

# Environmental Methods for Transport Noise Reduction

Edited by **Mats E. Nilsson**  
**Jörgen Bengtsson**  
**Ronny Klæboe**



**CRC Press**

Taylor & Francis Group

Boca Raton London New York

---

CRC Press is an imprint of the  
Taylor & Francis Group, an **informa** business

A SPON BOOK

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2015 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works  
Version Date: 20140909

International Standard Book Number-13: 978-1-4822-8877-3 (eBook - PDF)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>

and the CRC Press Web site at  
<http://www.crcpress.com>

---

# Contents

---

<i>Preface</i>	<i>xiii</i>
<i>Glossary</i>	<i>xvii</i>
<i>Contributors</i>	<i>xxi</i>
<i>The HOSANNA project</i>	<i>xxv</i>

## **1 Introduction to traffic noise abatement** **1**

JENS FORSSÉN, WOLFGANG KROPP, AND TOR KIHLMAN

- 1.1 *Background* 1
- 1.2 *Principles of Noise Reduction* 2
  - 1.2.1 *Source strength* 3
  - 1.2.2 *Propagation effects* 8
  - 1.2.3 *Noise indicators* 16
- 1.3 *Concluding Remarks* 16
- References* 17

## **2 Innovative barriers** **19**

JÉRÔME DEFRANCE, PHILIPPE JEAN, FAOUZI KOUSSA,  
TIMOTHY VAN RENTERGHEM, JIAN KANG, AND YULIYA SMYRNOVA

- 2.1 *Introduction* 19
  - 2.1.1 *Receiver zones* 19
  - 2.1.2 *Objectives* 20
- 2.2 *Urban Streets* 21
  - 2.2.1 *Building low-height vegetated barriers* 21
  - 2.2.2 *Adding low-height vegetated interlane barriers* 23
  - 2.2.3 *Building low-height gabion barriers* 24
- 2.3 *Tramways* 25
  - 2.3.1 *Building low-height earth berms* 25
  - 2.3.2 *Building low-height, sonic crystal-assisted barriers* 27
  - 2.3.3 *Adding low-height vegetated intertrack barriers* 28

- 2.3.4 *Building low-height vegetated barriers at the edges of bridges* 29
- 2.4 *Motorways* 30
  - 2.4.1 *Covering conventional rigid noise barrier with vegetation substrate* 30
  - 2.4.2 *Adding a row of trees behind a conventional noise barrier* 33
  - 2.4.3 *Adding vegetated caps on top of conventional noise barriers* 35
  - 2.4.4 *Building low-height earth berms along embanked infrastructure* 37
  - 2.4.5 *Building complex-shaped earth berms* 38
  - 2.4.6 *Building low-height vegetated barriers at the edges of bridges* 41
- 2.5 *Railways* 42
  - 2.5.1 *Building low-height earth berms along embanked infrastructures* 42
  - 2.5.2 *Building complex-shaped earth berms* 44
- 2.6 *Summary of Conclusions* 45
- References* 46

### 3 Acoustic performance of vegetation and soil substratum in an urban context 47

KIRILL HOROSHENKOV, AMIR KHAN, HAIDJ BENKREIRA, AGNES MANDON, AND RENÉ ROHR

- 3.1 *Introduction* 47
- 3.2 *Experimental Setup and Measurement Procedures* 48
- 3.3 *Effect of Moisture on Soil Absorption* 50
- 3.4 *Modelling of the Acoustical Properties of Soils* 53
- 3.5 *Low Growing Plants* 56
- 3.6 *Modelling of the Acoustical Properties of Plants* 57
- 3.7 *Absorption of Soil in the Presence of a Plant* 68
- 3.8 *Modelling the Random Incidence Absorption Coefficient of Soil with and without Plants* 71
- 3.9 *Conclusions* 75
- References* 76

