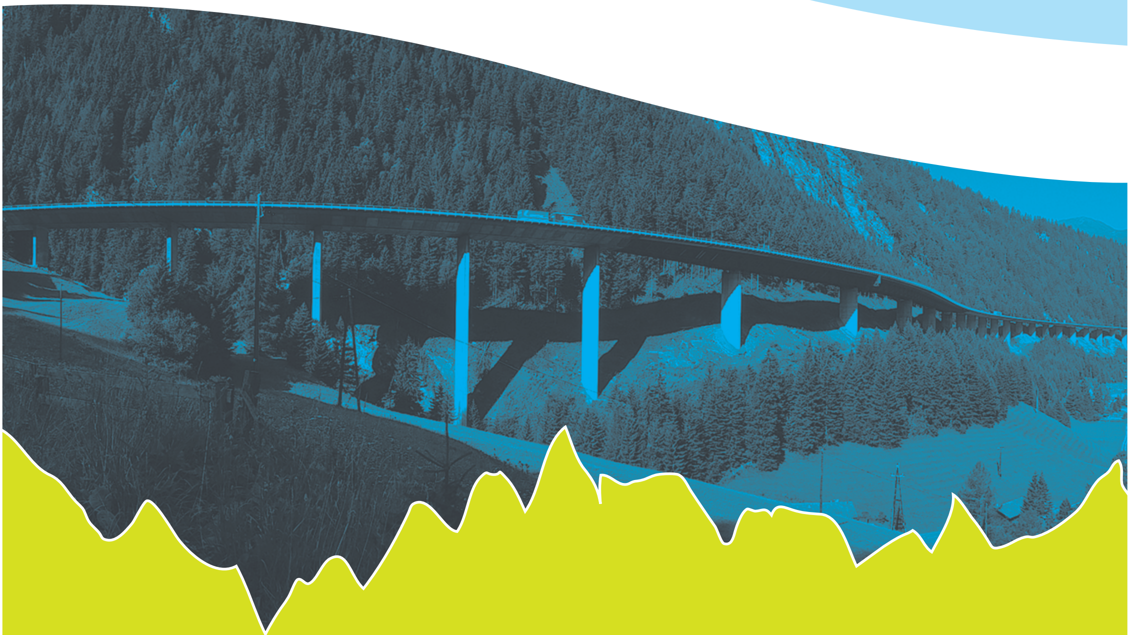
ALPNAP

Air Pollution, Traffic Noise and Related Health Effects in the Alpine Space

ALPNAP
Project Consortium



A Guide for Authorities and Consulters

Alpine Space
Interreg III B

ALPNAP (Project Consortium)

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1 INTRODUCTION

1.1 Background and purpose

The Alps: living space, recreation resort and transit area

The Alps are one of the most important natural reserves in Europe. Encompassing 191.000 km^2 they cover about two percent of the continent. The Alps are also the living space for 13 million people which are approximately two percent of the European population. With 68 people per km^2 the population density of the Alps is therefore of the same order of magnitude as the average population density of Europe. Additionally, the Alpine arc which is 950 km long and on average 250 km wide, is a topographical barrier that separates major economic centres and urban agglomerations in Europe (Italy – France, Italy – Germany). Even the lowest pass (Brennero/Brenner) has an altitude of approx. 1350 m above sea level. However, the mountains also act as a barrier between the intra-Alpine residential areas. In addition, the natural beauties and mountain sports resorts attract a high number of tourists. With 500 million overnights and 120 million holyday guests per year the Alps are one of the most prosperous tourist regions in the world.

Free trade within the European Union has increased and is still increasing the demand for the transport of commodities across the Alps. This has caused growing freight traffic along the Alpine transit routes. Between 1980 and 2005 the total transport volume across the Alps has more than doubled and amounted to 193 million tons[1] in 2005. The railway transport shares 33 percent of the total freight transport volume (2005). However, that proportion varies from country to country (65 percent in Switzerland, but only 14 percent in France and 31 percent in Austria). The cross-Alpine freight traffic adds to the regional and local inner-Alpine transport of goods. According to Eurostat the relative shares of transit traffic, source and destination traffic, and domestic traffic in Switzerland and Austria (number of trucks in 1999) are 44, 23 and 33 percent, respectively. This reflects conflicting interests between local/regional and large-scale economics. Passenger traffic is dominant in terms of the number of vehicles. Traffic counts at the Austrian motorway A12 (at Hall near Innsbruck) resulted in a share of 86.8 percent passenger traffic. Near the Brennero/Brenner pass (motorway A13) where commuter traffic only plays a minor role, the share of passenger cars amounts to only 75.6 percent. Passenger traffic is also increasing, but only at approximately half the rate of the freight traffic.

Air pollution and noise in a sensitive region with distinct peculiarities

The increasing transport volume makes air pollution and noise a growing problem in the Alps and solutions are urgently needed. When compared to the flat regions the environmental burden in mountainous areas is much more enhanced. In its report “Transport and Mobility in the Alps” the

[1] Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation (Swiss Confederation): Alpinfo 2005, Alpenquerender Güterverkehr auf Strasse und Schiene

1 Introduction

Permanent Secretariat of the Alpine Convention[2] clearly states: "*The relief and the narrowness of many valleys limit the air volume for reception of emissions and have amplifying effects on traffic noise. In addition the particular meteorological conditions like inversions and local wind systems impede the rarefaction and transportation of pollutants*."

The following facts aggravate the environmental situation in the mountains in comparison to that in flat terrain:

– Due to complex topography, the transport infrastructure is limited to a rather small number of corridors along valleys and across passes where traffic emissions concentrate.

– Most villages and towns in the Alps are also concentrated along the valleys, especially those with major motorways and railway lines. Therefore a rather large portion of the Alpine inhabitants live in close proximity with the cross-Alpine transport corridors and are consequently are exposed to the adverse environmental effects of transit traffic with negative consequences to their health and general well-being.

– Mountainous topography, with its often deep and narrow valleys, reduces the volume of air into which the mass of air pollutants and noise energy can disperse. This gives rise to an increased concentration of air pollutants and higher noise levels in comparison to flat terrain outside the mountains.

– The atmosphere in the Alps, i.e. the transport medium for air pollutants and sound waves, is influenced considerably by the complex underlying topography. This leads to specific meteorological phenomena (frequent stagnation, valley and slope wind circulations, foehn, etc.) which often impair a quick dilution of pollutions and noise thus causing high concentrations over longer periods or increased noise levels.

– The ecosystems in the mountainous area of the Alps are very sensitive, in particular in elevated regions where they are also exposed to climatic stress. Alpine forests have an important protective function against avalanches and land slides. Therefore, air pollution has more negative consequences than would occur outside the mountains. Both air pollution and noise contradict tourist's expectations and jeopardise the development of recreational areas.

Sustainable transport policies need scientific support

While the transport volume continues to rise, conflicts between economic and ecological interests are expected to intensify. Therefore, actions on a political level are often ambiguous. Completing Alpine routes (both road and rail) is a specific request in the White Paper "European Transport policy 2010" as well as from the Trans European Transport Networks (TEN-T). On the other hand the Sixth Community Environment Action Programme stipulates in its Article 7 "achieving levels of *air quality* that do not give rise to significant negative impacts on and risks to human health and the environment" and "substantially reducing the number of people regularly affected by long-term average levels of *noise*, in particular from traffic which, according to scientific studies, cause detrimental effects on human health". The programme also states that "environmental policy-

[2] Alpine Convention: Report on the State of the Alps. Special Edition 1: Transport and Mobility in the Alps, 2007.

making, given the complexities of the issues, needs to be based on best available scientific and economic assessment, and on knowledge of the state and trends of the environment."

In the Transport Protocol of the Alpine Convention member states have committed themselves to support a sustainable transport policy in the Alps, to promote the shift of freight transport from road to rail, to dispense with the construction of major trans-Alpine roadways, and to construct inner-Alpine roads only if their compatibility with the environment is ensured. The transport protocol especially aims at stepwise reduction of air pollution and noise emissions of all transport modes on the basis of the best available technology. It further demands that environmental standards and indicators must be adapted to the special situations of the Alpine space. However, not all member states of the Alpine Convention have yet ratified this protocol.

New infrastructures will change the emissions and thus the environmental impact. Significant consequences are expected to occur as a result of new railway tunnels (NEAT tunnels across the Gotthard and Lötschberg massifs in Switzerland, the Brennero/Brenner base tunnel between Austria and Italy, and the Fréjus base tunnel between France and Italy) which are under construction or in planning. The same holds true for administrative measures (e.g. night-time heavy traffic ban) and incentives for either modal shift or co-modality in freight transport. Extended road tolls and the introduction of an Alpine transit rights trading system are other instruments which are currently being discussed. Such means may partly improve the situation, but may also produce contradictory effects, or introduce new sources of noise while air pollution is reduced. However, until now arguments and decisions still lack solid scientific background and reliable environmental impact assessments still suffer from the fact that standard prediction tools have very limited applicability in valleys and may be subject to large errors.

Previous projects on air pollution and noise in the Alpine environment

Meteorological processes, air pollution and noise including their effects on health have been investigated during numerous national and European projects. Although a complete survey of these projects cannot be given here, some of them are worth mentioning.

During the years 1990 to 1992 air pollution was investigated along the Brennero/Brenner cross-section from Garmisch-Partenkirchen (Germany) to Rovereto (Italy) within the project MEMOSA (Measurement and modelling of air pollutants in the Alps), funded by the states of Bavaria and Tyrol and the autonomous provinces of Bolzano and Trento. Several research aircraft were used to measure the concentration of various pollutants in the atmosphere of the Loisach, Inn and Adige/Etsch valley. Model simulations supplemented these activities. A similar project was simultaneously performed in Switzerland (POLLUMET). As a French counterpart the project POVA (Pollution des vallées alpines) was conducted between 2001 and 2004. Most recently two interrelated EUFAR[3] projects targeted the Austrian Lower Inn valley (INNAP: Boundary-Layer Structure in the Inn Valley during High Air Pollution; INNOX: NO_x Structure in the Inn Valley during High Air Pollution) where meteorology and NO_x concentrations were measured with instrumented aircraft. The results of these projects are partly described in Chapter 7 of this book.

[3] EUFAR: European Fleet for Airborne Research – an Infrastructure Cooperation Network of the European Commission HPRI programme under FP5/FP6.

Noise has not been investigated on a large scale in the Alpine region. Noise related projects have mostly aimed at distinct areas. Comprehensive studies on noise and its effects on health were carried out along the Tyrolean and South Tyrolean parts of the Lower Inn valley (Unterinntal) – Brennero/Brenner – Isarco/Eisack corridor, partly in relation to the Brennero/Brenner base tunnel environmental compatibility assessments.

Steps towards a dialogue between researchers and administrations

A systematic, Alpine-wide cooperation of experts was missing in the past and the dialogue between researchers and administrations was not very intensive. The ALPNAP project ("Monitoring and Minimisation of Traffic-Induced Noise and Air Pollution Along Major Alpine Transport Routes") with its partners from universities and research centres was designed to overcome these deficiencies.

It was the objective of ALPNAP to describe the Alpine-specific processes that determine air quality and noise in Alpine valleys and to collect innovative scientific tools and evaluation methods that allow measurement, assessment, and prediction of air pollution and noise as well as their impact on health. These tools and methods were applied to selected areas and situations in order to demonstrate their abilities and to elucidate the complexity of the processes involved. Finally, recommendations for authorities and consultants were worked out how to best assess the environmental impact of administrative measures, incentives and new infrastructure, thereby properly considering the complexity of natural processes in the Alpine region.

The added value of ALPNAP was increased by a coordinated cooperation with the contemporaneous project MONITRAF ("Monitoring of Road-Traffic Related Effects and Common Measures"), a network of regional transport and environment administrations in the Alps. The objectives of MONITRAF were to develop comprehensive measures that aim at reducing the negative effects of road traffic, while simultaneously enhancing the quality of life within the Alpine region.

1.2 Contents of this book

Targeted readers

This book is directed at experts in governmental authorities and consulting bureaus in the Alpine area or other mountainous regions who are involved in air quality and/or noise assessments, the planning of new transport infrastructure and corresponding environmental compatibility studies, or the planning of regulations with the aim of reducing the environmental impact of traffic and its consequences to public health. For these target groups the book provides a collection of science-based methods and tools and recommendations for their use and application. The book is also suited to newcomers in the Alpine region who want to learn about the peculiarities of natural processes which are responsible for the transport of air pollutions and the propagation of noise in the complex topography of mountainous regions. Eventually, this book can be used for the education of students in meteorology, acoustics, geography, transport sciences and engineering at universities or engineering schools.

The chain from base data to environmental impact assessments

This book describes the whole assessment chain beginning with the utilisation of base data (traffic flow, topography, demography, etc.) via observation and modelling of the mountain effects on the atmosphere, the dispersion of air pollutants and the propagation of noise, up to the health and environmental impact assessment. The schematic flow chart in Fig. 1.1 shows the sequence of data processing. A more detailed introduction into the content of the book is given in the following paragraphs.

Basic data resources and emission inventories

Chapter 2 provides an overview of basic data and emission models. In the first four sections basic data needed for the assessment of air pollution and noise related problems are described. These include demographic data, topographic data, traffic and transport infrastructure data, and routine meteorological data. Data sources and existing monitoring networks are described. In the fifths section emission models are introduced which enable the calculation the emission rates (both air pollution and noise) from given traffic flow and fleet composition data. Finally, emission inventories are described.

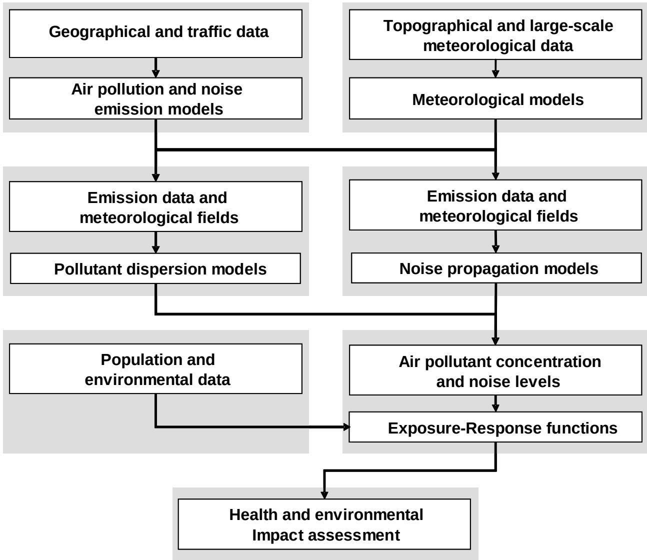

Fig. 1.1 Schematic representation of the assessment chain from base data to environmental impact on health.

Subject-oriented description of processes, tools and methods

Chapters 3 – 5 deal with meteorology, air pollution, and noise, respectively. These chapters are organized in a uniform manner: The first section gives a short introduction and provides definitions and background knowledge. The second section describes mountain-specific processes relevant for the dispersion of air pollutants and the propagation of noise in Alpine topography. Peculiarities which differ from the processes typical of flat terrain are addressed. The third section summarises state-of-the-art observation methods, provides an overview of instruments with their specific properties and abilities and describes appropriate measurement strategies. The forth section introduces simulation models, gives an overview of different model types, their advantages and shortcomings, abilities and limitations, and their respective suitability. Benefits and costs are also addressed. The last section deals with evaluation methods, statistics, indices and types of presentations.

Impact assessments

Chapter 6 concerns the impact assessment. Its first two sections introduce the issue and focus on the health and well-being, in particular with satisfaction with life, annoyances, sleep disturbances and general health aspects. These aspects are presented through a wide variety of examples and comparisons with previous studies. The last sections are devoted to assessment methods based on indices and/or exposure-response functions and finally address the monetisation concepts.

Integrated demonstrations and application to target areas

Chapter 7 is supplementary to the subject-oriented Chapters 2 – 6 and provides demonstrative applications for selected target areas along the Brennero/Brenner and Fréjus corridors. The demonstrations of tools and methods comprise emission, meteorology, air pollution and noise aspects in an integrative manner. The Brennero/Brenner and Fréjus corridors are the two transit axes with the largest freight transport volume across the Alps. With 20 percent (41.7 tons in 2004) the Brennero/Brenner corridor (Italy-Austria) shares the largest volume of commodities that were transported over the 15 most important Alpine transit routes. The Fréjus (France-Italy) and Gotthard (Switzerland) corridors follow with a share of 13 percent in each case. Both selected transverses (Brennero/Brenner and Fréjus) are transit routes for road and rail.

All analyses for the Brennero/Brenner corridor refer to two selected “hot spots”, namely (1) the Lower Inn valley (Unterinntal, Austria) between Kufstein (German-Austrian border) and Innsbruck and (2) the Adige/Etsch valley between Bolzano/Bozen and Verona (Italy). Analyses for the Fréjus target area include the Maurienne Valley between Chamousset and Modane in France and the Susa valley between Torino and Bardonecchia/ Bardonnèche/ Bardonescha in Italy. A cartographic overview of the target areas is shown in Fig. 1.2.

Fig. 1.2 Position of the ALPNAP target areas in the Brennero/Brenner and Fréjus corridor. Map modified from Wikipedia under the Creative Commons Attribution ShareAlike 2.5 licence (http://creativecommons.org/licenses/by-sa/2.5/).

Chapter 7 also presents the measurement results and related simulations of two campaigns which were carried out between November 2005 and February 2006 in both sub-target areas of the Brenner corridor. In addition the chapter comprises scenario assessments.

Recommendations

Chapter 8 provides a selection of recommendations for end users from an applied-science point of view. These include a recommended practice for Alpine air quality and noise assessments, support for planning of new infrastructure and traffic regulation measures, and the benefit of interregional, transnational consultations and the cooperation between science and research with local, regional and national administrations and decision makers on a political level.

2 Base data and emissions

Due to the relief in Alpine regions the spatial distribution of transport infrastructures (road and rail) and traffic emissions of air pollutants and noise are different from those in “flat” regions. The aim of this chapter is to describe base and emission data and tools to calculate these data which are needed to predict air and noise pollutions. Two types of emission sources can be distinguished: static or mobile ones. In this book the emphasis is laid on mobile sources, i.e. the vehicles on roads and railways. Static sources, such as industry, construction, agriculture, housing (e.g. domestic heating) can be principally registered in emission inventories which describe their average emission rates as a general function of daytime, season or temperature. However, emission inventories are often not complete and do not account for actual changes (e.g. temporary shut down of combustion processes, change of fuel or fuel composition, etc.). Hence, there is a strong need for comprehensive and accurate emission inventories of static sources with a high spatial and temporal resolution.

Characterizing the environment is a challenge which involves many parameters that influence pollutant dispersion and noise propagation and thus the environmental impact on human beings. The main information required is: topography, meteorology, human-made features (e.g. buildings, tunnels, viaducts, road embankment, and noise barriers), vegetation, traffic data, road characteristics and population data. Nowadays, Geographic Information Systems (GIS) are a versatile platform for analysing, visualizing, and sharing information between scientists, planners and administrations.

2.1 Topography

2.1.1 General

Topographical data are needed for the simulation of all physical and chemical processes in the atmosphere (meteorology, transport of pollutants, propagation of noise) since the Earth’s surface exerts a decisive influence on these processes. In mountainous regions topographical data are needed in high spatial resolution and quality. Topographical data include the information about the terrain elevation (“orography”) and the land use which determine the aerodynamic and thermodynamic characteristics of the ground (roughness, optical and acoustical reflectivity, etc.).

2.1.2 Terrain elevation

Generally, topography refers to a representation of the ground surface, including features such as population density, vegetation, land coverage, soil use, buildings, etc.; thus quite a wide variety of information. An important part of the topography and sometimes mistaken for the topography is the Digital Terrain Model (DTM). The DTM often comprises much of the raw dataset, which may have been acquired through different techniques such as photogrammetry, remote sensing, image analysis, land surveying. The Digital Elevation Model (DEM) is actually a subset of the DTM.

A Digital Elevation Model is a digital representation of ground surface topography in matrix or grid format with a given horizontal resolution. The quality of a DEM is determined by the accuracy of the elevation at the data points (absolute accuracy). A free DEM of the whole world called GTOPO30 (in a horizontal resolution of 30 arc seconds, approx. 1 km) is available, but its quality is variable and only suitable for applications in the global and regional scale. A much higher quality DEM from the Shuttle Radar Topography Mission (SRTM) is also freely available for most of the globe and represents elevation at a 3 arc second resolution (approximately 90 m). Higher quality DEM are often available from the local agencies and their horizontal resolution is between 10 and 50 m. In order to access the benefits of advanced dispersion modelling systems, the horizontal DEM resolution should be at least 25 m.

2.1.3 Land use

Another important database to be used especially in meteorological and air quality simulations is the Corine Land Cover 2000 (CLC2000, Bossard et al., 2000), produced by the European Environment Agency (EEA) and its member countries within the European Environment Information and Observation framework EIONET. It is based on the results of satellite imaging elaboration programme undertaken jointly by the Joint Research Centre of the European Commission and the EEA (EEA, 2002). The CORINE framework consists of a computerised land cover inventory. CLC2000 is based on the photo-interpretation of satellite images. An important feature is that this database is based on standard methodology and nomenclature. The land cover is given on different levels with finer classification from level to level. For example the first level description comprises: artificial surfaces, agricultural areas, forest and semi-natural areas, wetlands and water bodies. Then, for instance the second level description of agricultural areas is further specified as: arable land, permanent crops pastures and finally heterogeneous agricultural areas[1]. Land and water surface characteristics are an important input for meteorological, air pollution, noise propagation and climate models in order to resolve the surface-atmosphere transfer of momentum, heat, and mass. Important parameters such as the albedo (i.e. the optical reflectivity), the acoustical impedance (which determines the acoustical reflectivity), the thermal inertia (heat capacity and conductivity), the aerodynamic roughness (roughness length) and porosity, and the soil moisture depend on the land cover characteristics. For example, the near surface temperature crucially depends on the land cover (e.g. sea, forest, barren ground) and soil characteristics (e.g. soil type and moisture).

