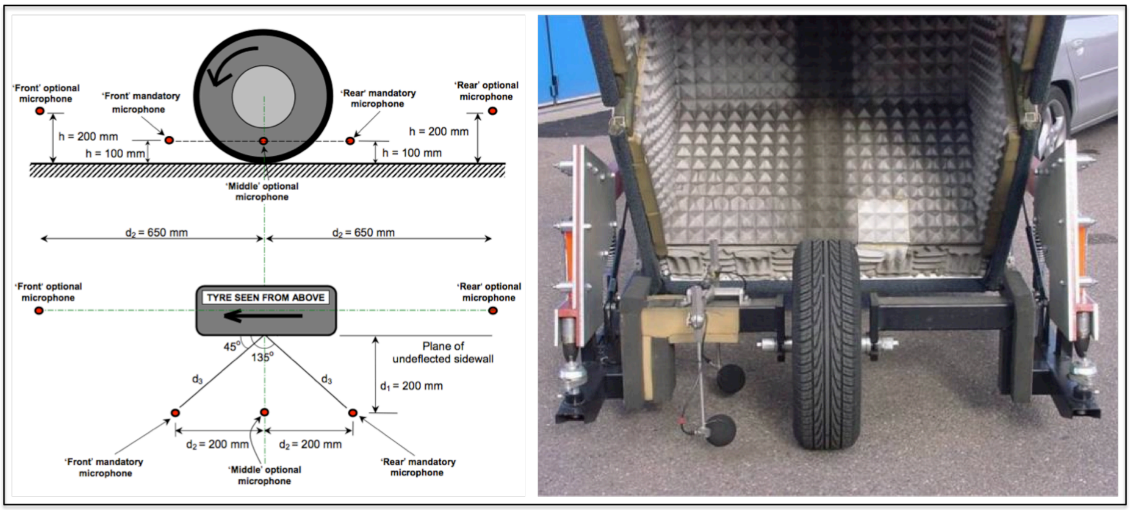

Figure 2.21 Layout of the CPX microphone positions (left) [72] and picture of a trailer equipped for CPX noise testing (right) [73]

2.4.3 On-Board Sound Intensity method (OBSI)

The On-Board Sound Intensity method (OBSI) is regulated by the AASHTO TP 76 standard: it is a method for measuring tire/pavement sound intensity near the tire/pavement interface and it allows various pavements and texture to be compared [74].

A-weighted sound intensity levels are measured at the standard reference speed of 96 km/h, whereas acceptable alternative measurement speeds include 72, 56 and 40 km/h [73]. Use of the Standard Reference Test Tire is required, as defined in ASTM F 2493 [75].

Since sound intensity is linked to a direction, it is not as simple to measure as sound pressure, but a common technique is to use a probe consisting of two microphones spaced apart by specified distance [76]. Probes are located in parallel to the tire, with either a vertical or horizontal setup. Use of two probes is optional [74].

Measuring both the amplitude and phase of sound at the two microphones gives the probe directional characteristics and allows for the direction of sound sources to be determined [76].

Advantages of using sound intensity instead of sound pressure for measuring tire-pavement noise at the source include that the directional characteristic of the probe provides for accurate measuring of a specific noise source, while attenuating sounds from other sources in other directions, such as engine or exhaust noise. Furthermore, sound intensity is believed to be less contaminated by wind noise generated while the vehicle is moving. OBSI measures are also well correlated with roadside measures, such as SPB [76].

In Figure 2.22 the layout of the testing equipment required by the OBSI method is represented, as well as a picture of a two-probe vertical setup.

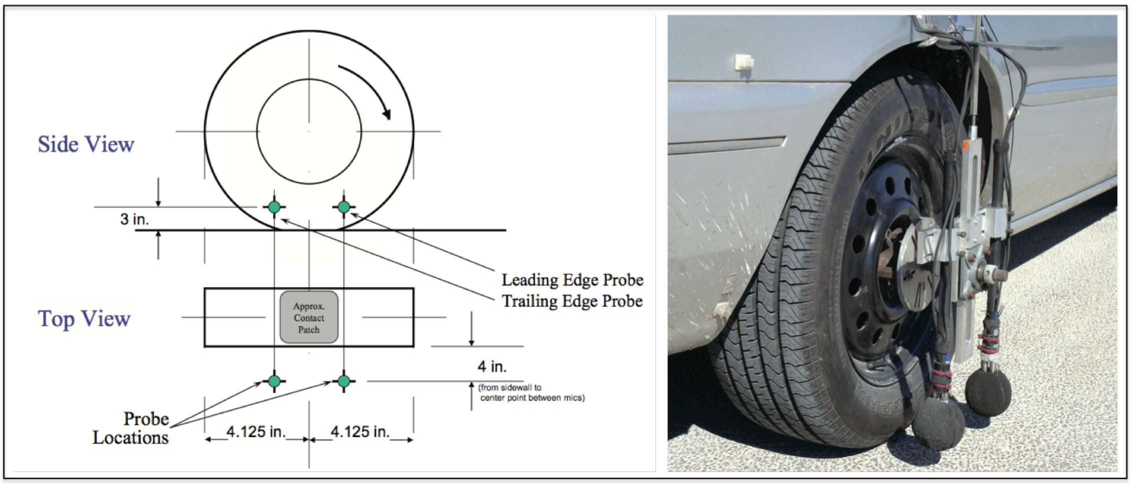

Figure 2.22 Layout of the OBSI microphones and probes locations (left) and picture of two-probe vertical setup (right) [76]

2.4.4 Methods to measure the coefficient of sound Absorption

Sound absorption of road pavements can be evaluated in laboratory by means of an impedance tube or in situ with specific equipment.

The determination of the coefficient of sound absorption in impedance tubes can be calculated with the standing wave ration or with the Transfer-function method: the methods are regulated, respectively, by the ISO 10534-1 and 10534-2 Standard [77].

The Transfer-function method is generally much faster than that of ISO 1534-1. It involves the use of an impedance tube, two microphones at specific locations inside the tube and a digital frequency analysis system for the determination of the sound absorption coefficient of the samples for normal sound incidence.

Plane waves are generated by a loudspeaker in a tube: the decomposition of the interference field is achieved by the measurement of acoustic pressures at two fixed locations using wall-mounted microphones or an in-tube traversing microphone, and subsequent calculation of the complex acoustic transfer function, the normal incidence absorption and the impedance ratios of the acoustic material [77].

A layout of the testing equipment required by ISO 10534-2 is represented in Figure 2.23, along with a close-up picture of an impedance tube with its loudspeaker.

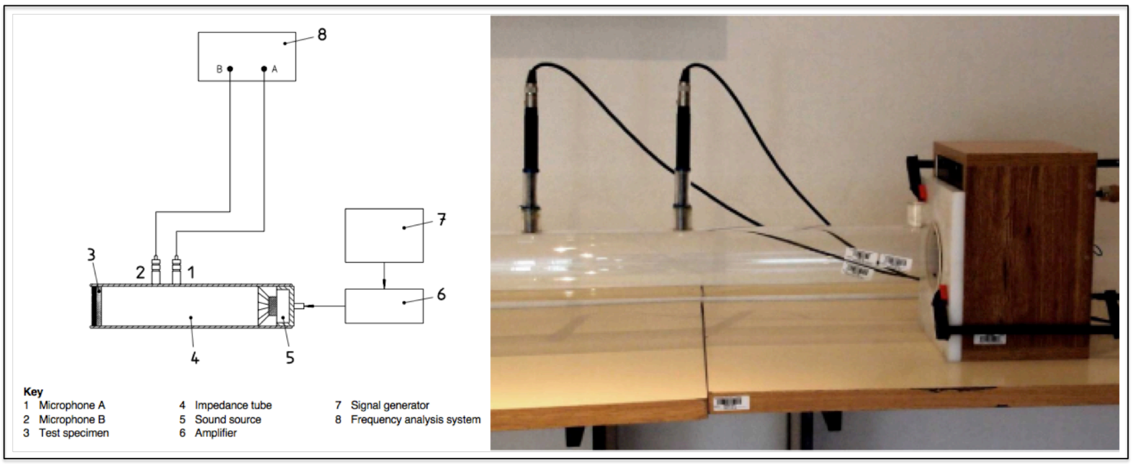

Figure 2.23 Layout of the testing equipment required by ISO 10534-2 (left) [77] and close-up picture of an impedance tube with its loudspeaker (right) [78]

The determination of the coefficient of sound absorption of road surfaces in situ is regulated by the ISO 13472-1 standard [78]. Normal incidence is assumed by this method, whereas it can be applied at oblique incidence with some limitations. The test method is intended for the determination of the sound absorption properties of test tracks, according to ISO 10844, for the determination of the sound absorption properties of road surfaces in actual use, and for the comparison of sound absorption design specifications of road surfaces with actual performance data. The method involves a sound source, driven by a signal generator, positioned above the surface to be tested and a microphone located between the source and the surface.

The measurement is based on the assessment of the transfer function between the output of the signal generator and the output of the microphone. This transfer function is composed of two factors, one coming from the direct path, i.e. from the signal generator through the amplifier and loudspeaker to the microphone, and a second coming from the reflected path, i.e. from the signal generator through the amplifier, loudspeaker and surface under test to the microphone [79].

2.4.5 Additional noise tests for tire/pavement noise evaluation

Other methods aimed at comparing road surfaces and different pavements include the Controlled Pass-by (CPB), the Coast-By method (CP) or the Laboratory Drum method.

The CPB and the CP methods are similar to the SPB method and they share the same principles, with some variations in the testing methodology. In the CPB methods, for instance, only two or more vehicle cars are employed, most often cars: since the properties and test speed are known and can be kept controlled, the comparison of road surfaces may be performed with relatively few runs. In the CP method, a single vehicle is used with different test tires [3].

In the Laboratory Drum method, a drum facility is used with a test tire mounted so that it can roll against the drum, while one or more microphones is/are mounted close to the test tire. The drum shall be equipped with a testing surface that resembles an actual road [3]: therefore, the drum should also be made as large as possible to make the surface looks as flat as possible [22].

Conclusions

Some noise testing techniques have been elaborated to measure tire/pavement noise at the source, i.e. close to the contact patch, and at roadside locations.

Previous studies have attested that some pavement types behave as quiet pavements, i.e. road surfaces that provide lower noise levels than conventional ones.

Tire/pavement noise is caused by a set of noise generation and amplification mechanisms, which occur in the contact patch between the tire and the road surface. Therefore, to design a quiet pavement it is important to analyse those mechanisms and understand why the choice of specific mix designs and pavement materials provide better acoustic characteristics to the pavement.

Analysing both asphalt and cement concrete road pavements, in fact, it appears that whereas AC pavements are generally quieter than CC ones, surface texture optimization enables some CC pavements to perform as quiet pavements.

Research on low-noise pavement surfaces and quiet pavement has focused on the impact of surface texture and pavement materials to better understand how these characteristics impacts on noise performance. Moreover, research has focused on the evolution of acoustic characteristics of pavements with time and on possible environmental factors that can affect tire/pavement noise. These aspects are discussed in the following chapter.

3 PAVEMENT WEARING COURSE CHARACTERISTICS AFFECTING TIRE/PAVEMENT NOISE

Introduction

Wearing course characteristics and environmental conditions can affect the acoustic characteristics of road pavements. Surface texture, unevenness, porosity, layer thickness, adhesion, friction and pavement stiffness are all believed to have different degrees of influence on tire/pavement [3].

Pavement age, presence of distresses and surface texture modifications with time are also believed to affect acoustic characteristic of the pavement and contribute increasing the overall road noise levels [8].

Furthermore, environmental conditions have an impact on tire/pavement noise: differences in noise measurements on similar pavement types can be due to a combination of environmental, tire, loading and vehicle/operator variables [10]. Previous studies have shown decreased noise levels in AC pavements as temperature increases, while mixed results were found in PCC pavements [11]. As a consequence, there can be as much as a 9 dB(A) difference for a single pavement type and up to 14 dB(A) difference between the noisiest and quietest pavement under similar conditions [60].

Wearing course characteristics change with noise emission levels over time and these aspects have also to be considered when designing quiet pavements [60].

The effects of surface texture, pavement materials, temperature and aging on tire/pavement noise will be discussed in this chapter.

3.1 Surface properties and their impact on tire/pavement noise

Acoustic characteristics of road pavements are influenced in different ways by their surface properties. Other surface parameters involved are the way the surface material affects heat radiation/absorption, as well as whether the surface is wet or dry: their influence, though, is secondary or not even related to road surface specification [55].

3.1.1 Surface texture

Surface/pavement texture is defined as the deviation of a pavement surface from a true planar surface. According to some specific ranges of texture wavelength, surface texture can be characterized as follows [80]:

- macrotexture: the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of 0.5 to 50 mm;
- microtexture: the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of less than 0.5;
- megatexture: the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of 50 to 500 mm;
- unevenness: the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of 0.5 to 50 m.

According to the texture wavelength, surface texture is involved to several effects related to the tire/pavement interaction, such as rolling resistance, ride quality, friction, vehicle and tire wear, and tire/pavement noise. Ranges in terms of texture wavelength and spatial frequency of texture and unevenness are shown in Figure 3.1, along with their most significant, anticipated effects.

The relationship between surface texture and tire/pavement noise is complex. The noise generated by tire/pavement interaction, in fact, is greatly influenced by pavement surface characteristics such as gradation, macrotexture, age, and presence of distresses [3].

Surface texture and other wearing course characteristics have a different potential influence on tire/pavement noise. Unevenness operates a minor effect, while microtexture has a low to moderate influence. The degree of influence performed by megatexture on tire/pavement noise is high, and the degree performed by macrotexture is even very high. A very high influence is also due to porosity. The thickness of layer also highly affects noise, especially for porous surfaces, whereas friction is considered to perform a low-moderate effect. The influence performed by stiffness is still uncertain, but some studies consider it to be moderate [3].

Previous researches have shown that increasing texture amplitudes at wavelengths in the range 0.5 to 10 mm may reduce noise generation mechanisms, particularly at high frequencies generally above 1 kHz [81] [55].

Texture wavelengths in this range, in fact, accord with dimensions associated with the small asperities in the surface which are thought to influence some aerodynamic mechanisms of tire/pavement noise generation, especially air pumping. Increasing texture amplitudes at wavelengths in the range 0.5 to 10 mm is believed to reduce the air resonating in the grooves of the tire tread pattern and the road surface. The increase in texture allows the air trapped between the tire and the road surface to be released less suddenly, generating less noise [55].

In addition to this high frequency noise effect, low frequency components behave differently: increasing texture amplitudes at wavelengths in the range 10 to 500 mm causes noise levels to increase, particularly at frequencies generally below 1 kHz [55].

The tire/pavement noise mechanisms affected by this wavelength range is thought to be associated with tire tread impacts with the road surface. As the texture increases, vibration levels set up in the tire carcass due to the tread impact increases: as a consequence, higher noise levels are generated, especially at frequencies below 1 kHz [55].

Above 1000 Hz, absorption properties and reduction of air-pumping phenomenon are predominant [82].

An important consideration is related to the way surface texture is applied: in fact, the relationship between texture amplitudes in the megatexture range with noise is different for randomly textured surfaces than that of surfaces with a transverse texture [55].

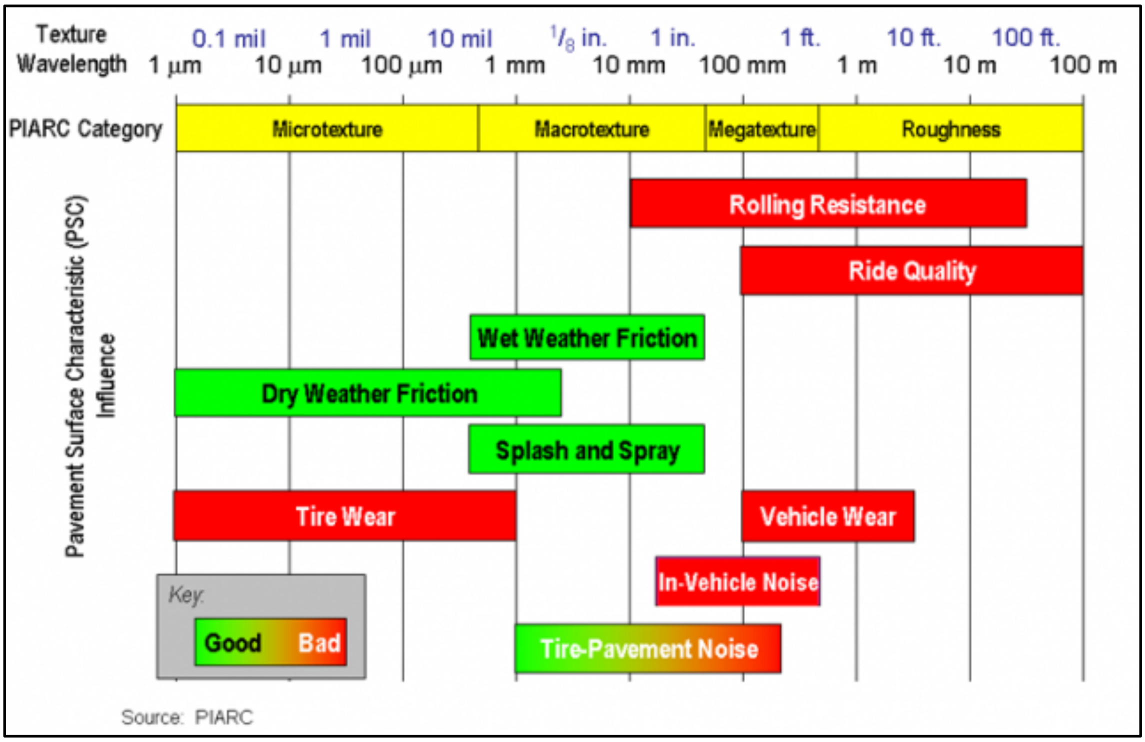

Figure 3.1 Ranges in terms of texture wavelength and spatial frequency of texture and unevenness with their most significant effects [81]

Effects on noise are displayed in Figure 3.2 for a range of surfaces with either transverse or random textures: in the image, pass-by noise levels are represented for light vehicles travelling at 90 km/h. Regression lines corresponding to the method of texturing are very different, showing that noise levels on transverse textures are significantly higher for a given amplitude, compared to the corresponding ones for randomly textured surfaces [55].

The explanation for this effect can be related to forces acting on a tire travelling on a transverse texture: those forces are more synchronised across the width of the tire than for random texturing, enhancing higher vibrations in the tyre and producing more noise [55].

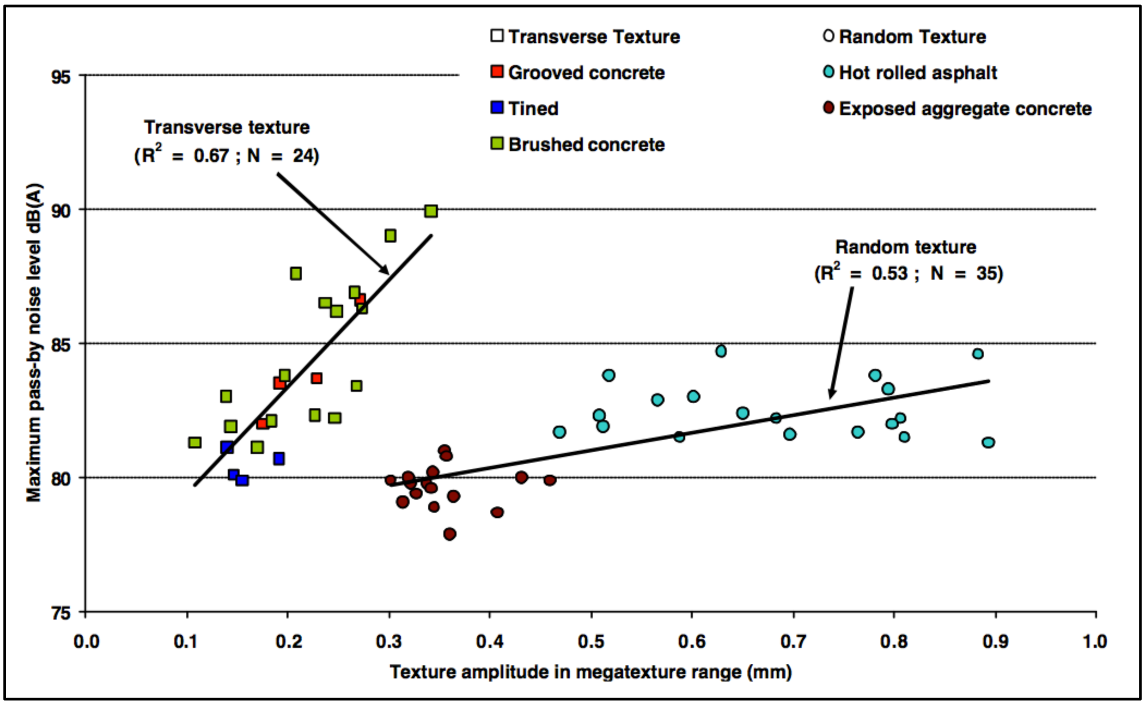

Figure 3.2 Variation in vehicle pass-by noise level and texture amplitudes in the megatexture range [55]

The ways in which texture is formed with respect to the vertical plane are also different.

Positive texture is formed by particles or ridges protruding above the plane of the surface. Typically, this kind of texture is formed by applying chippings to essentially smooth surfaces and rolling them, as well as by removing the surrounding matrix to expose aggregate particles. It is typical for rolled asphalt and brushed concrete surfaces [55] [62].

On the contrary, the term negative texture can be applied to materials in which the texture largely comprises voids between particles, whose upper surfaces form an essentially flat, smooth plane. It is typical of thin surfaces and grooved concrete [55] [62].

Positive texturing is generally considered to encourage higher levels of vibration in the rolling tire, whereas negative textures contribute to the lower noise levels [55] [60]. In Figure 3.3, a representation of positive and negative texture is displayed.

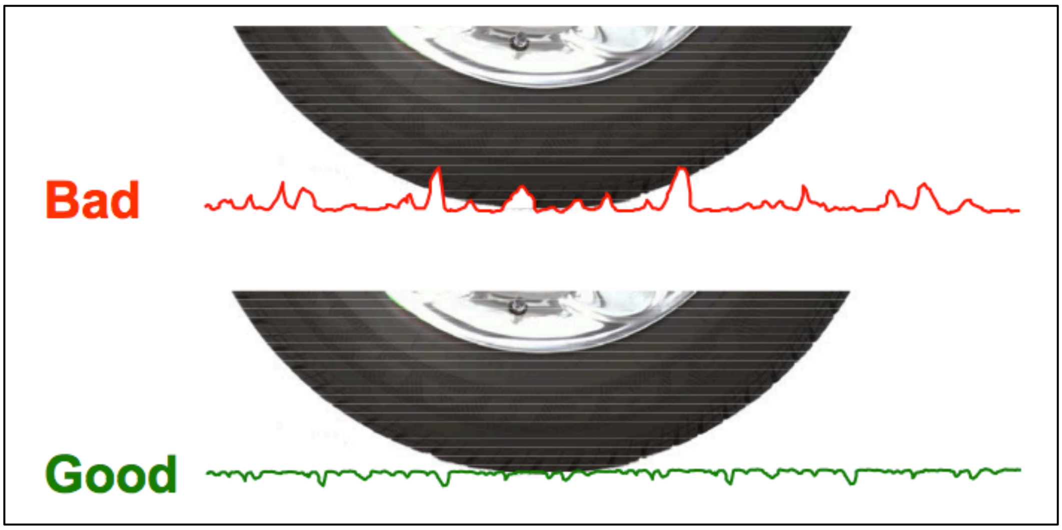

Figure 3.3 Representation of positive and negative surface texture [62]

With respect to the shape, homogeneity, spacing and orientation of the aggregates, some considerations can therefore be made. Previous studies, in fact, observed that aggregates with cubic shape and homogeneous orientation are related to lower levels of noise, whereas noise levels increase when aggregates are sparser and with non-homogeneous or elongated shape, and with non-homogeneous orientation or even depressed position [64] [84].

Different configurations of aggregate shape, homogeneity, space and orientation are represented in Figure 3.4 with the respective noise trend.