### 4 Acoustical characteristics of trees, shrubs, and hedges 79

TIMOTHY VAN RENTERGHEM, DICK BOTTELDOOREN, JIAN KANG, KIRILL HOROSHENKOV, AND HONG-SEOK YANG

- 4.1 *Introduction* 79

- 4.2 *Absorption by Leaves* 80
  - 4.2.1 *Measuring leaf absorption* 80
  - 4.2.2 *Measuring leaf vibrations* 83
- 4.3 *Reflection and Diffraction by Vegetation* 84
- 4.4 *Scattering by Vegetation* 85
  - 4.4.1 *Measuring scattering by a pile of leaves in the laboratory* 85
  - 4.4.2 *Scattering by a single tree* 87
  - 4.4.3 *Visualising scattering in the multiple layers in a vegetation belt* 88
- References* 89

## 5 Designing vegetation and tree belts along roads 91

TIMOTHY VAN RENTERGHEM, KEITH ATTENBOROUGH, AND PHILIPPE JEAN

- 5.1 *Introduction* 91
- 5.2 *Designing Vegetation Belts Near Roads* 92
  - 5.2.1 *Introduction and research methodology* 92
  - 5.2.2 *Acoustical effects operating in a vegetation belt shown to be additive* 92
  - 5.2.3 *Interactions between sound waves and vegetation belts* 93
  - 5.2.4 *Planting schemes for tree belts* 95
- 5.3 *Improving Microclimatology by Vegetation* 104
  - 5.3.1 *Reducing nocturnal temperature inversion effects* 108
  - 5.3.2 *Reducing wind effect near noise barriers* 109
- References* 116

## 6 Noise reduction using surface roughness 119

KEITH ATTENBOROUGH, IMRAN BASHIR, TOBY J. HILL,  
SHAHRAM TAHERZADEH, JÉRÔME DEFRANCE, AND PHILIPPE JEAN

- 6.1 *Ground Effect and Its Modification by Roughness* 119
  - 6.1.1 *Some results of outdoor experiments* 119
  - 6.1.2 *Ground effect as an interference phenomenon* 122
- 6.2 *Laboratory Data* 125
  - 6.2.1 *Laboratory measurements* 125
  - 6.2.2 *Diffraction-assisted rough ground effect* 128
  - 6.2.3 *Surface waves: generation and absorption* 130
- 6.3 *Field Data from Brick Configurations* 133
  - 6.3.1 *Measurements with a loudspeaker* 133
  - 6.3.2 *Drive-by tests* 134

- 6.4 *Predicted Effects of Roughness on Road Traffic Noise* 135
- 6.4.1 *Numerical predictions* 135
- 6.4.2 *Parallel walls versus lattices* 138
- 6.4.3 *Height profiles and clusters* 141
- 6.4.4 *Grooves and recessed lattices* 143
- 6.5 *Predicted Effects of Roughness Configurations around Railways* 146
- 6.6 *Predicted Effects of Surface Roughness on the Acoustical Performance of Berms* 148
- 6.7 *Meteorological Effects on Roughness-Based Noise Reduction* 149
- 6.8 *Conclusion* 151
- References* 152
- 7 Porous ground, crops, and buried resonators** 153
- KEITH ATTENBOROUGH, SHAHRAM TAHERZADEH, IMRAN BASHIR,  
JENS FORSSÉN, BART VAN DER AA, AND MANUEL MÄNNEL
- 7.1 *Porous Ground and Crops* 153
- 7.1.1 *Replacing hard ground with soft ground* 154
- 7.1.2 *Reduction of tramway noise after replacing asphalt with grass* 159
- 7.1.3 *Replacing a road with hard strips in otherwise soft ground* 160
- 7.1.4 *Combined effects of crops and ground* 161
- 7.1.5 *Acoustically soft strips and patches* 162
- 7.2 *Predicted Effects of Ground Treatments around Railways* 164
- 7.2.1 *Introduction of grassland* 164
- 7.2.2 *Gravel strips* 166
- 7.2.3 *Porous concrete slab track* 168
- 7.3 *Road Traffic Noise Reduction Using Buried Resonators* 168
- 7.3.1 *Resonators buried in porous road surfaces* 170
- 7.3.2 *Resonators buried in hard ground* 171
- 7.4 *Conclusion* 174
- References* 175
- 8 Vegetation in urban streets, squares, and courtyards** 177
- JIAN KANG, MAARTEN HORNIKX, TIMOTHY VAN RENTERGHEM,  
YULIYA SMYRNOVA, JENS FORSSÉN, CHRIS CHEAL, DICK BOTTELDOOREN,  
HONG-SEOK YANG, JIN YONG JEON, HYUNG SUK JANG,  
SHAHRAM TAHERZADEH, KEITH ATTENBOROUGH, AND AGNES MANDON
- 8.1 *Acoustic Potential of Green Roof and Green Wall Systems in the Urban Context* 177