2.1.4 Transport route characteristics

The steepness of roadways determines the power and gear setting as well as the braking activity of vehicles and thus determines the air pollution and noise emissions.

The location, height and length of viaducts, noise barriers and tunnels are important in air pollution and noise modelling applications. For instance, at bridges air pollutant emissions are diluted very effectively by prevailing stronger winds and the time and distance until they reach the ground. At road embankments and tall noise barriers a similar effect happens in addition to increased wall deposition losses of air pollutants at the noise barriers. While outdoor noise is efficiently reduced by tunnels, air pollutants are released at the tunnel entrances or separate ventilations. The characteristics of the road surface (asphalt, concrete, topping) and the rail/track system (rigidity of ballast

[1] Further details can be found under http://terrestrial.eionet.europa.eu/CLC2000.

and sleepers, state of rail grinding) are important parameters to determine the noise emission of road and rail vehicles.

2.2 Traffic

For emission and subsequent air pollution modelling the average traffic volume, the driving situation determined by speed limits or the road type including the number of lanes, the fleet composition concerning emission (e.g. EURO 3, EURO 4) and vehicle classes are important data. The location of tunnel portals or additional ventilation stacks is important in micro-scale air pollution modelling applications. In the planning process of by-passes and tunnels the location of tunnel portals is an important issue. At tunnel portals integrated emissions from the entire length of the tunnel are released resulting in very high concentrations there. If the atmospheric dilution and transport conditions are unfavourable near a portal or additional tunnel ventilation stack exposure limits may be significantly exceeded. At tunnel portals, emission source strengths, exit velocities, temperature differences and the traffic influence on the tunnel jet should be taken into account. In Öttl et al. 2002 and Öttl et al. 2003b a model approach is presented.

2.2.1 Road traffic

Traffic data and their specification are one of the most important parameters in modelling air pollution and noise. Generally, the availability of traffic data is very heterogeneous depending on the road type (motorways, national network), management authorities and the country. Therefore only examples of road traffic data can be given here. The examples refer to the two transit corridors that are used to demonstrate the environmental assessment methods and tools (see Chapter 7).

2.2.1.1 Brenner corridor

The Brennero/Brenner corridor links the Adige/Etsch Valley on the Italian side with the Inn valley on the Austrian side. The Brennero/Brenner Pass (1374 m ASL) is the major road transit route between Austria/Germany and Italy.

Emission modelling activities were carried out for the motorway A12 on the Austrian side and the A13/A22[2] on the Italian side. For the A22-Autobrennero motorway (from Modena to the Brennero/Brenner pass), transit data are available on a daily basis at

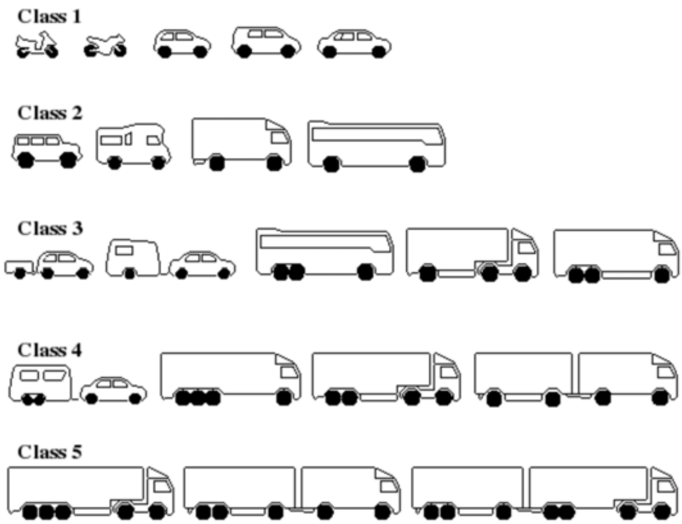

Fig. 2.1 Motorway toll classification adopted in Italy.

[2] Motorway number on the Italian side.

the motorway toll-points and are divided into heavy and light vehicles. Fig. 2.1 gives an overview of the toll class specification used in Italy.

– Class 1 includes vehicles classified as a “light vehicle”, that is motorcycles and four-wheeled vehicles with height < 1.30 m corresponding to the first axle.
– Class 2 includes four-wheeled vehicles with height > 1.30 m corresponding to the first axle, for example buses, trucks, vans and camper vans.
– Class 3 includes six-wheeled vehicles and tractor-trailers; it also includes cars with two-wheeled caravans and cars with two-wheeled trailers.
– Class 4 includes eight-wheeled vehicles and convoys. This class also includes the cars with four-wheeled caravans and cars with four-wheeled trailers.
– Class 5 includes ten (or more)-wheeled vehicles and tractor-trailers.

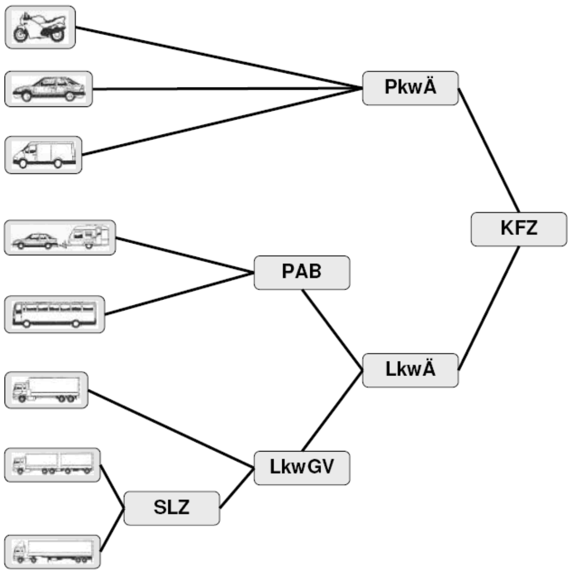

Fig. 2.2 Schematic of automatic traffic count vehicle classes used at traffic count stations in Austria. “KFZ” is the total number of counted vehicles. “PkwÄ” denotes a car type similar grouping encompassing LDV and motorcycles; “LkwÄ” denotes a HDV type similar grouping.

In practice, these data are generally available after a couple of months because collecting the data from different operating societies on the different sub-sections of the national motorway network and post-processing are time consuming.

Within Austria detailed traffic count data have been obtained by ASFINAG. For the sub-target area in the Inn Valley east of Innsbruck around Schwaz (see Fig. 7.1 in Chapter 7.1.1) the emissions of three road types were calculated. The motorway (A12), the class-A roads (federal highways B171, B181 and B169) and Class-B roads (state roads) were digitalised within this model domain. Automatic traffic count data are available in a time resolution of 1 hour.

The traffic count station Vomp is located at the A12, Pill at the A-road B171 and Stans at the B-road L215. These traffic count data have been processed to obtain one year average daily traffic volumes (ADTV) and diurnal and monthly cycles were derived to be used in the air quality modelling studies (see Chapter 7). Further ADTV data for Weer, Vomp Ost, Schwaz Ost (all B171) and Wiesing (L215) were processed and assigned to the respective road sections. The Fig. 2.2 shows the different vehicle classes obtained from automatic traffic count stations. The algorithm to distinguish between different classes is based on the number of axels (inductive loop) and the vehicle length (optical measurement). Unfortunately, light duty vehicles (LDV) can not be differentiated. That means that this vehicle type is assigned to a “car similar type” henceforth termed ‘Cars’.

LkwGV corresponds to heavy goods vehicles. Several traffic count stations (mainly at A-roads and B-roads) only differentiated between a “car similar type” (“PkwÄ”), a “truck similar type” (“LkwÄ”) and tractor-trailer combinations (“SLZ”), see Figure <traffic-count>. Therefore, due to the lack of more precise information tractor-trailer combinations, trucks without trailers, coaches and cars with caravans were assigned as one class, henceforth termed heavy duty vehicles (HDV).

The results of normalised diurnal cycles are shown in Chapter 7. Here, the interference of emissions with meteorological conditions is of special interest from the view point of measures like night time driving bans or temporal speed limits in order to reduce the exposure concentrations.

It should be noted that a major traffic data deficiency is due to the unknown fleet emission standard specification (EURO classes). In practice, the registration statistics and drop out probabilities are used in emission modelling applications or for emission inventories. However, this approach must be modified to be used at trans-national corridors since the share of diesel cars or the emission standards of HDV on long distance routes may vary significantly. For the modelling activities within RA-E a survey of the HDV emission standards revealed that the HDV fleet on the A12 and A13/A22 motorway is quite modern (Hausberger, 2006).

2.2.1.2 Fréjus corridor

The Fréjus corridor links the Maurienne (France) and Susa (Italy) valleys separated by the approximately 3500 m high Mont Cenis massif (see Fig 7.94 in Section 7.3.1.1). It can be crossed using two routes, either the Fréjus tunnel traverse or the Mont Cenis pass (2081 m). In the French section of the corridor, two parallel main roads wind up the Maurienne valley: the A43 (E70) highway and the RD 1006 (route departementale, former national road RN6). These two roads separate before Modane: the A43 ends temporarily and continues by the RN566 before becoming A43 again after the Fréjus tunnel. At the border the A43 changes its name to A32 (E70) on the Italian side. The A32 goes through the Susa valley towards Torino. After the tunnel, the national road SS335 goes along the A32 and joins the SS24 in Oulx. The other trans-border national road RD1006, crosses the Alps over the Mont Cenis pass and becomes the SS25 on the Italian side. Thereafter, the SS25 goes down to the Susa valley to join the SS24 near Susa. Then, both transit routes the A32 and SS24 pass almost parallel towards Torino.

The traffic counting practices vary from France to Italy due to the different national networks and different organization of the toll systems. For the national road RN6 and RD 902, the traffic data were obtained from the local road administration on a day by day basis for 2004 based on six permanent traffic counting stations (five along the RN6, in the upward direction, Argentine, Pontamafrey, Saint-Michel de Maurienne, Orelle et Mont-Cenis and one along the RD902 in Bessans). Inductive loops embedded in the road are used and available traffic count data are: daily total traffic separated into Light Vehicles (LV) and Heavy Vehicles (HV), for the different road sections and directions, on an hourly basis. Moreover, the magnetic sensors are able to measure the vehicle length. The vehicles are arranged into four classes from 0 to 25.5m. From these data, the classes [7.0 – 9.0 m] and [9.0 – 25.5 m] provide an estimate of HDV traffic. From the hourly data given separately for the light and heavy vehicles in front of three permanent traffic counting stations in Argentine, Pontamafrey and Orelle, during two weeks in 2003, spreadsheets were compiled on an hourly basis, class by class (LV and HV) for workdays, Saturdays, Sundays and holidays (see Chapter 7).

For the A43, permanent traffic counting stations or toll systems, managed either by “Société Française du Tunnel Routier du Fréjus” SFTRF (the French highway A43 manager) have been used to process the data for emission modelling. Information from transactions at the toll stations is of particular interest because it allows distinguishing more precisely between different vehicle classes. Table 7.2 in Section 7.1.2.1 shows the kind of raw data obtained and the three different classes identified. This level of information was not available for the entire A43. To get around this difficulty, and keep this primary information, which is particularly relevant for regulating pollutants emission, it is possible to use data from the permanent counting stations and to propagate the distribution observed at the pay toll all over the different homogeneous sections. Because the type of local exchanges between the highway and the secondary network are not precisely known, a bias, probably a lowering, is introduced to the data.

On the Italian side, traffic data on national roads (SS335, SS24 and SS25) are detected both by the network of permanent traffic counting stations, managed directly by the Province of Torino, and by mobile counting stations, managed by the Province of Torino in cooperation with ARPA Piemonte. Permanent traffic counting stations use the following approach: an inductive loop, embedded in the roadbed, creating a magnetic field that relays the information to a counting device at the side of the road. The detections check in continuous single passages, classified lane by lane and as light/heavy vehicles depending upon the "magnetic mass". Hourly aggregations are made afterwards. Mobile traffic count stations use optical and electronic counting devices. The monitoring time is variable, usually from a few hours up to a week. The detections are divided by class in light/heavy vehicles depending on the vehicle length (limit value ≥ 5 m).

Highway traffic count data on highways are provided by the concessionaire societies, which collect and register data at toll stations: hourly vehicle passages by direction and by payment class. Hence, five classes based on axel number have been aggregated as light/heavy vehicles).

2.2.2 Railways

Although diesel locomotive trains may contribute to air pollution, the main annoyance caused by railways is related to noise emission. The "historical" railway linking Saint-Michel de Maurienne to Susa (now Chambéry to Torino), was inaugurated in 1871 and is still the only railway line between the northern Alps and Italy. Due to the transportation demands at that time, the engineers planned the line deep in the valley. So, the railway was literally going through the villages. The increasing traffic volume in freight and passenger trains now makes it a primary source of annoyance.

Tab. 2.1 Classification of trains

Train type	*Applied Categorisation*
Freight	Freight
Goods	Freight
Regional train	Regional train
International train	International train
High speed train	International train
Isolated locomotive	Freight

The railway was completely electrified in 1976; Diesel traction is therefore rare. As a consequence of the Mont Blanc tunnel accident in 1999, it was decided to experiment with an intermodal piggy-back technique developed by the manufacturer Lohr. Since Nov 2003, the "Autostrada Ferroviaria Modalohr" (AFM) allows quick loading of entire lorries on special rail wagons and carries them between Savoy and Piedmont. The AFM system is a first step in promoting a modal shift between the two countries. On the French side, the infrastructure itself is managed by "Réseau Ferré de France" providing the traffic data. These data are given according to six train types (freight, goods, regional train, major line train, TGV high speed train, isolated locomotive). A maximum speed is attributed for each type of train and for each railway section. At the same time, each kind of train has a commercial speed. The reference speed used for numerical acoustical simulations is the minimum of both limits.

For the sake of homogeneity and simplicity between France and Italy, but without being simplistic regarding the acoustical model, the six different train categories can be aggregated into three main classes: freight, regional, and international trains (Tab. 2.1).

The data obtained from “Réseau Ferré de France” also allowed us to describe the distribution of traffic throughout a typical week, and for the “day”, “evening”, and “night” daily periods according to the European Directive on Environmental Noise.

On the Italian side only data regarding passenger trains were available. Therefore, it was assumed that the freight traffic is conserved through the tunnel. Here, there is a need for the harmonisation of data with the international traffic.

2.3 Population data

The location and density where people live is represented by the population distribution. In general, the population distribution is uneven, depending upon several physical factors. In alpine regions sparsely populated areas are often alternated by densely populated ones. Main factors which affect the population density are the topography, natural resources such as arable land and climate.

Mountainous areas are less populated because of the rough climate, lower fraction of natural resources (i.e. agricultural land), lack of commodities (raw materials) and infrastructures. Hence, the shape of the relief strongly affects the population distribution, with a concentration along the valley floor, facilitated by more favourable conditions for agriculture, industry and trade.

Population data are usually derived by censuses and are aggregated by “census areas”. The “census area” is a homogeneous portion of a municipal territory defined by physical elements (e.g. streets, rivers, mountain ridges), each containing a number of inhabitants ranging from some hundreds to a few thousand. Therefore, the population density within this project was derived using this minimum aggregation level. The gridded representation, i.e. the population density given on a regular grid, can also be derived from this level and may be useful when comparing population data with other environmental data. It should be noted that at a higher aggregation level, e.g. the population over an entire municipality would not be sufficiently resolved when dealing with phenomena on a smaller spatial scale, e.g. noise propagation.

Population data are needed to assess the annoyance or exposure to noise or air pollutions. The level of precision required for this task should be high enough to identify the location of exposed people. However, the aim was also to propose a methodology versatile enough to be adapted to other sites. The compromise has been realised by choosing for the Maurienne valley, the IRIS database proposed by INSEE, the French National Institute for Statistics and Economic Studies. This data base, updated in 2000, is available in cartographic form (MIF/MID), and is divided in areas comprising approximately 2000 people.

2.4 Geographic information systems

In handling the vast amounts of spatially distributed data as previously discussed, Geographic Information Systems (GIS) have been proven as a versatile tool for scientists, experts and decision makers. GIS systems are used in environmental assessment processes and facilitate decision-making. The effectiveness of GIS as a decision support tool essentially comes from the graphical and easily understandable display of data in the form of maps. In a geographic representation the level of data aggregation (i.e. the spatial scale at which data are collected) is obviously affected by the available amount of information. In fact, the smaller the area, the more specific are the results. At the same time, when data is analysed at a detailed scale, there is greater imprecision and potential scattering. Conversely, at larger scale an averaging effect can arise. For example, population data given on a region basis would not be sufficient to derive population density on a smaller scale, even if the map representation has a higher geographic detail. Other attributes expected to be related to data aggregation effects include the domain size and the data dispersion. Therefore, the data arranged together in different GIS layers should be as uniform as possible, or they should be homogenised to have a comparable spatial resolution and significance.

The development and adoption of GIS tools nowadays is largely motivated by the growing demand for efficient management of spatially distributed data, particularly those coming from remote sensing techniques and modelling application. This task is therefore not negligible and implies the developing process of procedures for data retrieval, archiving, geographical referencing and – finally – visualization. Besides these operations, a GIS approach is naturally linked to instruments for statistical analysis and image processing that are often required in pre- and post-processing of data.

Preliminary work is necessary to organise all the available GIS information layers; this approach must be used, for example, for all the results obtained from the numerical simulations described in the following chapters. The first step is to gather all the morphological information, namely the digital terrain models, demographic data and land coverage. An important issue is to bring together data that has been derived from different sources, and has been geographically referenced with different systems. For example, the reference systems in Italy for both geographical and plan coordinates vary, in total 13 systems can be listed. The problem not only applies to gridded data (such as digital elevation model, land coverage, etc.), but also to vector data, for example such as the highway track (line data) or the position of the automatic weather stations and air quality stations (point data).

A common problem is the need of interfacing different geographic reference systems adopted for different sources/types of data as well as for overlaying models inputs/outputs with other relevant spatial information (e.g. topography, land cover, population, etc.). In order to simplify the interpretation of results all relevant information should be converted to one reference system. In fact, the ultimate goal of the application of GIS tools to the sets of environmental data and to other information layers, is to provide both scientists and decision-makers with readable informational and analytical spatial support, and also to facilitate visualization and dissemination of spatially distributed data.

2.5 Air quality emission modelling and inventories

Good estimations of the total emission levels (the “cause”) are basic to rebuild the actual exposure situation (the “effect”). Proper accuracy of the relative contributions of single emission groups – like traffic or heavy duty traffic – is essential for a meaningful determination of responsible polluters and the evaluation of steering measures. For modelling air quality an adequate spatial resolution of emission data is required. In addition, information about the temporal emission characteristics is relevant, as the impairing effect of some emission quantity on the air quality depends strongly on its time of release. As an extreme example the same emission is rapidly diluted on a summer day with deep convection while it may affect the valley atmosphere for a long residence time when released in a winter's night under persistently stable conditions.

2.5.1 Emission inventories

Emission inventories segregate emissions of pollutants of interest from a number of causing sections. A frequently used classification discerns emissions from industry, small consumers (mainly heating installations in private households and small trade and business), traffic, energy supply, agriculture and other sources. The provided temporal and spatial resolutions depend mainly on the underlying method, where, basically, two different types can be distinguished.

On the one hand, national federal offices are obligated to annually report national emissions according to UN standards issued by UNECE or UNFCCC. These requirements are implemented in the EU-directive (2001/81/EG) on national emission ceilings ("NEC-directive"), which fixes maximal emission limits for every member state. The applied method follows the EMEP/CORINAIR guidelines, published by the EEA. Total national emissions are calculated based on the amount of fuels sold. The international comparability and yearly updates are main advantages of this procedure. In order to obtain higher spatial resolutions, these national sums are broken down to provincial states in some counties (e.g. Austria) by using statistical surrogate data (e. g. fuel and energy amounts, number of inhabitants and employees, factory locations etc.).

In contradiction to this "top-down" calculation method, the second type of emission inventories – usually produced on a more local scale (provinces) – follows a "bottom-up" approach. Herein emissions of all sources are quantified separately, e.g. by means of traffic counting, questionnaires, regional statistics. Traffic emissions for example are calculated on the basis of traffic counts (for different vehicle categories), registration statistics and surveys to determine fleet compositions, emission factors, speed regulations and road gradients. Often based on traffic count data, the traffic volume in data void areas is determined by traffic modelling. Estimations of heating emissions are often based on population census data, prevalent types and ages of heating systems (on the spatial scales of small administrative units). Industrial emissions are derived from interrogating every single company about emission measurements or surrogate data such as fuel consumption etc .

This method of emission estimation implements a multitude of local information on a high spatial resolution, typically a community scale (ranging from 1 to 100 km²). However, the transformation of these data to regular grids is not a standard procedure (see also Section 2.4).

As these investigations are very time and cost demanding, yearly updates are not feasible. Actually, update intervals in the range of five years are realistic. In Tyrol/Austria for example emissions from traffic (main and secondary roads), and domestic heating (base year 2001 for census data, 2004 for emission factors) are calculated and available, work on emissions from industry is currently in progress. Unfortunately industrial and energy supply emissions could not be used in the framework of ALPNAP.

Non-uniform proceedings – caused amongst others by a varying data basis and a multitude of production processes and special machinery – constrict their interregional comparability.

Methodological differences between "bottom-up" and "top-down" emission inventories can also yield to systematically different results. Exemplary, the Austrian federal environmental agency describes the extreme influence of refuelling heavy duty vehicles and passenger cars in Austria but consuming it abroad. As fuel charges are significantly lower in Austria, results from the standardised "top-down" method, i.e. using total amounts of fuel sold, are considerably biased. Published discrepancies are striking: while this standard method shows an increase in NO_x-emissions from the traffic sector of 33 % from 1990 to 2004, consideration of this “refuelling tourism” leads to a decrease of 38 %.