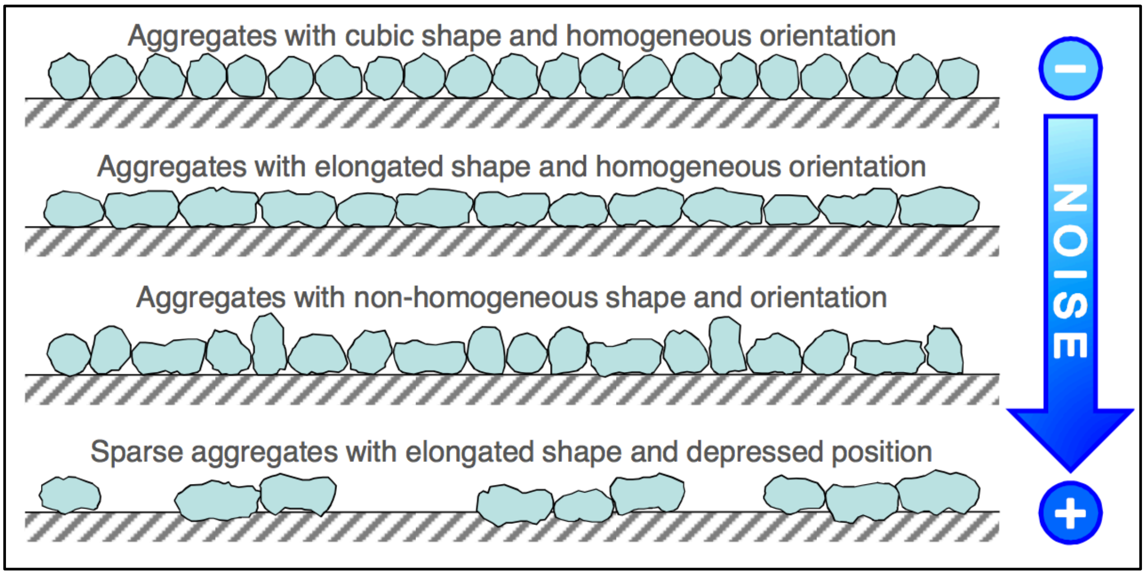

Figure 3.4 Aggregate type and related noise trend [64] [84]

Whether the texture is isotropic or anisotropic, i.e. orientated, effects on tire/pavement noise can be different. A surface texture can be considered isotropic when it is almost random, whereas an anisotropic texture is mostly periodic. Anisotropic textures are usually those of the following pavement types: transverse grooved cement concrete, longitudinally grooved cement concrete, brushed cement concrete, burlap drag cement concrete, block or interlocking block pavements, paving stones, ground surfaces. Bituminous surfaces may also be treated to obtain anisotropic textures, but it is usually uncommon [3].

Tire/pavement noise of anisotropic surface are enhanced if the texture is transverse, while it is usually relatively lower when the texture is longitudinal. When travelling transversely over the direction of the texture, in fact, the impact will be in-phase all over the directional texture and the tire rubber will be more deflected. Also, if the texture contains grooves, they can contribute to causing pipe resonance [3].

Furthermore, within any given pavement type there is considerable variation that is believed to be due to uncontrolled or unreported pavement construction and design variations: this aspect also has an impact on the acoustic performance of the pavement [60].

3.1.1.1 Surface texture indicators and tire/pavement noise

Limited studies have been focused on the impact of unevenness on tire/pavement noise, providing poor correlation [3].

Several researches, instead, have been carried out to analyse a possible correlation between macrotexture and microtexture indicators with tire/pavement noise, as well as between skid resistance and noise.

Researches involving British Pendulum Number (BPN) tire/pavement noise provided poor or, however, limited correlations. Limited correlations have also been observed between synthetic surface texture indicators, such as Mean Texture Depth and Mean Profile Depth, unless when the tire is sufficiently smooth with a low tire tread depth [3] [85]. The Mean Texture Depth is the texture depth obtained with the volumetric patch method [86].

The Mean Profile Depth is defined as the average value of the profile depth over a certain distance, i.e. the baseline [80].

In 1970, researches from Sandberg and Descornet observed some relations between tire/pavement noise spectra and surface texture spectra [85].

Two surface texture parameters to estimate rolling noise can be the following ones [3] [85]:

- $L_{TX,4}$: it is the surface texture level of the octave band at 4 mm, constituted by third octaves at 3.15, 4 and 5 mm. This surface texture level represents a good indicator in the field of high-noise frequencies (f>1000 Hz).
- L_{TX63}: it is the surface texture level of the octave band at 63 mm, constituted by third octaves at 50, 63 and 80 mm. This surface texture level represents a good indicator in the field of low-noise frequencies (f<1000 Hz).

ISO/CD 13473-5 Standard also indicates LTX,63 as a good surface texture indicator performing a predominant role in the tire/pavement noise generation mechanisms [85]. Some other parameters involving geometric and spectral analyses of surface texture spectra, also providing good correlation with tire/pavement noise [85].

3.1.2 Porosity

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" [55]. It is a term that refers to the air voids that exists between the particles in the pavement [3].

Although defining a porous surface in terms of its void content has not been internationally established, previous studies provided the following classification of road surfaces, according to their porosity [55]:

- dense layers: air void content of 4-9%;
- semi-dense: air void content of 9-14%;

- semi-open: air void content of 14-19%;
- open layers, also defined as porous layers: air void content over 19%.

Porous surfaces are effective in reducing tire/pavement noise through sound absorption and other mechanisms [62] [55]. In fact, increasing surface porosity reduces the compression and expansion of air trapped in the tire tread, decreasing the noise generated by aerodynamic mechanisms, such as air pumping and air resonant tire noise [55] [3]. Especially, pavement porosity tends to reduce aerodynamic noise above 1500 Hz [60].

Increasing the porosity generally enhances the acoustic absorption, leading to a reduction of the horn effect [55]. Other parameters that influences sound absorption include [87] [88] [55] [3]:

- thickness of the porous layer: it influences the peak of maximum sound absorption in the frequency spectrum. Increasing layer thickness lowers the fundamental frequency of maximum absorption and its harmonics;
- air flow resistance in the pores of the surface: a high air flow resistance encourages sound energy dissipation, whereas a too high air flow resistance prevents the acoustic waves to penetrate into the layer. The optimum range of the air flow resistance depends on the layer thickness of the layer;
- tortuosity: it influences the air path through the surface layer, which will be dependent upon the shape of the interconnecting voids. The more tortuous the air path, the lower the fundamental frequency of maximum absorption.

Evidences indicate that the noise reduction of porous surfaces is statistically highly correlated with the product of residual air voids and layer depth [55].

3.1.3 Pavement stiffness and damping capacity

Pavement materials can affect tire/pavement noise due to variations in vibration attenuation and damping capacities [89].

Surface characteristics referred to as the mechanical impedance or stiffness of the surface has been associated with noise generation relating to impact mechanisms. The mechanical impedance of road surfaces is usually several orders of magnitude higher than that of the rubber in the tyre tread [55]. Lowering the road mechanical impedance will tend to reduce the tread block impact forces transmitted into a tire, leading to a reduction of the tire vibration levels and, therefore, of noise generation [55] [60]. Pavements with stiffness characteristics approaching that of a tire, in fact, can be quieter than those that are more typical of asphalt concrete and cement concrete in use today [62].

From the data gathered in the United States to date, the absolute noise levels of Portland cement concrete (PCC) are usually higher than the levels measured in asphalt concrete (AC) pavement; it has been discussed in previous chapters, though, that PCC surface textures can be modified to achieve large reductions in tire/pavement noise [7]. In the case of an asphalt mixture, the viscoelastic property has been found to be one of the main factors influencing tyre/pavement noise [89] [90].

Some authors believe that asphalt rubber friction courses, for instance, reduce the tyre/pavement noise because they act as an acoustic absorber due to the increased viscoelastic nature of the asphalt mix, as well as because the air is pushed through the layer voids, avoiding air compression under the tire [90]. The increased viscoelastic characteristics asphalt rubber friction courses come from a high asphalt binder content and, possibly, from the inclusion of crumb rubber [90].

In the case of poro-elastic road surfaces, pavement materials are designed with a minimum rubber content of 20% by weight: this is believed to lower pavement stiffness and to lead to a decrease of tire/pavement noise [55].

The target of a very low stiffness is difficult one to meet, as durability of such soft pavements can be highly compromised [62].

3.1.4 Age effect of the surface on tire/pavement noise

Acoustic characteristic of a road pavement change over its service life. For some pavement surface, the effects can be rather small, for others it may be significant [3]. Generally, acoustic performance of road surfaces tends to stabilize after an initial period of 1 to 2 years of trafficking [55]. Quieter road surfaces tend to increase tire/pavement noise over this initial period, whereas surfaces, which exhibit initial higher levels of noise, tend to remain stable or have even shown some noise reductions [55] [3].

However, after this initial period of stabilization, some surfaces can exhibit significant increases in noise, particularly as the surface reaches the end of its life [55]. Age and presence of distress generally increase the overall noise levels [8], especially vibration generated noise [9].

As the pavement gets older, the following phenomena can occur [3] [9] [91] [92] [93]:

- structural damage and distresses, such as aggregate polishing, ravelling, cracks, potholes, bitumen bleeding;
- aggregates can break, pull-out or smoothen;
- mega- and macrotexture modifications due to traffic compaction and environmental factors;
- microtexture modifications, mainly due to polishing effect of tires passing over the surface;
- pavement stiffness modifications due to traffic compaction;
- clogging of air voids in porous wearing courses;
- chemical effects of weather and road salts.

Severe ravelling after long periods of heavy trafficking, cracking and the hardening of the bitumen due to long-term exposure can all contribute to higher levels of tire/pavement noise of AC pavements. Cement concrete surfaces can also exhibit similar characteristics: grooved concrete, after a period of heavy trafficking, can show fraying of the grooves, resulting in shallow/wider spacing that can cause higher noise levels [94] [55].

For porous pavement, voids tend to clog and this generally leads to increases of the noise generated from air pumping [95] [9]. The use of de-clogging machines using high-pressure water can only been partially successful. Double-layer porous systems have proved to be more successful, though, than single porous layers [55].

Bitumen bleeding can also lead to changes in the noise emission [9]. In asphalt pavements, as the bitumen film is worn off by the traffic, the effects on noise of this initial bitumen film is not clearly documented, since most noise measurements are usually conducted when this film has been already worn off [9] [96].

The impact on noise caused by the presence of a distress, is usually quite localized in the nearby area: a few ten meters back and in front of the area affected by the distress, the noise level is not affected [9] [97]. However, previous studies have determined that, as the pavement gets older, noise levels from asphalt pavements usually increase even before significant pavement deterioration begins to occur [9].

Some factors that might influence acoustical aging of road pavements before significant pavement distresses occur can be the following ones [9]:

- excessive “post” compaction because of traffic load;
- aggregates can be pressed further down in the mortar and the openness of the surface structure is reduced;
- change in the orientation of the aggregate because of traffic loads;
- clogging in the open structure of communicating pores in the upper part of porous pavement layers;
- average driving speed might have an influence on the clogging process;
- ordinary pavement maintenance and cleaning operations;

- in the event of patchwork pavement repair, surface structure can be modified;
- snow and ice removal procedures, salting, and ploughing, which can potentially influence the surface structure;
- studded tires and/or snow chains have an effect on the surface structure and can create distresses;
- meteorological conditions like rain water, sun, snow, freeze-thaw and oxidation;
- ultraviolet radiation from the sun.

Besides age, some of the indicators could be relevant in evaluating the effects of pavement age on acoustic performance. These indicators can be [9]:

- accumulated traffic load on relevant driving lane [total vehicles/lane/year],
- Accumulated light vehicles on relevant driving lane [light vehicles/lane/year].
- accumulated heavy vehicles on relevant driving lane [heavy vehicles/lane/year].
- traffic speed and acceleration/deceleration, including geometric parameters.

Climate zone, winter maintenance procedures and the use of studded tires and/or snow chains can also potentially define some basic parameters that influence the tire pavement noise emission over time [9].

Previous studies carried out by the Arizona Department of Transportation (ADOT) involving acoustic characteristics of Asphalt Rubber Friction Courses (ARFC) with different ages, observed a noise increase in CPX measurements of about 0.55 dB per year [9]. Another American study carried out by the Department of Transportation in Washington State, involving different dense-graded asphalt concrete and open graded noise reducing pavements, observed an average noise increase in OBSI measurements of 1.8 dB(A) per year for dense-graded AC pavements and of 3.6 dB(A) per year for open graded AC pavements [9].

A research carried out in Norway on newly laid pavements, in areas where use of studded tires is common and with long winter season, observed a noise increase of 2-4 dB(A) just after the first winter. In the following years, the increase was about 0.5-1.0 dB(A) per year, as depicted in Figure 3.5. In the image, CPX test results at 50 km/h are shown with respect to pavement age.

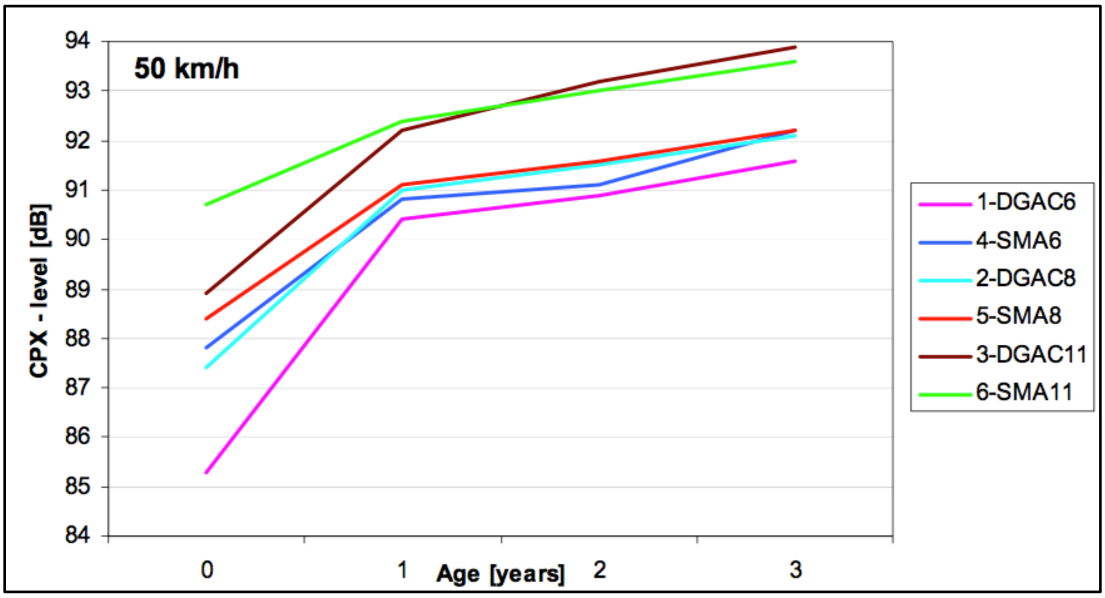

Figure 3.5 CPX measurements at 50 km/h and age of various AC pavements in Norway [9].

In the European SILENCE project, for which a series of CPX noise measurements were performed on asphalt pavements with different kinds of distress, a difference of 2-3 dB(A) was observed between a pavement section with severe alligator cracking and a section with no distresses and the same pavement type [96] [9].

Studies carried out in France on porous asphalt and conventional AC pavements observed that a great part of porous surfaces showed a noise level increase for light vehicles of about +5.5 dB(A) between 1 and 10 years. Conventional AC pavements provided increase in noise levels of about +3 dB(A) between 1 and 7 years [55].

3.2 Environmental effects on tire/pavement noise

Many factors can cause differences in noise measurements on similar pavement types, and they can be due to a combination of environmental, tire, loading and vehicle/operator variables [10]. Some environmental factors can affect tire/pavement noise in different ways and with different degrees of influence.

Wind conditions, for instance, can create air turbulence noise in the microphones, producing high background noise levels at low frequencies. Therefore, measurements should not be taken when the wind speed exceeds 5 m/s and appropriate protective devices, such as windscreens, should be used. Aerodynamic effects due to air turbulence induced by wind can also occur around the testing vehicle: whereas this contribution is not assumed to be significant at speeds below 120 km/h for cars and 90 km/h for heavy trucks, this issue has not been studied sufficiently yet. Furthermore, refraction of sound can occur due to temperature and wind vertical gradients and, as a consequence, sound propagation may be diverted [3].

Regarding air humidity, no effects has been reported on tire/pavement noise, as long as the humidity is not so high as to cause water to condense on the road surface [3].

Tire/pavement noise can also be influenced by temperature [3]. Previous studies in AC pavements have shown decreased noise levels at the tire/pavement interface with increasing temperature, whereas mixed results were found in PCC pavements [11].

3.2.1 Air and Pavement Temperature effect on tire/pavement noise

Pavement temperature is directly related to air temperature and it can play a significant role in the final acoustic behaviour of AC pavements. Besides, tire temperature can also be significant: rolling tires, in fact, increase their temperature due to different mechanisms of friction, until a constant value that depends on the type of tire, on the pavement temperature and on its surface texture [98].

Temperature effect on road pass-by noise attested a smaller effect on PCC road surfaces than asphalt ones: for bituminous surfaces, the effect can be higher on dense asphalt pavements than on porous surfaces [99].

A wide range of tire/pavement noise variations due to temperature has been observed in the literature. For instance, a previous research observed that an increase in pavement temperature leads to a reduction of tire/pavement noise levels up to 0.12 dB(A)/°C for AC surfaces [98] [100]. Other studies involving tire/pavement noise at 50 km/h of semi-dense asphalt pavements, quantified a decrease in sound levels equal to 0.06dB(A)/°C [98].

A Dutch study involving several tyre/road combinations, including truck tires, measured air temperature coefficients equal to 0.04 and 0.13 dB(A)/°C on two dense bituminous road surfaces, whereas lower values have been obtained for porous bituminous road surfaces, between 0.02 and 0.05 dB(A)/°C. Air temperature coefficients between 0.05 and 0.13 dB/°C have been observed on three cement concrete road surfaces, with the same set of tyres [99] [100].

In the European Directive on tires 2001/43/EC, the required temperature coefficients relative to pavement temperature depends both on the tire and the temperature: 0.03 dB(A)/°C above 20 °C, and 0.06 dB(A)/°C below 20 °C for passenger car tyres, whereas it is equal to 0.02 dB(A)/°C for light commercial truck tires, and null for heavy commercial truck tires [102].

Another study [99] noted a small temperature effect on cement concrete road surfaces, with a temperature coefficient of 0.03 dB(A)/°C. The authors of this study specified that this particularly small effect may be due to the relatively smooth texture of the two concrete surfaces tested. The same study observed a linear variation of pass-by noise for dense bituminous surfaces, with an overall temperature coefficient of 0.1 dB(A)/°C with respect to air temperature and equal 0.06 dB(A)/°C with respect to pavement temperature. In the case of porous asphalt surfaces, the authors quantified a lower temperature effects on tire/pavement noise, calculating an air temperature coefficient of 0.06 dB(A)/°C and of 0.04 dB(A)/°C with respect to pavement temperature [99].

A Danish-Californian study, involving OBSI noise testing on various pavement types, reported no big difference between temperature corrections for dense graded asphalt and open graded asphalt. For the former, an air temperature coefficient equal to-0.061 dB/°C was measured, whereas for the latter, the coefficient was equal to -0.052 dB/°C. The correction factor for cement concrete pavements was observed as equal to -0.043 dB/°C, lower than that for AC pavements [101].

Overall, noise levels were observed to decrease from 0.001 dB(A)/°C to 0.14 dB/°C with respect to air temperature and it has even been mentioned that a positive coefficient has been observed with a specific tire [3], concluding that there is no generic law applicable to all the tires on the market [3] [99].

The pavement temperature is believed to influence the medium and high frequency noise and the mechanisms responsible for sound generation. Some authors believe that this phenomenon can be due to a reduction in impact and vibration mechanisms resulting from a decrease in the stiffness of the asphalt surface [98]. Other studies reported that spectral analysis of pass-by noise measurements showed that the effect of temperature on noise emissions is important at low frequencies and at high frequencies above 1kHz, whereas it is minimal in the medium frequency range [99].

Temperature effect can therefore be related to generating mechanisms rather than propagating mechanisms: at lower frequencies the effect can be explained by a reduction in road and tire stiffness when temperature increases, while the effect at higher frequencies could be explained by adhesion sensitivity to temperature [98] [99]. In AC pavements, some authors have also observed that the higher the temperature, the more viscous the material and tire, leading to a lower tire/pavement noise [90].

Hence, some general observations regarding temperature corrections to tire/pavement noise measurements can be summarized as follows [101]:

- the air temperature has an important influence on the tire/pavement noise test results;
- tire/pavement noise can be approximated as linearly dependent on temperature;
- the temperature coefficient varies significantly for different tire types;
- the temperature coefficient is generally smaller for heavy vehicles than for light vehicles;
- at low frequencies, the temperature coefficient is generally low, whereas it is higher at frequencies above 1000 Hz. The temperature coefficient is also different for different pavement types.
- the temperature coefficient seems to be lower for cement concrete pavements than for asphalt concrete pavements;
- the difference in temperature coefficients is different within asphalt pavement types and almost vanishes when many different tires are considered;
- the temperature coefficient appears to be higher for dense asphalt concrete than for open/porous asphalt pavement.

However, although noise level increases as the air and the tires and pavement gets colder, this increase is not at always so large that it can explain some increases observed in winter periods [9]. Research has been unanimous to conclude that there is a general tendency that the tire/pavement noise levels decrease a little in the summer periods, probably due higher temperature in the summer.

Conclusions

Tire/pavement noise is caused by a set of interaction between the tire and the road surface. This interaction leads to vibrational and aerodynamical effects involved in noise generation and amplification mechanisms.

Low-noise surfaces and quiet pavements are designed to minimize tire/pavement noise and to operate on its mechanisms to reduce noise at the source. This objective can be achieved by a specific pavement design, which takes into account all the wearing course characteristics that affect tire/pavement noise, such as pavement materials, surface texture, porosity, and other characteristics related to the selected pavement type.

Other aspects significantly involved in tire/pavement noise are pavement age and environmental conditions, especially air and pavement temperature.

Research is still in progress on these topics and further insight is needed to achieve a complete knowledge of the acoustic behaviour of asphalt and cement concrete pavements over their service life.

4 CASE HISTORY 1: ACOUSTIC CHARACTERISTICS OF COLD-LAID MULTIPURPOSE MICROSURFACINGS

INTRODUCTION

Slurry microsurfacing is an economical maintenance intervention that provides effective skid resistance and surface evenness within a thin layer, improving road safety [84] [103]. The Department of Civil, Chemical, Environmental and Materials Engineering has developed, in collaboration with Valli Zabban S.p.A., Krause Italia S.p.A. and the municipalities of Crespellano, Ozzano dell'Emilia and the Province of Bologna, an innovative application of slurry seal, capable of gathering in a single material various technical solutions to fulfil both functional and environmental aspects.

The purposes of this innovative material are: restoring skid resistance, sealing surface cracking, reducing tire/pavement noise, including crumb rubber from tires as a recycled material and reducing atmospheric emissions by means of the cold-laying technique. The possibility has also been explored of using porphyritic aggregate, as an alternative to the conventional basaltic one, to improve the aesthetic characteristics of the material, due to the reddish colouring of the aggregate.

The objective of this case study is to evaluate how the use of innovative materials and optimized surface texture can impact on tire/pavement noise. For this purpose, surface texture and roughness evaluation has been carried out with the volumetric method and with a 3D laser scanner, while skid resistance testing has been done with the skid tester to calculate the British Pendulum Number (BPN). Tire/pavement noise evaluation has been carried out with the Statistical Pass-by (SPB) method before and after paving to compare the acoustic characteristics of the existing pavements with the new microsurfacing.

The experimentation has been divided into the following steps:

- pre-qualification of the materials and the mix design in laboratory to select the mixtures with suitable mechanical performances;
- in-situ testing to evaluate skid resistance performance, surface texture and tire/pavement noise characteristics of the existing pavements;
- laying of selected mixtures;
- repetition of skid resistance, surface texture and noise testing;
- data analysis on test results to compare before and after paving scenarios.