- 8.2 *Studied Cases* 179
  - 8.2.1 *Reference configurations* 179
  - 8.2.2 *Case A: single street* 179
  - 8.2.3 *Case B: urban square with a trafficked street on one side* 179
  - 8.2.4 *Case C: street with a completely enclosed courtyard* 180
  - 8.2.5 *Case D and Case E: street and a courtyard with a façade opening* 181
  - 8.2.6 *Configurations with green measures* 181
- 8.3 *Traffic Model and Prediction Approaches* 183
  - 8.3.1 *Traffic model* 184
  - 8.3.2 *Prediction models* 184
  - 8.3.3 *Measures of green roof and green wall effects* 185
- 8.4 *Effect of Vegetation* 185
  - 8.4.1 *Case A* 185
  - 8.4.2 *Case B* 187
  - 8.4.3 *Case C: vegetated courtyard façades* 188
  - 8.4.4 *Case C: vegetated roof barriers* 188
  - 8.4.5 *Case C: vegetated courtyard T=Roofs* 189
  - 8.4.6 *Case C: combination of (nonflat) roof shape and vegetated roof* 189
  - 8.4.7 *Case C: combination of treatments* 190
  - 8.4.8 *Cases D and E: vegetated opening to courtyards* 190
- 8.5 *Summary* 191
- References* 192

## 9 Perceptual effects of noise mitigation

195

MATS E. NILSSON, DICK BOTTELDOOREN, JIN YONG JEON,  
 MARIA RÅDSTEN-EKMAN, BERT DE COENSEL, JOO YOUNG HONG,  
 JULIEN MAILLARD, AND BRUNO VINCENT

- 9.1 *Introduction* 195
- 9.2 *Noise: Psychoacoustics of Noise Mitigation* 196
  - 9.2.1 *Case study of low, vegetated barriers* 197
  - 9.2.2 *Perceptual effects of soft and hard ground along tramways* 200
- 9.3 *Soundscape: Wanted and Unwanted Sounds in Interactions* 205
  - 9.3.1 *Auditory masking and noticeability* 206
  - 9.3.2 *Adding wanted sounds* 209
- 9.4 *Environment: Audio-Visual Interactions* 213

## 9.5 Concluding Remarks 216

## References 217

## 10 Economic analyses of surface treatments, tree belts, green façades, barriers, and roofs 221

RONNY KLÆBOE AND KNUT VEISTEN

- 10.1 Introduction 221
  - 10.1.1 Societal cost-benefit analyses in HOSANNA 221
  - 10.1.2 Economic analyses of six groups of measures 223
  - 10.1.3 Benefit-cost ratios applied for ranking projects within groups 224
  - 10.1.4 It is really projects, not measures, that are assessed economically 225
- 10.2 Economic Analyses of Green Roofs and Roof Barriers 225
  - 10.2.1 Extensive roofs, roof barriers, and surface treatment alternatives 225
  - 10.2.2 Input to the economic analyses 225
  - 10.2.3 Three measures are cost efficient, one of which is robustly efficient 227
- 10.3 Economic Analyses of Vegetated Façades 228
  - 10.3.1 Input to the economic analyses 228
  - 10.3.2 Economic analyses of two vegetated façade openings 228
  - 10.3.3 All vegetated facade projects are robustly efficient when aesthetic appreciation is included 231
- 10.4 Economic Analyses of Surface Treatments 232
  - 10.4.1 Lattices with and without maintenance 232
  - 10.4.2 Cost calculations 232
  - 10.4.3 Land usage costs 232
  - 10.4.4 Clearance, construction, and maintenance costs 233
  - 10.4.5 Noise reduction benefit calculations 234
  - 10.4.6 The relationship between noise reduction and “kverks” 236
  - 10.4.7 Noise reduction impacts for residents in 74 buildings 237
  - 10.4.8 Alternative with maintenance to prolong life span is robustly efficient 238
- 10.5 Economic Analyses of Low, Vegetated Barriers 238
  - 10.5.1 Prototype of low, vegetated barrier 238
  - 10.5.2 Maintenance costs dominate 239