2.5.2 Emission models

There are different approaches in calculating road transport emissions, which are often subject on the availability of various input data and the demands of the output data. Instantaneous emission models e.g. PHEM (Hausberger, 2003, Hausberger and Rexeis, 2004), and EMPA (Ajtay and Weilemann, 2004) calculate emissions on a second by second basis, which requires input of driving cycles as a time series (vehicle speed and road gradient, optional gear or engine speed) and very detailed information on engine and vehicle specifications (engine maps for each emission component, dynamic correction functions, gear ratios, etc.). For an emission model which focuses not on single vehicles in precisely defined driving situations but on the assessment of fleet emissions in a road network, a more aggregated approach is appropriate because:

– the complexity of an instantaneous emission model and the amount of required input data for a detailed simulation for all vehicles in each segment of the fleet would hardly make the calculation of the emissions in a road network practical (e.g. the user would have to provide driving cycles on a second by second basis for each vehicle category in each road section)
– the loss of accuracy from the simulation side when changing to a more aggregated model approach is much smaller than the inaccuracy which arises from uncertainties linked to the composition of the fleet and the presumed average driving behaviour

Therefore, the emission models COPERT (Ntziachristos and Samaras, 2001) and NEMO (Network Emission Model, Rexeis and Hausberger, 2005) which both use an aggregated approach have been used in the framework of ALPNAP. Their basic model physics as well as the in and output of both models are discussed in the next few sections. The important parameters in road transport emission modelling are average traffic volume and an appropriate knowledge of the fleet composition (e.g. share of HDV). The driving situation determined by the road type including the number of lanes or speed limits as well as the slope of the roads are additionally important input parameters in emission modelling.

2.5.2.1 NEMO

The model “NEMO” (Network Emission Model) has been developed for the calculation of vehicle emissions in road networks. It combines a detailed calculation of the fleet composition and emission simulation. With its flexible model structure NEMO is completely applicable for the evaluation of different case scenarios. The features implemented into the model for example enable illustration of the effects of varying the driving behaviour (e.g. traffic calming) or of special actions having an effect on the fleet composition (e.g. promotion programs for diesel vehicles with exhaust post-processing) on the fleet emissions.

This model is consistent with the models PHEM (Passenger car and Heavy duty vehicle Emission Model; a detailed simulation tool for energy consumption and emissions of passenger cars and heavy duty vehicles), GLOBEMI (global modelling of scenarios concerning emission and fuel consumption in the transport sector, Hausberger, 1997) and the “Handbook emission factors for road transport” (HBEFA2.1, 2004). PHEM has been developed in several international and national projects, namely the EU 5th research framework programme ARTEMIS, the COST 346 initiative and the German-Austrian-Swiss cooperation on the Handbook of Emission Factors (Hausberger, 2002).

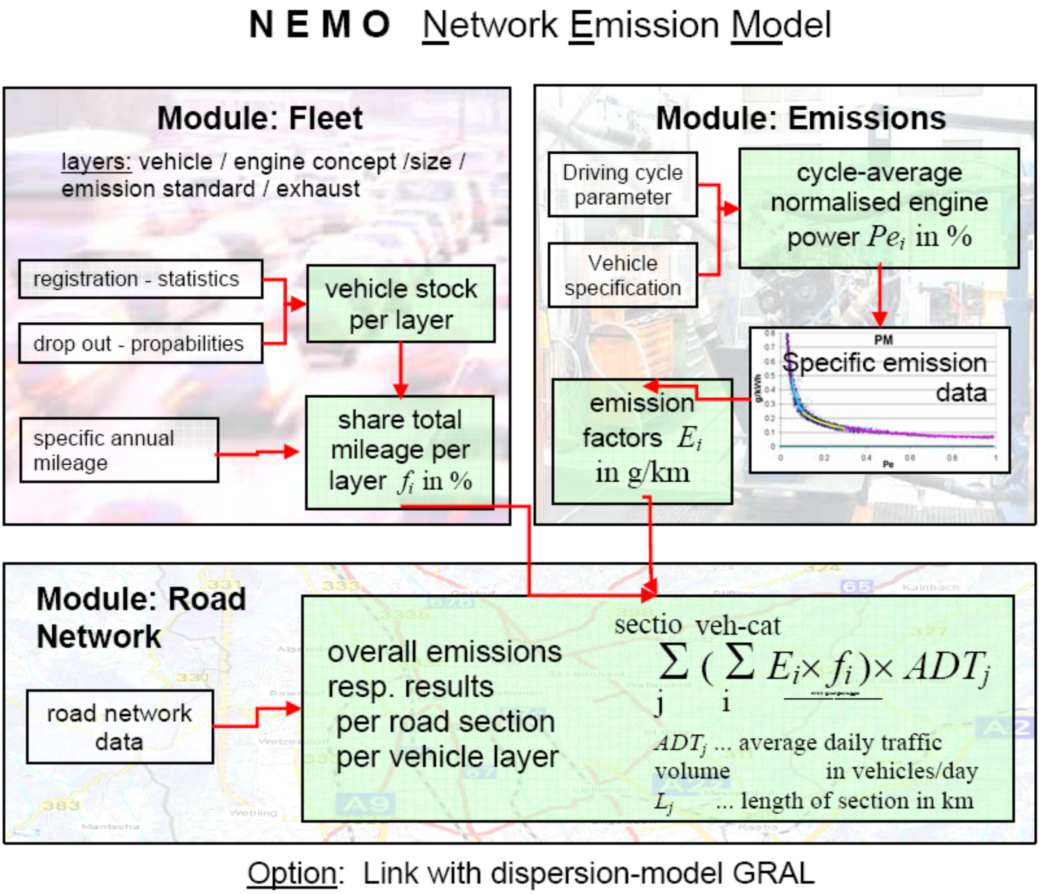

Fig. 2.3 Schematic of the Network Emission Model - NEMO developed at TU Graz.

NEMO is able to compute emissions of NO_x, PM10, (exhaust and non-exhaust), CO_2, CO, NO_2, SO_2, NMHC (non-methane hydrocarbons), Benzene and others for each road section. PM10 non-exhaust emission factors are based on Gehrig et al. (2003). In practice, roads are divided into sections (often up to thousands) to account for their exact position (horizontally and vertically) and road gradient. Further model input are traffic volumes, fleet composition for the specific years, and average speed. If the exact fleet composition is unknown, NEMO uses a fleet composition based on registration statistics and the type of the road.

The basic physical principle of the NEMO approach for simulation of vehicle emissions is the strong correlation of engine specific emission behaviour (emissions in grams per kilowatt-hour engine work) with the average cycle engine power in a normalised format, which is valid for all engines inside a certain vehicle category, engine concept and emission standard.

NEMO consists of three major modules (see Fig. 2.3):

– The "Fleet Module" calculates the detailed fleet composition concerning different vehicle types and engine concepts (e.g. gasoline or diesel), size-class (differentiating factor: capacity or maximum allowable gross weight), engine sizes, emission standards (e.g. Euro 1) and post-processing of exhaust. This information is based on the Austrian registration statistics and drop out probabilities for the respective year of interest.

- The "Emission Module" simulates the vehicle emissions for different layers in the vehicle fleet based on the respective vehicle specifications, driving cycle parameters and engine specific emission functions. These functions are based on post processed simulation results of the model PHEM and data from HBEFA2.1. The simulation results of PHEM are based on engine test bed and chassis dynamometer emission measurements at the Institute for Internal Combustion Engines and Thermodynamics at the Technical University of Graz.
- The "Road Network Module" combines the information of the fleet and emission modules and road network data to finally yield the emission output on the road section under consideration.

Further detailed information about NEMO can be found in Rexeis and Hausberger (2005).

Examples of application

The model is designed for user-friendly and efficient use based on a default data set for fleet and driving behaviour. All required input data which have to be supplied for standard calculations are combined in a single input file ("network-file"), where each single data-line contains all the needed information for a particular driving direction of a given street section:

- length of street section in km
- average road gradient in %
- road category (urban, rural, motorway)
- Average Daily Traffic (ADT) in vehicles per day
- average vehicle speed for the different vehicle categories (in km/h); free input or choice from a default set of traffic situations for each road category

For the calculation of standard traffic situations the model itself calculates the values for the kinematic parameters based on the average vehicle speed of the different vehicle categories and the road category.

Additional data, which can be provided to NEMO for each street section in the network-file, are:

- share of HDV and average daily traffic (ADT) for particular vehicle categories such as light duty vehicles (LDV), coaches, tractor-trailer combinations or lorries if available from traffic surveys or traffic counts
- kinematic parameters for the definition of special driving behaviour
- additional information (such as geographic coordinates, road width) required for a link of NEMO with the dispersion model GRAL ("Graz Lagrangian Model", which has been in development at the Institute for Internal Combustion Engines and Thermodynamics since 1999, for details see Section 4.4.2.3).

For all given road sections, NEMO calculates the emission output (in kilograms per kilometre and hour) and provides the sum of total emissions for defined sub networks (in tons per year). All results are split into subtotals for the single vehicle categories in order to assess the shares of the total emission output.

In Fig. 2.4 the relative contributions of different vehicle classes as modelled with NEMO are illustrated for the three different street network types used in the computations. Although passenger cars cover 77 % of the driven distances (km) on the motorway A12, passenger cars emit only about 36 % of the NO_x. On the other hand, tractor-trailer combinations cover 10 % of the distances driven, but emit 40 % of the NO_x emissions. A similar behaviour can be found for the PM10 exhaust emissions and to a lesser extent for SO_2, fuel consumption and CO_2, accordingly.

The results for A-roads and B-roads are qualitatively the same. They are different due to the lower share of HDV, different heavy goods vehicles and coaches/urban bus fleet composition, as well as assumed different Euro classes (larger Euro-0 and Euro-1 share).

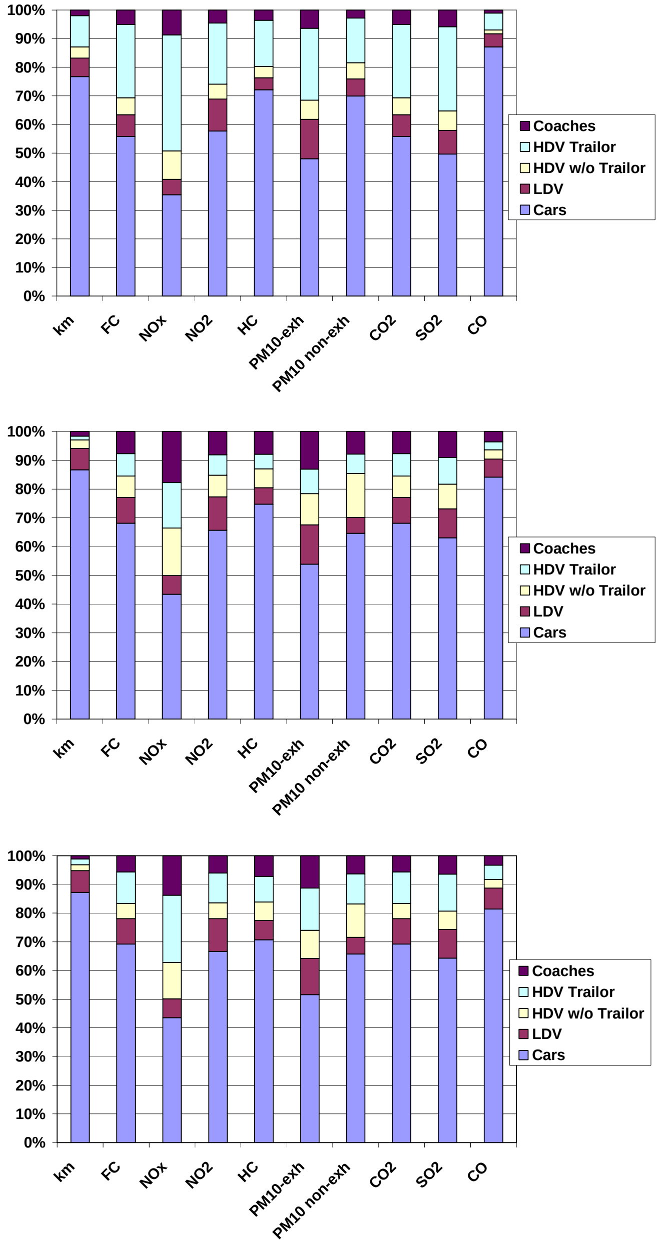

Fig. 2.4 Estimates of relative contributions to air pollution for the Lower Inn valley motorway (A12) top panel, "A-Road" traffic middle panel and "B-Road" traffic bottom panel.

2.5.2.2 COPERT

The COPERT III emission model (Ntziachristos and Samaras, 2001) uses another methodology to be used for emission calculations of entire street networks. In this procedure, adopted by the European Environmental Agency, emissions of all regulated air pollutants (CO, NO_x, VOC, PM_{10}, CH_4, SO_2, C_6H_6) are estimated on the basis of fuel consumption for different vehicle categories: passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles. Estimated emissions are divided in three source types: hot emissions (produced during thermally stabilised engine operation), cold emissions (occurring during engine start; fuel evaporation. Total emissions are then calculated as the product of activity data and speed-dependent emission (see schematics in Fig. 2.5). The emission factor is generically defined for every street and vehicle type as $EF = f$ (road,vehicle).

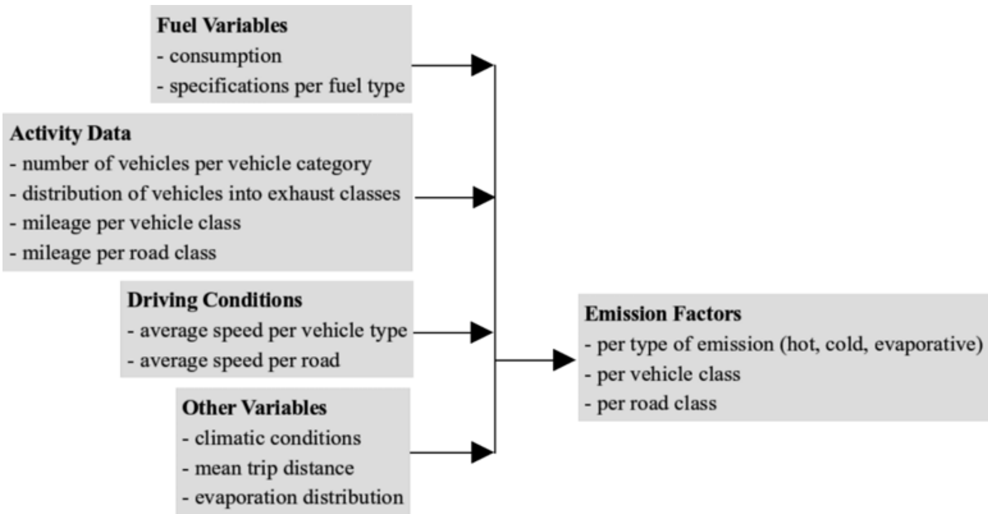

Fig. 2.5 COPERT flow diagram

Fig. 2.6 presents an example of the estimated vehicles fleet composition for the A22-Autobrennero motorway and of the computed emission factors for the regulated pollutants.

The relative contributions shown in Fig. 2.6 are based on the average national fleet composition. However, the share of HDV on the A22 is significantly larger since the Brenner/Brennero is the major transit route between Italy and Austria/Germany. Hence, the total NO_x and PM10 emissions on the A22 might be significantly increased. HDV, which are significantly lower in number than private cars, are major primary PM10 and to NO_x emitters (thus to secondary particulate matter). In contrast, diesel and unleaded gasoline fuelled passenger cars are the main emitters of VOC and CH_4. Many heavy duty vehicles from Eastern Europe, which do not conform to European emission standards or only to EURO 0 or EURO 1, may dramatically increase total emissions.

In Tab. 2.2 an example of the COPERT III classification is reported. In COPERT III, emissions originate from three different sources: the thermally stabilised engine operation (hot), the warming-up phase (cold start) and fuel evaporation. The emissions of most pollutants during the warming-up period are many times higher than during hot operation and a different methodological approach is required to account for emissions during the cold start period. Furthermore fuel evaporation during the day (only relevant for gasoline) results in emissions of non-methane hydrocarbons by a different mechanism than exhaust emissions. For the traffic situations considered in this report (i.e. transit traffic) cold emissions may safely be neglected.

Tab. 2.2 Example of COPERT III methodology vehicle classification.

Code	Engine Classification	Legal classification
	Passenger cars (sector 1)	
1	Gasoline < 1.4 l	PRE ECE
2		ECE 15/00-01
3		ECE 15/02
4		ECE 15/03
5		ECE 15/04
6		Improved Conventional
7		Open Loop
8		Euro I – 91/441/EEC
9		Euro ll – 94/12/EC
10		Euro III – 98/69/EC Stage 2000
11		Euro IV – 98/69/EC Stage 2005

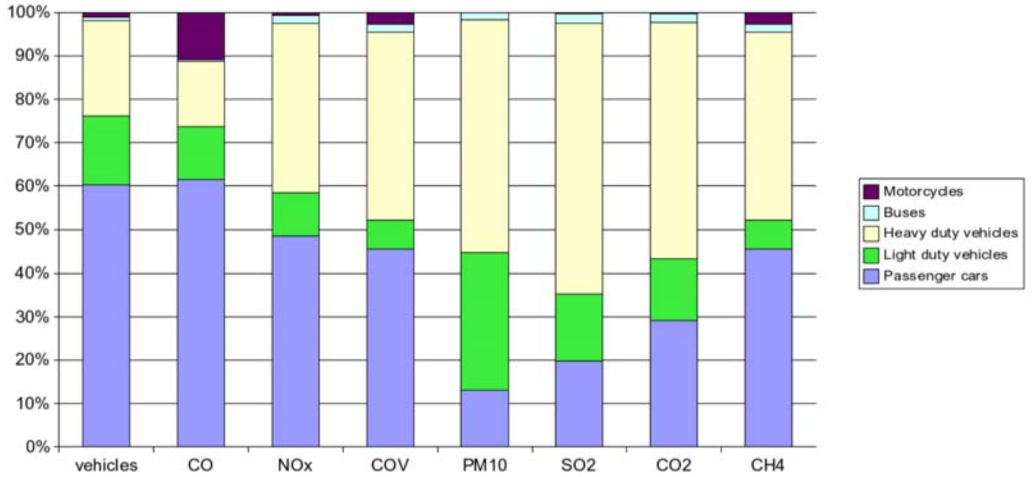

Fig. 2.6 Estimate of relative contributions to pollution for the motorway traffic

Vehicle emissions depend to a large extent on the engine operation conditions (i.e. driving or traffic situations). Therefore, traffic situations are at least classified into urban, rural or motorway traffic to account for variations in engine operation performance. Typical speed ranges for a motorway is approximately 90 km/h for heavy duty vehicles and 130 km/h for light duty vehicles and passenger cars, also depending on traffic conditions.

The calculation of total emissions is made by combining activity data for each vehicle category with appropriate emission factors. These emission factors vary according to provided input data (namely driving situations and climatic conditions). Information on fuel consumption and specifications is required too, in order to maintain a fuel balance between provided figures and computed values.

2.5.3 Modelling results of air pollution emissions

Subsequently, modelling results are presented to elucidate the general impact of important parameters such as speed, slope and fleet composition on NO_x, PM10 and HC (hydrocarbons). Results of emission modelling for the regional Lower Inn valley, the Fréjus section and the entire Brenner trans-section from the Austrian/German border – Brennero/Brenner Pass – Val d'Adige/Etschtal are presented in Chapter 7.

2.5.3.1 Road emissions

As illustrated within the previous sections, the number of parameters relevant for emission modelling is large. Here, the impact of speed and slope on an average fleet and the difference between cars, LDV and HDV in emissions is briefly discussed. Fig. 2.7 illustrates the impact of different traffic situations given by motorway speed limits on total NO_x, HC and PM10 emissions for a fleet with 50,000 vehicles and 16 % HDV. The HDV share consisted of 23 % single trucks, 66 % tractor-trailer combinations and 12 % coaches. The computations were run with NEMO, the input data were chosen on the basis of the A12 motorway traffic near Vomp. Interestingly, the effect of reducing the speed from 100 km/h to 80 km/h is larger than reducing from 120 km/h to 100 km/h.

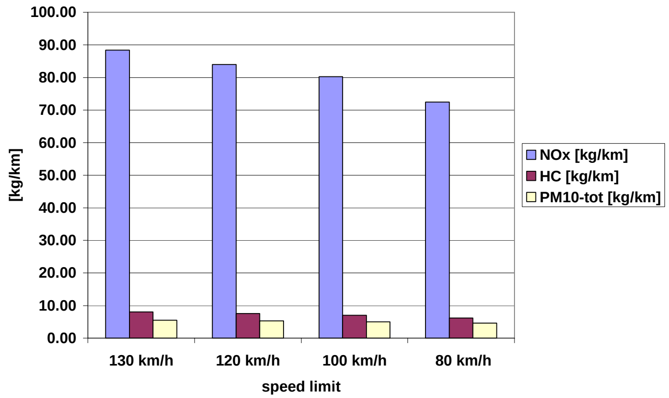

Fig. 2.7 Fleet average NO_x, HC and PM10 (exhaust and non-exhaust emissions) for four different traffic situations. The modelled speeds differ from given traffic situations or speed limits (see text).