4.1 MIX DESIGN

The mix design phase was based on physical considerations related to noise generation and amplification mechanisms. Various bituminous mixtures for cold-laid microsurfacings have been designed and tested in laboratory: they contained either basalt aggregates or both porphyry and basalt aggregates. In some mixtures, a fraction of crumb rubber was also included equal to 1.5 % on the mixture weight. Then, they were mixed with Portland cement, which would act as a catalyst, water and 60% bitumen emulsion modified with latex.

Figure 4.1 depicts the basaltic and porphyritic aggregates used in the preliminary lab test to select mixes for multipurpose microsurfacings.

Figure 4.1 Basaltic and porphyritic aggregates used in the mixes for cold-laid multipurpose microsurfacings.

In Figure 4.2, there are depicted crumb rubber used in some of the mixes, the latex to modify the bituminous emulsion used in the preliminary lab tests, as well as the addition of the emulsion mixtures for lab tests.

Figure 4.2 Crumb rubber (left), addition of latex to the emulsion (centre) and bituminous emulsion added to lab mixes (right).

The bituminous mixtures have been studied by varying the aggregates type and gradation, as well as the contents of rubber and binder. Gradation has been modified by varying the maximum size of the coarse aggregate, limited to 8 mm, to achieve a particle size distribution as discontinuous as possible. Modifying the content of rubber and the percentages of cement and bitumen emulsion has also varied the mixture stiffness. In Figure 4.3, gradation curves are displayed of the mixtures with only basaltic aggregates (BB) and with both basaltic and porphyritic aggregates (BP).

The mix design phase started analysing the design characteristics of the conventional asphalt concrete with basaltic aggregates. Therefore, the minimum content of basaltic sand has been quantified, necessary for the development of the asphalt concrete consistency, as well as the minimum amount of bitumen emulsion. For this aspect, the low affinity between crumb rubber and bitumen was a major factor, compared to the porphyritic and basalt aggregates.

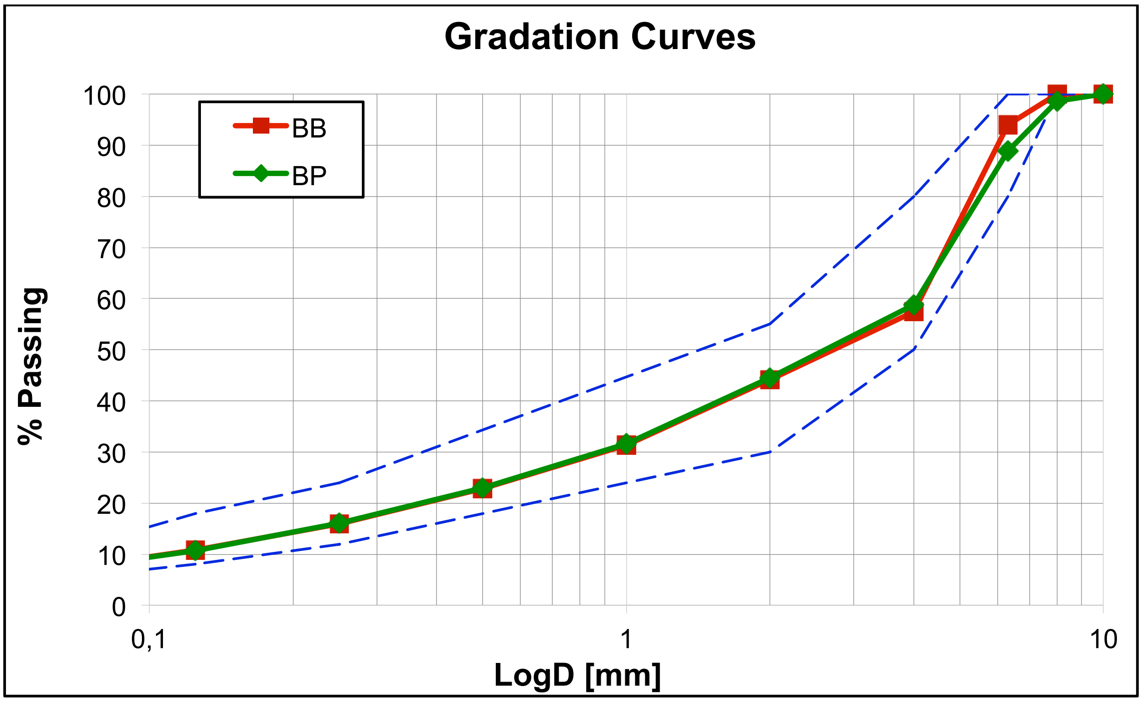

Figure 4.3 Gradation curves of the mixtures.

The time necessary for the slurry emulsion to begin breaking has been measured for each mixture. Characteristics of consistency and the quality of the aggregate bituminous coating have also been evaluated.

Four mixtures have been selected for the in-situ application: one with only basaltic aggregates, one with basaltic sand and porphyritic coarser aggregate, and the same two mixtures, where a part of the sand fraction has been replaced by crumb rubber. The mix design characteristics are reported in Table 4.1.

Table 4.1Mix design of the selected mixtures

Mixtures	% 0/3 mm basalt	% 4/8 mm basalt	% 4/8 mm porphiry	% crumb rubber on total weight of the mixture	% cement on total weight of aggregates	% emulsion on total weight of aggregates	% water on total weight of aggregates	breaking time [sec]	initial time for grip [min]
KmodBB	50	50	0	0	1.0	12.0	7.0	195	5'
KmodBBp	47	50	0	1.5	1.0	14.0	7.0	215	5'
KmodBP	50	0	50	0	1.0	13.0	7.0	195	5'
KmodBPp	47	0	50	1.5	1.0	14.0	7.0	195	5'

As it can be observed in the table, mixtures with coarse porphyritic aggregates have a percentage of emulsion 1% higher than the mixtures with only basaltic aggregates. This is due to the fact that porphyry has a lower affinity to bitumen than basalt and additional emulsion was required to satisfy the preliminary tests. The same happens with crumb rubber, where an additional 2% of emulsion was required, compared to the 12% in mixtures with only basalt and to the 13% in mixtures with basaltic and porphyritic aggregates.

The four selected mixtures provided the best performances to the preliminary laboratory tests amongst all the mixtures. They provided the same initial setting time, equal to 5 minutes and a very good evaluation to the consistency test, as defined by the International Slurry Surfacing Association (ISSA) Standard TB-102 [104]. The consistency test can be highly dependent on the manual ability of the operator: however, it is considered to be a quick and simple test providing a reliable initial indication about the strength of the mixture and about the affinity between the bitumen and the aggregate. Values of the all specimens indicated a satisfactory mix design.

Specimens also showed an aggregate covering which can be visually evaluated as a percentage of 100% in the mixtures of only basaltic aggregates and of 75% in the basaltic and porphyritic mixtures.

In Figure 4.4, two mixture specimens are depicted: one represents a specimen at the end of the consistency test (ISSA TB-102), the other shows the full aggregate covering of a mixture specimen with only basaltic aggregates.

An initial verification of time required for traffic opening can be measured for slurry seals by means of the ISSA Standard TB-102: this was recorded after 40 minutes and attested that all the tested mixtures can be successfully used when a fast intervention is required.

Additional tests were carried out to evaluate the physical and geometrical properties of the aggregates: these tests were the Sand Equivalent Test (ES) (UNI EN 933-8) [105], the Methylene Blue Test for fine aggregates (MB) (UNI EN 933-9) [106] and the Los Angeles Test (LA) to determine the resistance to fragmentation (UNI EN 1097-2) [107].

Figure 4.4 Specimen used in the Consisency Test (left) and aggregate covering of a basaltic-mixture specimen (right).

The MB test was performed only on fine basaltic aggregate, being it the same for all the mixtures. The Value of Blue (VB) resulted equal to 3.3 g/kg. The ES test, also performed only on the fine basaltic aggregate, returned an average percentage rate equal to 67.3%. The LA test gave a weight loss of 18% for basaltic aggregate and 20% for the porphyritic one.

Cohesion Tests (UNI EN 12274-4 and ISSA TB-139) [108] [104] and the Wet Track Abrasion Tests (UNI EN 12274-5 and ISSA TB-100) [109] [104] were performed to characterize the bituminous slurries and to select the mixtures with the best physical and mechanical performance. In Figure 4.5, pictures of the Wet Track Abrasion Test and the Cohesion Test are shown.

Test results of the Cohesion Test showed that all the tested specimens returned positive results, providing strong cohesion to the surface torsion force. Wet Track Abrasion Test results attested that for all the mixtures the values are within the limit of acceptance, established by the ISSA standard [104] as 538 g/m^2. Values were recorded of about 220 g/m^2, with the sole exception of the PB mixture, providing a value of about 380 g/m^2.

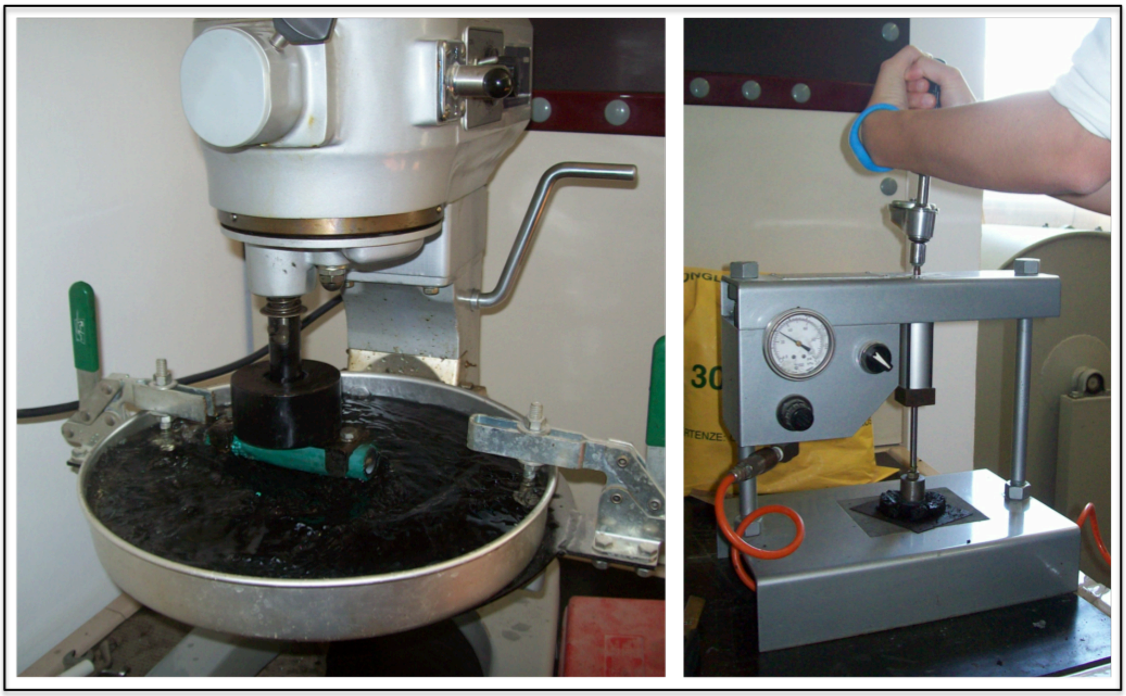

Figure 4.5 Wet Track Abrasion Test (left) and Cohesion Test (right).

4.2 DESCRIPTION OF THE TEST SITES

Three road stretches have been made available by as much Municipalities for the purposes of this research. Every section has different geometric and traffic characteristics, which allow evaluating the durability and the effectiveness of the tested materials with time.

The characteristics of the three road sections are the following:

- IV November street in the municipality of Crespellano. The road stretch is about 180 m long and between 5.45 and 5.75 m wide. It has two lanes, one per direction. The pavement surface appears homogeneous, with some transverse cracking, crossing the entire pavement section;
- E. Nardi street in the municipality of Ozzano dell'Emilia. The road stretch is about 245 m long and 9 m wide. It has a single carriageway with one lane per direction of travel, with sidewalks on both sides. Intermittent patching can be observed along the road stretch;

- Provincial Road nr. 4 "Galliera", belonging to the Province of Bologna and crossing the municipality of San Giorgio di Piano. It is about 500 m long and between 7.30 and 7.50 m wide. The road has two lanes, one per direction of travel and quite a high traffic flow, as it is a major transport collector to Bologna.

Every section is located in a sensitive context, because residential areas, schools and commercial sites are located in the areas adjacent to the roads. A reduction of tire/pavement noise would therefore be particularly perceived by local communities and prioritized by municipalities. A front view of the three road stretches can be observed in Figure 4.6.

Figure 4.6 View of the experimental road sections in Ozzano dell'Emilia (left), Crespellano (centre) and San Giorgio di Piano (right).

4.3 TESTING METHODOLOGY: FRICTION, TEXTURE AND NOISE

The testing methodology to evaluate the wearing course characteristics of the experimental multipurpose microsurfacing, compared to the existing pavements, consisted of carrying out testing surveys before and after the microsurfacing was paved. The same procedure was made to assess tire/pavement noise characteristics.

Some standard tests were selected to evaluate the pavement wearing course characteristics. These tests are: the Sand Patch Test (HS) to measure the average surface macrotexture with the volumetric method (UNI EN 13036-1 and ASTM E 965) [110] [86], and the test of the British Pendulum Number (BPN), also called as Pendulum Test Value (PTV), (UNI EN 13036-4 and ASTM E 303) [111] [112] to measure the surface skid resistance.

The BPN and HS tests were performed following a pattern consisting of 10 longitudinally-equidistant road points, located for both runs and selected as to cover the entire road stretch.

The Statistical Pass-By (SPB) method was selected as a standard test to investigate tire/pavement noise characteristics. SPB method is representative of the actual perception of road noise by receptors located close to the road. For these measurements, a sound level meter was placed roadside, 7.5 m from the lane axis and 1.2 m above the ground.

According to the standard [70], the sound level meter measures the peak value of A-weighted sound pressure levels recorded for each vehicle passing-by. Hence, sound level meter shall be placed in a straight, flat stretch of road and in an area without sound reflecting obstacles. Background noise shall be negligible compared to the sound peak at the time of the vehicle passage.

The SPB Standard requires the measurement of at least 100 cars and 80 trucks (30 dual axes and 30 multi-axes), driving within the selected reference speed range. Since the road sections were located in urban areas, the lower speed range was selected of 45-64 km/h.

To achieve a high consistency of the noise tests, while complying with the standard requirements, a specific vehicular sequence was set in addition to the existing road traffic. The vehicle sequence was composed of both light and heavy vehicles and it was used in every site. Driving speed was set by on-board cruise control devices. Vehicle speeds were also verified by a speedometer in the experimental site of San Giorgio di Piano: the speedometer was placed on the centreline of each run.

A route was chosen in every test site for the vehicle sequence, so that each vehicle of the sequence would be able to pass by the Sound Level Meter at a speed included in the speed range, avoiding speedups and decelerations within 30 meters before and after the device.

In Figure 4.7, there are represented both the route run by the vehicle sequence and the location of the roadside measurement point in Ozzano dell'Emilia.

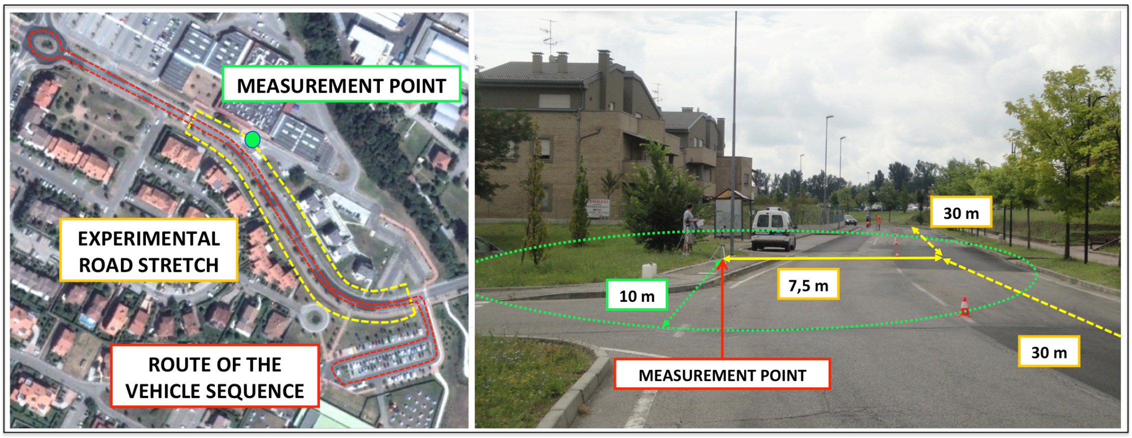

Figure 4.7 Route of the vehicle sequence (left) and measurement point (right) in Ozzano dell'Emilia.

Finally, additional surface texture tests were carried out on the multipurpose microsurfacing in every test site. For these measurements, four test points were selected close to the sound level meter location, two points per run.

4.4 PAVING OF MULTIPURPOSE MICROSURFACING

The laying of the multi-purpose microsurfacings has been carried out according to the conventional technique. In each experimental site, a sole aggregate mixture had been selected to be laid in one lane. Crumb rubber was added in the mixture for the remaining lane: hence, it was possible to evaluate the effects of the addition of crumb rubber, surrounding and operating conditions being equal.

In the road stretch of San Giorgio di Piano basaltic mixtures KmodBB and KmodBBp have been used, whereas in Crespellano and Ozzano dell'Emilia basalt and porphyry mixtures KmodBP/KmodBPp have been laid.

A specific dispenser of the mixer-spreader machine has been used to include crumb rubber into the mixture.

In each site a double layer has been laid, composed as follows:

- a first a basaltic microsurfacing 0/4 mm to regularize the existing pavement surface;
- a multi-purpose microsurfacing 0/8 mm according to the respective mixture selected at the mix design phase.

In Figure 4.8, there are depicted a close-up picture of the microsurfacing in San Giorgio di Piano and a picture of the construction phase in Ozzano dell'Emilia.

Figure 4.8 Close-up picture of the multipurpose microsurfacing (left) and construction phase in Ozzano dell'Emilia (right).

Unexpected problems occurred during in Crespellano at the construction phase, mainly due to a sudden decrease in air temperature, from 30°C to 19°C, and to the not yet perfectly calibrated paving technique. These factors may have affected the actual emulsion settlement conditions and, as a result, this, a major aggregate loss occurred in Crespellano in the within a few days after paving, compared to the other two experimental sites. Whereas a certain aggregate loss is usually typical for cold-laid microsurfacings, in Crespellano that loss was a little higher than in the other sites.

With respect to the typical characteristics of slurry seals, construction works were brief and regular traffic opening was prompt on both lanes. Therefore, inconvenience for road users was minimal. An view of the microsurfacing about one month after construction is shown in Figure 4.9 for all the experimental sites.

Figure 4.9 Multipurpose microsurfacing in Crespellano (left), Ozzano dell'Emilia (centre) and San Giorgio di Piano (right).

4.5 <u>TEST RESULTS AND DATA ANALYSIS</u>

Skid resistance and surface texture tests were carried out approximately one month after construction on every experimental site, according to the testing methodology previously described. Test results have been compared to evaluate how wearing course characteristics and tire/pavement noise changed due to the laying of the multipurpose microsurfacing, assuming the same operating and testing conditions.

4.5.1 SKID RESISTANCE AND SURFACE TEXTURE

Test results confirmed that the tested pavements provided acceptable values of BPN and macrotexture, attesting that all the pavements were still in conditions of safety, even though they would require a rehabilitation treatment in near future. The experimental road sections, thus, were all suitable for the application of microsurfacing to enhance friction.

After an apt time lag of about one month, during which the experimental pavements had been open to regular traffic, the final stage of the experimentation was ready to be completed by carrying out post-paving tests.

By a direct comparison between pre- and post-paving data of all the three experimental sites, it can be observed that pavement surfaces underwent an increase in values of BPN and macrotexture with the application of the multipurpose microsurfacings. The peak in BPN enhancement can be observed in Ozzano dell'Emilia, where values increased of about 16.6 BPN units. The maximum increase of HS values occurred in San Giorgio di Piano, equal to 0.56 units. Test results of BPN and HS are reported in Table 4.2.

Table 4.2 Test results of BPN and HS

Indicator	Crespellano		Ozzano dell'Emilia		San Giorgio di Piano	
	KmodBP	KmodBPp	KmodBP	KmodBPp	KmodBB	KmodBBp
BPN before	57.3	60.0	54.1	55.1	60.7	55.0
BPN after	72.5	71.5	70.7	61.9	67.1	68.4
HS before	0.59	0.55	0.78	0.75	0.53	0.45
HS post	0.93	0.97	0.85	0.89	0.98	1.01

Additional surface texture testing was carried out by means of 3D portable triangulating laser scanner. In each experimental site, four sample areas were identified: two points per run and all close to the measurement point for the noise testing. The four points were also located on the zones having the highest probability to be part of the wheel track.

The triangulating laser scanner can measure, in a suitable reference system, the coordinates of all the points in which, under the specifications of the instrument, it is possible to discretize the targeted surface. The results consist of a point cloud of three-dimensional points, which can be turned into a mesh, i.e. a continuous digital copy of the real surface, by applying triangulation algorithms to the point cloud.

The laser scanner was set on the “macro” mode, corresponding to an accuracy of 0.127 mm on the measured coordinates, a field of view of 13x10 cm on the object and an operating distance from the pavement of about 20 cm.

In Figure 4.10, the location of the four measurement points in San Giorgio di Piano and the 3D representation of one of the four scanned areas are represented.

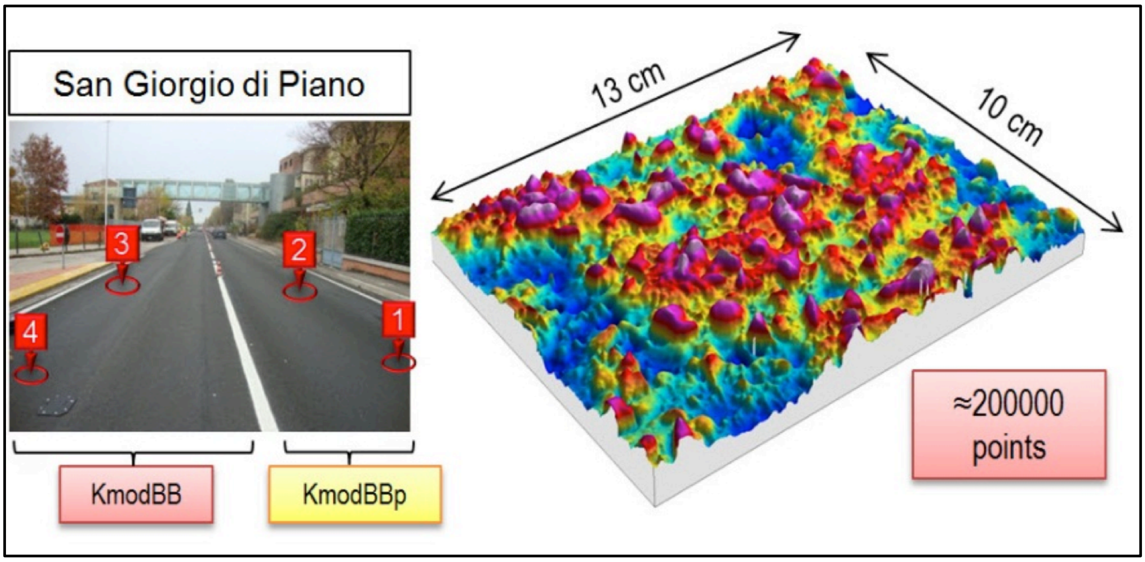

Figure 4.10 Measurement points in San Giorgio di Piano (left) and 3D representation of one of the scanned areas (right).

Test were performed to obtain a 3D representation of the analyzed surface, by which it is possible to calculate some indicators of classical 2D approach, according to ISO 13473-2 [113], as well as their respective 3D counterparts. By means of laser scanner, in fact, it is possible to extend the 2D approach to a 3D level, calculating the indexes not just on profiles, but considering the entire 3D scan.

The Mean Profile Depth (MPD) index is the result of an average of two points on a single profile. Roughness (R_a) can be defined as the ratio between the area and the length of each profile, calculated on 9 profiles. Other indexes are the Skewness (R_{sk}) and the Kurtosis (R_{ku}) calculated on profiles as required by the ISO 13473-2 standard.

Test results are reported in Table 4.3: in the table, S_a, S_{sk} and S_{ku} represents, respectively, R_a, R_{sk} and R_{ku} parameters calculated on a surface, instead that on a 2D profile. Maximum MPD values are observed in San Giorgio di Piano: the same occurs for Roughness.