- 10.5.3 *Valuation studies of aesthetics of low, green barriers are needed* 240
- 10.6 *Economic Analyses of Source + Propagation Measures* 240
  - 10.6.1 *Types of configurations* 240
  - 10.6.2 *Lattice in combination with two-layer, open porous road surfaces* 242
  - 10.6.3 *Absolute and marginal kverk to dB(A) ratios* 242
  - 10.6.4 *Special considerations when analysing combinations* 244
  - 10.6.5 *Adding dual porous asphalt (with/without resonators) makes solutions robustly efficient* 245
- 10.7 *Economic Analyses of Tree Belts* 246
  - 10.7.1 *Tree belts used alone and in combination with artificial elements* 246
  - 10.7.2 *Properties of artificial elements* 247
  - 10.7.3 *Cost of tree belts* 247
  - 10.7.4 *Cost of artificial elements* 248
  - 10.7.5 *Tree belt 200 m long, 15 m wide to protect a community* 248
  - 10.7.6 *Average kverk reduction as a function of stem size* 249
  - 10.7.7 *Amenity/aesthetic effect of the tree belt* 250
  - 10.7.8 *Carbon sequestration* 250
  - 10.7.9 *Tree belt alternatives considered* 250
  - 10.7.10 *Tree belt alternatives with artificial elements are best economic performers* 251
- 10.8 *Economic Analyses: Simplified Version* 251
  - 10.8.1 *The virtue of economic analysis: societal cost-benefit analysis* 251
  - 10.8.2 *Harmonizing one-time investments and annual benefits* 252
  - 10.8.3 *Cost-effectiveness analyses (CEA)* 253
  - 10.8.4 *Cost-benefit analysis (CBA)* 254
  - 10.8.5 *Monte Carlo simulations* 254
- 10.9 *Charting the Unknown: Aesthetic Appreciation* 255
  - 10.9.1 *We choose to include aesthetic benefits in the economic considerations* 255
  - 10.9.2 *The aesthetic/amenity value of urban greenery* 256
  - 10.9.3 *Valuations studies of vegetated walls/roofs* 256
  - 10.9.4 *Unit value €2010 2.4 per person per year per square metre wall/roof* 257

10.9.5	<i>Valuations studies of urban trees</i>	257
10.9.6	<i>Unit value €2010 0.50 per person per year per square metre canopy</i>	259
10.10	<i>Concluding Remarks</i>	260
	<i>References</i>	260
	<i>Index</i>	265

---

## Preface

---

Exposure to noise from roads and railways is widespread, and the problem is increasing, primarily as a consequence of the continuous urbanization and growth of the transport sector. Traffic noise causes annoyance and sleep disturbance, and it interferes with rest, concentration, speech communication, and learning. There also is increasingly strong support for a causal link between long-term exposure to road traffic noise and cardiovascular disease, including hypertension and myocardial infarction.<sup>1</sup>

The most effective noise-mitigation method is to reduce noise emissions at the source, for example, by means of regulations demanding quieter engines, tires, or road surfaces, or by limiting traffic flow volumes and introducing stricter speed limits. However, such methods are often difficult to implement for economic, city planning, or political reasons. Therefore, at-source noise reduction must be complemented with methods that act on the noise during its path to the receiver. The aim of this book is to encourage the use of new and environmentally friendly methods of this kind.

*Environmental Methods for Transport Noise Reduction* presents the main findings of the research project HOListic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means (HOSANNA). The project aimed to develop a toolbox for reducing road and rail traffic noise in outdoor environments by the optimal use of vegetation, soil, and other natural and recycled materials, in combination with artificial elements.