The main reason for this inconsistency is that according to HBEFA 2.1 the "actual" mean speed of the passenger car fleet may differ from the given traffic situation in order to more accurately reproduce the real traffic situation. At 120 km/h and 130 km/h there is no deviation, but the modelled average speed at a speed limit of 100 km/h is actually 110 km/h and at a speed limit of 80 km/h it is 85 km/h. Hence, the real modelled differences in speed are 10 km/h and 25 km/h respectively. The speed and emissions of HDV is unaffected until 100 km/h, the modelled average speed is 86 km/h. At a speed limit of 80 km/h the model average speed is 83 km/h. It should be noted, that at around 80 km/h real driving speed, there is an optimum in the emission situation for both passenger cars and HDV in NO_x and PM10 emissions. The impact of the real constant speed of a diesel car, gasoline car and tractor-trailer

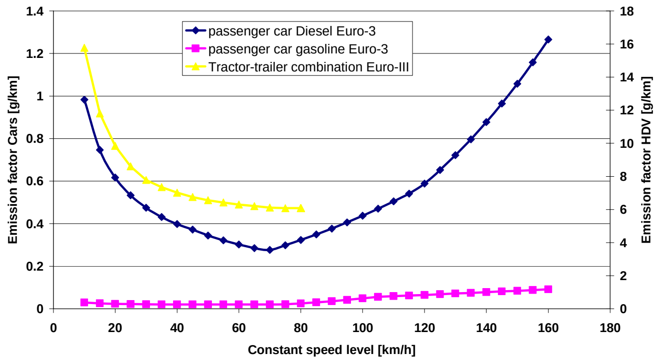

Fig. 2.8 Fleet average emission factors for Euro-3 Diesel and gasoline

combination fleet on NO_x emissions is shown in Fig. 2.8. These idealised driving conditions were modelled with NEMO based on the assumption that the optimum gear was used and the acceleration terms describing the dynamics of the traffic were set to zero. It should be noted, that the effect of e.g. using a lower gear may lead to significantly increased emissions in NO_x, PM10 and particle number concentrations (e.g. Uhrner et al., 2007).

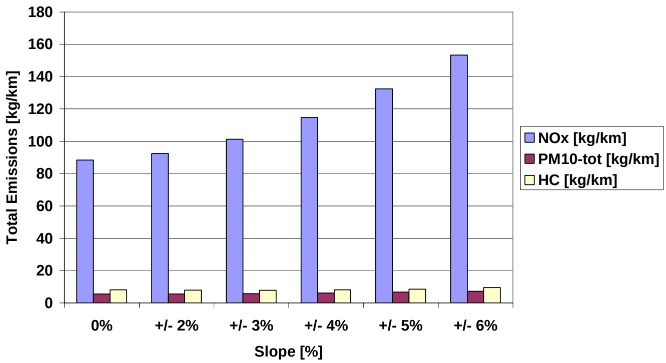

Fig. 2.9 total motorway emissions (DTV: 50,000, HDV: 16 %, speed limit 130 km/h) as a function of steepness.

As an example for the same fleet composition (16 % HDV) and a motorway speed limit of 130 km/h the impact of the road gradient (slope) on total NO_x, PM10 and HC for 25000 vehicles going uphill and 25000 vehicles going downhill is illustrated in Fig. 2.9. Exemplary results for an A-road situation are shown in Fig. 2.10, here the ADT was reduced to 10,000 and the HDV share was kept to 16%. An increase in slope to 6% results for the given motorway situation in a NO_x emission increase by a factor of ~1.8, and for the A-road by a factor of ~2.3. The relative increase is more pronounced for NO_x than for HC and PM10. It should be noted, that with an increasing share of HDV and increasing slope the emissions are increased, especially concerning NO_x. Firstly, the class "HDV" emits more NO_x than the cars and LDV grouped as "Car" by about a factor of 7 in Fig. 2.11. Secondly, the emission increase with slope is steeper for HDV.

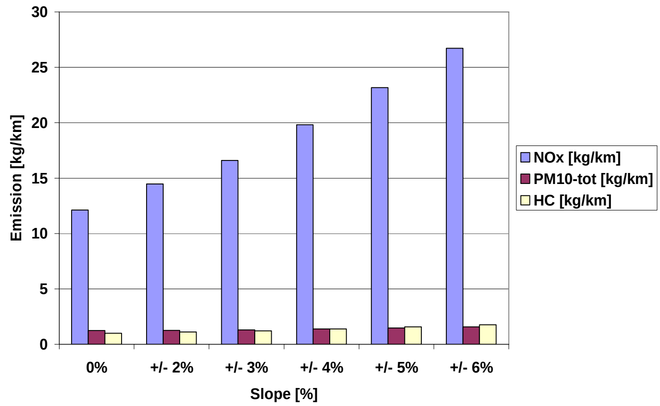

Fig 2.10 Total A-road emissions (DTV: 10000, HDV: 16 %, speed ~80 km/h) as a function of steepness.

2.5.3.2 Railway emissions

Railway is considered to be the least polluting mode of transportation. Railways emit about 1–3 % of the of the total transport sector emissions in Europe. In contrast, almost 90 % of the emissions are credited to road transport. However, it must be considered that in Europe, the number of passengers × km (pkm) transported by road is about 87 % compared to 7 % by rail. For freight transport, the distribution is 48 % and 9 % respectively, considering tonnes × km of transported goods (tkm). Furthermore, the INFRAS, 2004 study of the "external costs of transports" in Europe (EU 17) revealed that, for base year 2000, the total cost attributed to air pollution due to transport of passengers by road is 23 times larger than by rail. For freight these costs are 52 times larger for road traffic than rail. The results did not consider further costs due to climate change. These numbers fall to 1.9 (passenger transport) and 5.1 (freight) when relating the costs to pkm and tkm.

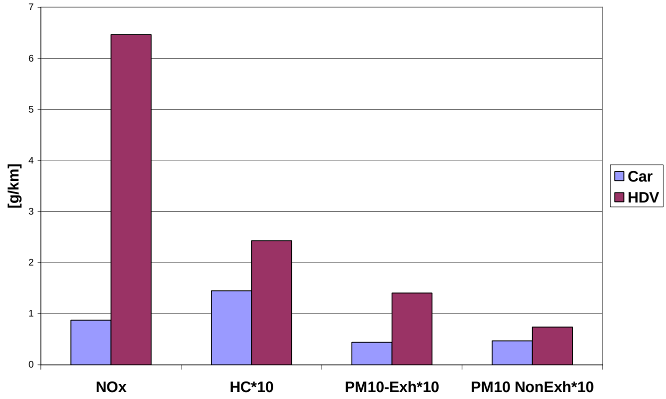

Fig. 2.11 Average emissions factors for motorway (speed limit 130 km/h) for average class "Car" which comprises cars and LDV and class "HDV" which comprises trucks, tractor trailer and coaches. Note, the HC, PM10 exhaust and PM10 non-exhaust emissions are multiplied by a factor of 10, i.e. they are a factor of 10 lower than displayed in the graph.

The problem may be quite different when studying air pollution at the local scale. In many European countries diesel powered locomotives are used. There are studies which point out that in areas with a large diesel locomotive frequency (stations, terminals) railway exhaust emissions can contribute significantly to ambient NO_x or PM concentrations. For instance, in busy terminal stations, NO_2 concentrations may reach values comparable to those produced by motorways (UIC and CER, 2006). However, in this particular study there were several other static emission sources. Generally, contributions from railways to ambient concentrations are small (a few µg/m^3 NO_x) even near busy lines and railway shunting yards.

Abrasion of wheels, rail, catenaries, contact shoes of pantographs, and in particular brake wear is also suspected to be a significant source of PM emission. At the moment, very few publications are available on these topics. The most relevant data come from studies carried out in Switzerland where PM emissions are a real concern. Gehrig, R. et al., 2007 present results of an "extended and representative field study" performed on two different sites: a railway station and a busy line. In this study, the main constituent of PM10 is iron, long-term average measurements reveal concentrations of about 1 µg/m^3 Fe at a distance of 10 m from the railway tracks rapidly decreasing with larger distance from the railway tracks.

Beyond the fact that the experimental characterisation of train emissions is a complex task, the European Parliament and Council extended the Directive 97/68/EC dedicated to "the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery" (NMRM) to cover new diesel engines for railway vehicles. New limit values for NO_x and PM10 are defined and will be applied according to two graduated stages (IIIA and IIIB) with deadlines programmed in 2009 and 2012. It should be noted, that limit values for PM10 imposed by stage IIIB (0.025 g/kWh) are significantly lower than the values proposed for stage IIIA (0.2 g/kWh), and will call for major technical improvements. The NMRM amendment also imposes that the traction units that will be re-engined in the future should meet Stage IIIA or IIIB limits. These new emission standards demonstrate the will of the EC to decrease emissions from all transport modes at the same time.

Due to the small impact in comparison to road traffic (small share of diesel traction) and the lack of precise data, railway pollutant emissions were not considered explicitly in the ALPNAP project. Considering the current state-of-the-art, taking railway emissions into account as an independent parameter would have uselessly complicated the present work.

2.6 Noise emissions

Noise emission due to roads and railways are the result of a complex combination of multiple mechanical sources. From the macroscopic point of view, traffic noise emissions depend on: the traffic volume and fleet composition, the dynamics of the traffic flow and the individual driving behaviour (on roads), the average speed and the properties of the road pavement or railway tracks. The quality of these input data is of major importance to perform accurate modelling of noise propagation and noise exposure. It is also widely known that acting directly on sources is the best way to control the negative effects of noise and justifies the need for surveys of noise emissions on a high qualitative level.

In the following paragraph, the origins of road and railway noise are briefly addressed. The techniques to characterise and integrate them in simulation models are also presented.

2.6.1 Road traffic noise modelling

"Road noise" is defined as the superposition of sound energy emanating from: cars, motorcycles, heavy vehicles. This emission can generally be associated with two physical phenomena of mechanical origin: the first one is linked to the engine-exhaust chain, the second one is due to the mechanical contact between tires and the road. Depending on the speed and the kind of vehicle, motor noise and tire-road noise compete: for light vehicles, it is considered that above 50 km/h tire-noise dominates, whereas the limit is between 50 – 80 km/h for heavy vehicles. Below these limits motor noise is predominant. A series of European Directives has been adopted to lay down limits for the noise level of the mechanical parts and exhaust systems of vehicles with a maximum speed of more than 25 km/h (70/157 adapted by 1999/101).

The most accurate and rigorous way to simulate roadway noise would be to model each individual source (vehicle) and its dynamic behaviour. This approach, allows a continuous description of noise events, and refers to the so called "microscopic models" (Leclercq and Lelong, 2001). It is of great interest for estimating noise exposure in urban areas where irregular traffic conditions are observed. However, this methodology requires high level information regarding unitary emission properties, and the accurate description of traffic dynamics. Fortunately and historically, macroscopic methods, using integrated data, are available and are adapted to the computation of commonly used noise indicators such as L_{den}, or L_{night} (chosen as the official European noise indicator in the scope of the Directive 2002/49/CE). More details can be found about these indicators in Chapter 5.

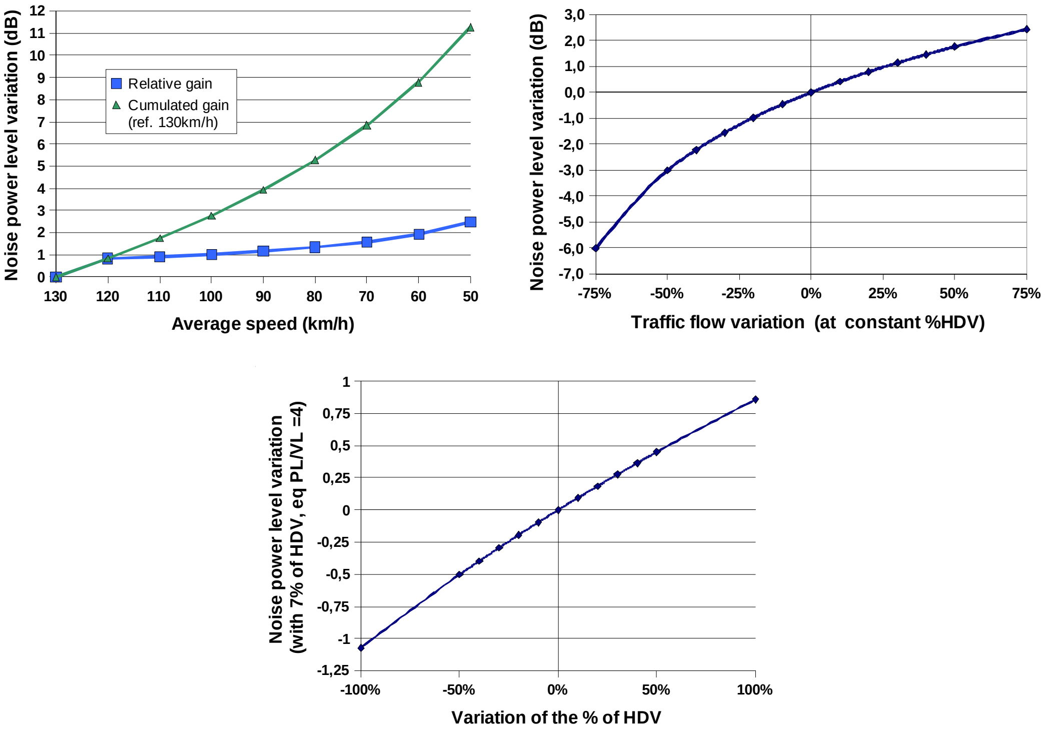

Fig. 2.12 Noise power level variations as functions of three road traffic parameters: average speed (top left), traffic flow variation (top left), variation of the percentage of HDV.

A simulation technique based on a macroscopic approach is used in the model MITHRA to simulate the noise sources. There, roads are considered as homogeneous line sources. Several categories of roads can be defined in this way: motorway, major road, expressways, primary or secondary urban road. The kind of road pavement (bituminous, concrete, porous, etc.) is also an important input parameter of the model. For each homogeneous road section an acoustic power per meter L_w is attributed depending on traffic characteristics. For instance in the MITHRA model the main inputs are

– the traffic flow rate: in first order L_w is a linear function of 10 log(Q), where Q is the flow rate. This means that doubling the traffic flow corresponds to an increase of 3 dB on the power level.
– the percentage of heavy vehicles,
– the average speed of vehicles (V): L_W varies roughly linearly as 20log(V), meaning that a ±10 km/h variation of V leads to about ±1 dB.
– an acoustic factor giving the equivalence between light and heavy vehicles, and which depends on the slope of the road
– a constant added to L_w to account for the dynamic behaviour of traffic: 0 for fluid flow, +2 dB for “pulsed” traffic, and +3 dB in case of high acceleration sections.

Fig. 2.12 illustrates the sensitivity of L_w to three of these parameters. L_W may also integrate the road pavement properties. This aspect of special interest in the ALPNAP project is discussed below.

2.6.2 Acoustical characterisation of road pavement

The tire-road noise emission is difficult to quantify as it depends on the characteristics of two separated elements: the contact between the tread and the surface leads to vibrations of the tyre structure generating low frequency airborne noise (<1 kHz). Higher frequency noise is also generated by the "air-pumping" effect produced when the air layer between the two moving parts is compressed. The road pavement characteristics (roughness, porosity) play a key role in this noise generating process. During the last few decades, lots of pavement technologies have been proposed and significant noise reductions can be achieved using e.g. porous asphalt concrete (PAC) or small chip size rolling surface (thin or very thin asphalt concrete). The result is, that differences up to 13 dB have been recorded looking at emissions properties, between PAC and dense asphalt concrete (DAC), see Brosseaud and Anfosso-Lédée (2005).

The real performance of these surfaces is strongly linked to the in situ construction process. Moreover, the acoustic durability of such materials is a critical issue and measurements are needed to assess their noise reduction potential with ongoing wear and tear. Deviations of more than 10 dB in performance can be noticed between road pavements of the same kind.

Several techniques have been proposed to measure the acoustic performances of road pavement: Close-proximity method (CPX - ISO/CD 11819-2) measures the noise emission from a standard passenger car tyre when rolling over a road surface, Pass-by method (ISO 362) measures the noise of an isolated vehicle passing in front of a static microphone. In this section, a method recently developed in France and used during the ALPNAP project is presented.

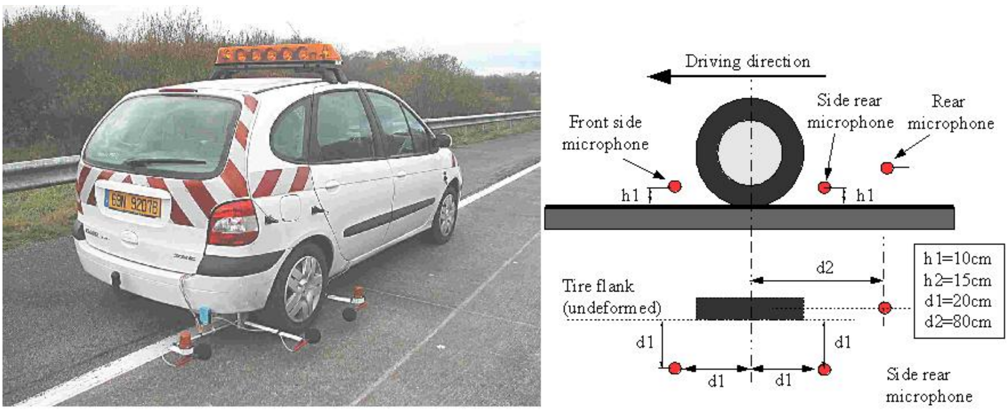

Fig. 2.13 CPX measuring vehicle (left) and detail scheme of the positions of microphones (right)

The acoustical set-up is attached to a special vehicle, and three microphones record the acoustical field near the rear tire of the car. Two of them are placed on one side of the tire, and the third one behind the tread (see Fig 2.13). By controlling the coherency between microphones, this technique enables reduction of bias errors due to background traffic noise. Continuous measurements are performed as the vehicle is running at 90 km/h on motorways and at the speed limit of national roads (90 km/h). During the experimental run, the position and the speed of the vehicle are precisely recorded with a GPS, synchronised with the noise levels measurements. The method gives one measurement every 10 m corresponding to a spatial "$L_{eq,10\mathrm{m}}$". Special events, such as the passing of a heavy lorry, the presence of a side obstacle, are systematically annotated. Traffic conditions can vary from one place to another, which is why only measurements made when the vehicle is running steadily between 40 and 110 km/h are stored.

The recorded noise levels are compared to those corresponding to a standard road pavement (semi-granular concrete asphalt BBSG 0/10). A classification based on 3 dB step classes is used to compare the roads' emission property. This deviation can be directly applied to the sound power level used in the numerical models. In this case the acoustic property of the pavement in the model should approach those of the reference road pavement.

A temperature correction is also taken into account as the tire/road noise is strongly influenced by the rubber stiffness.

The reference noise level, depending on the vehicle, is a function of the speed (*V* in km/h) and is calculated using the following formulae:

$$L_{\mathrm{pc\ BBSG0/10}} = 33.5 + 33.0\log(V) \qquad \text{in dB(A)}$$

The temperature correction leads to a modification of the measured noise level:

$$L_{\mathrm{pc\ V}} = L_{\mathrm{pc\ measured\ V}} + 0.1(T - 20) \qquad \text{in dB(A)}$$

With *T* being the average measured temperature in °C and $L_{\mathrm{pc\ measured\ V}}$ the average noise level every 10 m.

The deviation is simply computed using:

$$E = L_{\mathrm{pc\ V}} - L_{\mathrm{pc\ BBSG0/10\ V}} \qquad \text{in dB(A)}$$

E is then compared to the six road pavement classes as defined in Tab. 2.3.

The geo-referenced measurements and classes are integrated in a GIS tool to provide a graphic visualisation of the road performance over long itineraries. Moreover, this information can be used in noise simulation tools: deviation E is applied directly to the power level associated with the road. For easier handling in the simulation tool, the level of information detail can be decreased, for instance by reducing the resolution from 10 m to 100 m. This integration should however be performed on sections where a sufficient homogeneity of pavement property is established. Such a method has been applied to characterise all the major roadways in the Fréjus and Susa valleys (see Chapter 7).

Tab. 2.3 Classification of road pavement according to the continuous noise measuring method.

Road pavement classes	Deviations from BBSG 0/10 (3 dB intervals)
Far from noisy	≤ – 4,5
Not very noisy	- 4,5 < – ≤ – 1,5
Fairly noisy	- 1,5 < – ≤ +1,5
Noisy	+ 1,5 < – ≤ +4,5
Very noisy	+ 4,5 < – ≤ +7,5
Strong degradation	> + 7,5
Tunnel	/
No data	/

3 Meteorology

The state of the atmosphere controls the transport and dispersion of air pollutants as well as the propagation of sound. Studies of air pollution and noise need to take into account the atmospheric conditions, and any method for assessment and prediction needs to rely on meteorological expertise. Mountains exert a strong influence on atmospheric motions, the distribution of temperature, and all other meteorological variables. Proper consideration of mountain-specific processes and influences is thus a necessary precondition for assessment and prediction methods applied in those areas. Especially high-pressure systems create conditions of stagnation and recirculation in Alpine valleys and basins, which, combined with strong vertical stability, can reduce the dispersion of air pollutants emitted in these areas, sometimes drastically. This is a major reason why the Alpine space has to be considered a sensitive region in comparison to many other European regions.

Meteorological information – wind speed and direction, temperature, turbulence, surface heat flux, etc. – can be obtained from measurements or from meteorological models. Both options have their limitations and advantages and may be used in combination.

This chapter introduces basic knowledge about these mountain-specific processes, and about measurement, evaluation and modelling methods coping with these peculiarities.

3.1 Mountain-specific atmospheric processes

3.1.1 Climatic features of the Alpine region

The Alps lie at the intersection of three different climate types: the Atlantic climate in the west, the Pannonian climate in the east, and Mediterranean climate in the south. The Atlantic climate is characterised by humid conditions in all seasons and relatively abundant precipitation with a maximum in summer. It has the small annual temperature amplitudes. The Pannonian climate is relatively dry and has the largest annual temperature amplitudes. Regions which are influenced by the Mediterranean climate, the precipitation has maxima in spring and especially in autumn; the summers are often hot and less frequently interrupted by the passage of fronts.