Statistical Skewness expresses the asymmetry of the distribution curve of roughness: when it is close to zero, as it happens in all sites, the distribution of peaks and valleys of the surface texture profile is almost symmetric.

Kurtosis, instead, expresses the flattening index of the surface profile: it can be lower, higher or equal to 3. If the value is higher than 3, the distribution curve is more pointed, suggesting that the corresponding surface texture can be considered less uneven. On the contrary, values lower than 3 suggest an uneven surface texture. Test results obtained by 3D Laser scans are reported in Table 4.3.

Table 4.3 Laser Scanner test results

	Surface Texture Index	**Crespellano**		**San Giorgio di Piano**	
		KmodBP (1,2)	KmodBPp (3,4)	KmodBB (3,4)	KmodBBp (1,2)
D^2	MPD [mm]	1.06	1.05	1.24	1.27
	R_a [mm]	0.42	0.45	0.48	0.57
	R_{sk}	0.03	-0.46	0.14	-0.15
	R_{ku}	3.09	3.31	2.99	2.41
D^3	S_a [mm]	0.47	0.49	0.52	0.60
	S_{sk}	0.05	-0.48	0.15	-0.13
	S_{ku}	4.01	3.25	2.98	2.81

In San Giorgio di Piano, both materials KmodBB and KmodBBp have an index lower than 3, whereas in Crespellano there is a discontinuity between the two lanes and the values range up to 4 for the KmodBP mixture.

Surfaces with S_{ku} values higher than 3 show lower values of MPD, Sa, and Ra: it expresses sparse presence of coarse aggregates, causing a smooth texture.

Therefore, according to the previous indexes, the tested pavements in San Giorgio di Piano have potentially the largest contact patch at the tire/pavement interface.

4.5.2 TIRE/PAVEMENT NOISE

Noise testing was carried out with the Statistical pass-by (SPB) method before and after the microsurfacing was paved in every test site. Post-paving tests were performed about one month after the intervention.

In Figure 4.11, post-paving SPB measurements are displayed in San Giorgio di Piano, along with a close-up view of the sound level meter.

Figure 4.11 SPB noise testing in San Giorgio di Piano (left) with a close-up view of the sound level meter and its display (right).

According to the SPB standard [70], the statistical pass-by index was calculated for every pavement type in order to provide an objective value to compare different pavements. The index is not an equivalent sound pressure level, but can be used to describe the relative influence of the road surface of such levels of a standard mix of light and heavy vehicles [70].

The SPBI is calculated as follows:

$$SPBI = 10 \cdot Log_{10}\left[W_1 \cdot 10^{\frac{L_1}{10}} + W_{2a} \cdot \left(\frac{v_1}{v_{2a}}\right) \cdot 10^{\frac{L_{2a}}{10}} + W_{2b} \cdot \left(\frac{v_1}{v_{2b}}\right) \cdot 10^{\frac{L_{2b}}{10}}\right] \text{ [dB]}$$

where:

L_1,L_{2a},L_{2b}= Vehicle Sound Levels for vehicle categories at the reference speed;

W_1, W_{2a}, W_{2b}= weighting factors for vehicle categories;

v_1, v_{2a}, v_{2b}= reference speeds of individual vehicle categories.

Vehicle sound levels at the reference speed are calculated for each vehicle category by means of a linear regression analysis of maximum A-weighted sound pressure levels on speed, in a logarithmic scale, for each vehicle pass-by. A regression line shall be fit to the data points for each separate vehicle category by means of the least square method [70]. Then, vehicle sound levels at the reference speed are calculated as the ordinate sound level of the regression line at the corresponding reference speed. For the low-speed category, used in this study, the reference speed is equal to 50 km/h. The method of calculation of the vehicle sound level is represented in Figure 4.12 for the light vehicle category in one of the three experimental site: in the image, the red square corresponds to a random light vehicle, whereas the green dot represents the vehicle sound level L_1 for the vehicle category, based on the performed measurements.

By SPB tests it is possible to evaluate how the multipurpose microsurfacing affects tire/pavement noise reduction in the experimental sites. Test results are reported in Table 4.4: in the table, it can be observed that the maximum reduction in SPBI value is equal to 2.2 dB(A) and it corresponds to the KmodBBp mixture in San Giorgio di Piano, compared to the previous asphalt pavement. Noise reduction of the KmodBB mixture in San Giorgio di Piano, paved on the opposite run, is equal to 0.7 dB(A).

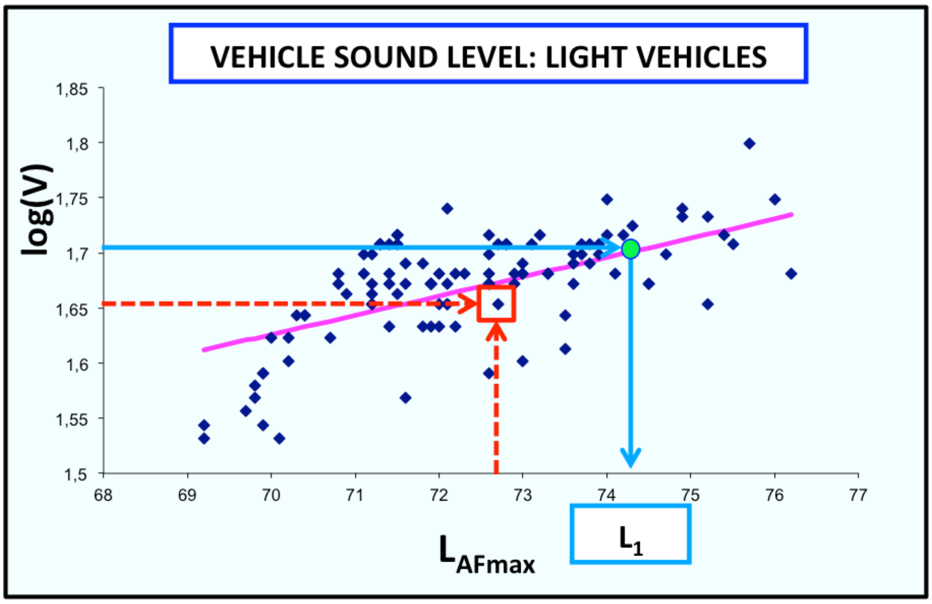

Figure 4.12 Linear regression analysis to calculate vehicle sound levels

In Ozzano dell'Emilia, tests returned similar results for both KmodBP and KmodBPp mixtures: the respective noise reduction is equal to 1.5 dB(A) and 1.6 dB(A), compared to the previous pavement.

In Crespellano, on the contrary, SPBI values remain substantially unaltered. The causes of this lack of noise level decreasing may be related to construction and ambient conditions, aggregate loss after paving, as well as to possible similarities with the acoustic performance of the previous pavement.

Table 4.4 SPB test results

<table>
<tr><th colspan="2"></th><th colspan="4">CRESPELLANO</th><th colspan="4">OZZANO EMILIA</th><th colspan="4">SAN GIORGIO DI PIANO</th></tr>
<tr><th colspan="2"></th><th colspan="2">KmodBP</th><th colspan="2">KmodBPp</th><th colspan="2">KmodBP</th><th colspan="2">KmodBPp</th><th colspan="2">KmodBB</th><th colspan="2">KmodBBp</th></tr>
<tr><th colspan="2"></th><th>Before</th><th>After</th><th>Before</th><th>After</th><th>Before</th><th>After</th><th>Before</th><th>After</th><th>Before</th><th>After</th><th>Before</th><th>After</th></tr>
<tr><td rowspan="2">Light vehicles</td><td>Lveh</td><td>71.3</td><td>71.3</td><td>70.7</td><td>70.6</td><td>69.4</td><td>67.8</td><td>69.9</td><td>69.4</td><td>75.8</td><td>75.5</td><td>75.0</td><td>74.2</td></tr>
<tr><td>Mean speed</td><td>49.0</td><td>50.0</td><td>49.8</td><td>50.1</td><td>50.0</td><td>50.1</td><td>50.0</td><td>50.1</td><td>44.3</td><td>44.4</td><td>43.6</td><td>46.9</td></tr>
<tr><td rowspan="2">Heavy vehicles</td><td>Lveh</td><td>79.8</td><td>79.8</td><td>79.5</td><td>79.7</td><td>77.8</td><td>76.4</td><td>80.2</td><td>77.4</td><td>84.8</td><td>83.7</td><td>84.5</td><td>79.7</td></tr>
<tr><td>Mean speed</td><td>45.5</td><td>45.1</td><td>46.2</td><td>44.9</td><td>45.5</td><td>44.9</td><td>45.7</td><td>44.9</td><td>41.8</td><td>42.0</td><td>40.5</td><td>45.1</td></tr>
<tr><td colspan="2">SPBI</td><td>73.4</td><td>73.4</td><td>72.9</td><td>72.9</td><td>71.4</td><td>69.9</td><td>72.9</td><td>71.3</td><td>78.1</td><td>77.4</td><td>77.4</td><td>75.2</td></tr>
</table>

4.6 WEARING COURSE IMPACT ON TIRE/PAVEMENT NOISE

With respect to the surface texture, the designed multipurpose microsurfacings are more porous than the conventional pavements existing in the three experimental sites before the experimentation. The presence of more air voids in the microsurfacing can provide reduction effects of noise generation mechanisms related to air overpressure in the tire tread voids, involved in air pumping phenomena, as long as the macrotexture is limited to the 1-10 mm range. This condition is verified in all the designed mixtures and can be indirectly confirmed by all the HS test results.

Poor correlations, though, can be observed between BPN and HS values with SPBI tire/pavement noise indicators.

Taking into consideration shape, homogeneity, spacing and orientation of the aggregates, it can be observed that the surface texture of the multipurpose microsurfacing in San Giorgio di Piano has a homogeneous aggregate distribution, whereas in Crespellano the surface texture is less homogenous. Assuming the surface texture of the existing pavements are similar to each other, in San Giorgio di Piano the noise reduction can be considered higher than in Crespellano, taking into account the respective acoustic boundary conditions.

Variations of the pavement stiffness can also be involved in the noise reduction observed in San Giorgio di Piano and in Ozzano dell'Emilia. In fact, assuming that the presence of crumb rubber has reduced the surface stiffness for the miscrosurfacing containing rubber, it can be stated that the addition of this waste to the mixtures can contribute to the noise reduction.

CONCLUSIONS

In this case study, cold mixtures for slurry microsurfacings have been developed combining adequate functional requirements with environmental characteristics related to road noise and to the use of a crumb rubber as a recycled material.

Slurry microsurfacing can be considered an economic maintenance solution capable of extending the life-cycle of the pavement by restoring frictional properties and providing, in this case, a certain noise reduction. Whereas the observed noise reduction is limited, it should be taken into consideration slurry microsurfacing technique is mainly a maintenance intervention of low thickness: therefore, noise reduction should be expected to be lower than that of conventional sound-absorbing porous asphalt.

Test results have attested poor correlation between surface texture and tire/pavement noise, both for BPN and HS indicators. However, laser scanner has turned out to be an useful tool for the roughness characterization of these surfaces and future additional tests can be carried out to clarify possible correlation between some volumetric indicators and tire-pavement noise.

5 CASE HISTORY 2: TIRE/PAVEMENT NOISE OF THE CPATT-TEST TRACK PAVEMENT SECTIONS

INTRODUCTION

Different pavement types can differ for their frictional and acoustic characteristics, for their durability and they can show a different response to age and environmental conditions.

The Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo operates an experimental road to investigate the impact of axle loads and environment on flexible and rigid pavement structure and to compare performance of innovating paving materials.

The CPATT test track is characterized by two loading configurations: the southbound lanes is run by heavy loaded trucks moving garbage, whereas the northbound lane by unloaded trucks, providing information on the impact of loaded trucks on pavements.

In this research, an evaluation of the surface characteristics was carried out of the wearing course and the acoustic performance on long term for the different pavement types. The different sections had been subject to the same load and climate conditions conditions; therefore, this analysis enables evaluating the behaviour of different materials with a consistent relative comparison.

Data analysis and visual evaluation contributed understanding how surface texture and pavement materials influenced tire/pavement noise characteristics on long term.

Visual evaluation permits assessing distribution and severity of surface distresses amongst the sections and between loaded and unloaded lanes.

5.1 CPATT TEST TRACK DESCRPTION AND LOCATION

The CPATT Test Track is located in the Region of Waterloo Waste Management Site and it is a full-scale accelerated research facility, 1294 m long and 8 metres wide. This test road is made of different pavement sections with various asphalt and cement concrete mixes to allow researchers monitoring the performance of each section in the Canadian environment under heavy truck loadings.

A first portion was constructed in 2002 including five sections with various, original asphalt surface mixes: Hot-Laid 3 (HL3), Polymer-Modified Asphalt HL3 (PMA), Stone Mastic Asphalt (SMA) and SuperPave (SUP). In 2007, four conventional Jointed Plain Concrete Pavement (JPCP) sections were added with a varying percentage of Recycle Concrete Aggregate (RCA): 0%, 15%, 30% and 50% respectively. A third portion was constructed in 2009 with a HL3 mix with Recycled Asphalt Shingles (RAS). A plan of the CPATT Test Track sections has been portrayed in Figure 5.1, including a front view of one of the sections.

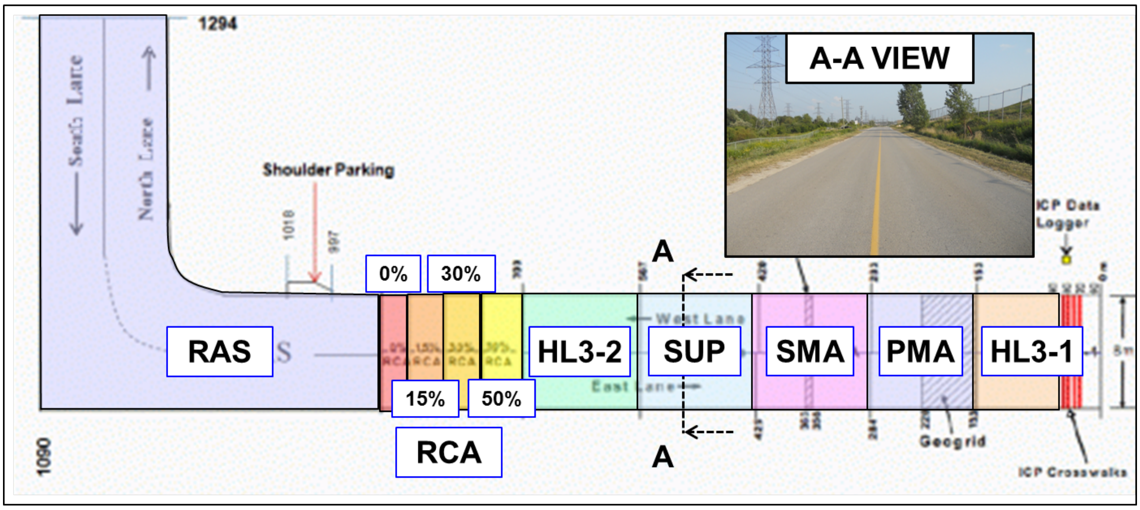

Figure 5.1 Plan view representation of the CPATT Test Track and its sections

The traffic travelling on the test track is mainly composed of heavy vehicles and it includes about 33,500 garbage trucks, running the test track every year on each way.

Their traffic can be equivalent to 149,000 single axle loads (80 kN ESALs) annually in the loaded direction or 4,265,000 ESALs over the pavements 20-year design life.

The pavement structure is quite similar among the flexible sections, as the sole wearing course varies, while the underlying layers share the same materials and thickness. Asphalt concrete wearing courses, in fact, were placed on a 150 mm thick compacted granular material (Granular A) layer and a 450 mm thick of Granular B as a subbase. Subbase and subgrade are separated by a geotextile.

The pavement structure in the rigid sections, instead, is composed of 250 mm of Portland cement concrete, 100 mm of asphalt stabilized open graded drainage layer (OGDL) and 450 mm of Granulal B material, the same as the flexible sections. The two types of the pavement front sections have been depicted in Figure 5.2.

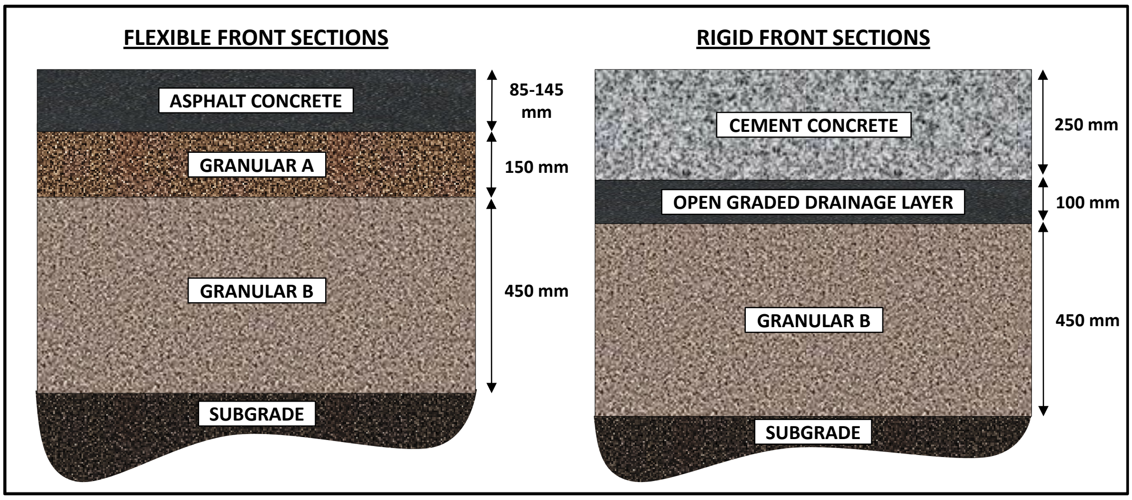

Figure 5.2 Front view representation of rigid and flexible pavement sections.

Layer thickness of every section is summarized in Table 5.1: in the table it can be noticed that only for Stone Mastic Asphalt and Superpave sections, asphalt concrete layer is composed of two layer: their wearing course is made of the respective material and an additional HL3 layer underneath.

Table 5.1: thickness of every pavement section of the CPATT Test Track

PAVEMENT STRUCTURE	Pavement Type									
	RAS	RCA-0	RCA-15	RCA-30	RCA-50	HL3-2	SUP	SMA	PMA	HL3-1
Surface Layers (s) [mm]	145	250	250	250	250	90	50 (SUP) 50 (HL3)	55 (SMA) 50 (HL3)	85	90
Base Layer [mm]	150	150	150	150	150	150	150	150	150	150
Subbase [mm]	450	450	450	450	450	450	450	450	450	450

5.2 WEARING COURSE CHARACTERISTICS EVALUATION

Surface characteristics of the wearing course can affect ride quality, road safety and tire/road noise. Surface distresses can impact road safety and road user behaviour, as well as different levels of surface texture can affect roughness, friction and tire/pavement noise.

Pavement surface has been assessed through visual evaluation, roughness, skid resistance and surface texture measurements: test results of different pavements have been compared. Distress manifestations have been assessed amongst the different sections and, at the same time, their transverse distribution has been observed within the same section.

5.2.1 ROUGHNESS/SMOOTHNESS EVLUATION

The SurPRO 3500 is a rolling surface profiler intended for roads and other mainly plain structures, such as floors and runways. It captures unfiltered true elevation profiles and, as it has co-linear wheels, it is particularly suitable for wheel rut profiling. Its profile accuracy is of ±2 mm/50 m and the operating temperature ranges between 0°C and 50 °C.

Measurements have been taken in every section in the wheel tack of both the North, loaded lane and the South, unloaded one.

Data have been elaborated with the ProVAL software to calculate the International Roughness Index (IRI) (ASTM E-1926-08) [114] for every section with the same pavement type. Within the same section, IRI has been calculated over fixed intervals of 10 meters and results have been subsequently averaged by arithmetic means to quantify the overall value. To calculate the overall value of IRI, the final cut-off segment of every section has been neglected when shorter than 10 meters. This has not happen only in the PMA, loaded lane as the final segment was exactly 10 meters long.

Results have been displayed in Figure 5.3: in the graph data are classified according to the types of pavement and lane. It can be noticed that usually values of IRI are higher in the loaded lane than in the unloaded lane.

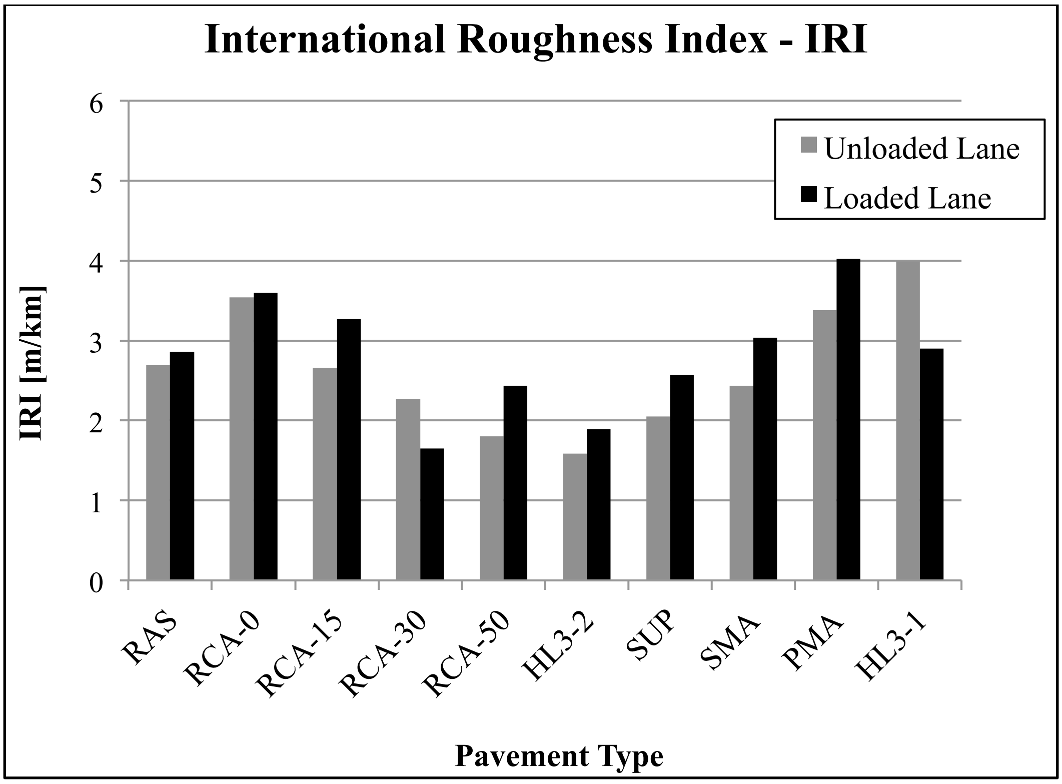

Figure 5.3: Values of IRI for every test section and lane.

The IRI data ranges between 1.59 m/km, measured in the HL3-2 unloaded lane, and 4.02 m/km, measured in the PMA loaded lane. If one considers the overall value of every pavement section (both lanes), IRI ranges from 1.74 m/km in the HL3-2 section, up to 3.70 m/km for the PMA section.

According to the ASTM standard, IRI values below 2.3 m/km are indicative of high quality asphalt pavements, providing comfortable ride at speeds over 120 km/h. Values around 4 m/km can be compared to surfaces without defects, with moderate corrugations or large undulations but still able to provide comfortable rides at high speeds. Thus, all the pavement sections can be considered to have good smoothness, especially by taking into account their age, the loads they are subjected to and the actual use of the facility, where the speed limit is of 40 km/h. The profile test results do not show an evident difference between asphalt and concrete sections. Apart from the RCA-0% section, the Portland cement concrete sections account for some of the lowest IRI values amongst all the test track sections.

5.2.2 MACROTEXTURE AND SKID RESISTANCE EVALUATION

Testing to evaluate surface texture and friction was also completed on all the CPATT test track sections. The Mean Texture Depth (MTD), according to ISO standard 13473-1 [110] and the British Pendulum Number (BPN), according to ASTM standard E303-93 [112] were determined throughout all experimental sections.