The HOSANNA project studied a number of abatement strategies that might achieve cost-effective improvements using new barrier designs; planting of trees, shrubs, or bushes; ground and road surface treatments; and greening of building facades and roofs. Vegetated areas and surfaces are greatly appreciated in both urban and rural environments. The beneficial effects of greening mean that the costs of new greening or of maintaining existing green surfaces are often easy to justify, even without considering the benefit of environmental noise reduction. The thrust of the HOSANNA project was to find better ways of using vegetated surfaces and recycled materials to reduce road and rail traffic noise and improve the perceived

sound environment. The noise reduction was assessed in terms of sound level reductions, perceptual effects, and cost–benefit analyses.

Traffic noise situations are often complex and a single noise mitigation measure is seldom sufficient. Some of the options we discuss in this book each lead only to 2 to 3 dB(A) reduction in noise, so an appropriate combination of measures is needed to obtain a larger effect. Other individual noise abatements are expected to reduce noise by 10 dB(A) or more. It should be noted that most of the estimated noise reductions have been calculated using advanced numerical methods, rather than measured in real situations, so a nonnegligible uncertainty is expected in real situations. To minimize this uncertainty, the estimation methods have all been validated and are applied in situations that are as realistic as possible. In addition, the impairment in performance due to meteorological effects has been estimated for selected cases by modelling the effects of mean wind and turbulence.

The methods presented in this book act by exploiting various acoustic phenomena that influence sound during their paths from source to receiver. Chapter 1 (Forssén et al.) reviews the general principles of outdoor noise propagation, and specifically those phenomena that are relevant for the efficiency of the mitigation methods, which are introduced in Chapters 2 to 8.

The conventional noise control solution is to erect noise barriers, and much has been learned over the years about noise barrier design.<sup>2</sup> However, there is still room for new ideas, as is evident in Chapter 2 (Defrance et al.), where solutions like low-height vegetated barriers and vegetated barrier caps are discussed.

Chapter 3 (Horoshenkov et al.) presents detailed analyses of the acoustic performance of plants and soil, and illustrates how the acoustic absorption of soils can be enhanced by selecting the right type of low-growing plants. Chapter 4 (Van Renterghem et al.) presents corresponding results for hedges, trees, and tree belts, and their effect on reflection, diffraction, and scattering of sounds. Chapter 5 (Van Renterghem et al.) provides design tips for planting trees and tree belts along roads. Planting schemes may take advantage of several acoustic phenomena, such as multiple scattering in tree belts and upward refraction by trees planted close to noise barriers.

Sound travelling directly from source to receiver will interact with sound reflected from the ground, a phenomenon called *ground effect*. Chapter 6 (Attenborough et al.) suggests a new set of noise control options that uses the ground effect. Examples are the distribution of small protruding elements or grooves over the ground in such a way that the ground effect cancels sound in a frequency range that will reduce the noise from surface transport. Chapter 7 (Attenborough et al.) follows this up by discussing how different ground types give rise to different ground effects, and how this knowledge can be used to choose grounds for improved noise reduction. This chapter also includes a section on how to improve the noise-reducing

potential of porous asphalt by burying resonating chambers and resonators, which act on a specific frequency region of the noise.

Chapter 8 (Kang et al.) shows how vegetation on facades and roofs can improve the acoustic environment in urban streets, squares, and courtyards, in addition to the aesthetic and ecological benefits of increasing the amount of greenery in the city. Although the acoustic effect of single measures, such as vegetation on a single facade, may be small, combined measures may lead to substantial noise reduction.

The main part of this book discusses noise reduction in terms of sound pressure levels. This gives a fair indication of the corresponding improvement of the perceived acoustic environment. However, noise mitigation also changes the frequency composition and variability of the mitigated noise at the listener location, and may influence the audibility of other sounds in the environment as well as changing visual features of the environment. Such perceptual effects of noise mitigation are discussed in Chapter 9 (Nilsson et al.). Chapter 10 (Klæboe and Veisten) takes evaluation a step farther, and presents economic analyses of noise mitigation measures, using as examples several of the measures proposed in the previous chapters. In the analyses, costs and benefits of a noise mitigation project are valued and the project is considered cost efficient if it cost less than the total value of the benefits. These analyses show that many of the proposed methods have the potential of being cost efficient, in several cases robustly so.