In general, precipitation maxima are found along the border regions of the Alps, and a relative minimum in their interior. Highest precipitation values occur in the areas exposed to northwesterly air flows and in two distinct areas on the southern side, the region of Ticino and surroundings on one hand and the Italian-Slovenian border region on the other hand.

The wind at lower atmospheric levels is strongly influenced by the topography. Except for situations dominated by foehn, by thermally-driven winds and strong cold front passages, the flow near the Alps is parallel to the edge of the mountains. Inside the mountains, winds are channelled by the valleys most of the time, because the valley atmosphere is usually stably stratified, prohibiting or damping vertical motions. For theses reasons, average wind speeds in valleys and even more in basins are lower than in regions outside the mountains, in spite of the fact that crests and peaks often have high wind velocities. Calm periods (usually defined as wind velocities less than 1 m/s) are much more frequent there than over the plains. This has substantial negative impacts on air quality.

A special situation can by found in the Po Basin in the south of the Alps, being surrounded by mountains on three sides. Though it may appear as a large plain to the visitor, it has more of characteristics of a basin than of a plain. In the cold season, it experiences persistent periods of high atmospheric stability and low wind speed similar to inner-Alpine basins, with corresponding consequences for air pollution.

The existence of the Po Basin is an important asymmetry between the northern and the southern side of the Alps, in addition to the already mentioned issue of Atlantic versus Mediterranean climate. Another asymmetry is found with respect to foehn winds, which are important for cleaning out polluted air masses on both sides. On the northern side, foehn is south foehn, i.e. associated with southerly winds. Southerly winds occur ahead of cold fronts and are associated with stable atmospheric stratification, making it rather difficult for the flow to penetrate into the valleys, especially in the cold season. The north foehn of the southern Alps is associated with northerly winds, often occurring right after the passage of a cold front. Cold air is usually stratified moist-adiabatically, and the onset of north foehn brings less warming and thus occurs more easily. The Piedmont region of the western Po Basin experiences foehn with westerly winds. Foehn situations where the foehn wind does not touch the ground are particularly critical for the dispersion of pollutants because of the development of a strong elevated inversion (Natale et al., 1999).

3.1.2 General aspects of boundary layer meteorology

Dispersion of air pollutants and transmission of noise is influenced mainly by the lowest layers of the atmosphere. The layer next to the ground, affected by turbulent fluctuations of wind, temperature, and other meteorological quantities is called atmospheric boundary layer (ABL). This part of the atmosphere is strongly influenced by its interaction with the underlying ground. This includes mechanical effects through surface roughness, vegetation canopy and buildings as well as thermal effects through the net effect of the different heat fluxes (incoming and outgoing solar and long-wave radiation, turbulent fluxes of sensible and latent heat, ground heat flux in the soil, and melting of snow cover).

The ABL over flat or hilly terrain has a characteristic diurnal cycle. During daytime, heat input from the surface leads to a growing well mixed layer, up to typical heights of 1 – 2 km. It is characterised by static instability and well-established turbulence. Air pollution is well mixed in the ABL and there is some exchange with the free atmosphere. Noise (see Section 5.2 for details) experiences upward refraction. After sunset, cooling from the ground forms a shallower and stable ABL. Vertical exchanges are damped by the stable stratification and turbulence decays, restricting the dispersion of air pollutants. Inversions also affect the propagation of noise by downward refraction. During night, the higher parts of the mixing layer transform into a statically neutral “residual layer”, where air pollution and humidity in the formerly mixed layer are trapped by a capping inversion. In mountain areas these thermal processes trigger circulations along the slopes, which feedback on the thermal structure of the valley atmosphere and lead to very different phenomena (see below). In such complex conditions, it is difficult to apply the concept of a boundary layer or mixing layer (see Seibert et al., 2000, for method to be used over flat terrain).

3.1.3 Thermally driven wind systems

In mountain areas, winds are generated by temperature differences if large-scale flows are weak or absent. Air tends to flow from cold to warm regions horizontally, and upward or downward under the influence of buoyancy if it is warmer or colder than the environment (called “anabatic” and “katabatic” winds, respectively). Three different circulations can be discerned, slope winds, valley winds, and a mountain-plain circulation. All these are called thermal or thermally-induced wind systems. These wind systems were already studied in the 1930ies and 1940ies by Wagner, Ekhart, and Defant (Whiteman and Dreiseitl, 1984). The most famous graphical depiction of the slope and valley wind system (Fig. 3.1) was first published by Defant (1949). A more recent overview is provided by Vergeiner and Dreiseitl (1987). Thermally driven winds are sometimes called "autochthonous" wind circulations because they are generated in the area. On the contrary, wind which is driven by transient pressure systems is accordingly called "allochthonous".

During daytime, the relevant mechanisms can be described as follows. The first driving force is the heating of the layer of air along the slopes by insolation. This causes the air to move upwards along the slopes (Fig. 3.2). As a compensation, air in the middle of the valley (or along the other slope – see discussion below on asymmetries) is subsiding. This process leads to adiabatic warming of the whole valley atmosphere, so that the energy input at the slopes is transferred also to the rest of the valley (Vergeiner and Dreiseitl 1987). At the same time, this subsidence stabilises the atmosphere and impedes the growth of the convective boundary layer from the valley bottom, resulting in what has been called the "stable core" of the valley atmosphere, which in larger valleys will remain throughout the day.

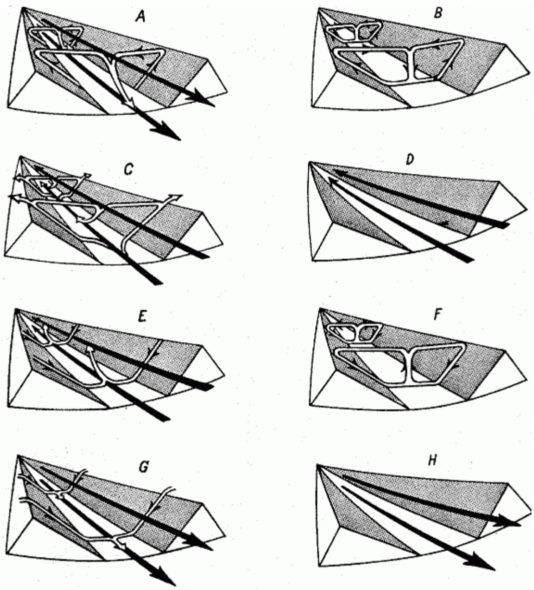

Fig. 3.1 Schematic view of a valley and the thermal circulation (slope and valley winds) during a typical day (Defant 1949).

Valleys do not heat up homogeneously. The volume of air below an imagined horizontal surface enclosing the topography (lid) is smaller higher up in the valley (Fig. 3.3) and largest over a plain, where nothing is filled by mountains. The same amount of available energy will therefore lead to stronger heating rates in a valley than over a plain. Furthermore, heating rates will be bigger in small valleys than in large ones, and will also increase along large valleys (Fig. 3.4). The resulting gradients set into motion a wind along the valley axis, sucking air from the forelands into the valley and continuing until the valley's end.

Less evapotranspiration[1] caused by the sparser or lacking vegetation in the high mountains or albedo[2] effects (more dark forests) have also been invoked as a possible explanation. They may contribute in some situations, but the volume effect described above is generally considered the decisive mechanism for valley winds.

Due to the stronger warming of the atmosphere in the Alpine valleys compared to the adjacent plains, the thermal expansion of the air is stronger and constant pressure surfaces at the Alpine crest level are bulging up over the Alps, causing higher pressure there as compared to their surroundings, driving a circulation back from the Alps towards the surrounding plains. This circula-

[1] evapotranspiration is the sum of evaporation and plant transpiration.
[2] albedo is the optical reflectivity of the ground surface.

tion normally is not measurable, because it occurs over a thick layer of air so that the associated velocities are small compared to the superimposed large-scale winds.

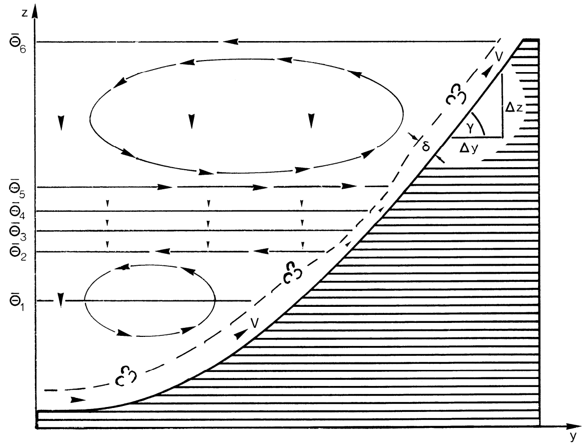

Fig. 3.2 Valley cross section illustrating anabatic slope winds and compensating subsidence. There is the tendency to form two circulation cells separated by a strong inversion in mid-valley (Vergeiner, 1982).

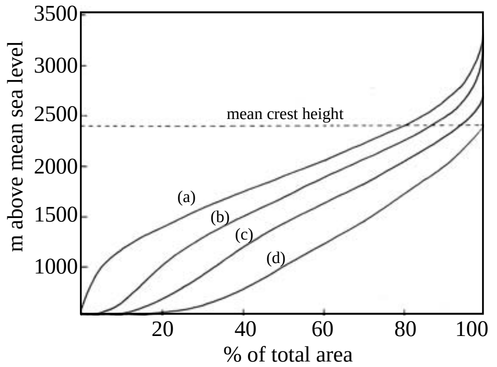

Fig. 3.3 Area-height distributions, percentage of total area of the region. (a) catchment of Sill river, (b) catchment of Inn between Zirl and Jenbach – with Sill river, (c) catchment of Inn river between Zirl and Jenbach – without Sill river, (d) Inn valley near Innsbruck. After Steinacker (1984).

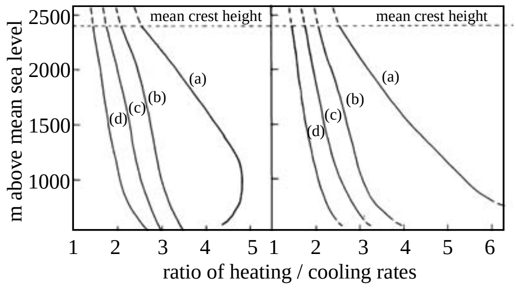

Fig 3.4 Ratio of the heating/cooling rates in the valley to those over the plain. Labelling as in Fig. 3.3**.** After Steinacker (1984).

The situation during night-time is more or less reversed. A complication arises, however, from the different phase delays of the circulations discussed. While upslope winds follow changes in the insolation within minutes, the valley-wind circulations will continue until the along-valley temperature and pressure gradients have reversed. As substantial volumes of air are involved, this can take hours, depending on the size of the valley. Therefore it is common that in the evening shortly after sunset, slope winds are downslope and even valley winds in small tributaries are already down-valley, while the wind in the main valley still blows into the valley, and vice-versa in the morning (Fig. 3.5).

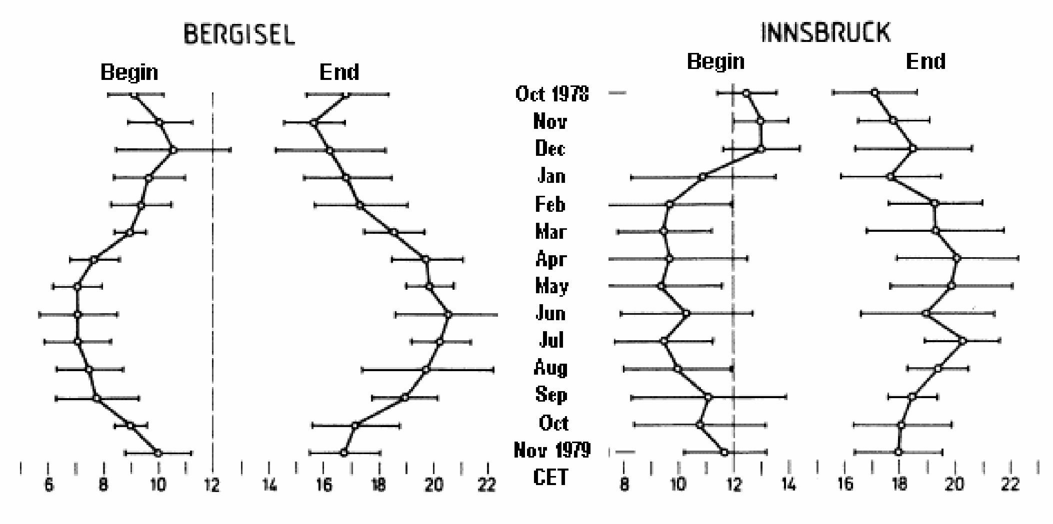

Fig. 3.5 Times of begin and end of the up-valley phase of the valley wind and its standard deviation as a function of the month. Left: Wipp Valley, station Bergisel at the lower end of the valley near Innsbruck. Right: Inn Valley at Innsbruck After Dreiseitl et al., 1980.

One should also be aware that in large valleys with low inclination of the valley floor, the along-valley circulation is driven by horizontal gradients of the mean valley temperature and the resulting pressure gradients only. Such valley winds are not katabatic or anabatic winds like the slope winds. Therefore, the nomenclature “in-valley / out-valley” (Taleinwind / Talauswind in German) is preferable to “up-valley / down-valley” (Talaufwind / Talabwind). Especially in German literature, the wording “valley wind / mountain wind” (Talwind / Bergwind) has also been used, but it is much less clear and accurate, especially with respect to the separation of valley and slope winds.

For geometrical reasons, easterly slopes (i.e., slopes oriented towards east) receive the highest input of solar energy in the morning, southerly slopes around noon and westerly slopes in the evening. Sufficiently steep northerly slopes do not receive direct solar radiation at any time of the day in winter. For these reasons, the development of slope winds changes a lot during the day and it can be asymmetric between the two valley sides. In a north-oriented valley, asymmetries are small around noon. On the other hand, in an east-west oriented valley, upslope winds are likely to develop only on the southerly slope during winter, while the northerly slope may experience downslope wind even during daytime. Such situations can give rise to a cross-circulation over the whole valley.

Another important influence factor are surface properties which affect the conversion of incoming solar radiation to sensible heat. Albedo, the reflectivity of the surface for solar radiation, is the most important factor. Forests have the lowest albedo (appear darkest), whereas snow has a high albedo. Moist ground can evaporate, thus taking away energy from the sensible heat. Vegetation, especially forests, evaporate much more than bare ground because of the transpiration of the plants, and on dry rock there is no evaporation.

Slope winds from different slopes meet on the mountain crests, valley winds are forced to rise towards the interior ends of the valleys and meet over the peaks. This causes convergence and upward motion along crests. If there is sufficient moisture content, the lifting condensation level can be reached over these structures, and cumulus clouds may start to form (Fig. 3.6). Thus, convective cloudiness and precipitation is coupled to the terrain especially in fair-weather periods.

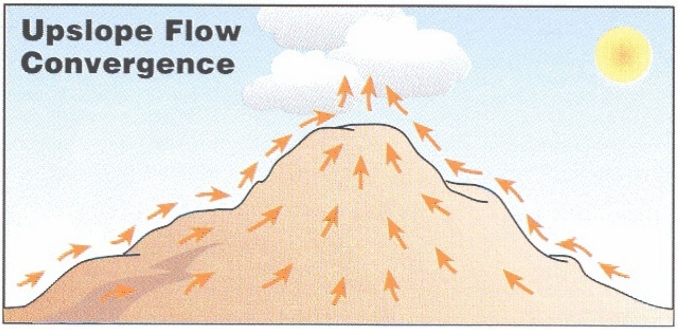

Fig 3.6 Schematic depiction of the convergence of upslope winds over peaks (Whiteman, 2000).

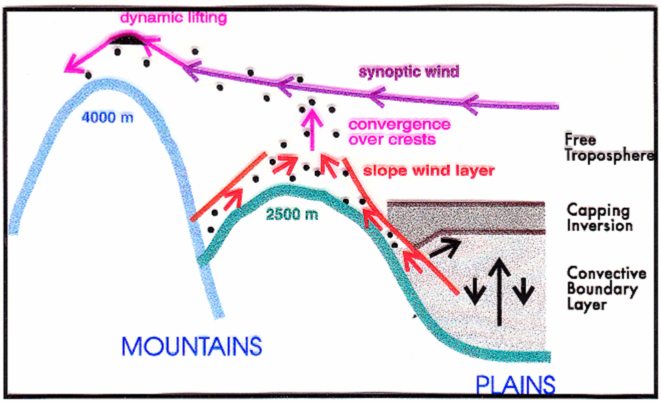

Fig. 3.7 Schematic representation of the interaction of convective mixing, slope wind circulation, orographic convection and orographic lifting in the transport of air pollution from the plains and valleys to the high mountains (Seibert, 1996).

The thermal circulation scheme as described above is season-dependent, as can be seen in Fig. 3.5. It is best developed during the transitional seasons, spring and autumn. As the circulation is driven by the sun, it follows the variation of solar elevation during the year more closely than near-ground temperatures, which are influenced by the delaying effect of the soil temperatures. Therefore, while meteorological seasons are normally defined as DJF, MAM, JJA, SON (i.e., December, January, February for winter, etc.), with respect to the thermal circulations a phase shift of about one month should be considered (e.g., winter as NDJ, etc.). During summer, deep convective boundary layers can be observed in fair-weather conditions, embedding the lower mountains and thus weakening the thermal circulations which work effectively only with stable ambient stratification. During the winter, the sunny period is short and the solar elevation low, therefore the daytime phase of the system is not well pronounced and valley winds – especially in large valleys – may be out-valley throughout the day, or at least most of the day.

The thermal circulations are the major reason why standard methods for assessing the boundary-layer parameters, especially the mixing height (Seibert et al., 2000), have very limited applicability in mountainous terrain. A combination of slope and valley winds, convection at crests, and dynamic lifting can transport polluted boundary-layer air to the level of the highest Alpine peaks, where it is injected into the free atmosphere and carried off by ambient winds (Fig. 3.7, see also Henne et al., 2004).

3.1.4 Inversions in valleys and basins

Usually, temperature decreases with height in the atmosphere, on the average by approx. 0.6 °C / 100 m. If, on the contrary, the temperature is increasing with height in the atmosphere, this situation is called an inversion. It is a very stable stratification, where turbulence is weak or absent. It should be noted, however, that any stratification with a temperature lapse rate of more that -1 °C / 100 m (i.e., when the temperature is decreasing with height by less than 1 °C per 100 m) is already stable, and the threshold of 0 °C / 100 m, denoting the border to a real inversion, has no special physical significance. The more stable, the weaker is turbulence, until a critical condition is reached where turbulence may disappear completely. Thus, even if we speak about inversions in this chapter, much of it also applies to situations with approximately isothermal stratification (just-not-inversions).

Over land, inversions normally form during nights with clear sky or few clouds and not too high wind velocities. This already explains why they are more common and stronger in valleys and basins: compared to the plains, these locations are shielded from the wind and thus the near-ground air cools down more strongly (Vergeiner et al., 1978). Katabatic downslope winds transport more cold air, so that cold-air pools build up. In winter, nights are longer and insolation is weaker, therefore inversions are more frequent and stronger in the cold season. In Alpine valleys and basins, it is common that cold-air pools pile up from day to day under high-pressure conditions, as they are associated with weak winds. Because they are so stable, it becomes more and more difficult to erode or sweep them out by frontal passages. Warm fronts, due to being connected with stable stratification, are usually not affecting these persistent inversions much. Cold fronts need to have a sufficient strength in order to replace the cold-air pools. If they do, they often arrive as so-called masked cold fronts, meaning that they bring a drop of temperature only above the inversion, while at the valley bottom the temperature is higher in the fresh cold air than previously with the inversion. Foehn is another mechanism for removing inversion layers, though in winter the foehn flow often does not break through to the valley floors on the northern side of the Alps as the inversions tend to be too strong.

If sunshine occurs during daytime in the course of an inversion episode, it may warm the air close to the valley floor and establish a shallow convective boundary layer. However, in the cold season solar radiation is usually not sufficient to break up the inversion from below. Then, the convective boundary layer is capped by a so-called elevated inversion. The inversion type found during night (or other situations with zero or downward sensible heat flux, such as over a snow cover with weak solar radiation) is called ground-based inversion.

An elevated inversion acts almost like a lid on the valley or basin and limits the volume of air available for dilution of pollutants emitted there. As there are side walls, the only ways for polluted air to be removed (or fresh air to be advected) are along-valley and within the slope wind layer. Along-valley winds are usually weak during winter high-pressure episodes. Slope winds are diabatic and thus able to penetrate even a strongly stable layer such as an inversion. However, the mass flux in the slope wind layer is controlled by the strength of the stable stratification on one hand and the intensity of the diabatic heating (for upslope winds) or cooling (for downslope winds) on the other hand (Vergeiner and Dreiseitl 1987). A typical example of transport of pollution in the slope-wind layer with detrainment and asymmetric cross-valley circulation was observed during the ALPNAP measurement campaign in the Inn Valley and is presented in Section 7.1.

Due to these mechanisms, air pollution modelling in Alpine valleys is extremely complicated.