Four locations were selected in every test section in order to be representative of the actual conditions perceived by road users. Two points in the wheelpath were selected in each lane, one in each half of the section length.

In order to maintain consistency with the subsequent noise testing program, the four points in the RAS section were all located in the tangential segment parallel to the other test sections.

The skid resistance results have been depicted in Figure 5.4: in the graph, it can be noticed that comparable results have been measured for both flexible and rigid sections.

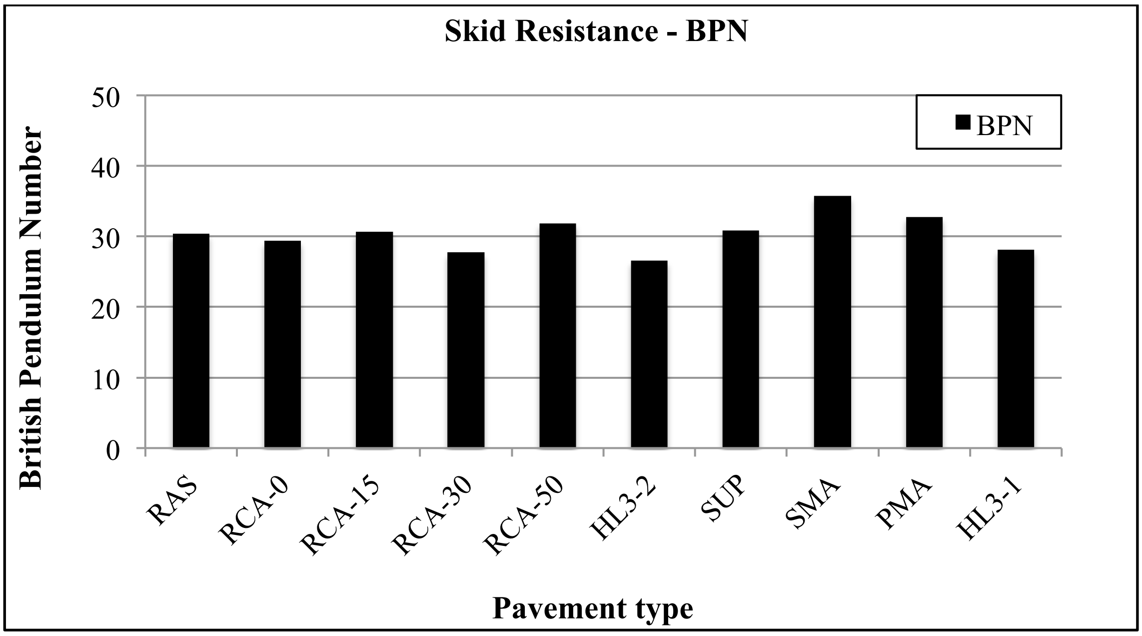

Figure 5.4: Values of BPN for test sections.

Mean texture depth results are represented in Figure 5.5. It can be observed that slightly higher MTD values have been measured in the asphalt pavements, compared to the concrete pavements.

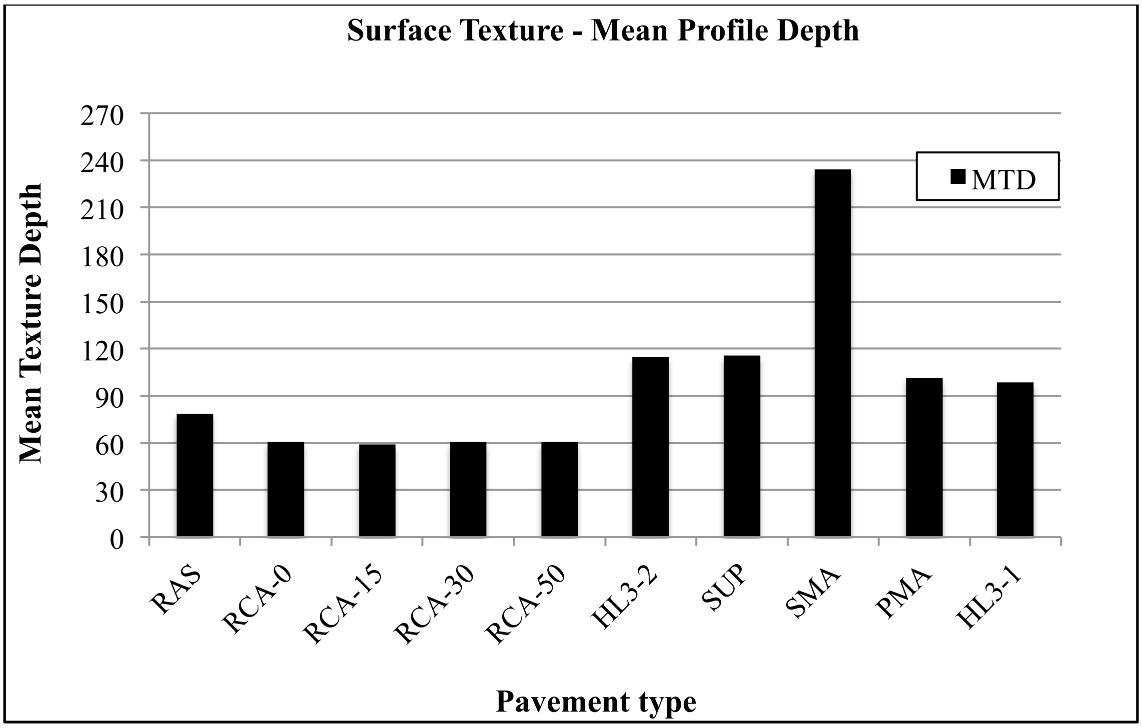

Figure 5.5: Values of MTD for test sections.

Some observations can be made from skid resistance and surface texture data. The peak value for both BPN and MTD values was obtained in the Stone Mastic Asphalt section, confirming the high-quality surface characteristics that are expected from this material, even 10 years since paving. The relatively high values of MTD seen in the SMA are expected if one takes into consideration the peculiar characteristics of this kind of asphalt mix, characterized by a high coarse aggregate content.

The rigid sections all displayed similar results in MTD, but the BPN results were slightly more variable. This observation can be related to the texturing methods applied during paving. Three different texturization methods were applied to the rigid sections. A portion of longitudinal tining was applied to all sections, while small portions of the RCA 30% and the RCA-15% sections were transversely tined. The RCA-0% control section and a small portion of the RCA-15% were textured using a burlap drag, which is a contributing factor to the slightly higher values of MTD results.

From a volumetric point of view, longitudinal and transverse tining does not seem to have a great impact on MTD values, judging from the consistent and expected results. On the contrary, the differences in BPN are likely related to the different surface finishing methods used on these sections.

5.2.3 VISUAL EVALUATION

Visual condition surveys were carried out to evaluate the severity, extent and distribution of surface distresses. The condition surveys were performed using the methods outlined in the Ministry of Transportation of Ontario (MTO) pavement evaluation manuals.

Being the newest section, the RAS segment provides excellent ride quality, with few distresses. A slight centreline crack is present throughout the section, which may have occurred due to poor longitudinal joint construction, as well as to frost action and moisture changes, typical of the Canadian environment in the site area.

A small patch of severe ravelling can be observed in part of the paved shoulder. One isolated pothole is also present in the section, which may have possibly occurred due to frost action.

The distresses in the rigid sections are distributed equally among all sections [115]. Good quality ride is provided in all four sections. Intermittent ravelling of moderate severity can be observed, possibly due to both abrasion from traffic loads and environmental causes, which allow loosened pieces to be removed by traffic. Frost action and freeze/thaw cycles can also contribute to the phenomenon. Some moderate joint spalling is present in all sections and is believed to generally be caused by excessive local stresses, resulting from a combination of traffic loads and the effects of expansion, warping and curling. Infiltration of debris into joints may also prevent unrestrained slab movement, contributing to the damage observed. However, no evidence of major structural damage can be observed.

The HL3-2 section shows frequent slight pavement edge cracks, possibly caused by insufficient bearing support and/or excessive traffic loading near the pavement edges. Frost action and poor drainage at pavement edges and shoulders can also be possible causes of this distress. Slight, intermittent alligator cracking is present in this segment, which can be attributable both to insufficient bearing support of the pavement structure, as well as to a stiff or brittle asphalt mix at cold temperatures. Slight longitudinal wheel track cracking can also be observed. This type of cracking can likely be attributed to overloading when the pavement is weakest, i.e. the early spring.

In the Superpave section, ride quality is also good. Severe, frequent alligator cracking and longitudinal wheel track cracking are present in this stretch of the test road, possibly due to the aforementioned causes. Potholes have occurred at the pavement joints between this section and the adjacent ones, as well as in the areas of alligator cracking.

The SMA section also provides good ride quality. Severe and moderate longitudinal wheel track cracking are frequent in this section. Slight, intermittent pavement edge cracks are also observable.

Very slight wheel track rutting can be observed, possibly caused by an unstable asphalt mix, due to high temperature, high asphalt content or low viscosity of binder. Poorly compacted structural layers, unstable shoulder material, not capable of an adequate lateral support, and unstable granular bases or subbases are other possible causes of this phenomenon. Transverse cracks are present in the road section as well. Possible causes include natural shrinkage of the asphalt due to very low temperatures, the high temperature susceptibility of asphalt cement binder, frost action and reflection cracks. Potholes have also occurred at the pavement joints.

Good ride quality can be perceived in the PMA section. Distresses include slight intermittent pavement edge cracking, a few slight longitudinal mid-lane cracks, very slight alligator cracks and a few very slight transverse cracks.

The HL3-1 section also has good ride quality. Observed distresses include a few slight pavement edge cracks and intermittent slight alligator cracking.

Figure 5.6: View of various distresses in the CPATT Test Track flexible sections.

Figure 5.6 shows some examples of distresses in some CPATT test track asphalt pavements. In the left image, alligator cracking in the PMA section is shown and in the right picture, a pavement edge crack is visible in the HL3-2 section.

In Figure 5.7, some distresses are depicted of the rigid sections of the test track. In the left image, ravelling is present on the left lane of the RCA-15% section, while in the right picture joint spalling and corner cracking are shown in the RCA-30% section.

Figure 5.7: View of various distresses in the CPATT Test Track rigid sections.

In general, ride quality is still good among all the older flexible sections, as well as in the rigid ones. The best ride quality is provided by the RAS section, the newest one at only four years old. Distresses are generally more frequent and more severe in the older asphalt sections. Moreover, they are usually more often located in the northbound (loaded) lane.

5.3 TIRE/PAVEMENT NOISE EVALUATION

Noise tests were carried out to measure the coefficient of sound absorption, by means of the impedance tube method, and noise emission by means of the Close Proximity (CPX) and On Board Sound Intensity (OPSI) methods.

5.3.3 EVALUATION OF NOISE ABSORPTION CHARACTERISTICS

The coefficient of noise absorption has been measured on core samples, removed from the test track pavements, by means of the Impedance Tube method, in accordance with the ISO 10534-2 standard [116].

Three samples were cored from each pavement section for noise absorption testing. Selected samples were cut to a length of 76 mm and gently washed to remove dust and soil particles, which may affect the subsequent measurements. As common practice, a foam strip was taped around the core to prevent energy dispersion while performing the noise tests, as seen in Figure 5.8. In the image, core samples have been ordered according to the CPATT test track map, seen in Figure 5.1.

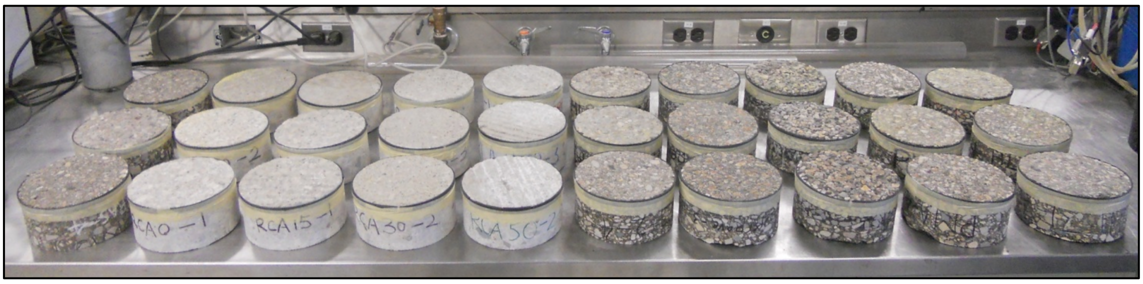

Figure 5.8: Core samples selected for noise absorption testing.

The sound absorption test consists of using an impedance tube, two microphones and a digital frequency analysis system to determine the sound absorption coefficient for normal incidence. Plane waves are generated by a loudspeaker, serving as the noise source inside the tube. The loudspeaker is connected to one end of the tube and a test sample is mounted at the other end of the tube. Sound pressures are measured by two microphones fixed near the sample. Subsequently, the two complex transfer functions of the two microphone signals are determined, by which the sound reflection factor and, thus, the coefficient of sound absorption can be computed. The layout of the sound absorption test can be seen in Figure 5.9.

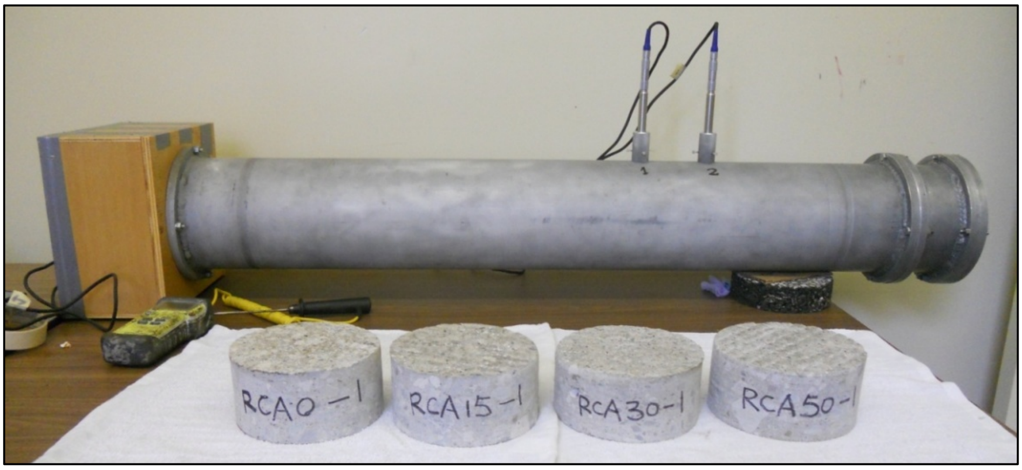

Figure 5.9: Layout of the impedance tube test

The results of the impendence tube testing are displayed in Figure 5.10. From the graph, it can be observed that the coefficient of sound absorption is lower than 0.1 at every measured frequency and for every sample type. Therefore, the intrinsic sound absorption characteristics of these pavement materials can be considered to be very low, and consequently, have an almost negligible impact on tire/pavement noise reduction.

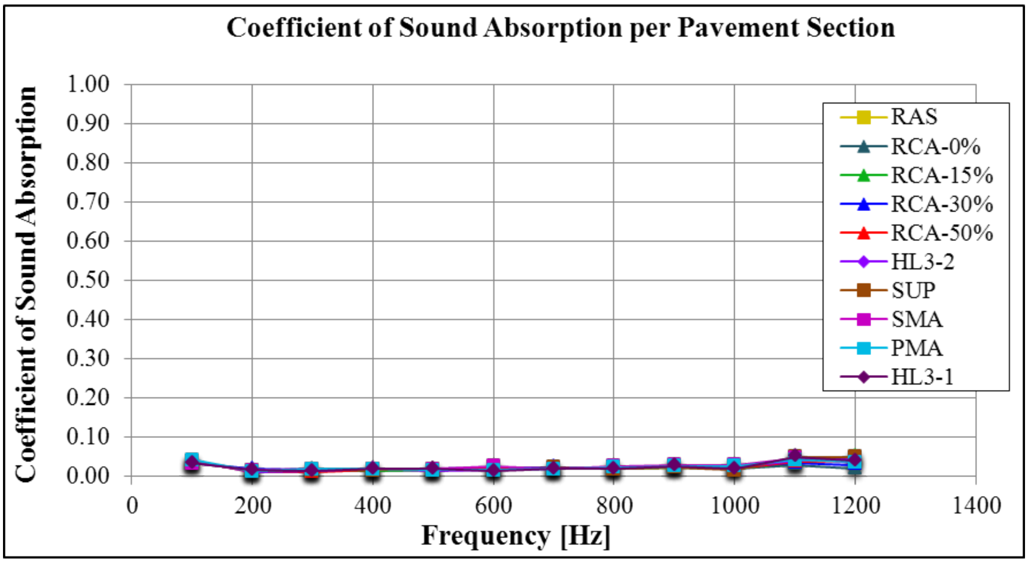

Figure 5.10: Coefficient of noise absorption for different pavement type.

According to the ISO standard, the frequency range for this test is limited to 1200 Hz due to the diameter of the tube, equal to 150 mm.

5.3.4 EVALUATION OF NOISE EMISSION CHARACTERISTICS

Sound pressure and intensity levels at the tire/pavement interface have been measured in parallel using the Close Proximity method and the On-Board Sound Intensity method. A suitable frame was been installed on the CPATT vehicle to allow simultaneous testing. The frame supports the two microphones configurations required by the two different standards. Figure 5.11 displays the setup for noise testing.

Figure 5.11: Layout of the CPX and OBSI noise testing setup.

As the CPX and OBSI Standards also require different types of tire, the regular tire of the vehicle was used for the measurements. Every section has been run multiple times to achieve a minimum length of 200 m and an averaging time of 10 s, as a result of merging the minimum requirements for both standards. Also, the measurements were performed at the reference speed of 56 km/h, according to the OBSI Standard.

5.3.4.1 CLOSE-PROXIMITY METHOD EVALUATION

For the Close Proximity (CPX) sound emission testing, the average A-weighted sound pressure levels emitted at the tire/pavement interface are measured over a specified road distance by at least two microphones, located close to the tires.

Although not using the specified reference speed, the main purpose of this research is compare different pavement sections under the same conditions and relative comparisons can still be made regardless of the selected reference speed.

Since test sections should be essentially straight, only the tangential segment of the RAS section, parallel to the other test sections, has been measured. The section located after the curve was not tested. The excluded segment was not evaluated for BPN or MTD either.

Maximum and Equivalent sound pressure levels were measured at different frequency in the 25-10000 Hz range for each microphone; arithmetic averages of the signals were subsequently calculated. In Figure 5.12, the overall maximum and equivalent sound pressure levels are reported for every pavement section. In the graph, it can be observed that the noise range of overall maximum noise levels is about 5-6 decibels and as a general trend, rigid sections are noisier than the flexible sections.

Slight variation can be observed in the equivalent sound pressure levels, compared to the maximum ones. In fact, noise range is around 2 dB(A) and comparable noise performance can be observed between rigid sections and some flexible ones, such as PMA, SMA and Superpave sections. The RAS section is the quietest, whereas SMA, usually considered a quiet pavement type, has provided a high sound pressure value, as loud as the rigid section ones.

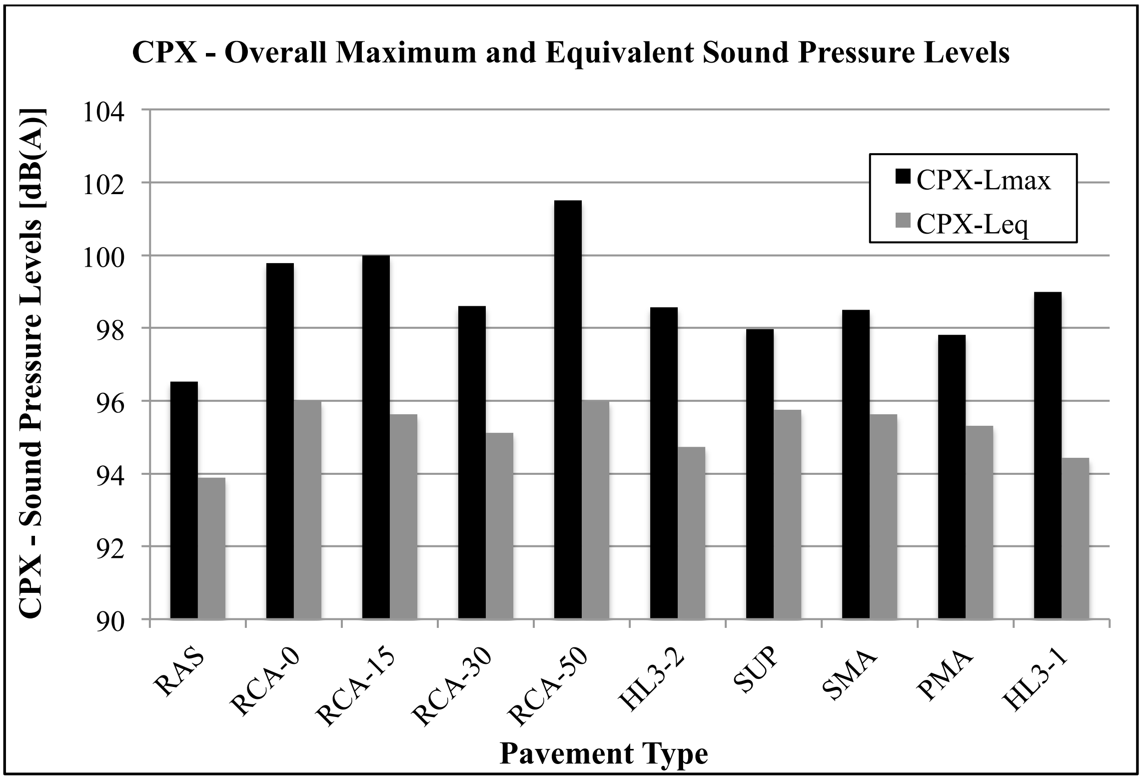

Figure 5.12: Overall CPX maximum sound pressure levels for each pavement section.

5.3.5 ON-BOARD SOUND INTENSITY EVALUATION

The OBSI method allows for the determination of A-weighted sound intensity levels at defined points near the tire/pavement interface. One-third octave band resolution has been used to perform sound intensity measurements in a frequency range of 200 to 10000 Hz. Tests have been performed at the reference speed of 56 km/h and averaged over 10 seconds.

In Figure 5.13, the overall maximum and equivalent intensity levels are reported for every pavement section. In the graph, it can be observed that the maximum level noise range is about 4-5 decibels and in general, the rigid sections are noisier than the flexible ones.

Some little variations can be observed in the equivalent levels, compared to the trend of the maximum values. In fact, noise range is around 2 dB(A) and comparable noise levels can be observed in both the rigid sections and flexible sections, with the exception of the RAS section, which is the quietest.

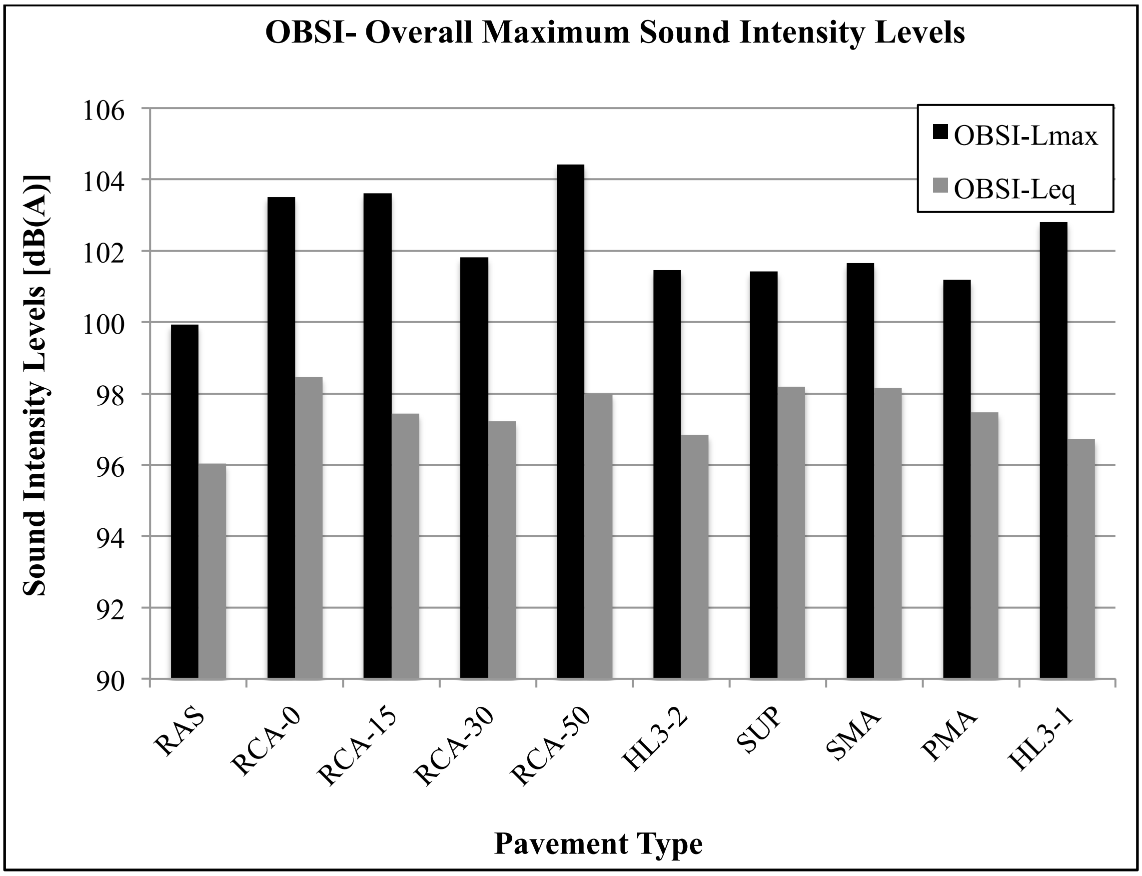

Figure 5.13: Overall OBSI maximum sound intensity levels for each pavement section.