Mats E. Nilsson, Jörgen Bengtsson, Ronny Klæboe (Editors), and  
Jens Forssén (HOSANNA project leader)  
*On behalf of the HOSANNA project*

## REFERENCES

1. WHO. 2011. *Burden of disease from environmental noise*. Copenhagen World Health Organization Regional Office for Europe.
2. Kotzen, B., and C. English. 2002. *Environmental noise barriers. A guide to their acoustic and visual design*, 2<sup>nd</sup> ed. Oxford, UK: Spon Press.



---

# Glossary

---

**Absorbent materials** Sound absorbents or absorbing materials reduce the reflection of sound as a result of being porous so that air particle motion associated with sound is able to penetrate and its energy is converted into heat by friction with the walls of the pores.

**Absorption coefficient** Result of measuring the sound-absorbing property of a surface, usually frequency and angle dependent. The measurement is made at normal incidence in an impedance tube or at random incidence in a reverberation chamber.

**Absorption of sound** The process by which sound energy is converted to heat. This can happen in the atmosphere through air absorption, nonporous boundary friction or interaction with a porous boundary.

**Acoustically hard/soft** A surface that reflects all of the sound that arrives at it is described as acoustically hard, whereas a surface that absorbs some or all of the sound that arrives at it is called acoustically soft.

**Atmospheric turbulence** Random irregular motion or fluctuation in temperature of fluid (e.g., air) induced by wind friction with the ground or by uneven surface heating. It scatters sound to an extent that increases with frequency. In the atmosphere, it reduces ground effects and the acoustical performance of barriers.

**Auralisation** A method of simulating a real (e.g., an outdoor) hearing experience in a laboratory or through a virtual environment.

**Benefit–cost ratio** The ratio between the cash value of benefits accruing from a (noise reduction) action and the costs of implementing the action.

**Berm** An earthen barrier or bank of earth that may be used for noise control. Frequently, berms are made from soil removed during associated construction activities and planted to improve appearance.

**Damping ratio** A dimensionless measure of how rapidly oscillations decay.

**Diffraction** The physical phenomenon by which sound bends around the edges of an obstacle, e.g., the top of a noise barrier.

**Diffraction grating** A regularly spaced array of obstacles to a sound wave that causes enhanced reflection or cancellation when the wavelength, spacing, and angle satisfy certain conditions.

**Diffuse** A sound field at a receiver is considered to be diffuse if it contains components travelling in all directions.

**Drag** Drag (sometimes called *air resistance*) is a type of friction that results in forces acting opposite to the relative motion of any object moving with respect to a surrounding fluid.

**Drag coefficient** The drag coefficient is a dimensionless quantity that is used to quantify the drag or resistance experienced by an object moving in a viscous fluid.

**EA** See excess attenuation.

**Excess attenuation** Attenuation of outdoor sound in excess of that due to wavefront spreading and, possibly, air absorption.

**Flow resistivity** A measure of the ease with which air can pass in and out of a porous surface. Specifically, it is given by the ratio of applied pressure gradient to resulting volume flow per unit thickness of material.

**Geometric spreading** The physical phenomenon by which sounds spread from a source after generation. This means that sound levels will reduce from distance alone. Spherical spreading and cylindrical spreading are special cases giving rise to 6 dB and 3 dB reduction per doubling of distance, respectively.

**Ground effect** The physical phenomenon (interference) through which sound reflected from the ground and travelling to a receiver along the reflection path either reinforces or cancels sound that arrives at the receiver directly.

**Impedance** The ratio of pressure to normal velocity at a surface.

**Impedance tube** A rigid tube with a loudspeaker at one end and an acoustically hard termination at the other, along which it is possible to measure the pressure profile or the complex pressure (i.e., both magnitude and phase) at two or more fixed microphone positions or continuously using a probe microphone.

**Insertion loss** The insertion loss due to a mitigation measure is the difference between the sound levels at a given location without and with a mitigation measure. Usually stated in decibels (dB).