3.1.5 Large-scale influences

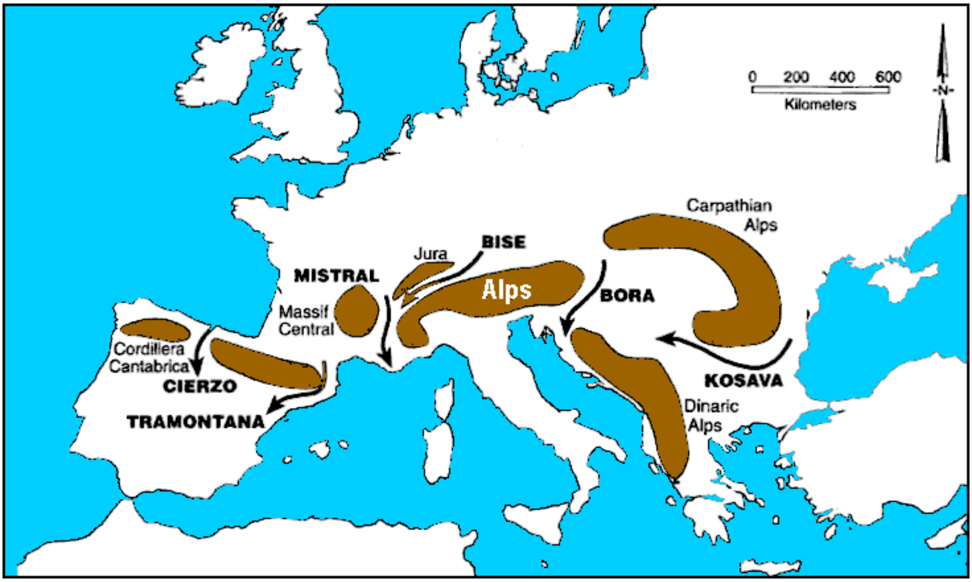

Fig. 3.8 Flows between the major mountain barriers in Europe (Whiteman, 2000).

If large-scale flows impinge upon a mountain range, the air can either go around or over the mountains. The fraction of around versus over is determined by the stability and velocity profile of the air flow on one hand and the height and shape of the mountain on the other. In the Alpine area, the "mistral" of the Rhone valley, the "bise" of the Swiss Midland and the "bora" of the Dinaric coast are branches of a flow around the Alps (Fig. 3.8). A situation where the flow goes over the mountains and where persistent clouds and precipitation form on the up-flow side of the Alps is called "Stau" in German, a word with no real English counterpart. The tendency towards upward motion of the air on the windward side is responsible for enhanced cloudiness and precipitation there. On the lee side, there is a tendency towards descending motion, culminating in strong downslope winds called foehn if the conditions are right (Fig. 3.9). Therefore, clouds tend to dissolve and precipitation is less or absent on the leeward side.

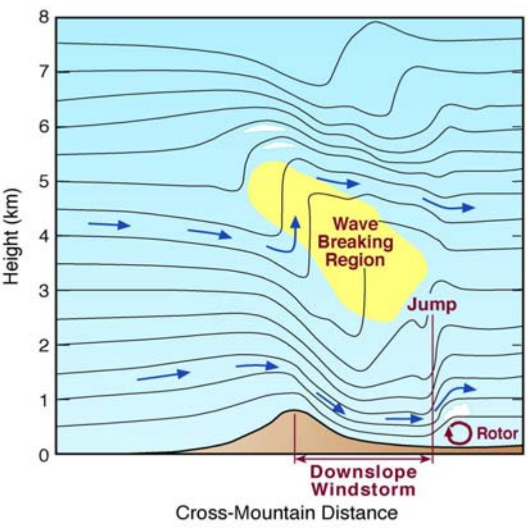

Fig. 3.9 Cross-section over an idealised mountain ridge with the development of a downslope windstorm (foehn). From Whiteman (2000).

A special but very relevant situation for the Alps is the Genova lee cyclogenesis. A cold front crossing the Alps with northwesterly flows can quickly reach the Gulf of Genova through the Rhone Valley. On the other hand, it needs many hours, sometimes days until it is able to cross the Alpine main ridge (Fig. 3.10). Thus a strong temperature gradient is forming south of the Alps which can lead to the formation of a secondary cyclone. In the mature stage of such a development, the cold front has just crossed the Alps and cold air is advected at lower levels while the cyclone in the south steers warm and moist air towards the Alps at higher levels. In these situations, heavy precipitation can fall on both sides of the main ridge.

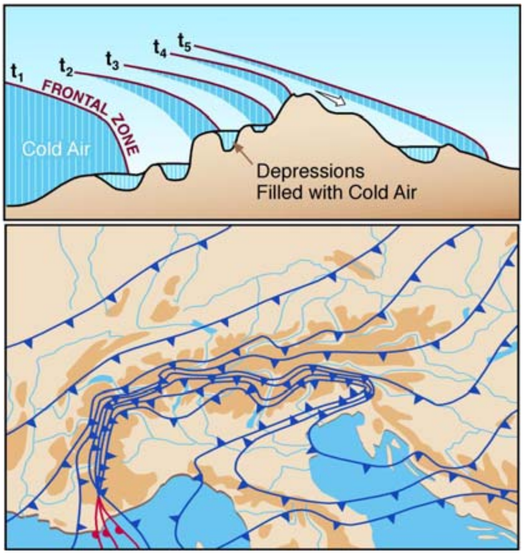

Fig. 3.10 Bottom panel: position of a cold front crossing the Alps at subsequent analysis times (interval 3 h) according to Steinacker (1987). Top panel: idealised view of corresponding vertical cross-sections (from Whiteman, 2000).

High-pressure systems are associated with weak winds and clear skies and thus the main reason for air pollution episodes. This holds both for the warm season, where ozone is the key pollutant which forms under the influence of sunshine, and in the cold season, when cold air pools trap primary pollutants such as nitrogen oxide and particulate matter. During the approach of a frontal system, often warm air is advected first at higher levels, making the situation even worse through increased stability. Often, it is observed that weaker frontal systems do not bring a change of the stagnant air masses in the valleys or the Po Basin. Associated winds have to be sufficiently strong and temperature contrasts big enough to remove the stably stratified air. Precipitation can improve the situation by wash-out. Thus the frequency and duration of pollution episodes inside the Alps are considerably higher than in its surroundings (except the Po basin).

Furthermore, thermal wind systems are not only present on days with small large-scale pressure gradients. The underlying mechanisms act also in other situations, provided there is sufficient sunshine and radiative cooling at night. Then the thermal and the synoptic (large-scale) influences overlay. Thus a large number of days have the typical diurnal pattern of wind direction change and associated effects on air pollution (see Section 4.2.2).

3.2 Observation methods

Operational networks provide input for weather forecasts, monitor the climate, and deliver data for operational purposes. Field campaigns – see Chapter 7 – may serve to obtain deeper understanding of processes, and/or features in a specific area.

There are different meteorological networks, operated by different organisations and for different purposes. In all countries, there is a national meteorological service, affiliated with the World Meteorological Organisation (WMO), carrying out observations according to WMO standards. The national meteorological services in the Alpine countries are listed in Tab. 3.1.

Tab. 3.1 National meteorological services in the Alpine countries with their web addresses.

Country	Name	Web address
Austria	Zentralanstalt für Meteorologie und Geodynamik (ZAMG)	www.zamg.ac.at
France	Metéo-France	www.meteofrance.fr
Germany	Deutscher Wetterdienst (DWD)	www.dwd.de
Italy	Aeronautica Militare, Servizio Meteorologico	www.meteoam.it
Slovenia	Agencija Republike Slovenije za Okolje	www.arso.gov.si
Switzerland	MeteoSchweiz/MeteoSuisse/MeteoSvizzera/Meteoswiss	www.meteoschweiz.ch

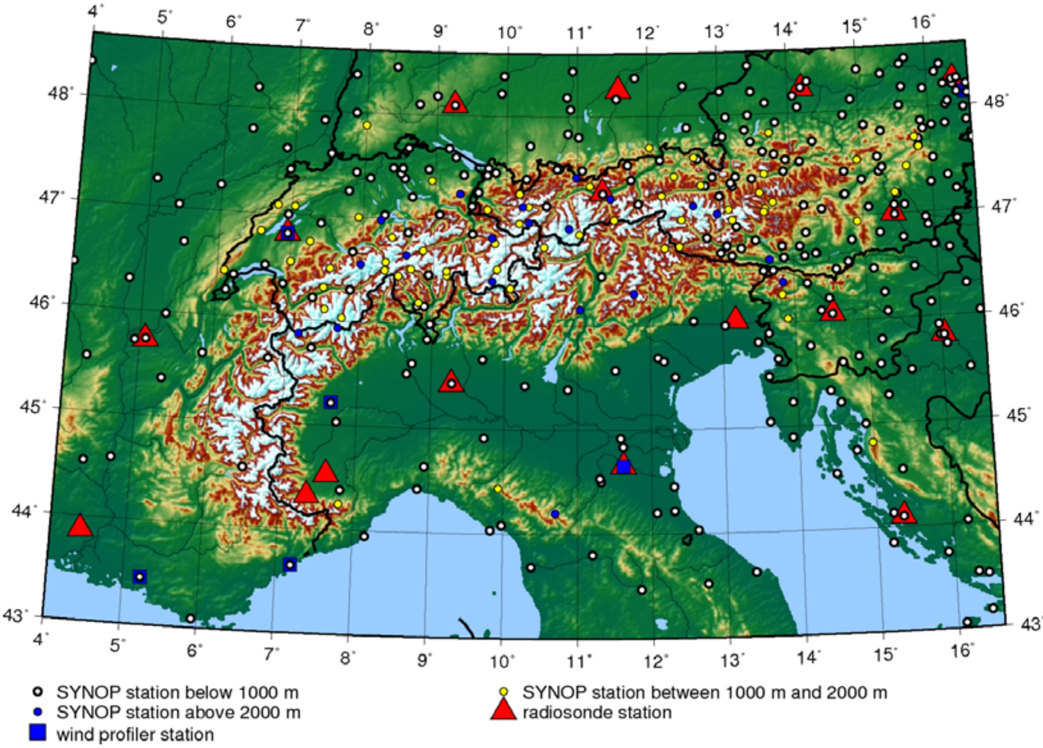

Fig. 3.11 Synoptic, radiosonde and wind profiler stations in the Alps and surroundings (stations for which data were received by ZAMG Wien in 2006).

3.2.1 Operational networks

3.2.1.1 SYNOP network

The SYNOP or synoptic network is operated for weather analysis and forecasting. Stations report at least wind, temperature, dew point, and precipitation. If the station is staffed, it will also provide cloud and visibility observations as well as present and past weather (such as fog, rain, thunderstorm, etc.) and, in the morning, snow height wherever appropriate. Data are 2 to 10 min means and are provided at intervals between 1 h and 6 h. Measurements are performed at the same time all over the world, e. g., at 00 UTC, 03 UTC, 06 UTC etc. The data are circulated internationally in real time. If the stations are equipped with automatic data acquisition systems, they may provide information also at shorter intervals, but these data are not available internationally.

Fig. 3.11 shows a map of the internationally available SYNOP stations in the Alpine area. It is obvious that the station density in the Alps is much less in France and Italy than in the other Alpine countries, and high-elevation stations are missing in the westernmost part of the Alps completely. Very similar to SYNOP data are METAR data which serve specifically aeronautical needs.

3.2.1.2 CLIMATE network

The CLIMATE network is operated to record the climate. The stations can be automatic or manual, or automatic with additional staff observations. In addition to the parameters of SYNOP stations, they often measure sunshine duration and/or solar radiation, too. Manual stations have only three observations per day, in the morning, noon and evening, at hours which vary from country to country and which refer to mean local time. Note that the timeframe depends on the geographical longitude of the station. Automatic data are often provided as hourly means. The data acquisition is not necessarily in real time. Data are often published in yearbooks. A subset of the data is exchanged internationally.

3.2.1.3 Upper-air network

The upper-air observation networks comprise conventional instruments such as radiosondes (TEMP), delivering temperature, dew point and wind as a function of height, and pilot balloons (PILOT) which only provide wind information. Radiosondes are small sensor packages carried by a rapidly ascending balloon which transmit a radio signal with the measurements to the ground stations. Winds are obtained by tracking the balloon by radar or GPS. Upper-air stations in the Alpine area are also shown in Fig. 3.11. Innsbruck is the only station in an Alpine valley. At most TEMP stations, soundings are made twice daily, around 00 and 12 UTC and distributed internationally in real time. While radiosoundings are unique in their capability to provide accurate vertical profiles of wind, temperature and moisture, their disadvantage for boundary-layer and air pollution studies is that the vertical resolution transmitted is often quite coarse. Full-resolution data may be available directly form station operators. Data at the so-called significant levels (1000 hPa, 850 hPa, etc., also called TEMP part A) alone are insufficient for air pollution studies. Horizontal displacement of the balloon during the ascent can be relevant especially over mountainous terrain. It is expensive to operate a radiosonde station. Wind profilers are increasingly used to complement the conventional upper-air network with continuous wind profiles, most often up to approx. 3000 m AGL; their data may or may not be distributed internationally.

In addition to national meteorological services, a variety of other institutions operate operational meteorological networks. Their instruments are less standardised and the observation locations not always chosen to be representative for a larger area, as is the case with the SYNOP and CLIMATE stations. The following is a list of typical operators of such networks:

- Regional meteorological services.
- Avalanche warning services. Stations are usually on mountains.
- Air pollution monitoring: Air pollution monitoring stations (see also Section 4.2.4) are usually also equipped with meteorological sensors, typically for wind, air temperature and humidity, atmospheric pressure and sometimes also solar radiation or net radiation.

- Road maintenance services.
- Special-purpose networks: Research institutions may run stations or networks for campaigns, but sometimes also in a monitoring mode over years.
- Private meteorological companies have also started to build station networks, partly in cooperation with municipalities. Data quality and accessibility may vary.

In view of these characterisations, it is highly advisable to visit and see stations before working with their data and properly analysing the meta-data, especially if the stations are not operated by a regular meteorological service. Also, data have to be quality-controlled, unless the operator has already done that (and even then it may be useful).

3.2.2 Meteorological instruments

3.2.2.1 Conventional meteorological sensors

Specifications for meteorological stations have been set up by WMO (1996). These include to measure wind speed and direction at 10 m above ground, air temperature and humidity at 2 m.

Concerning the frequency of sensor polling and averaging interval, the turbulent nature of the near-ground atmosphere has to be considered. Under most conditions, a turbulent fluctuation of wind, temperature and humidity occurs at time scales ranging from fractions of a second to many minutes. Normally, one would like to exclude these fluctuations from the results. Therefore, either sensors with a corresponding time constant have to be used, or an average has to be formed in the data logger, based on frequent polling. WMO standards for SYNOP station require an averaging time of 10 min for wind and 2 min for temperature. In air pollution modelling, 30 – 60 min averages are very common both for concentrations and wind. However, for process studies and for noise propagation, shorter averaging periods (e. g., 1 min) can be useful.

In mountainous regions harsh environmental conditions may occur. In particular, the presence of snow and the possibility of icing require sufficient heating of precipitation and wind sensors, in order to prevent failures or unreliable measurements (mostly underestimation).

3.2.2.2 Surface energy budget sensors

The surface energy balance (with net radiation, turbulent fluxes of sensible and latent heat, ground heat flux and contributions from precipitation as the main components) plays a crucial role for the local circulations and the boundary-layer.

Net radiation is usually measured by thermopiles, preferable to photovoltaic devices. Filters determine whether the short and long-wave components are measured separately (pyranometer, pyrgeometer) or whether the signal directly gives the net radiation i.e. the sum of the up- and downwelling components (net radiometer). Usually these measurements are hemispheric and refer to horizontal surfaces. In mountainous terrain however, adjustments to the sloped surfaces may be considered. The radiometers must be regularly calibrated. High quality radiation measurements require regular maintenance, especially to ensure proper alignment of the sensors and clean filters. Heating and ventilation of the sensors may help to prevent the deposition of dust, precipitation, dew or rime.

There are indirect and direct means to determine the *turbulent heat and vapour fluxes*. Indirect methods are the gradient, profile, and bulk transfer or Bowen ration methods (Arya, 1988; Stull, 1988). All of them are based on measurements of the vertical profiles of wind speed, air temperature and humidity at distinct levels on a mast. Direct measurements of the sensible flux are considered the most advanced method, based on 3D ultrasonic anemometers (at least 10 Hz resolution) measuring wind and temperature fluctuations (eddy correlation or variance methods; Stull, 1988). Optical (refractive) methods are employed for this purpose as well (scintillometer). The turbulent fluctuations of vapour (latent heat flux) can be directly determined in a similar way with optical devices (Lyman-alpha, Krypton, IRGA hygrometers). While the technology of these instruments is already well developed, their wide spread (long-term) use is still limited by the high costs and a need of intensive maintenance and processing of the large amounts of data. Regarding applications in mountainous terrain, the limited representativeness of point measurements must be considered. In katabatic winds, vertical flux divergences have to be taken into consideration.

The *ground heat flux* may be determined from measurements of the vertical subsurface temperature profiles (usually between 1 cm and 50 cm), which may be combined with so-called heat-flux plates allowing direct measurements at a specific level in the ground. Problems arise in presence of snow.

Generally, the presence of vegetation, snow or water requires more sophisticated approaches accounting e.g. for modifications of air flow within the stand (zero plane displacement), in depth absorption of penetrating solar radiation, or advection effects (water flow, snow drift) and phase changing processes (melt water production/refreezing). These effects are difficult to measure which is why they are often neglected or estimated indirectly.

These measurements should at least comply with the official standard of meteorological routine measurements (Brock, 2001; WMO, 1996).

3.2.2.3 Vertical structure

A detailed knowledge of the vertical structure of the air is essential for air pollution and noise. This is especially true in mountainous terrain, where the atmospheric state varies at short distances and within short periods of time.

Mast profiles

Mast profile measurements are effective tools within the lowest 10 to 20 m AGL. They are useful for the investigation of relatively shallow features (e.g., inversions, katabatic winds) or calculation of the turbulent fluxes from the gradients. Sensitive and well-calibrated sensors have to be used in order to resolve the small vertical gradients. Moreover, fetch requirements must be considered, which indicates a need on thorough site exploration. The vertical resolution of the measurements should be better close to the surface, because of the quasi-logarithmic profile.

Tethered balloons and kites

Tethered balloons and kites are useful for a range up to 1000 m above ground. The equipment consists of a large helium-filled balloon tethered to a winch on the ground. Sensor packages are suspended close to the balloon and their signals (e.g., air temperature, humidity, pressure, wind speed and direction) are transmitted to a ground-based receiver. There are two modes of operation yielding different kind of information. Quasi-continuous profile measurements can be performed while the balloon rises or descends, which provides a good spatial discretisation (< 1 m) in about 1-hour intervals. Alternatively, the balloon may be kept at a constant level above ground with several sensor packages mounted along the tether line. This strategy provides a good temporal resolution (10 s) of the measurements at the cost of vertical resolution. Special kites may also be used, especially with higher wind speeds. The application of this kind of measurements suffers from the high cost of the equipment and the need for operation personnel and limitations due to air traffic regulations. However, the ALPNAP field campaign has demonstrated the outstanding benefit of such measurements regarding air pollution and noise issues in complex terrain.

Car-based measurements

Car-based measurements are valuable for enhancing the spatial density of measurements in between stations of surface networks. Typically, their instrumentation comprises sensors for position (differential GPS), pressure, temperature, relative humidity and wind. They can also include air pollution parameters (see Section 4.3.1.1). Care must be given to proper mounting and to the response time of the sensors. Usually, the measurements require extensive post-processing to deal with inevitable disturbances. The design of a thorough measurement strategy is most useful in latter context (pre-surveying, regular passes of landmarks etc.). Examples can be found in Section 7.1.

Slope temperature profiles

Slope temperature profiles may also be considered to provide measures of the vertical temperature profile inside a valley (e.g., Dreiseitl, 1988; Whiteman et al., 2004). Measurements can be made with standard instruments, though often low-cost sensors with integrated data loggers are used. However, it is not trivial to obtain meaningful temperature gradients with this method. This turned out to be a problem with the low-cost sensors deployed in the Lower Inn valley target area, as discussed in Section 7.1, especially for daytime measurements. Terrain effects will vary from site to site, e.g. time of sun rise and set, shading, small-scale flow features, etc. A careful selection or correction of the data before gradients can be derived is required. Dreiseitl (1988) is an exemplary application of this technique to a profile in the Inn Valley north of Innsbruck. He used correction functions depending on station, the time of day and the global radiation.

A pair of valley and mountain stations can be considered as the simplest form of a slope profile. It allows at least rough conclusion on the stability of the valley atmosphere (Nickus and Vergeiner, 1984; Wotawa and Seibert, 2000).

Sodar and RASS

Vertical profiles of wind and turbulence, and the thermal layering of the boundary layer can be obtained from acoustic remote-sensing instrument Sodar (Fig. 3.12 left). They emit sound pulses into the air and record the frequency and intensity of the signal that is scattered back from the atmosphere. Wind and turbulence are measured from the Doppler shift in the sound frequency between emitted and backscattered signal. The thermal structure is estimated from the backscatter intensity. The acoustic frequency used is about 1500 Hz for long-range instruments (vertical range up to 1000 m) and about 4500 Hz for short-range instruments. A vertical resolution of 10 to 20 m and a temporal averaging over 10 to 30 min can be typically achieved.

The instrument is working best in the absence of external noise and rain. The vertical range for these variables from Sodar measurements depends strongly on the meteorological conditions and typically varies between a few hundred metres and about 1000 m.

Temperature profiles can be obtained by adding an electromagnetic component to a Sodar. Such a system is called a RASS (radio acoustic sounding system). The electromagnetic component of a RASS emits microwave radiation in the UHF band, receives the backscatter from the atmosphere, and analyses the frequency shift of the backscattered signal which is proportional to the propagation speed of the acoustic pulses. This speed is closely related to the air temperature, so that in this way the vertical temperature profile is determined. A vertical range of 300 to 800 m, a vertical resolution of 30 to 50 m, and a temporal resolution of typically 10 to 30 min can be achieved.

Both Sodar and RASS can be operated unattended in an automated mode. Access to the instrument must be restricted for the public because the direct impact of the sound pulses from a Sodar or the acoustic component of a RASS can harm the ear. A minimum distance to settlements of about 500 m is advisable. Proper power supply and unobstructed site characteristics are required since the Sodar is sensible to echoes from nearby obstacles.