5.6 WEARING COURSE IMPACT ON TIRE/PAVEMENT NOISE

Data analysis carried out to study the relation between noise and surface texture results provided very poor results of correlation between IRI values and CPX and OBSI data, where the coefficient of correlation is very close to zero. Therefore, whereas IRI can be useful to provide information about ride quality, roughness and can be considered an indicator of megatexture, in this study it has not been possible to predict acoustic performance of the test section from IRI values.

A correlation is also not well defined between MTD values and noise results, with no clear trend observed of data and a very poor correlation coefficient, with values close to zero. Previous researches have attested that MTD is not a good indicator to predict acoustic performance of road pavements, which is also confirmed by this study.

Also for BPN values a clear trend cannot be observed with noise results and the coefficient of correlation ranges from about 0.25 to 0.10 for equivalent sound pressure/intensity levels, whereas for maximum levels the correlation is close to zero.

However, an interesting observation can be made on the rigid sections: in fact, additional measurements taken on a segment of just longitudinal tining, part of which belongs to the RCA 50 % section and the remaining part to the RCA 30 % one, provided quieter results. Assuming that the 20% difference of RCA content does not affect the general properties of the material, the difference in sound pressure and intensity levels can be related to the surface texture finishing. Previous studies, in fact, attested that longitudinal tining is surface finishing, which provides better acoustic characteristics to rigid road pavements. Results are represented in Figure 5.14, where the term RCA-LT refers to noise results from the tested segment with just longitudinal tining.

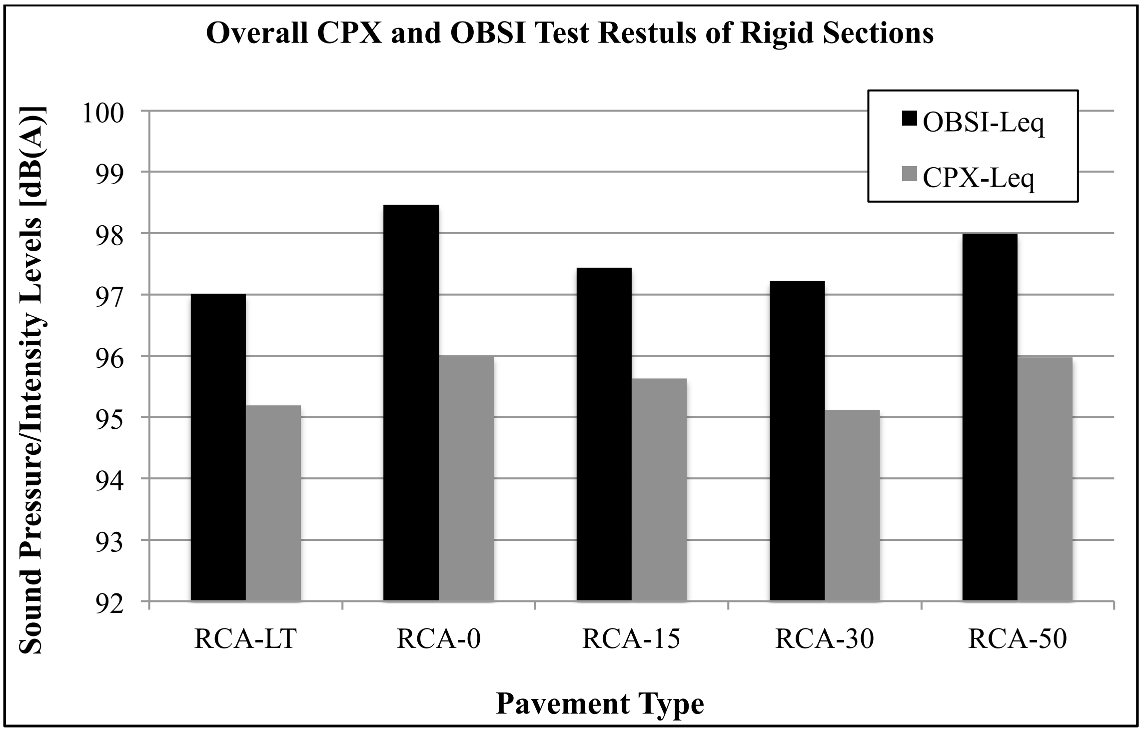

Figure 5.14: Overall OBSI and CPX equivalent sound levels for rigid sections.

CONCLUSION

The experimentation has provided information about long-term characteristics of the wearing course and acoustic performance of various road pavements under the same load and climatic conditions.

A combination of harsh climatic conditions, severe free thaw cycles and heavy loads impacted some pavement types more than others: whereas some distresses can be observed in every test pavement, signs of structural distresses can only be observed in few older sections and more frequently in the loaded lane.

From the acoustic point of view, the RAS section proved to be the quietest of the test track, according to previous studies which that a smooth surface with uniform aggregate shape and distribution can reduce tire/pavement noise. RAS section is also the most recent one: an objective comparison with other pavement types would require a few more years of monitoring.

Stone Mastic Asphalt section has provided the highest values of friction and surface texture indicators, with good smoothness values. However, this section provided some of the highest results of tire/pavement noise amongst asphalt sections. Although this result can be unexpected, since SMA is usually considered a quiet pavement, its acoustic performance is inclined to decrease over time.

Similar observations can be done of the Superpave section, which provides good results of friction, smoothness and surface texture, but with more evident signs of distresses and poor acoustic characteristics. Comparable results can be observed in the remaining asphalt sections.

Interesting observations can be made about rigid sections, which provided comparable results even though the RCA content is different. All the sections provided very good ride quality and average skid resistance, despite the lower surface texture results typical of smooth concrete pavements. Minor signs of distresses are present, but none of them appears to be structural. Noise absorption characteristics are very low, but similar to the other sections.

About tire/pavement noise evaluation, it can be noticed that whereas maximum tire/noise levels are usually higher, equivalent sound levels are comparable to the asphalt sections, both for CPX and OBSI measurements. Moreover, the special measurements taken in a segment with sole longitudinal tining provided overall equivalent sound intensity/pressure levels even lower than some asphalt sections. As for the RAS section, though, objective comparisons with other pavement types would require a few more years of monitoring, especially if one considers that concrete pavements are expected to provide longer service life.

6 CASE HISTORY 3: TIRE/PAVEMENT NOISE OF HIGHWAY PAVEMENTS IN SOUTHERN ONTARIO

INTRODUCTION

Pavement age and temperature are known to have an influence on the acoustic characteristics of the pavement itself. The research project discussed in this chapter was carried out with the purpose of evaluating acoustic characteristics of various pavement types, with a special focus on aging and temperature effect on tire/pavement noise.

A set of various asphalt and cement concrete road pavements in Southern Ontario has been selected to carry out noise testing in collaboration with the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo.

The CPATT equipped a vehicle with world leading testing equipment for sound pressure and sound intensity measurements in parallel at the tire/pavement interface.

Six road stretches were tested on both runs and measurements were taken at early morning and late afternoon to maximize the temperature ranges Two test results have therefore been provided for each road segment at similar surrounding conditions, except for pavement and air temperatures.

Relation between sound intensity and sound pressure results could have been evaluated, as well as correlation between noise and temperature of the same road stretch.

Some test sections had previously been tested in 2007-2008 by the CPATT personnel: hence, comparisons have been done between old and new results to assess aging effect noise levels.

6.1 DESCRIPTION OF THE SELECTED ROAD STRETCHES

Various highway stretches have been selected with different pavement materials and surface finishing. The list of roads include three asphalt sections, two of them made of Stone Mastic Asphalt (SMA) and one made of hot-laid asphalt (HL3), and three rigid sections made of Portland cement concrete (PCC): two of them with transverse tining and one with longitudinal tining.

Detailed information of the selected roads is summarized in Table 6.1. In the table, it can also be observed that the 401 section located in the Toronto area in the nearby of the Paerson International Airport has been constructed last year and it had been completed a few months before testing, whereas the other sections were from 6 to 9 years old.

Table 6.1: Description of the selected road sections

Pavement Type	Test Site Location	Highway	Year of Construction
SMA	London area	401	2005
PCC-Transverse Tining	Toronto - Pearson Intl. Airport area	401	2013
PCC-Transverse Tining	Windsor area	401	2005
PCC-Transverse Tining	Toronto-Brampton	410	2007
SMA	Crosshill area	Regional 11	2004
HL3	Crosshill area	Regional 11	2004

As previously described, measurements have been taken both at early morning and late afternoon to maximize the temperature range. Air and pavement temperatures, measured at the time of testing, are reported in Table 6.2.

Temperature ranges in London and Windsor test sites are higher: measurements in those sites, in fact, have been taken two weeks later than in the other test sites.

Table 6.2: Air and pavement temperature in the test sites

		Air Temperature		Pavement Temperature	
		Morning	Afternoon	Morning	Afternoon
SMA - London - 401	East	8.1	22.5	1.8	23.2
	West			2.2	23.5
PCC-TT - Toronto- 401	East	18.8	23.8	16.8	27.0
	West			17.4	27.3
PCC-TT - Windsor- 401	East	8.1	21.8	7.8	28.4
	West			8.3	28.6
PCC-TT - Brampton- 410	North	17.0	23.8	14.0	26.6
	South			14.3	27.0
SMA - Crosshill- Reg 11	North	18.0	26.0	17.6	31.4
	South			17.1	31.9
HL3 - Crosshill- Reg 11	North	18.0	26.0	17.2	30.6
	South			17.5	30.9

6.2 NOISE TESTING METHODOLOGY

CPX and OBSI tests were done in parallel by means of a suitable frame, set up to support two sound probes required by the CPX test, and a central probe required by the OBSI test, with the configurations required according to the respective standard.

The test procedure was selected to combine and fulfil as many test requirements as possible of the two different tests: therefore, when possible, the more restrictive requirement was selected of the two standards.

Tests have been performed at 100 km/h, close the speed required by the OBSI standard equal to 96 km/h, whereas the CPX standard requires 110 as reference speed. In this case, an exception to the standards has been made.

Measurements have been averaged over 10 seconds: therefore, every tested road segment results as 266 m long, fulfilling both OBSI and CPX minimum specifications which require, respectively, a minimum length of 200 m and 120 m.

Also, as the CPX and OBSI Standards require two different types of tire, an exception had to be made in order to perform the two tests at the same time and the regular tire of the vehicle has been used for the measurements.

The time frame when the measurements were carried out, both in the morning and in the afternoon, was selected to widen the pavement temperature range as much as possible: in the morning, when the pavement has been cooled down during the night, surface temperature is expected to be much lower than in late afternoon, when the pavement has been exposed to daily warmer temperatures. These time frames also coincide with the ones at which previous studies [115] recorded maximum daily change in curling and warping phenomena typical of concrete pavement slabs. These daily changes in concrete slab shapes are due to the temperature differential occurring within the slabs, created by ambient temperature modifications.

In Figure 6.1 there are depicted the CPATT's testing vehicle with the noise equipment and a close-up view of on of the tested pavement, the SMA pavement in Crosshill.

Figure 6.1: CPATT's test vehicle for noise measurements (left) and close-up view of the SMA pavement in Crosshill (right).

6.3 TIRE/PAVEMENT NOISE TESTING

6.3.1 ON- BOARD SOUND INTENSITY (OBSI) EVALUATION

The OBSI method provides the determination of A-weighted sound intensity levels at defined points near the tire/pavement interface. Maximum and averaged Sound Intensity levels were measured with one-third octave band resolution in a frequency range of 200 to 10000 Hz.

Maximum Sound Intensity values are displayed in Figure 6.2: in the image, both morning and afternoon test results are shown.

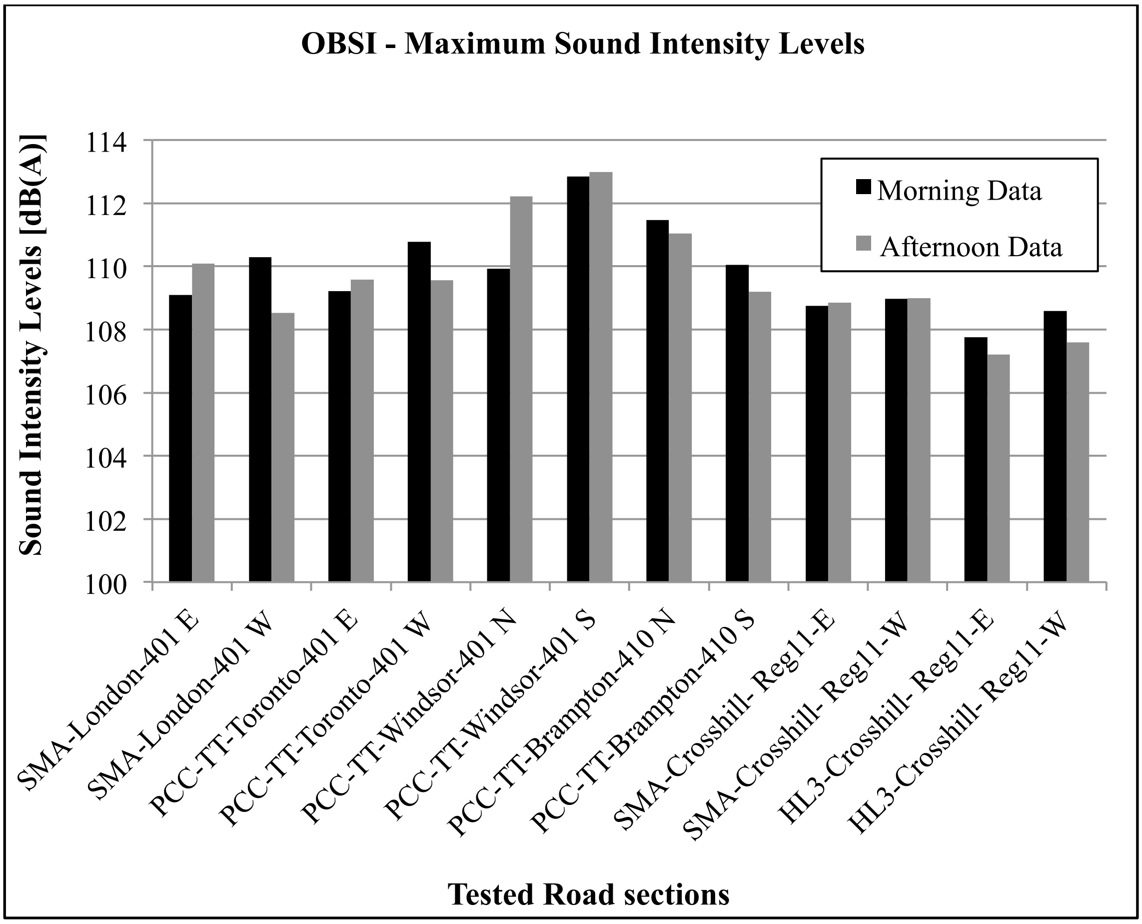

Figure 6.2: Maximum On-Board Sound Intensity (OBSI) values of the selected road stretches.

In the image it is visible that, as a general trend, morning data are usually slightly higher than afternoon data, when the pavement temperature is lower.

Asphalt pavements appear to be generally quieter than concrete pavements: the quietest section is the HL3 pavement in Crosshill, followed by the SMA sections in Crosshill and in London. The quietest concrete pavement is the one located in Toronto, which is also the newest one, whereas the loudest sections are the oldest concrete ones located in Windsor.

Equivalent Sound Intensity values can be observed in Figure 6.3, where both morning and afternoon data are reported.

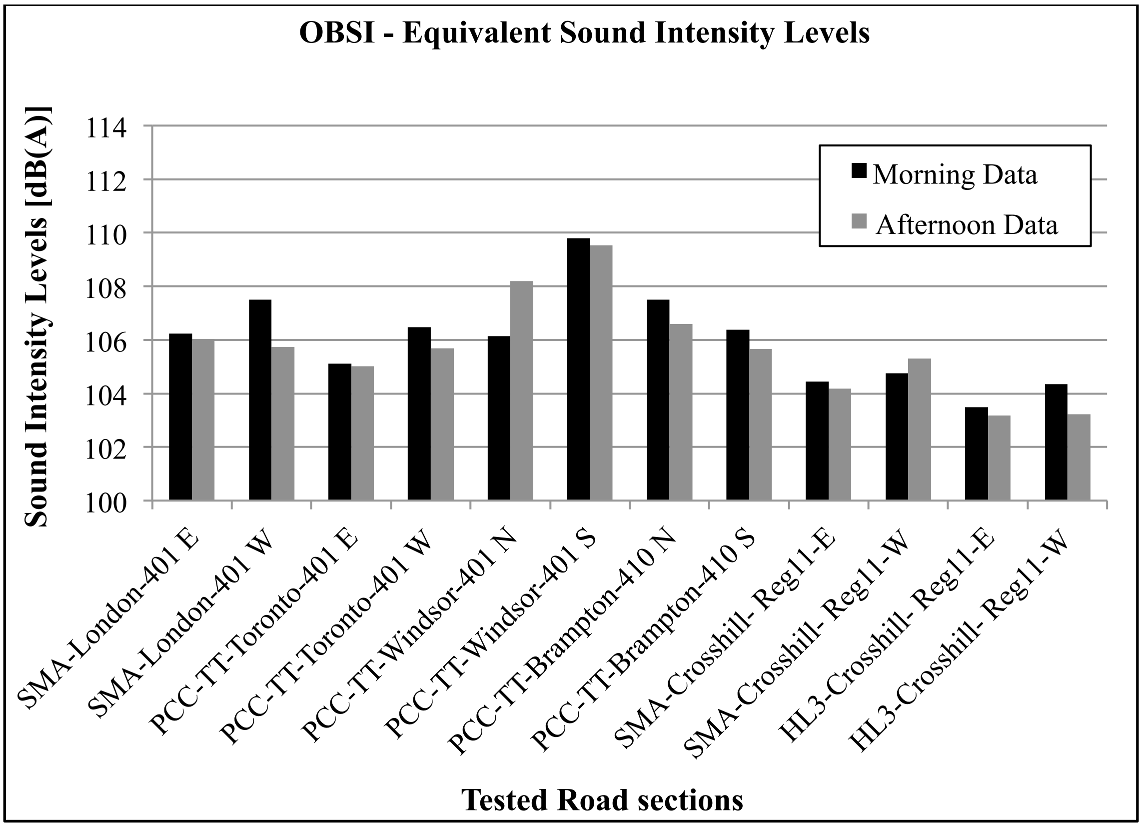

Figure 6.3: Equivalent Sound Intensity Levels of the selected road stretches.

In the image it can be noticed that the noise trend is similar to the one observed for maximum levels, with the exception of the SMA section in London, which appears to be louder than some PCC sections, such as the one located in Toronto.

Some general considerations can be done about OBSI maximum and equivalent test results. Consistency of measurements is attested by the similar values taken at the two different times of the day. Moreover, it is possible to observe that, as a general trend, morning data are slightly higher than afternoon data.

6.3.2 CLOSE-PROXIMITY (CPX) EVALUATION

In the CPX method, the average A-weighted sound pressure levels emitted at the tire/pavement interface are measured over a specified road distance by at least two microphones, located close to the tyres.

Maximum and averaged Sound Pressure levels were measured with one-third octave band resolution in a frequency range of 200 to 10000 Hz. In Figure 6.4, maximum sound pressure levels of all road section have been represented, showing test results taken both in the morning and in late afternoon.

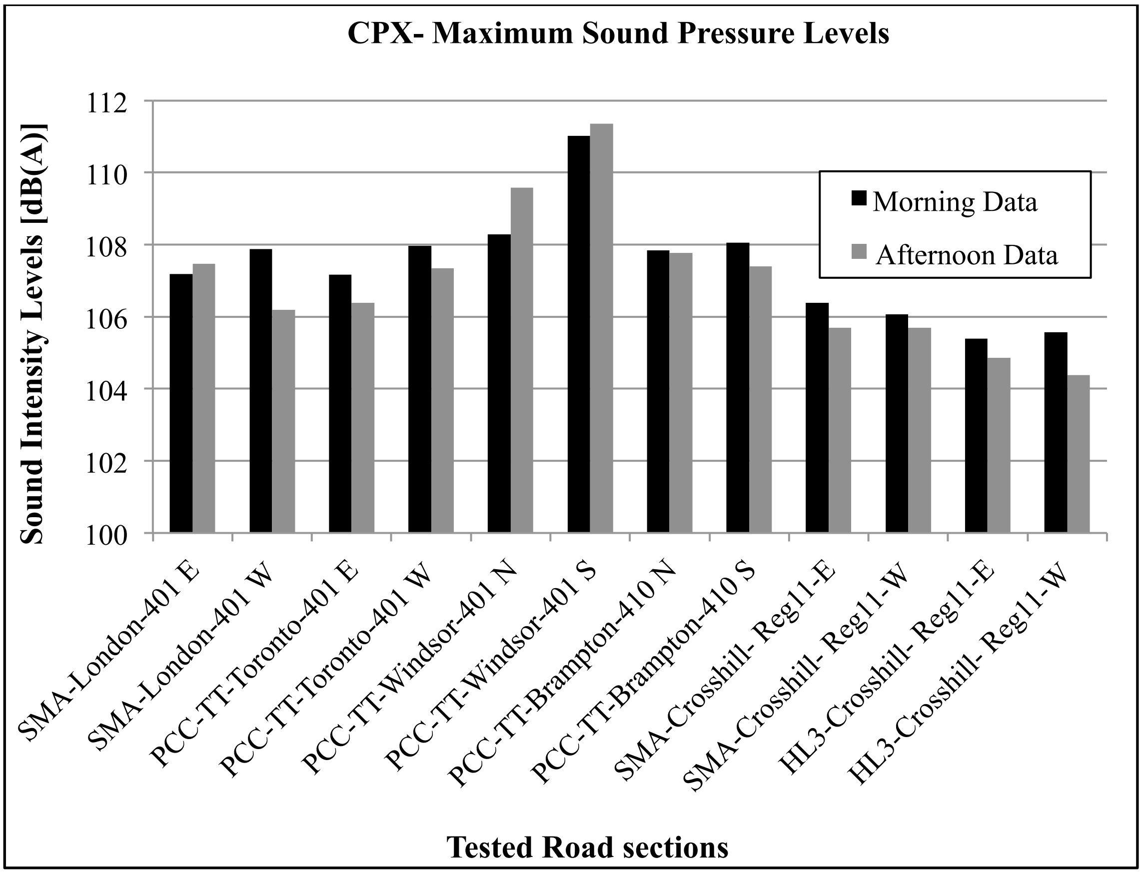

Figure 6.4: Maximum Sound Pressure Levels of the selected road stretches.

In the Figure it is possible to observe that the HL3 pavements in Crosshill are the quietest, followed by the SMA sections in Crosshill. This result is consistent with the previously described OBSI maximum noise levels.