**Insolation** Amount of sunlight incident on a surface.

**Leaf area density** Leaf area per unit volume (can be one-sided or two-sided).

**Loudness** The perceived intensity of sounds (unit: sone). Also the output of a psychoacoustic model of the perceived loudness of sounds.

**Loudness level** The loudness of a sound, expressed as the level of an equally loud 1-kHz tone (unit: phon). Also, the output of a psychoacoustic model of the perceived loudness of sounds.

**Notice event** An auditory event that is noticed by a listener in a given environment.

**Open porosity** Volume fraction of interconnecting pores that open to the surface of a material.



- Porosity** Total fraction of a material occupied by pores including “dead end” ones.
- Porous asphalt** An asphalt mix of stones and binder in which a gap in the stone size distribution is deliberately created so as to result in air-filled voids.
- Pressure resistance** *See* flow resistivity.
- Pressure resistance coefficient** *See* flow resistivity.
- Reflection** The process by which the sound incident on a surface is directed away from the surface. During specular reflection, the sound is directed away from the surface at the same angle from the surface as that made by the incident sound. Reflection represents a special form of scattering when the scattering object is very large compared with the incident wavelength.
- Reflection coefficient** The fraction of incoming sound intensity that is reflected.
- Refraction** The process involving change of sound speed by which the direction of sound penetrating a surface or region is changed.
- Resonator** A structure that resonates. If an undamped structure is vibrated at the frequency of resonance (resonant frequency), the amplitude of vibration grows arbitrarily large. Typical resonators include damping and can be used to absorb sound near the resonance frequency.
- Reverberant room** Sometimes called a *reverberation chamber*, a room specially constructed with acoustically-hard surfaces, non-parallel walls, and aids to diffusion.
- Scattering** The process by which an obstacle influences incident sound. It depends on the relative size of the obstacle compared to an incident wavelength. If the obstacle is very small compared with the wavelength, its influence is small, but the combined influence of multiple scattering may be significant if there is a large number of small obstacles per unit volume.
- Scattering coefficient** The fraction of incoming sound power that is scattered.
- Sonic crystal** A regularly spaced array of (usually acoustically hard) scattering objects giving rise to stop and pass bands in acoustic transmission at frequencies that depend on the centre-to-centre spacing.
- Soundscape** The overall acoustic environment, including sounds from all audible sources.
- Specular reflection point** The position on a reflecting surface at which the angle of incidence is equal to the angle of reflection.
- Substrate** An underlying layer (a substratum). Material on which plants grow or are attached.
- Substratum** *See* substrate.
- Surface wave** A wave in the close vicinity of the ground surface characterized by cylindrical spreading and exponential decay with the height above the surface.

**Thermal dissipation** Conversion of mechanical energy to heat. Inside a pore of a porous material it accompanies heat transfer between compressions and rarefactions of the pore fluid and pore walls during the passage of a sound wave.

**Tortuosity** A measure of the deviation of streamline flow from a straight line through a porous material.

**Transfer function** The ratio of signals at two positions in a signal processing chain.

**Transfer matrix approach** A method of modelling sound propagation through a layered system in which the velocities or pressures at each interface are included in a matrix.

**Viscous loss** Conversion of mechanical energy into heat through fluid viscosity.

---

# Contributors

---

**Keith Attenborough**

Engineering and Innovation  
The Open University  
Milton Keynes, United Kingdom

**Imran Bashir**

College of Engineering  
Maths and Physical Sciences  
University of Exeter  
Exeter, United Kingdom

**Haidj Benkreira**

School of Engineering, Design  
and Technology  
University of Bradford  
West Yorkshire, United Kingdom

**Dick Botteldooren**

Department of Information  
Technology  
Ghent University  
Ghent, Belgium

**Chris Cheal**

School of Architecture  
University of Sheffield  
Sheffield, United Kingdom

**Bert De Coensel**

Department of Information  
Technology  
Ghent University  
Ghent, Belgium

**Jérôme Defrance**

Centre Scientifique et Technique  
du Bâtiment (CSTB)  
Marne de Vallée, France

**Jens Forssén**

Applied Acoustics  
Chalmers University of  
Technology  
Gothenburg, Sweden

**Toby J. Hill**

Engineering and Innovation  
The Open University  
Milton Keynes, United Kingdom

**Joo Young Hong**

Department of Architectural  
Engineering  
Hanyang University  
Seoul, South Korea