Ceilometer

The height of the well-mixed atmospheric boundary layer (mixing-layer height, MLH) can be estimated from a ceilometer (Fig. 3.12 right). The MLH bounds the vertical dispersion of pollutants emitted near ground. A ceilometer is an optical remote-sensing instrument which emits a vertical laser beam and then records the intensity of backscattered light. The instrument is eye-safe. Normally, these instruments are used for detection of cloud-base height. MLH can be inferred from vertical gradients in the signal intensity under the assumption that the particle load in the atmosphere has adjusted to the thermal structure of the atmosphere. The typical vertical range of this instrument is 4000 m, the vertical resolution is 7.5 m, and the minimum temporal resolution is 15 s.

Fig. 3.12 Long-range Sodar (left), ceilometer (right; white device with aerosol samplers in the background).

3.2.3 Representativeness and measurement strategies

3.2.3.1 Spatial representativeness

The complexity of mountainous regions defines a wide range of spatial scales characterised by various degrees of inhomogeneity in terms of land cover (i.e. rural, urban, etc.), valley width and mountain height, presence of isolated obstacles, etc. Required spatial resolution of meteorological measurements depends on the application. For air quality issues, processes may involve local, regional or transnational scales; meteorological information should correspond to these different scales. Meteorological data collected at the very same sites of air quality stations – as usually done in air quality networks – may be of limited spatial representativeness, especially when these stations are located in urban or sub-urban areas (see Oke, 2004, for a brief discussion of representative meteorological measurements at urban sites). Examples of integration of meteorological measurements at different scales are discussed in Chapter 7.

3.2.3.2 Temporal representativeness

This issue is particularly relevant for short-term measurement campaigns. They should be compared with long-term climatological series from reliable reference stations close to the area of interest. This is necessary because of the seasonality of the meteorological phenomena and to account for variability from year to year. Another relevant factor is the frequency of specific weather patterns, like long ground-based inversions in winter time or thermal wind systems.

3.3 Modelling of atmospheric parameters

Due to the complexity of the flow fields in the Alpine region (Section 3.1), point measurements in space and time (Section 3.2) are not sufficient. Therefore, numerical models can be used to generate data on dense spatial grids and with high temporal resolution, though it is important to also consider their limitations.

To assess the physics of transport and diffusion of pollutants, air-quality models require detailed meteorological fields, such as wind and turbulence, thermodynamics fields, precipitation, cloud cover, boundary layer fluxes and parameters as input. An appropriate description of meteorology encompasses the atmospheric processes that influence and determine the evolution of emissions and chemical transformations.

The main state variables used in air quality modelling are horizontal and vertical wind components, turbulence intensity (expressed as turbulent kinetic energy and/or eddy diffusivities), surface fluxes (of momentum, heat and moisture), boundary layer depth, temperature, water vapour mixing ratio, precipitation, cloud fraction and liquid water content. Additional parameters may be used by some air pollution models. For the meteorological variables used in noise assessment we refer to Section 5.2.2.

The meteorological variables may be supplied by measurements and/or by modelling systems. In Fig. 1.1 in Chapter 1 a schematic view of the whole modelling chain considered in the ALPNAP project and the specific part related to the meteorological modelling is presented.

3.3.1 Types of models

Two groups of meteorological models may be identified which can produce input data for air quality models, *diagnostic* models, analysing observations at certain points in time and space, and *prognostic* models, numerically integrating the non-linear dynamic and thermo-dynamic equations of motions.

3.3.1.1 Diagnostic models

Diagnostic models produce gridded meteorological fields from sparse observation data by interpolation. Mass consistency is imposed through the continuity equation. The interpolation scheme may include modules to account for topographical effects in the observing area. This kind of model cannot produce meteorological forecasts. On the other hand, it is able to reproduce the local characteristics of the atmospheric circulation if good-quality observed datasets are available; they can provide meteorological fields at required resolutions. The diagnostic model thus is expected to reproduce the main flow features well near the measurement locations, while for regions not covered by observations reasonable results cannot be expected. Diagnostic models like CALMET and MINERVE (briefly described in Section 3.3.3.1 and applied in Sections 7.2 and 7.3) can be used to build the flow field in an area where observations are available, and as a post-processing tool for prognostic models, as explained later.

3.3.1.2 Prognostic models

Prognostic models are based on the dynamical equations of atmospheric motion and the conservation equations for mass, heat and water (or other quantities and substances) species. Generally it is possible to choose between the non-hydrostatic equations and the hydrostatic approximation. The latter assumes the hydrostatic equilibrium between the vertical component of the pressure gradient force and the gravity force. This leads to a simplified version of the vertical equation of motion and the mass continuity equation. Hydrostatic assumption is appropriate for scales bigger than 10 km. Non-hydrostatic processes become important when vertical motions in the atmosphere are rapidly varying. The non-hydrostatic approach is in general needed when the ratio of the height to the length scale of atmospheric motions is much less than the unity. This can happen in complex orography, especially in connection with mountain ridges and with deep convection. Mesoscale models normally include non-hydrostatic effects when the spatial grid is smaller than 5 – 10 km. However, thanks to the improvement of computer resources, non-hydrostatic models became the dominant choice in the framework of dynamical modelling.

The prognostic models are intended to simulate the atmospheric processes and to provide a realistic prediction on the development of the meteorological conditions. They solve the equation of atmospheric dynamics and thermodynamics using a three-dimensional grid, and employ a number of parameterisations to estimate sub-grid scale phenomena and to calculate the quantities related to surface and boundary-layer processes, turbulence, radiation, convection and formation of clouds. Parameterisations are also applied for the energy transfer between the atmosphere and the Earth’s surface. Boundary conditions need to be formulated for the lateral boundaries and the model top. Models differ in the choice and range of options for the parameterisations, in the different methods for initialising the simulations (including also data assimilation), in handling the boundary conditions, in the coordinate systems and domain nesting as well as in the numerical procedures for solving the equations.

For simulations of the meteorological conditions in the Alpine area, the main choice are mesoscale models, built to model the atmosphere at horizontal scales ranging from a few kilometres to several hundred kilometres, with a typical grid resolution down to the order of 1 km. Application of these models to larger domains is possible but limited by their demand in computational effort. The main advantage of this kind of models in highly inhomogeneous terrain is their ability to account for the influences of topography on the flow field, like valley and slope winds. On one hand, they are usually driven (initial and boundary conditions) by the meteorological fields generated by output from global models, such as ECMWF analyses, which represent the synoptic-scale influences. On the other hand, with the help of grid nesting, they can reach horizontal resolutions high enough to reproduce also the main features of the local meteorology.

Many different models are presently used in the scientific community and by operational services, for example RAMS, MM5, ARPS, ETA, WRF, FITNAH, HIRLAM, and BOLAM.

A description of some modelling systems is included in Section 3.3.3.2 and, for applications in Chapter 7.

3.3.1.3 Specific aspects of numerical meteorological models

Numerical models adopt a grid system for calculation, both in the horizontal and vertical direction. While the size of the simulation domain may range in the horizontal direction from some ten to several hundreds of kilometres, the horizontal resolution lies in a range of approximately 0.1 to 2.5 km for applications in complex terrain. In the vertical direction, the computational levels are chosen to yield higher resolution near the ground. The coordinate system is not rectangular because it is transformed in a way that the lowest model layer coincides with the surface (so-called terrain-following coordinates, see Fast (2003) for a more detailed description of this aspect). When pollutant transport within a valley is studied, a sufficient number grid points must be located inside the valley to properly resolve the topographical forcing of the wind and other quantities. Some studies (Hanna and Chang, 1992) have shown that for mesoscale models at least 1 km grid spacing is needed to resolve certain relevant flows.

The simulated values of the meteorological variables obviously should be compared with measured data to make sure that adequate results are being produced. If the outcome is negative, appropriate measures need to be taken, until this model validation process has positive outcome. Suggestions for the comparison between model output and observed data are given in Section 3.4.

In the case of diagnostic models, observed surface weather data and vertical profiles of wind and temperature (when available) form the input, while turbulent quantities are parameterised. In this case, a check is possible by removing a few measurements at a time (e.g., data provided by a single weather station) from the input data, and checking whether the overall results are substantially affected or not. Pre-processors that interpolate and extrapolate the measured data in space and time are run as the main step in these models to produce gridded meteorological fields. Therefore, the diagnostic meteorological models run require continuous feeding of measured meteorological data.

Prognostic models also may ingest observations via data assimilation techniques, both as initial fields and during the simulation through nudging procedures. Nudging can use the synoptic data fields as well. However, problems can arise since in general the number of measurement points and their representativeness (in relation to the model grid cell size) may be insufficient or produce conflicting interference with the background fields calculated by the simulation. In such conditions, measurements hardly provide a useful input to the model chain. Generally spoken, in many mesoscale applications the availability and representativeness of observation data is such that they would tend to worsen instead of improving the simulation, because of introducing noise.

There are two alternative approaches for the interface between meteorological and dispersion models: *off-line*, running the dispersion model from a time sequence of previously calculated and stored meteorological outputs, or *on-line*, by integrating the air quality model with the meteorological model into one code (see also discussion in Section 4.4.2.1). The offline approach, thanks to the independency of meteorological and dispersion simulations, offers the advantage of repeatability and flexibility of air-quality impact assessment. In the online case, the integrated modelling system allows the dispersion model results to have a feedback effect on the meteorological fields, as for instance the distribution of aerosols affecting radiation (Physick and Trini Castelli, 2005).

Accurate simulation of turbulence is fundamental for properly describing the diffusive processes in air pollution models (Chapter 4). Thus, more sophisticated models, able to resolve the variation of turbulent fluxes with high spatial and temporal resolution, may be desirable. In the case of diagnostic models, a sophisticated meteorological processing tool is usually needed to prepare proper fields of turbulence for the air pollution model. The choice of turbulence parameterisation may strongly affect the dispersion of pollutants (Ferrero et al., 2003) and it can be particularly important for stably-stratified or nocturnal boundary layers, or when strong wind shear is present. Furthermore, the diffusion and deposition of pollutants near ground can be strongly influenced by the surface friction and the heat flux at the surface. Advanced models contain more refined turbulence parameterisations and include the varying surface effects depending on the area of study and the scale of interest.

The vertical coordinate systems may be different between the meteorological and dispersion models, so that model outputs may need to be interpolated, which in turn could create numerical aliasing and reduce the effects of the terrain on the meteorological fields. The simplest dispersion models, like the Gaussian ones, are not designed to make use of such high-resolution fields.

Long-wave and short-wave radiation parameterisations are used to simulate incoming, outgoing and reflected radiation including the effects of clouds (Antonacci and Tubino, 2005) and surface properties (Holtslag and Van Ulden, 1983). Most mesoscale models include an explicit cloud microphysics scheme and are thus able to simulate rain and snow fall. Schemes may include not only the falling of precipitation particles, but also the evaporation from these particles. For air quality simulations, precipitation data are needed for calculating wash-out. Prognostic models generally also include parameterisations for convection to simulate vertical transport of heat and moisture in a column of air as found in convective clouds (cumulus, shower and thunderstorms clouds). These schemes are valid only on coarser grids, while with grid spacing of a few kilometres or less these processes are explicitly resolved by the model.

Some studies indicate that utilising a coarse prognostic meteorological model to provide input to a diagnostic model creates an attractive option for generating accurate meteorological input for air quality modelling studies, even for long-term simulations up to a year (see, e.g., Hanna et al., 2001, and Robe et al., 1998).

3.3.2 Benefit and costs

3.3.2.1 Diagnostic models

The main benefits of diagnostic models are their good representativeness of local circulation when sufficient observations are available, and the possibility to use the full information contained in measured data as well as to calculate the meteorological fields with high resolution, typically a few tens of metres. Moreover, since each analysis is generated by an independent set of observations, no accumulation of errors in time is produced. Diagnostic models require very little computational effort and the time for a run is generally short (for example, the runtime for 1 year simulation over a 100 × 100 km domain with 250 m horizontal resolution is on the order of 1 to 2 days on a 3 GHz CPU). Furthermore, the computational costs involved in running a coarse prognostic meteorological model and introducing its output into a finer resolution diagnostic model are significantly lower than running a fully nested prognostic meteorological model with the horizontal resolution of the diagnostic model. Less specialised training is required for running this kind of model compared to a prognostic model, but supervision by specialised personnel is important to avoid application in situations for which they are not appropriate and to discover eventual problems in the output. For these reasons, they are also used in real-time emergency response systems.

On the other side, since diagnostic models solve a very rudimentary set of equations only they can produce inconsistencies between variables and may be unable to properly reproduce some flow patterns, especially those introduced by topography. Their performance critically depends on the availability of measured data and their quality. It is difficult to accurately represent flows in regions with sparse data, like mountains. As the details in time and space of the meteorological fields produced are typically controlled by the observation data set, field campaigns providing dense data sets may be necessary to achieve the desired results. However, such campaigns are quite costly and limited in time.

3.3.2.2 Prognostic models

The major advantage of prognostic models is that they are scientifically sound, because they are based on the numerical solution of all relevant equations. They allow to simulate large-scale, regional-scale and local-scale atmospheric circulations, since they can assimilate global-scale model analyses and apply nesting techniques. With appropriate synoptic initial conditions and model set-up, they resolve regional and local-scale features even if there are no measured data representing these features. They also offer the possibility to conduct numerical experiments, to study effects of single processes and their possible impact on air quality. Due to their nature, prognostic models work independently of the availability of local meteorological measurements, apart for evaluation of model results. Thus, the need for expensive observation networks and field campaign is avoided or at least reduced. Observed data from the region of interest can be used in the simulation chain, the limitations discussed in Section 3.4.1 need to be considered.

A disadvantage is the need of a larger amount of input data. The models strongly depend on the quality of input data describing surface properties, such as soil moisture, soil temperature, snow cover etc., which are often neither well known nor available at the all scales. As a result, possible problems in the numerical procedures of the model or in its physics can propagate in time, decreasing their reliability after two-three days of simulation. This may affect their applicability in air quality modelling systems. Due to their complexity, prognostic models are computationally highly demanding, so that their use is limited by the availability of proper computational resources. Furthermore, to be properly used they need a deep understanding of the physics and numerics implemented in the code and experience in interpretation of results, which calls for highly specialised staff.

At present, the possibility of merging the best aspects of both diagnostic and prognostic models is being investigated. The output of a coarser resolution, mesoscale prognostic model may be refined by a diagnostic model in order to provide spatially more detailed meteorological fields (downscaling). This is particularly important in complex terrain, where meteorological variables may vary considerably with 1 km, which we may consider as the present resolution limit for mesoscale simulations. The possibility of combining the 3D gridded fields, predicted by a prognostic model, with local available measurements using a diagnostic model may lead to improvements in representing the small-scale features of the flow in complex topography. An example of this approach is illustrated in Chapter 7.

3.3.3 Typical models

In this section, some models are discussed more in detail, on one hand as typical representatives of their kind, and on the other hand because they were used in ALPNAP. Detailed results are presented in Chapter 7.

3.3.3.1 Diagnostic models

CALMET

The CALMET model (Earth Tech Inc., Scire et al. 1999) represents a diagnostic wind field generator, with overland and boundary-layer modules. It has the ability to combine the wind fields generated by prognostic models such as MM5 (Grell et al., 1994) with observational data through an objective analysis procedure.

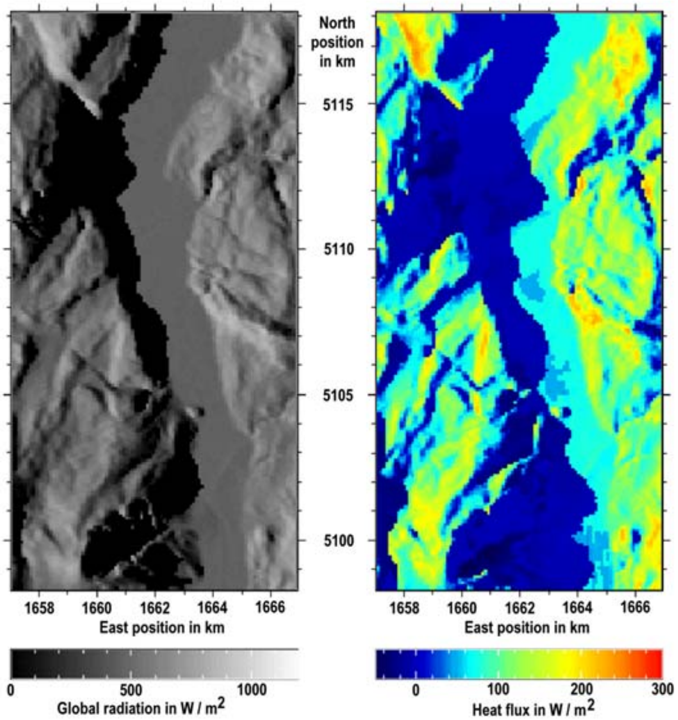

Fig. 3.13 Example of spatial variability in global radiation (left panel) and heat flux (right panel) due to complex topography

Being made for flat terrain applications, some modifications may be desired for diagnostic mass-consistent numerical models, to correct some of the implicit assumptions of uniform terrain. Special attention has to be paid when applying them in mountainous regions. If possible, they should be adapted to account for shadowing effects inducing spatial differences in the heat budget (see example in Fig. 3.13). The variability of resulting pollution concentrations is strongly influenced by spatial variations of the turbulent diffusivity. It needs to be ensured that meteorological fields in the lowest model layers are such that pollutants emitted from sources at the valley floor remain in the lower layers under conditions of stagnation and thermal inversion. In the preprocessing of diagnostic data, the region of influence of meteorological stations, used to interpolate the observed data to the grid, was modified so that it is no more simply circular but can have an irregu-

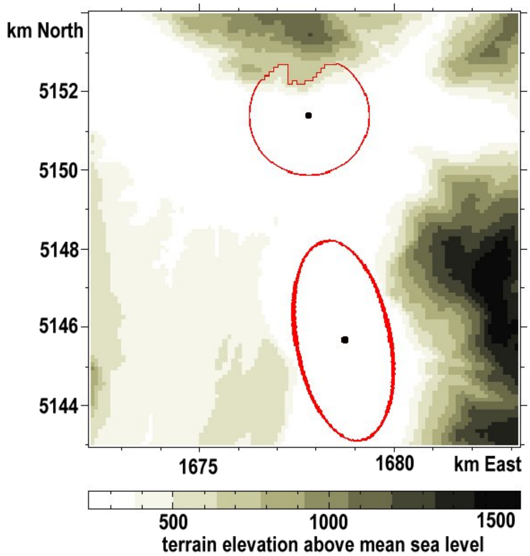

Fig. 3.14 Example of coverage area of meteorological stations in mountainous regions

lar shape depending on orographic structure of the area, thus better representing the flow especially near the valley floor and along the valley slopes (Fig. 3.14). The area of influence was taken to be elliptical, with the major axis oriented according to main flow direction induced by the valley. Moreover, vertical thresholds can be used for the spatial representativeness of the meteorological stations in the vertical. Concerning temperature, the estimates for the lowest model level were found to be quite accurate if an altitude correction was adopted. Otherwise, simple horizontal interpolation between two stations at the same altitude but separated by a mountain will produce non-realistic temperatures on the mountain. Since diagnostic meteorological models strongly rely on surface weather stations, the availability of Sodar wind profiles collected during campaigns would be of great relevance. This is the only choice if neither turbulent fluxes nor measured standard deviations of wind speed and direction are available. It is also possible to compute the turbulence intensity with the help of similarity theory (Stull 1988), which may, however, fail for completely calm (zero wind) conditions. This aspect needs particular attention because calm periods may be associated with very stable as well as convective boundary layers, both frequent in mountainous regions. The CALMET model incorporates an advanced diagnostic wind model, and in addition it produces mixing height fields and other meteorological parameters needed by the puff dispersion models CALPUFF, and CALGRID (see Section 4.4.2.3 and Chapter 7).

MINERVE

MINERVE is a 3D wind-field model for complex terrain. It produces a mass consistent wind-field using measured data from a meteorological network or 3D gridded fields produced by a larger-scale model. It also interpolates temperature and water vapour fields. The MINERVE model is a tool for studying the wind at local (5 – 50 km) and regional (50 – 500 km) scales. The main parameters are the wind (from near ground up to 1000 m AGL), the topography and terrain roughness, the atmospheric turbulence, the temperature and the humidity. The wind fields fulfil the first of the Navier-Stokes equations, namely mass conservation, taking into account terrain effect on the flow structure. The influence of atmospheric stability on flow over mountainous terrain is modelled by using a weighting factor, based on the ratio of the horizontal to the vertical wind component. The reconstruction of a wind field from observations with MINERVE requires topographic data, the location of the measuring sites, and the meteorological data (wind and, if possible, temperature and relative humidity) near ground, and in the upper air as vertical profiles at single points. At least one temperature profile should be available to account for the thermal stratification of the atmosphere. Depending on the number of data available, several interpolation procedures can be used. The main steps of the program are: (1) determination of an initial field by interpolation of available measured data; (2) adjustment to the final non-divergent field, consistent with boundary conditions and atmospheric stability. The results are stored in a file format compatible with several freely available postprocessors.

Using such a mass-consistent model in cascade after a mesoscale prognostic model allows detailing the flow in some areas of interest, like in proximity of urban centres. An example of this downscaling approach is illustrated in Fig. 3.15, showing the wind velocity field derived from a RAMS (see Section 3.3.3.2) prognostic model simulation at 1 km resolution over a subdomain of the Frejus-transect area compared to the field produced by downscaling to 100 m with MINERVE, which provides a more detailed flow. A more extensive discussion of this methodology is presented in Section 7.3.