Noise levels of the SMA sections in London and the PCC sections in Toronto and Brampton have provided comparable results. The PCC pavements in Windsor have provided the highest maximum sound pressure levels, which is also consistent with OBSI test results.

Equivalent sound pressure levels are displayed in Figure 6.5. Noise trends in the image are similar to the maximum sound levels, with the only exception of the SMA pavements in London, which here appear to be louder than the PCC sections in Toronto.

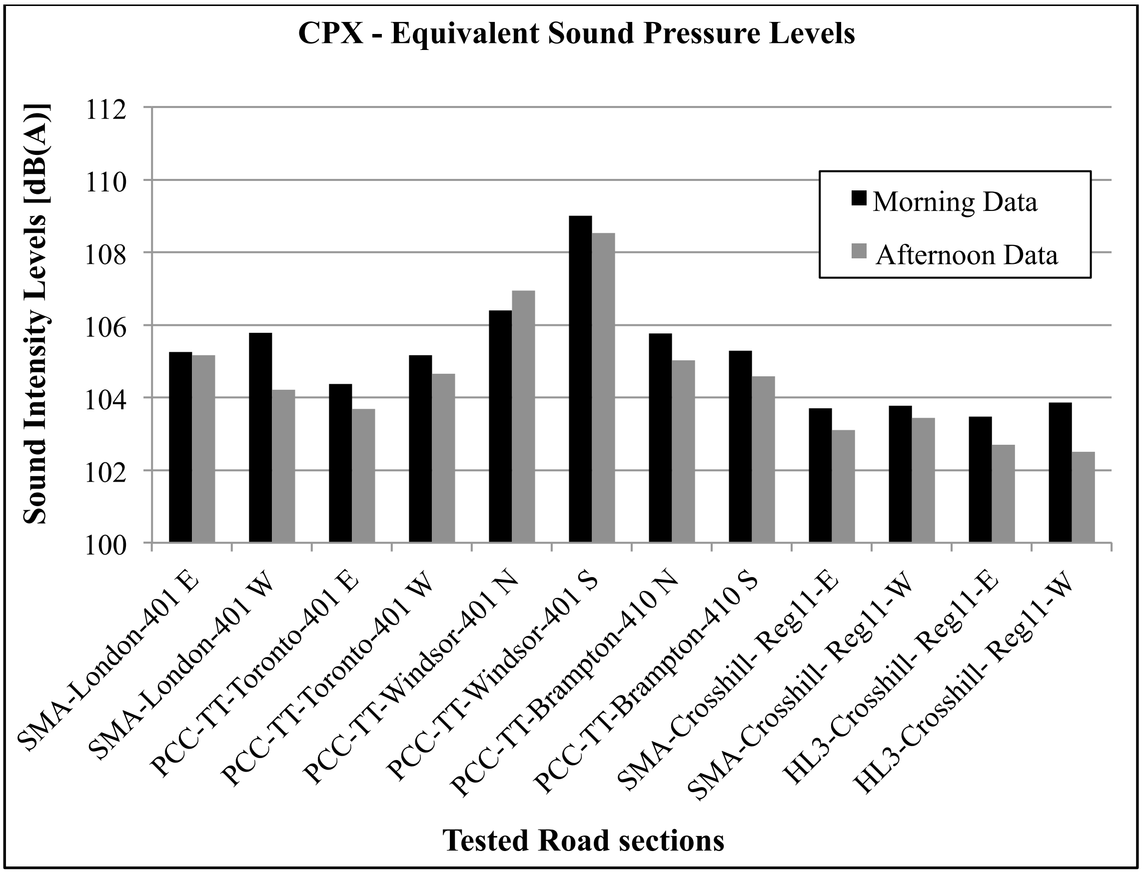

Figure 6.5: Equivalent Sound Pressure Levels of the selected road stretches.

As for the OBSI results, consistency of measurements is attested by the similar values taken at the two different times of the day: also in this case, as a general trend, morning data are slightly higher than afternoon data.

6.4 DATA ANALYSIS: TEMPERATURE EFFECT ON NOISE

Comparing the data measured in the same sections at different time of the day, it is possible to evaluate how temperature can affect tire/pavement noise values.

Whereas the correlation can be poor both for OBSI and CPX values, a trend can be observed in Figure 6.6, confirming a decrease in noise levels as temperature increases. A decrease in noise levels is reasonable and consistent with results reported in literature.

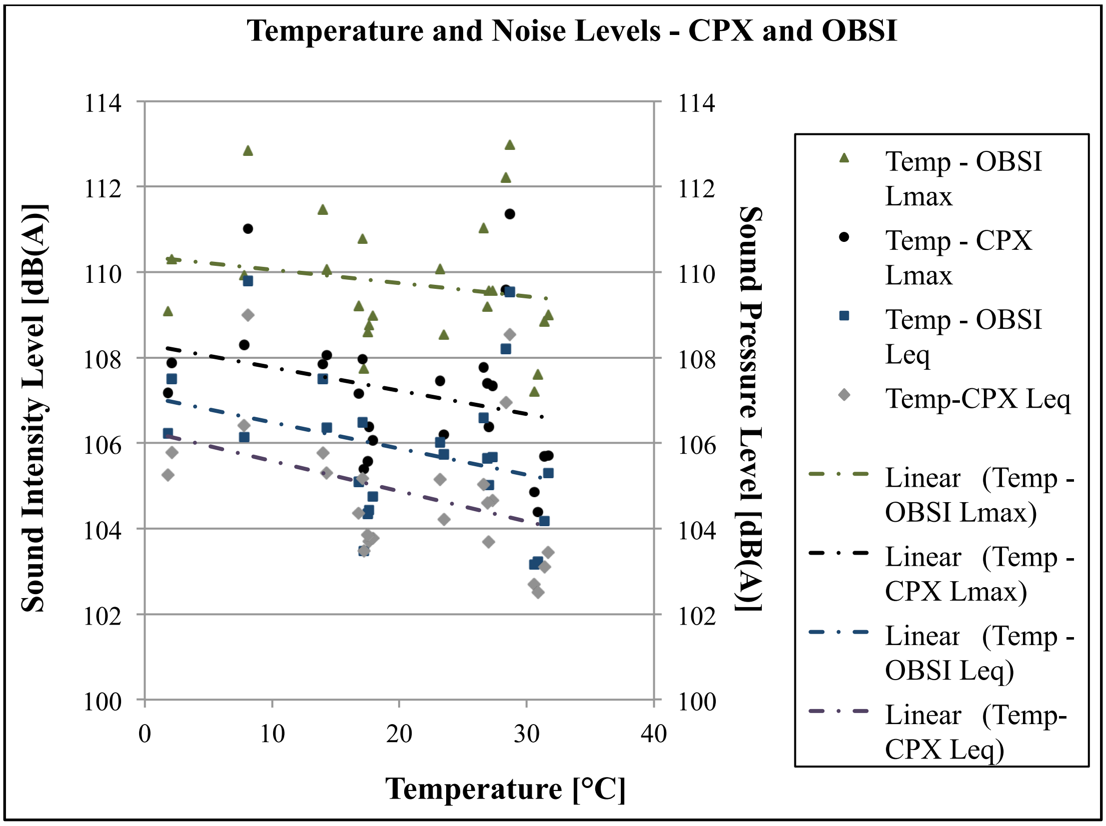

Figure 6.6: Temperature and CPX and OBSI values.

Correlation between OBSI and CPX values has also been calculated by means of a linear regression. In Figure 6.7 maximum and equivalent sound intensity and pressure levels have been displayed with their respective trendlines. Maximum and equivalent level data has been kept separated whether both the impulsive values, i. e. the maximum ones, and the averaged values, the equivalent ones, would share a similar correlation.

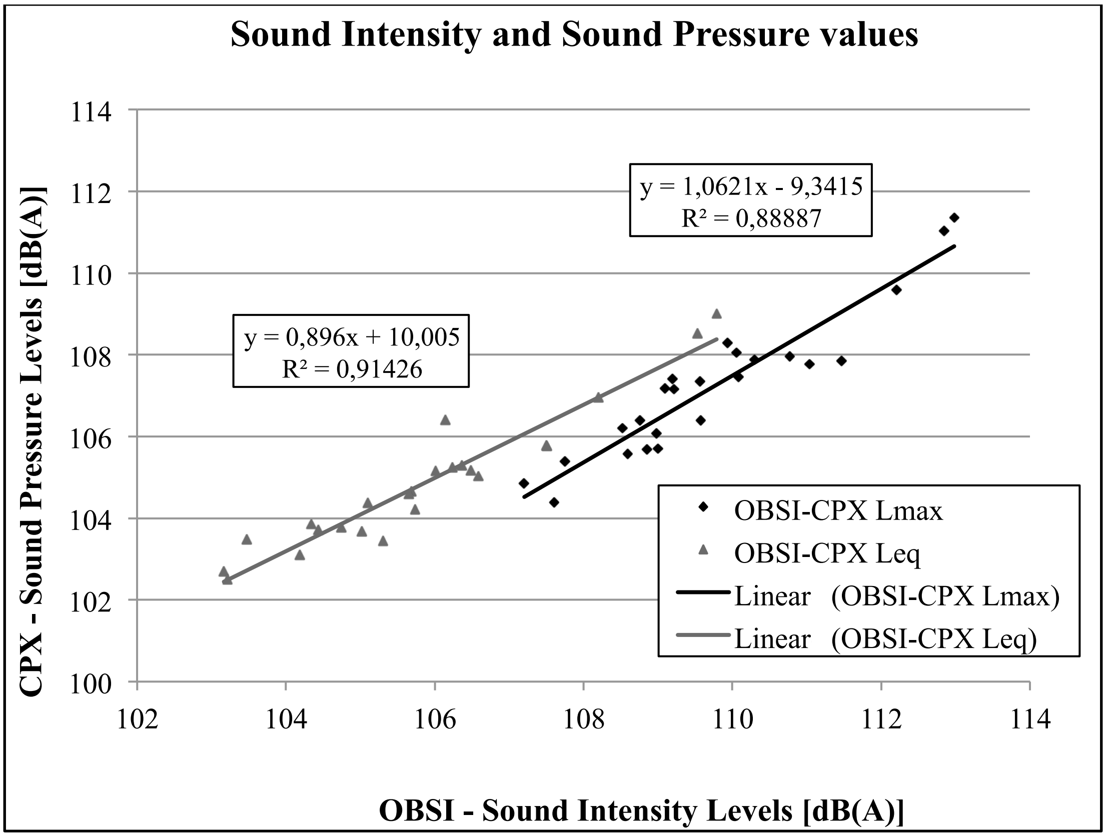

Figure 6.7: Linear regression between OBSI and CPX values.

In the image it is possible to observe that the coefficient of correlation is about 0.9 for both linear regressions and it is slightly higher for equivalent noise levels. A higher value of correlation is reasonable for equivalent noise levels than maximum ones, as the equivalent noise levels are averaged and, therefore, less sensitive to singular events than impulsive measurements.

6.5 DATA ANALYSIS: AGE EFFECT ON NOISE

Some of the selected road sections had already been tested in winter 2007 and spring 2008 with the CPX method. A comparison between old and new results would provide information about the aging effect on acoustic performance of the tested road pavements. A due clarification, though, ought to be made regarding the testing equipment: to screen microphones from wind disturbance and preventing wind to affect noise measurements, in 2007-2008 nose cones had been used, whereas in 2013 there have been used windscreens.

Maximum sound pressure levels of the 2007-2008 measurements are depicted in Figure 6.8, where a comparison with new results of the 2013 testing has been represented. As a general trend, it can be observed that latest values are higher than older ones, in some cases up to 4 dB(A).

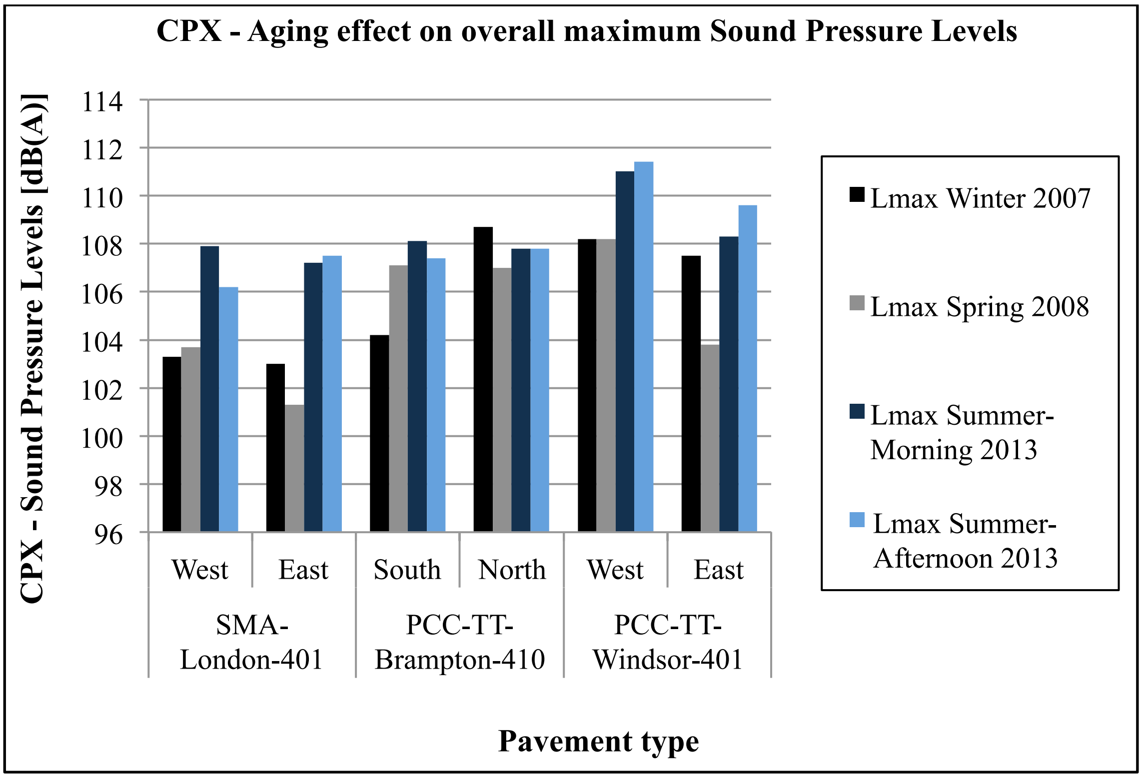

Figure 6.8: Aging effect on CPX overall maximum Sound Pressure Levels.

Test results of equivalent sound pressure levels are displayed in Figure 6.9, where the comparison between 2007-2008 and 2013 values are also represented. Older values are generally lower than latest values, attesting the trend observed for maximum sound pressure levels. In some cases, the difference can be up to 6 dB(A).

As related to the SMA and HL3 pavements located in Crosshill, older data available provide the peak frequencies for both CPX maximum and equivalent sound pressure levels. In 2007, the peak frequency of maximum sound pressure levels for the SMA section was 540 Hz, at which 103.8 dB(A) were measured. The peak frequency for equivalent sound pressure levels was 658 Hz and it provided 100.4 dB(A).

In 2013, though, the peak frequencies are higher but the levels are lower: the higher maximum levels were measured of 99.9 dB(A) at 800 Hz, whereas the higher equivalent level was 97.7 dB(A), still at 800 Hz.

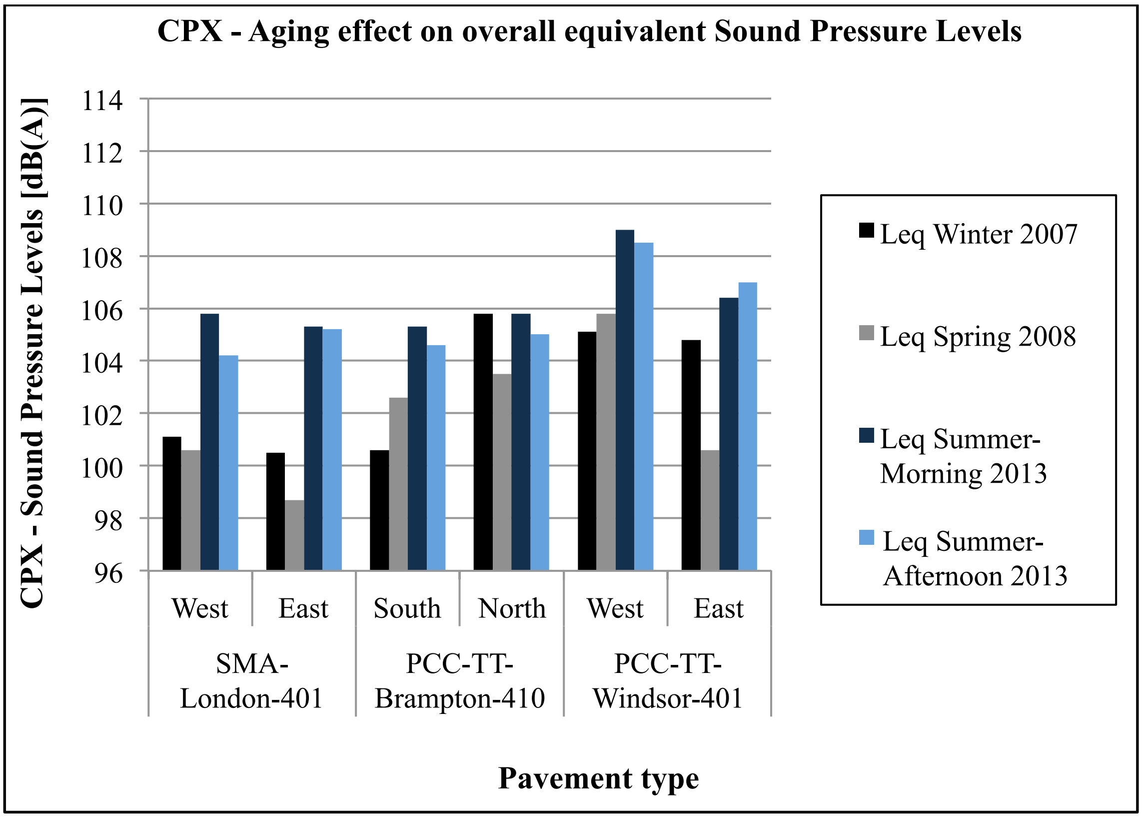

Figure 6.9: Aging effect on CPX overall equivalent Sound Pressure Levels.

For the HL3 section in Crosshill, the peak frequency of maximum sound pressure level was 583 Hz, at which 104.7 dB(A) was measured in 2007. The peak frequency for equivalent levels was 625 and it provided 101.7 dB(A). In 2013 the peak frequencies are much higher and, as for the SMA section, the sound pressure levels are lower: the higher maximum level was measured of 99.3 dB(A) at 1600 Hz, whereas the higher equivalent levels was 97.3, still at 1600 Hz. This change in frequencies can be explained by the evolution of surface texture which usually occurs with pavement aging.

The decrease in values, though, was not expected and it may be related to surrounding conditions at the time of the measurement. Nose cone protection of microphones from wind effects is limited: therefore, air turbulence at the time of measurements in 2007 may have been affected the results. Also, pavement temperature in 2007 may have also affected noise data.

As these assumptions cannot be easily verified, comments about testing data in Crosshill should be considered with care.

CONCLUSIONS

The evaluation of sound pressure levels and sound intensity levels was carried out of a set of roads in Southern Ontario, of different age and materials, with the CPX and OBSI methods in parallel.

Tested asphalt pavements appear to be quieter than the concrete ones. The HL3 and SMA asphalt sections in Crosshill, designed to be quiet pavements, were actually the quietest of all the tested road stretches.

The 401 rigid pavements, located in the nearby of Windsor, proved to be the loudest of all the tested sections. Both lanes of the 410 stretch in the Brampton area were the second highest pavements.

The new rigid pavement of 401 near the Toronto Paerson Airport provided similar noise results as the SMA section of 401, located in the London area. Since SMA is usually considered as a quiet pavement, it is interesting to observe how its acoustic performance may decrease in time, providing results comparable to new cement concrete pavement with transverse tining, generally considered as a finishing that contributes to increase noise.

Since surrounding conditions were similar during morning and afternoon tests, temperature effect on noise has been evaluated. As a general trend, test results show slightly lower values at late afternoon than at early morning, i. e. when pavement temperature was higher. A decrease in noise values can also be observed in the clear trendlines of CPX and OBSI linear regression models.

Correlation between OBSI and CPX data was calculated and the high values observed attest both the consistency of the data and the good relation between sound intensity and sound pressure levels.

Some of the selected road pavements had previously been tested by the CPATT personnel in 2007-2008 and noise results have been compared to evaluate aging effect on tire/pavement noise. All the pavements are currently louder than five-six years ago: the noise increase, though, is not uniform. Overall tire/pavement noise, in fact, generally increased from 1-2 up to 5-6 dB(A). The noise increase is higher in equivalent noise levels than in maximum noise levels.

The trends observed both in temperature and age effects on noise are consistent with previous research in literature.

CONCLUSIONS

Context-sensitive design/solutions can provide great benefits in transportation infrastructure, especially in road and highway engineering, achieving efficient technical solutions, while minimizing the impacts on human communities, wildlife and ecosystems.

The key factor in CSD/CSS is flexibility, which can encourage designers to tailor projects to the particular context where the infrastructure is or will be located. These tailored solutions can include a study to optimize the infrastructure location with respect to context and communities, use of sustainable materials, strategies and devices to reduce air, water or noise pollution, use of green materials to harmonize the infrastructure with the landscape and the context.

Since traffic noise is one of the most perceived impacts by human communities and ecosystems, engineering solutions were have been developed to screen sensitive receptors by means of noise barriers, or to reduce tire/pavement noise, which is the main factor involved in traffic noise. The use of low-noise surfaces and quiet pavements, i.e. road surfaces that provide lower noise levels than conventional ones, has proved to be effective for this objective.

To design a quiet pavement it is important to analyse noise generation and amplification mechanisms occurring at the tire/pavement contact patch. This can lead to specific mix designs and pavement materials, which provide better acoustic characteristics to the pavement.

The topic of quiet pavement design is complex. While asphalt concrete pavements are generally quieter than cement concrete ones, in fact, surface texture optimization enables some CC pavements to perform as quiet pavements. Hence, research on low-noise pavement surfaces and quiet pavement has focused on the impact of surface texture and pavement materials to better understand how these characteristics impacts on noise performance.

Other aspects significantly involved in tire/pavement noise are pavement age and environmental conditions, especially air and pavement temperature.

Some case studies have been analysed involving wearing course characteristics, which are known to have a direct influence on tire/pavement noise. Overall, the described case studies analysed the impact of pavement materials, surface texture and age effect on the acoustic characteristics of various pavement types, as well as the influence of temperature on noise.

The first case study confirmed the possibility of designing a maintenance intervention, such as cold laid multipurpose microsurfacing, capable of providing, in a thin layer, various technical and environmental characteristics related to road noise. Test results of this project confirmed poor correlation between surface texture and frictional indicators with tire/pavement noise. However, since laser scanner was successfully used to characterize surface texture with 2D and 3D indicators, this research has contributed to open possible research starting points involving correlation between volumetric indicators and tire-pavement noise.

In the second case study, similar relations with the first one have been analysed involving frictional and surface texture indicators with respect to tire/pavement noise of various road surfaces. The differences between this case study and the first one are related to the different pavement types, age, and environmental conditions, as well as to the different methodology used to measure tire/pavement noise. The analysed road sections, which had been subject to the same harsh climatic condition and heavy loads, provided different types of distresses and acoustic performance: these aspects allowed evaluating their different acoustic behaviour under the same surrounding conditions.

In the third case study, temperature and aging effects on tire/pavement noise have been studied of a set of roads with different age and pavement materials. Road sections were tested twice a day at different times, to maximize pavement temperature range: this enabled quantifying the difference in noise levels of the measurements taken at early morning, when the pavement temperature was low, and at late afternoon, when the pavement temperature was higher. A comparison has been made between current test results and old results of some of the road stretches, taken in 2007-2008: this allowed quantifying also the age effects on noise levels.