**Maarten Hornikx**

Department of the Built  
Environment  
Eindhoven University of  
Technology  
Eindhoven, The Netherlands

**Kirill Horoshenkov**

Department of Mechanical  
Engineering  
University of Sheffield  
Sheffield, United Kingdom

**Hyung Suk Jang**

Department of Architectural  
Engineering  
Hanyang University  
Seoul, South Korea

**Philippe Jean**

Centre Scientifique et Technique  
du Bâtiment (CSTB)  
Marne de Vallée, France

**Jin Yong Jeon**

Department of Architectural  
Engineering  
Hanyang University  
Seoul, South Korea

**Jian Kang**

School of Architecture  
University of Sheffield  
Sheffield, United Kingdom

**Amir Khan**

Bradford Centre for Sustainable  
Environments  
University of Bradford  
West Yorkshire, United Kingdom

**Tor Kihlman**

Applied Acoustics  
Chalmers University of  
Technology  
Gothenburg, Sweden

**Ronny Klæboe**

Institute of Transport Economics  
(TOI)  
Oslo, Norway

**Faouzi Koussa**

Centre Scientifique et Technique  
du Bâtiment (CSTB)  
Marne de Vallée, France

**Wolfgang Kropp**

Applied Acoustics  
Chalmers University of  
Technology  
Gothenburg, Sweden

**Julien Maillard**

Centre Scientifique et  
Technique du Bâtiment  
(CSTB)  
Marne de Vallée, France

**Agnes Mandon**

Canevaflor®  
Tarare, France

**Manuel Männel**

Müller-BBM  
Munich, Germany

**Mats E. Nilsson**

Gösta Ekman Laboratory  
Department of Psychology  
Stockholm University  
Stockholm, Sweden

**Maria Rådsten-Ekman**

Gösta Ekman Laboratory  
Department of Psychology  
Stockholm University  
Stockholm, Sweden

**René Rohr**

Canevaflor®  
Tarare, France

**Yuliya Smyrnova**

School of Architecture  
University of Sheffield  
Sheffield, United Kingdom

**Shahram Taherzadeh**

Engineering and Innovation  
The Open University  
West Yorkshire  
United Kingdom

**Bart Van der Aa**

Applied Acoustics  
Chalmers University of  
Technology  
Gothenburg, Sweden

**Timothy Van Renterghem**  
Department of Information  
Technology  
Ghent University  
Ghent, Belgium

**Knut Veisten**  
Institute of Transport Economics  
(TOI)  
Oslo, Norway

**Bruno Vincent**  
Acouité  
Lyon, France

**Hong-Seok Yang**  
School of Architecture  
University of Sheffield  
Sheffield, United Kingdom



---

# The HOSANNA project

---

This book is based on research conducted in the research project **H**olistic and **S**ustainable **A**batement of **N**oise by optimized combinations of **N**atural and **A**rtificial means (HOSANNA). The project aimed to develop a set of tools for reducing road and rail traffic noise in outdoor environments by the optimal use of vegetation, soil, and other natural and recycled materials in combination with artificial elements.

The project studied a number of green abatement strategies that might achieve cost-effective improvements using new barrier designs; planting of trees, shrubs, or bushes; ground and road surface treatments; and greening of building facades and roofs. The noise reduction was assessed in terms of sound level reductions, perceptual effects, and cost–benefit analyses.

The project was coordinated by Chalmers University of Technology in Gothenburg, Sweden (coordinator Associate Professor Jens Forssén), and involved 13 partners from 7 countries. The research received funding from the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 234306, collaborative project HOSANNA.



HOSANNA partners: Chalmers University of Technology (Sweden), CSTB (France), Canevaflor (France), IBBT Ghent University (Belgium), Müller-BBM (Germany), Open University (United Kingdom), City of Stockholm (Sweden), Institute of Transport Economics (TOI) (Norway), University of Sheffield (United Kingdom), University of Bradford (United Kingdom), Stockholm University (Sweden), Acoucité (France), and Hanyang University (South Korea).