From the data analysis of the described case histories, the following observations can be done:

- multipurpose maintenance interventions can be designed to enhance acoustic characteristics and reduce tire/pavement noise while providing effective technical requirements;
- use of cold-laying techniques can be a valuable alternative in multipurpose maintenance interventions, providing adequate technical and eco-friendly characteristics;
- optimized surface texture and use of crumb rubber to enhance pavement damping capacity has been successful in decreasing noise levels in slurry multipurpose microsurfacing;
- poor correlation has been observed between tire/pavement noise and sand patch test results within both similar and different pavement types. The same occurred with BPN values;
- as a general trend, asphalt concrete pavements provided lower maximum noise levels than cement concrete pavements;
- in some cases, comparable results of equivalent sound pressure and intensity levels have been observed between older AC pavements and more recent CC pavements;
- lower maximum and equivalent noise levels were observed on the same AC and CC road sections, when the pavement temperature is higher, surrounding environmental conditions being similar;
- higher noise levels have been observed on the same AC and CC pavement sections after some years, i.e. as the pavement age increased.

Test results and observations described in this dissertation are in line with previous researches in scientific literature and can provide a contribution in understanding the mechanisms involved in tire/pavement noise generation and amplification phenomena.

Further research can be carried out based on these experiences, involving acoustic characteristics of different maintenance interventions, continue monitoring of the acoustic performance of the tested AC and CC pavements, and providing additional results of the acoustic behaviour of pavements within daily and seasonal variations of pavement temperature.

Moreover, similar studies can be repeated with various tire models to identify possible effective matches between tire tread patterns and pavement materials and surface texture. Possible studies can also be focused on evaluating the effects of both pavement and tire temperature on noise.

Providing contributions in research on these topics can lead to relevant progress in understanding the degree of influence of tire and pavement characteristics on noise, as well as of the effects of age and environmental factors on pavement acoustic characteristics.

Insights on these topics can be relevant to provide guidelines for pavement and tire designs, as well as to gain experience that can be useful in context-sensitive design and solutions in transportation infrastructure, in order to reduce the exposure of human and ecosystems to noise.

REFERENCES

[1] *http://contextsensitivesolutions.org*;

[2] Forman R. T. T., Sperling D., Bissonnette J. A., Clevenger A. P., Cutshall C. D., Dale V. H., Fahrig L., France R., Goldman C. R., Heanue K., Jones J. A., Swanson F. J., Turrentine T., Winter T. C, 2003. Road ecology science and solutions. ISBN 1-55963-932-6 (hardcover) – ISBN 1-55963-933-4 (pbk.).

[3] Sandberg U., Ejsmont, J. A., 2004. Tyre/Road Noise Reference Book. Informex Ejsmont & Sandberg Handelsbolag, Harg, Kisa, Sweden.

[4] European Commission. Future Noise Policy – European Commission Green Paper. DG XI, European Commission, Brussels, Belgium.

[5] Bowles A. E., 1997. Responses of wildlife to noise. Wildlife and Recreationists: Coexistence through management and Research. Edited by R. L. Knight and K. J. Gutzwiller, 109-56. Washington D.C.: Island Press.

[6] Donovan, P. R., 2005. "Quieting of Portland Cement Concrete Highway Surfaces with Texture Modifications". Noise-Con, October 17th-19th, 2005, Minneapolis, Minnesota, United States of America.

[7] Donovan H., Panhwer N., Croteau J. M., 2012. 2010 Warm Mix Trials—City of Edmonton. In CTAA Annual Conference Proceedings-Canadian Technical Asphalt Association, 57:385.

[8] Weiguo, S., 2009. Urban Traffic Noise and Quieter Pavement Research. In Management and Service Science, 2009. MASS'09. International Conference on, 1–6.

[9] Bendtsen H., Lu Q., Kohler E., 2010. Acoustic Aging of Asphalt Pavements: A California/Danish Comparison. University of California Pavement Research Center.

[10] Donovan P. R., Lodico D., 2011. "Measuring tire-pavement noise at the source: precision and bias statement". National Cooperative Highway Research Program, Transportation Research Board of the National Academies, Project 1-44.

[11] Lodico D., Donovan P., 2012. "Evaluation of temperature effects for on-board sound intensity (OBSI) measurements". Transportation Research Board Annual Meeting, January 13th-17th, 2012, Washington, Washingon D.C., United States of America.

[12] Bendtsen H., Andersen B., 2005. “Noise-reducing pavements for highways and Urban roads – State of the art in Denmark”. Association of Asphalt Paving Technologists – Proceedings of the Technical Sessions v. 74.

[13] Zietsman J., Ramani T., Potter J., Reeder V., DeFlorio J., 2011. A guidebook for sustainability performance measurement for transportation agencies. National cooperative highway research program report 708. Transportation research board, Washington, D.C.

[14] O'Flaherty, 2002. Highways the location, design, construction and maintenance of road pavements (4th ed. ed.). Oxford: Butterworth-Heinemann. ISBN 978-0-7506-5090-8.

[15] Kaszynski, W., 2000. The American Highway: The History and Culture of Roads in the United States. Jefferson, N.C.: McFarland.

[16] Donnell E. T., Mason J. M. Jr., 2007. Context-sensitive design for highways and streets, Chapter 17 of “Handbook of Transportation Policy and Administration” Edited by Jeremy Plant. CRC Press 2007, Print ISBN: 978-1-57444-565-7, eBook ISBN: 978-1-4200-1702-1.

[17] Mahoney K. M., Mason J. M., Donnell E. T., 2003. Design exceptions and context-sensitive design. Institute of transportation engineers 2003 annual meeting and exhibit (held in conjunction with ite district 6 annual meeting), seattle, washington, 2003-8-24 to 2003-8-27.

[18] Mohl R. A., 2004. Stop the Road, Freeway Revolts in American Cities. Journal of Urban History July 2004 vol. 30 no. 5 674-706, doi: 10.1177/0096144204265180

[19] Rundell, G., 1985. Melbourne anti freeway protests. -during the 1970s-. Urban Policy and Research, v.3, no.4, Dec 1985, p.11-19 (ISSN: 0811-1146).

[20] *http://www.epa.gov/air/caa/requirements.html*

[21] *http://wilderness.nps.gov/document/WildernessAct.pdf*

[22] Sangiorgi, C. (2013). Context-sensitive design in Transportation Infrastructures – Part 1 [PowerPoint slides]. Retrieved from *http://campus.unibo.it/cgi/lista?annoAccademico=2013&codiceScuola=843884&codiceCorso=8211&codMateria=35397-341849&nav=i#top_documents*

[23] Congressional declaration of goals and policy, available at: *http://www.gpo.gov/fdsys/granule/USCODE-2011-title33/USCODE-2011-title33-chap26-subchapI-sec1251/content-detail.html*

[24] Federal Highway Administration (FHWA), U.S. Department of Transportation, 2007. Results of Joint AASHTO/FHWA Context Sensitive Solutions Strategic Planning Process. Summary Report March 2007.

[25] FHWA's Vital Few Goal — Environmental Stewardship and Streamlining: *http://www.environment.fhwa.dot.gov/strmlng/vfovervw.asp*

[26] Stamatiadis N., Kirk A., Hartman D., Hopwood T., Pigman J, 2009. Quantifying the Benefits of Context-sensitive solutions. National Cooperative Highway Research Program (NCHRP) Report 642.

[27] Lloyd, J. (2011). Road ecology. Retrieved from:
http://www.eoearth.org/view/article/155767

[28] Webster's Third New International Dictionary: The English Language Unabridged. 1986. Springfield, Mass.: Merriam-Webster.

[29] Smith, R. L. 1996. Ecology and Field Biology. New York: Harper Collins.

[30] National Research Council, 1997. Toward A Sustainable Future: Addressing the Long-Term Effects of Motor Vehicle Transportation on Climate and Ecology -- Special Report 251. Washington, DC: The National Academies Press.

[31] Ellis A., 2008. A Roadway Different: a context-sensitive solution for State Route 179 in Sedona, Arizona. PhD dissertation, Arizona State University.

[32] Liro, A., Geowacka I., Jakubowski W., Kaftan J., Matuszkiewicz A. J., Szacki J., 1995. National Ecological Network EECO- NET–Poland. Warsaw: Foundation IUCN Poland.

[33] Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

[34] Infra Eco Network Europe (IENE) website: *http://www.iene.info*

[35] Neuman T. R., Schwartz M., Clark L., Bednar J., 2002 . A Guide to Best Practices for Achieving Context Sensitive Solutions. National Cooperative Highway Research Program (NCHRP) Report 480, 2002.

[36] Doctor M., ?. Risk-Based Approaches To Highway Design: Achieving Flexibility and Implementing Context Sensitive Solutions. Briefing for the TRB Geometric Design Committee (AFB10)

[37] Federal Highway Administration (FHWA), 1997. Flexibility in Highway Design.7U.S. Department of Transportation.

[38] Mid-Atlantic National Environmental Policy Act (NEPA) – Environmental Assessments and Environmental Impact Statements. Retrieved at: *http://www.epa.gov/reg3esd1/nepa/eis.htm*

[39] The World Bank, 1997. Roads and the Environment - A Handbook. World Bank technical report no. 376. Edited by Koji Tszmokawa Christopher Hoban. Wadington, D.C.

[40] Daigle, P., 2010. A summary of the environmental impacts of roads, management responses, and research gaps: 65 A literature review. BC Journal of Ecosystems and Management 10(3):65–89

[41] Northern Territory Government, Government of Australia, ?. Roads and the Environment. A strategy for sustainable development, use and maintenance of Northern Territory Roads. Northern Territory Government, Department of Infrastructure, Planning and Environment. Government of Australia.

[42] McLean J. E., Bledsoe B. E., 1992. Behavior of metals in soils. Groundwater Issue. EPA/540/S-92/018, October 1992

[43] US Environmental Protection Agency, 1995. Controlling nonpoint source runoff pollution from roads, highways and bridges. Report EPA-841-F-95-008. Washington, D.C.

[44] Williamson, P., Evans P. R., 1972. Lead: Levels in roadside invertebrates and small mammals. Bulletin of Environmental Contamination and Toxicology 8:280-88.

[45] Zwaenepoel, A. 1997. Floristic impoverishment by changin unimproved roads into metalled roads. In Habitat Fragmentation & Infrastructure, edited by K. Canters, 127-137 Delft, Netherlands: Ministry of Transport, Public Works and Water Management.

[46] Brunekreef B., Holgate S. T., 2002. Air pollution and health. The Lancet, Volume 360, Issue 9341, 19 October 2002, Pages 1233–1242

[47] Künzli N., Kaiser R., Medina S., Studnicka M., Chanel O., Filliger P., Herry M., Horak F. Jr, Puybonnieux-Texier V., Quénel P., Schneider J., Seethaler R., Vergnaud J-C., Sommer H., 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment. The Lancet. Volume 356, Issue 9232, 2 September 2000, Pages 795–801

[48] Hoek G., Brunekreef B., Goldbohm S., Fischer P., Van den Brandt P. A., 2002. Association between mortality and indicators of traffic-related air pollution in the Netherlands: a cohort study. The Lancet, Volume 360, Issue 9341, 19 October 2002, Pages 1203–1209

[49] European Environment Agency, 2011. Landscape fragmentation in Europe. Joint EEA-FOEN report. EEA report num 2/2011.

[50] Iuell, B., Bekker, G.J., Cuperus, R., Dufek, J., Fry, G., Hicks, C., Hlavácˇ, V., Keller, V., B., Rosell, C., Sangwine, T., Tørsløv, N., Wandall, B. le Maire, (2003. Wildlife and Traffic: A European Handbook for Identifying Conflicts and Designing Solutions.

[51] Sauli G., Cornelini P., Preti F., 2006. Manuale di Ingegneria Naturalistica, Sistemazione dei versanti. Volume 3. Regione Lazio.

[52] Babisch W., 2000. Gesundheitliche Wirkungen von Umweltlärm- Ein Beitrag zur Standortsbestimmung (Health effects of environmental noise – a status report). Zeischrift für Lärmbekämpfung, 47 (2000), Nr. 3 (May).

[53] Hygge S., 1998. Cognition, children and exposure to transportation noise – Patterns of psychological effects. In N. Carter & R.F.S. Job (Eds.), Noise Effects ’98. Proceedings of the 7th International Congress on Noise as a Public Health Problem. Vol. 1 (pp. 340-345). Sydney, Australia: National Capital Printing ACT, Australia.

[54] Reijnen M. J. S. M., Veenbaas G., Foppen R.P.B., 1995. Predicting the effects of motorway traffic on breeding bird populations. Delft, Netherlands: Ministry of Transport, Public Works and Water Management.

[55] Various authors, 2006. Guidance manual for the implementation of low-noise road surfaces, FEHRL REPORT 2006/02. Phil Morgan editori (Transportation Research Laboratory). ISSN: 1362-6019ISBN: 90-9020404-0 / 978-90-9020404-8

[56] Garai, M., 2011. Applied Acoustics [PowerPoint slides]. Retrieved from: *http://acustica.ing.unibo.it/Courses/AA/aa_testi.htm*

[57] Baruffa R., Bruschi A., 2010. Acustica dei component edilizi. Dario Flaccovio Editore. ISBN: 978-88-0005-6

[58] Alauddin Ahammed M., 2009. Safe, quiet and durable pavement surfaces. PhD thesis, University of Waterloo, Canada.

[59] Picture retrieved from:
http://www.extron.com/company/article.aspx?id=loudnesscontrol_ts

[60] Bernhard R. J., Wayson R. L., 2005. An introduction to tire/pavement noise, final report, SQDH 2005-1 HL 2005-2. West Lafayette, IN: Institute for Safe, Quiet, and Durable Highways, Purdue University.

[61] Plotkin K. J., Montroll M. L., Fuller W. R., 1980. The generation of tyre noise by air pumping and carcass vibration. Proceedings of Inter-Noise 80, Miami, Florida, USA, 273-276.

[62] Rasmussen R. O., Bernhard R. J., Sandberg U., Mun E. P., 2007. The Little Book of Quieter Pavements. FWHA-IF-08-004. U.S. Department of Transportation.

[63] Transportation Association of Canada (TAC), 2012. Pavement Asset Design and Management. ISBN: 978-1-55187-341-9

[64] . World Road Association, 2010. Attenuazione del rumore stradale. Interventi di mitigazione sonora alla sorgente. Quaderni AIPCR, XXVI Road National Congress. Rome, October 27th-30th, 2010. ISBN: 978 88 905397 94.

[65] Picture retrieved from: *www.wikipedia.com*

[65] Picture retrieved from: *http://www.leca.ae*

[66] Descornet G., Goubert L., 2006. Noise classification of road pavements. Task 1: Technical background information. Draft report. European Commission Directorate-General Environment.

[67] European Asphalt Pavement Association (EAPA), 2007. "Abatement of traffic noise... the arguments for asphalt."

[68] Hall J.W., Smith K.L., Littleton P., 2009. Texturing of Concrete Pavements. National cooperative highway research program report 634. Transportation research board, Washington, D.C. 2009.

[69] Picture retrieved from:
http://www.michiganbuildingtrades.org/newspaper_2011/feb_25_2011.html

[70] ISO 11819-1, 1997. Acoustics- Measurement of the Influence of Road Surfaces on Traffic Noise-Part 1: Statistical Pass-by method. International Organization for Standardization, ISO 11819-1: 1997, Geneva, Switzerland, 1997.

[71] Picture retrieved from: *http://www.nordicroads.com/thin-layer-pavements-long-time-effect-of-noise-reduction/*

[72] ISO 11819-2, 2000. Acoustics- Measurement of the Influence of Road Surfaces on Traffic Noise-Part 2: The Close-Proximity Method. International Organization for Standardization, ISO/CD 11819-2: 2000, Geneva, Switzerland, 2000.

[73] Picture retrieved from:
http://www.highfrictionroads.com/index.php?q=node/18

[74] AASHTO TP 76, 2013. Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method. 2013-01-01.

[75] ASTM F2493, 2008. Standard Specification for P225/60R16 97S Radial Standard Reference Test Tire, ASTM International, Annual Book of ASTM Standards, West Conshohocken, PA.

[76] Rasmussen R. O., Sohaney R., Wiengand P, 2011. Measuring and reporting tire/pavement noise using on-board sound intensity (OBSI). Technical-

Brief report for the Concrete pavement surface characteristics program. National Concrete Pavement Technology Center.

[77] ISO 10534-2, 1998. Acoustics- Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes- Part 2: Transfer Function Method. International Organization for Standard- ization, ISO/CD 10534-2:1998, Geneva, Switzer- land, 1998.

[78] Picture retrieved from: Černík M., Mokrý P., 2012. Sound reflection in an acoustic impedance tube terminated with a loudspeaker shunted by a negative impedance converter. Smart Materials and Structures, vol. 21, n. 11.

[79] ISO 3472, 2002. Acoustics - Measurement of sound absorption properties of road surfaces in situ —Part 1:Extended surface method. International Organization for Standardization, ISO/CD 10534-2:1998, Geneva, Switzer- land, 1998.

[80] ISO 13473-1, 1997. Characterization of pavement texture by use of surface profiles-Part 1: Determination of Mean Profile Depth. International Organization for Standardization, ISO 13473-1997, Geneva, Switzerland, 1998.

[81] Sandberg U., Descornet G., 1980. Road surface influence on tyre/road noise - Parts I and II. Proceedings of Inter-Noise 80, Miami, Florida, USA, 259-266; 267-272.

[82] Picture retrieved from: *http://www.tcpsc.com/pavement-surface-characteristics/texture/*

[83] Dubois G., Cesbron J., Yin H.P., Anfosso-Lédée F., Duhamel D., 2013. Statistical estimation of low frequency tyre/road noise from numerical contact forces. Applied Acoustics 74 (2013) 1085–1093

[84] Sangiorgi C., Bitelli G., Lantieri C., Irali F., Girardi F., 2012. A study on texture and acoustic properties of cold laid microsurfacings, Procedia: Social & Behavioral Sciences, 53, pp. 223 - 234.

[85] Leandri P., 2008. Studio di pavimentazioni per la riduzione del rumore generato dal traffic stradale. PhD thesis, University of Pisa.

[86] ASTM E 965, 1996. Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique. ASTM International, Annual Book of ASTM Standards, West Con- shohocken, PA.

[87] Attenborough K., Howarth C. 1990. Models for the acoustical characteristics of porous road surfaces. Proceedings of INTROC 90 (International Tire/Road Noise Conference 1990), Gothenberg, Sweden, 177-191.

[88] Hamet J-F., Bérengier M. 1993. Acoustic characteristics of porous pavements: a new phenomenological model, Proceedings of Inter-Noise 93, Leuven, 1993, 641-646.

[89] Biligiri, K., P., 2013. “Effect of pavement materials’ damping properties on tyre/road noise characteristics.” Construction and Building Materials 49: 223–232.

[90] Biligiri K. P., Kaloush K., Uzan J., 2010. Evaluation of asphalt mixtures' viscoelastic properties using phase angle relationships. International Journal of Pavement Engineering, Vol. 11, No. 2, April 2010, pp. 143–152.

[91] Suo, Z., Wong W. G., 2009. “Analysis of fatigue crack growth behavior in asphalt concrete material in wearing course.” Construction and Building Materials 23 (1): 462–468.

[92] Mills, B. N., Tighe S. L., Andrey J., Huen K., Parm S., 2006. Climate change and the performance of pavement infrastructure in southern Canada: Context and case study. In EIC Climate Change Technology, 2006 IEEE, 1–9.

[93] Mills, B. N., Tighe S. L., Andrey J., Smith J. T., Huen K., 2009. “Climate change implications for flexible pavement design and performance in southern Canada.” Journal of Transportation Engineering 135 (10): 773–782.

[94] Franklin R. E., Harland D. G., Nelson P. M. 1979. Road surfaces and traffic noise. TRRL Report LR 896. TRL Limited, Crowthorne, UK.

[95] Bendtsen, H., Kohler E., Lu Q., Rymer B., 2010. “California-Denmark Study on Acoustic Aging of Road Pavements.” Transporta- tion Research Record: Journal of the Transporta- tion Research Board 2158 (1): 122–128.

[96] European Union, 2008. Detection Systems for Pavement Discontinuities. Overview of technologies and systems to detect pavement discontinuities including assessment of importance to noise reduction – Part 2. Berengier, Michel. LCPC, France. 13.2.2008. Part of the EU SILENCE Project.

[97] Ellebjerg L., Bendtsen H., 2008. Two-layer porous asphalt – lifecycle. Danish Road Institute/Road Directorate. Report 165, 2008.

[98] Bueno M., Luong J., Vinuela U., Teràn F., Paje S. E., 2011. "Pavement temperature influence on close proximity tire/road noise". Applied Acoustics 72, 829-835.

[99] Anfosso-Lédée F., Pichaud Y., 2007. "Temperature effect on tyre-road noise". Applied Acoustics 68, 1-16.

[100] Kuijpers A., 2002. Memo on temperature effects on tyre/road noise and on tyre stiffness. M+P.WG27/2002/2ak report, 2002. *http://www.silentroads.nl/*

[101] Bendtsen, H., Lu Q., Kohler E., 2009. Temperature influence on road traffic noise Californian OBSI measurement study Report 169. Danish Road Directorate, Danish Road Institute. ISBN: 978-87-92094-47-6

[102] European Directive 2001/43/EC of the European Parlament and of the Council of June 27th 2001.

[103] Sangiorgi C., Lantieri C., Volta E., Irali F., 2012. Microtappeti multifunzionali contro il rumore stradale. (n. 1475) Le Strade n°3 year CXIV, March 2012,pp. 90-06, ISSN 0373-2916.

[104] International Slurry Surfacing Association (ISSA), 1991. Design Technical Bulletins, 1990.

[105] UNI EN 933-8. 2012. Prove per determinare le caratteristiche geometriche degli aggregati - Parte 8: Valutazione dei fini - Prova dell'equivalente in sabbia. Ente Nazionale Italiano di Unificazione, Milano, 2012.

[106] UNI EN 933-9. 2009. Prove per determinare le caratteristiche geometriche degli aggregati - Parte 9: Valutazione dei fini - Prova del blu di metilene. Ente Nazionale Italiano di Unificazione, Milano, 2009.

[107] UNI EN 1097-2. 2010. Prove per determinare le proprietà meccaniche e fisiche degli aggregati - Parte 2: Metodi per la determinazione della resistenza alla frammentazione. Ente Nazionale Italiano di Unificazione, Milano, 2010.

[108] UNI EN 12274-4. 2003. Trattamenti superficiali con malte a freddo - Metodi di prova - Determinazione della coesione della miscela. Ente Nazionale Italiano di Unificazione, Milano, 2003.

[109] UNI EN 12274-5. 2004. Trattamenti superficiali con malte a freddo - Metodi di prova - Parte 5: Determinazione dell usura. Ente Nazionale Italiano di Unificazione, Milano, 2004.

[110] UNI EN 13036-1. 2010. Caratteristiche superficiali delle pavimentazioni stradali ed aeroportuali - Metodi di prova - Parte 1: Misurazione della profondità della macrotessitura della superficie della pavimentazione tramite tecnica volumetrica ad impronta. Ente Nazionale Italiano di Unificazione, Milano, 2010.

[111] UNI EN 13036-4. 2011. Caratteristiche superficiali delle pavimentazioni stradali ed aeroportuali - Metodi di prova - Parte 4: Metodo per la misurazione della resistenza allo slittamento/derapaggio di una superficie: Metodo del pendolo. Ente Nazionale Italiano di Unificazione, Milano, 2011.

[112] ASTM E303, 1993. Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester, ASTM International, Annual Book of ASTM Standards, West Con- shohocken, PA.

[113] ISO 13473-2, 2002. Characterization of pavement texture by use of surface profiles —Part 2: Terminology and basic requirements related to pavement texture profile analysis. International Organization for Standard- ization, ISO/CD 10534-2:1998, Geneva, Switzer- land, 1998.

[114] ASTM E 1926, 2008. Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements. 2008-06-01.

[115] Irali F., Kivi A., Smith J. T., Tighe S. L., Sangiorgi C., 2013. Recycled concrete aggregate in concrete pavements: a five year study on its effect on pavement performance. Transportation Association of Canada Conference and Exhibition, Winnipeg (Canada), September 22nd-25th 2013.

[116] ISO 10534-2, 2001. Acoustics - Determination of sound absorption coefficient and impedance in impedances tubes - Transfer-function method. 2001-10-31. International Organization for Standard- ization, ISO/CD 10534-2:1998, Geneva, Switzer- land, 2001.