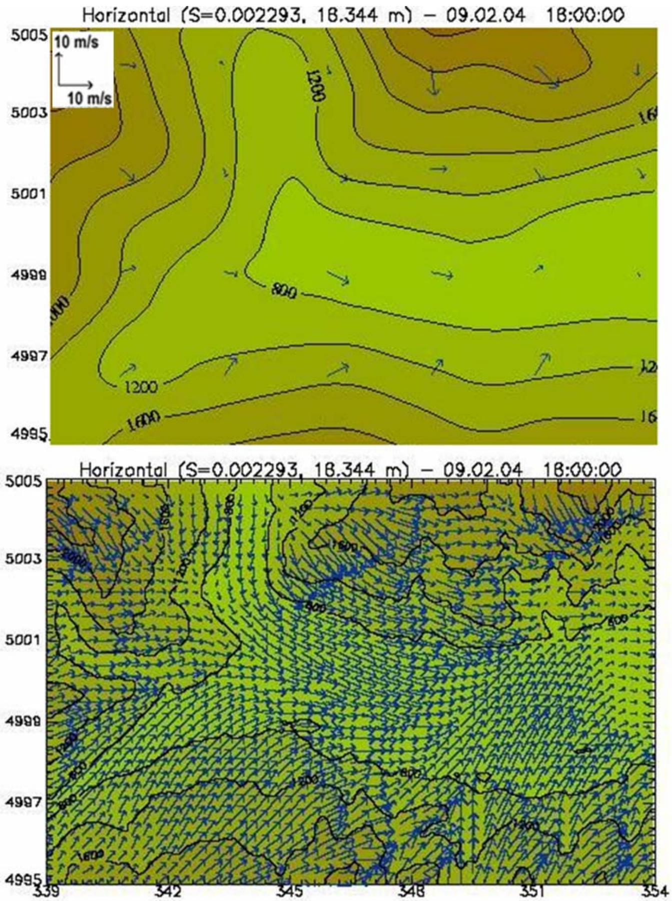

Fig. 3.15 Example of the wind velocity in a sub-domain area (15 × 10 km^2) with RAMS simulations at 1 km horizontal resolution (top) and after the downscaling with MINERVE (bottom) at 100 m resolution.

3.3.3.2 Prognostic models

MM5

The mesoscale model MM5[3] (Grell et al., 1994) is a Eulerian limited-area model with terrain-following sigma coordinates. The MM5 modelling system has been developed at the Pennsylvania State University and the U.S. National Centre for Atmospheric Research (NCAR) as a community mesoscale model with contributions from users worldwide. It is freely available from the NCAR web site. Important features of MM5 modelling system that permit a broad range of applications all over the world are (a) its multiple nesting capability, (b) non-hydrostatic dynamics, (c) its four-dimensional data assimilation capability, (c) a large number of number of physics options, and (d) portability to a wide range of computer platforms, including OpenMP and MPI systems.

In the last years, important improvements to the MM5 model for application in alpine topography were made by Zängl (2002a, 2002b, 2003a). These improvements are:

(1) Slope and shadowing are considered in the calculation of incoming solar radiation.

[3] see http://www.mmm.ucar.edu/mm5

(2) The upper “sponge” upper boundary condition is replaced by a “radiation” boundary condition so that vertically propagating gravity waves, which are often induced by topography, are better handled.

(3) A so-called *z*-diffusion is introduced, where horizontal diffusion is calculated truly horizontally and not on the model surfaces, to avoid spurious vertical transport and smoothing of temperature and moisture.

(4) A new vertical coordinate system is introduced on the base of the so-called SLEVE coordinates where the small-scale topographic effects decay more rapidly towards higher model levels than large-scale terrain features, allowing a more accurate calculation of advection.

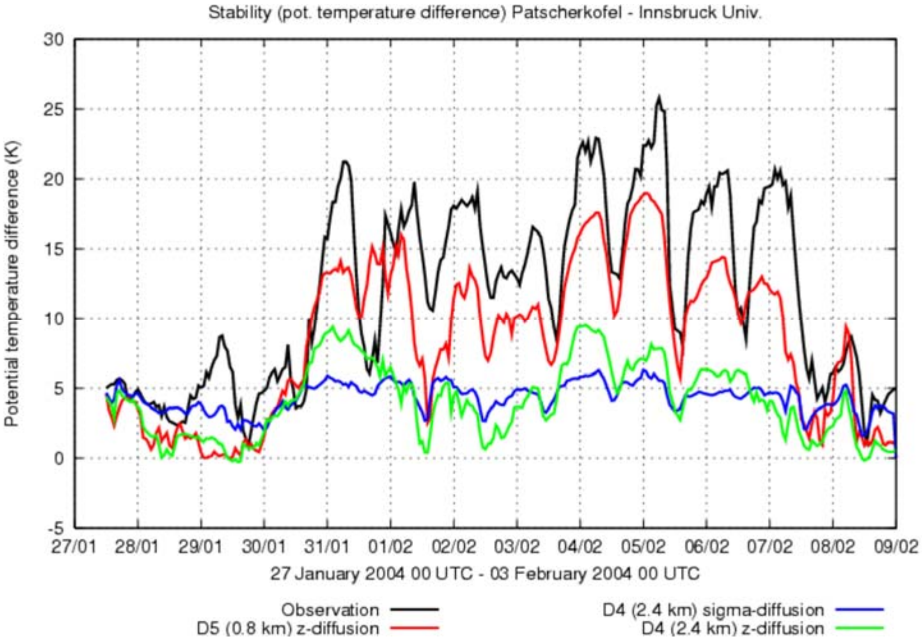

Fig. 3.16 Observed and simulated stability between “Innsbruck-University” (valley) and “Patscherkofel” (mountain), expressed as potential temperature difference during an air pollution episode in Feb 2004. Values exceeding 16 Kelvin correspond to inversion conditions. Simulations were carried out with MM5 V3.7.4 with different model settings (4 or 5 nested domains, with normal sigma diffusion and with *z*-diffusion).

Improvements (1) – (3) have been incorporated into the last version of MM5, V3.7. However, shadowing cannot be used in parallel computations on distributed-memory (MPI) systems. Zängl (2003b) showed that without these improvements the quality of simulations in the Alps with a grid size on the order of 1 km is not acceptable, especially for valley winds, whereas good results are obtained with the improvements, also known as Alpine MM5. In Fig. 3.16 an example of the sensitivity of the simulation to the diffusion parameterisation is reported for a case of stagnant conditions with strong stability and high pollution. The resolution used, 2.4 km, was not sufficient and an underestimation of stability resulted with two different diffusion schemes.

It is thus recommendable that prognostic numerical models for simulations in the interior of Alpine valleys include these kinds of improvements and to further investigate which horizontal resolution is sufficient to give realistic results, considering that at present 1 km is suggested as the upper limit in larger valleys.

An application of a version of MM5 without Zängl’s modifications to the Alpine region and a comparison of the model results with observations and with a simulation with another model (TVM) is described in Dosio et al. (2001).

RAMS

RAMS (Regional Atmospheric Modeling System: Pielke et al., 1992; Cotton et al., 2003) is a prognostic non-hydrostatic model that was originally developed from a mesoscale model and a cloud model at the Colorado State University. It is a highly versatile numerical code developed by several scientists in the 1980's. In the beginning of the 1990s, several modifications were introduced for physical processes, with new and very complex numerical schemes, and the computational part is now implemented for parallel computers. Today, the RAMS model represents one of the most developed computational systems in atmospheric numerical modelling and it is continuously improved through multidisciplinary work carried at research institutions all over the world. RAMS is designed to simulate a large range of atmospheric flows in a wide spectrum of scales, from local and regional to synoptic. It is basically a limited-area model, but may be configured, on one hand to cover an area as large as a hemisphere and, on the other hand, to simulate microscale phenomena because it has no lower limits in the domain size or to the model grid cell size. The model includes a large number of options for the simulation of physical processes in the atmosphere that can be selected by the user. The main features are hydrostatic and non-hydrostatic mode, two-way interactive grid nesting, terrain-following coordinates, and stretched vertical coordinates, nudging system, different options for numerical schemes, several upper and lateral boundary conditions and a set of parameterisations for physical processes. In particular, the two-way nesting provides a “zoom” from a large-scale area to smaller scale domains, and the non-hydrostatic option allows to represent all meteorologically relevant spatial scales. In the latest version RAMS6.0, a Cartesian grid is implemented and the so-called adaptive aperture method (Walko and Tremback, 2002) is used for defining the influence of buildings and dealing with arbitrarily steep topography, enabling simulation at high resolution. RAMS includes also a model for soil and vegetation temperature and moisture. Its major components are the atmospheric model, performing the actual simulations, a data analysis package, preparing the initial data for the model from larger-scale meteorological data, a post-processing model visualisation and analysis package.

To improve the performance of RAMS as meteorological driver for dispersion models at high resolution, studies on turbulence closures were performed in recent years (Trini Castelli et al., 1999 and 2001, Ferrero et al., 2001 and 2003, Trini Castelli et al. 2005 and 2006, Alessandrini et al., 2005, Reisin et al, 2007), and new turbulence closure schemes were implemented that are available in latest version RAMS6.0. The sensitivity to the turbulence schemes and to the successive turbulence parameterisations in dispersion model was analysed. Their effect on dispersion was investigated and some indications on proper choices can be taken from the literature cited above. Simulations in complex terrain were performed up to horizontal resolutions of some hundreds metres (like 250 m).

RAMS

RAMS can be used as the meteorological driver in air quality modelling systems like HYPACT (Hybrid Particle and Concentration Transport Model, Uliasz, 1993; Walko et al., 2001) and in the RMS system (Trini Castelli, 2000, Carvalho et al., 2002, Trini Castelli et al., 2003). The RMS modelling system is based on an off-line interface between RAMS and the stochastic Lagrangian particle model SPRAY (Tinarelli et al., 1994a and 1994b, Tinarelli et al., 2000), described in Section 4.4.2.3, through the parameterisation code MIRS (Method for Interfacing RAMS and SPRAY, Trini Castelli and Anfossi, 1997; Trini Castelli, 2000). MIRS is a module that refines the meteorological fields and calculates the boundary-layer and turbulence variables which are not directly provided by the meteorological model but needed by Lagrangian dispersion models. More details are given in Section 7.3.3.

GRAMM

GRAMM is the meteorological driver for the GRAL model system which was developed specifically for environmental assessment studies on the local scale in complex terrain. The model system uses special algorithms to account for low wind or calm conditions (Öttl et al., 2001; Öttl et al., 2005). Main features of GRAMM are the prognostic calculation of non-hydrostatic wind fields, on a tetrahedronal, terrain-following grid (Almbauer, 1995), implicit time integration, constant surface cooling in stable conditions, and spatially variable surface heat flux in convective conditions (accounting for shadowing effects of the topography). In contrast to diagnostic wind field models, dynamic effects due to the influence of obstacles on the flow can be well represented with a prognostic wind field modelling approach. Due to the numerical grid used, grid resolutions down to the decametre range can be used.

The initialisation of the flow computations is based on binned meteorological situations derived from local wind observations and stability classes. The latter are either derived from radiation balance measurements, temperature profiles or a combination of cloud cover, wind speed, season and time of the day. Based on wind field simulations for the complex nocturnal wind field of the city of Graz, Austria, during the DATE campaign (Almbauer et al., 2000) a simple, applicable method to compute wind fields in complex terrain with high horizontal resolution was developed (Öttl et al., 2000; Öttl et al., 2007).

In practice, a statistical classification of flow situations into J wind sectors, K wind speed categories and L (usually three) stability classes from a single point observation in the domain is carried out for each 30 minutes during one year. Then $J \times K \times L = N$ steady state simulations are run with the wind field model GRAMM. Thereafter, the same number of dispersion simulations is performed with GRAL.

3.4 Evaluation methods

3.4.1 Classifications and statistics

To present the results of the simulations of the atmospheric processes and meteorology, a comparison between the model predictions and observations is fundamental. For a proper understanding of this kind of comparison, it is worth recalling some general considerations. First of all, model outputs are volume averages defined by the horizontal and vertical grid resolutions Δx, Δy, Δz and refer to mean quantities, while the corresponding observations are often instantaneous and single-point values that may significantly differ from the averages; furthermore, the sites are generally non-uniform at the grid scale and the orography used in the simulations is generally smoother than the real orography. This may lead to significantly different heights of the measuring point and the simulation grid cell. It implies also that, because of the smoothed nature of simulation results, the finer structure in the observed profiles cannot be reproduced. On the other hand, observed meteorological variables are affected by stochastic uncertainty. According to many authors and to our experience, too, a variability of the hourly averaged wind speed on the order of 1 to 2 m/s over distances of a few kilometres can be observed even on flat homogeneous terrain due to mesoscale turbulence fluctuations. Instrumentation and averaging errors, unavoidable in any measurement, can affect comparisons.

For all these reasons, a point-to-point agreement between observed and predicted data cannot be expected and a good result is obtained when the main features of the measurements are reproduced by the simulation.

So far, model evaluations typically compare point measurements, from surface stations or vertical profiles, with volume-averaged model output. Comparisons are performed for the spatial distribution as well as for the temporal development. In general, the metrics to evaluate the model performances are based on statistical parameters such as correlation coefficient, mean bias, root-mean-square and normalised-mean-squared error, mean absolute error, fractional bias, and index of agreement. Classifications and related graphical representations, like frequency distributions, wind roses, stability classes, histograms, maps etc., support the model validation. To examine the effectiveness of meteorological simulations from the air-quality application standpoint, more specific approaches are needed to check those variables and parameterisation that may affect directly the air pollution simulation (Wilks, 1995; Gilliam et al., 2006). See also Section 4.5.

3.4.2 Indices and derived quantities

3.4.2.1 Potential temperature and vertical stability

As already explained, the vertical stability of the air is of extraordinary importance for the behaviour of the atmosphere and the dispersion of pollutants. A stratification is called stable if an air parcel that is moved up or down from its present position (e.g. by turbulence) experiences a buoyancy force driving it back towards its level of origin. In an unstable stratification, the sign of the buoyancy is opposite, e.g., an air parcel moved upward will become even more buoyant in its new environment and thus continue to rise (until it hits a stable layer). This stability, also called static stability, is determined mainly by the ambient temperature profile and to a relatively minor extent by the moisture profile. This is true outside of clouds, in clouds the processes are complicated by latent heat. The following rules hold (neglecting the moisture influence and with rounded values):

$$\frac{dT}{dz} < -1 \text{ K / 100 m or } \frac{d\theta}{dz} < 0 \qquad \text{unstable stratification;}$$

$$\frac{dT}{dz} = -1 \text{ K / 100 m or } \frac{d\theta}{dz} = 0 \qquad \text{neutral stratification;}$$

$$\frac{dT}{dz} > -1 \text{ K / 100 m or } \frac{d\theta}{dz} > 0 \qquad \text{stable stratification;}$$

$$\frac{dT}{dz} > 0 \text{ K or } \frac{d\theta}{dz} > 1 \text{ K / 100 m} \qquad \text{inversion.}$$

The numbers are thus because the dry adiabatic lapse rate, that is the temperature change in an air parcel moving vertically due to the compression or expansion as a function of ambient pressure, is –0.98 °C / 100 m as long as the movement is adiabatic, i.e., no warming or cooling by phase changes of the water content, radiation, etc. is taking place. Given two temperatures at different levels, e.g. from measurements, and the station heights, a small calculation is needed to find out whether the stratification is stable or not. To simplify stability investigations (and also for some different purposes), meteorologists have introduced the so-called “potential temperature” which is the temperature an air parcel would have if taken adiabatically to a reference pressure of 1000 hPa. This temperature is calculated as

$$\theta = T(1000\,\text{hPa} / p)^{R/cp}$$

where T is the absolute temperature in K (Celsius temperature + 273.15 K), p is the pressure in hPa, and the constant R/c_p has the value 0.286, or approximately as

$$\theta \approx T + z/100$$

where T is the temperature either in K or °C, and z is the measurement height above sea level in m.

Whenever stability is the most relevant feature for which temperature data are shown, it is therefore highly recommendable to convert them to potential temperature. Under conditions normally found in the Alps, the moisture influence can be neglected, but if one has moisture measurements available, it would be correct to replace the potential temperature by the virtual potential temperature. Because moisture units are tricky, we refer to meteorological text books for details. Again, this is only valid if the layer under consideration is not filled by clouds.

In a well-mixed atmospheric layer, again in the absence of the mentioned diabatic processes (no clouds), the potential temperature is vertically constant because it is conserved during movements to other pressure levels. Thus the potential temperature is called a conservative quantity. Also for moisture, there is a measure which is a conservative quantity, the water vapour mixing ratio. Not only water but also the amount of air pollutants can be expressed as mixing ratio, which is useful to compare values at different heights, an important aspect in mountain areas.

Inside of clouds, the so-called equivalent-potential temperature has to be used instead of potential temperature (refer to meteorological text books for details).

3.4.2.2 Sound refraction parameter

For the investigation of sound propagation, the vertical gradient of the sound speed, i.e. the phase velocity of sound waves, is an important parameter because it controls refraction and thus is decisive for whether horizontally propagating noise is strongly attenuated (upward refraction) or audible over a long range (downward refraction); see also Section 5.2. The sound speed c is mainly a function of the air temperature.

$$c \approx \sqrt{\kappa R T} \qquad \text{with } \kappa R = 403\,\text{m}^2\,\text{s}^{-1}\,\text{K}^{-1} \text{ and } T \text{ the temperature (in Kelvin)}$$

The sound speed decreases with height (upward refraction) if also the temperature decreases with height. Vice versa, it increases with height (downward refraction) in inversion layers. In contrast to air pollution problems, the use of the potential temperature is *not* convenient in assessing the atmospheric conditions for the propagation of noise.

3.4.2.3 Stagnation, recirculation and ventilation index

The term stagnation refers to low-wind speed conditions leading to accumulation of air pollutants. Recirculation can happen as a result of the diurnal oscillation of the wind in a valley, or occasionally through the interaction of a thermal valley wind and the synoptic wind. In this case, an air mass found at a certain time at a given section of the valley returns to this location after some time. If it remains inside the valley for the whole period, this also leads to accumulation of pollutants.

Allwine and Whiteman (1994) have introduced a method to quantify stagnation and recirculation using time series of the wind vector at single stations, by calculating (pseudo-)trajectories (paths of an air parcel transported with the wind) with the underlying assumption of horizontal homogeneity of the wind field. Though this assumption is a reasonable one along a valley, the method does not strictly depend on it. The preferred integration time T for the trajectories is 24 hours, corresponding to the period of the thermal valley wind circulation. They also introduced the notion of ventilation, defined through the exceedance of a given threshold for the wind run. While the notion of trajectories is most accessible for imagination, we can substitute it using the concepts of scalar and vector mean of the wind velocity in order to define easily the necessary quantities.

An example of this concept was applied for the Lower Inn Valley in ALPNAP, using Sodar data in addition to surface measurements. Stagnation was diagnosed with the length of the 24-hour wind path. A comparison between length of the added hourly wind paths, corresponding to the mean scalar velocity, and the distance between the station and the end of the 24-hour trajectory, corresponding to vector mean velocity, indicated that only the vector mean can correctly categorise the frequency of stagnant conditions, because of the tendency towards recirculation. Looking at scalar means, one would erroneously believe that stagnation is almost absent above the surface layer. Depending on the threshold applied, these conditions were, however, found in 30 % to 50 % of the days. If wind observations at 5 m are used instead of Sodar data, these resulting frequencies are 20 % higher.

3.4.3 Types of graphical representations

Typical representations used to analyse the meteorological fields are time series plots and vertical profiles at different times, possibly at different locations, time-height cross-sections, maps and contours of variables.

For vertical profiles, in meteorology, it is customary to use the height, above sea level or above ground, as the vertical axis in plots, even if it is the independent variable, because this is more intuitive. Meteorologists also use other vertical variables, such as pressure or a function of pressure, as the vertical axis in a coordinate system.

Cross-sections and time-height sections of temperature are usually intended to show the development of stability and the presence of warm or cold air masses. For both purposes, the potential temperature is the parameter to be shown. Where lines of constant potential temperature (called isentropes, because they also represent constant entropy) are horizontal and dense, there is a very stable layer, probably an inversion. If they are vertical, the stratification is neutral and there is a horizontal temperature gradient. Bundles of lines indicate air mass borders. If lines are inclined so that warmer values are below, this indicates an unstable stratification.

Meteorological model results are usually presented as contours on the surface and upper-air weather maps, or as flow vectors. Furthermore, so-called “meteograms” can display e.g. wind flags at each vertical level and for each time step (e.g. Fig. 3.17), or any other variable. Vertical profiles are helpful to depict the vertical variation of scalar quantities (temperature, relative humidity, dew point, etc.) over a single grid point. Models output can also be presented with the help of a 3D visualization tool as depicted in Fig. 3.18. Such 3D pictures are usually reserved for the presentation of selected features hard to visualise in a simpler way.

Wind roses are typically used to represent the frequency of wind direction at a single location over an extended period of time (months to years). They are also sometimes used to show computed wind speed and direction (or stability class) from gridded model output for selected locations (Fig. 3.19).

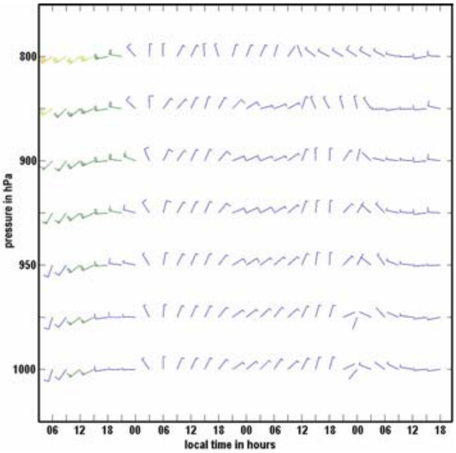

Fig. 3.17 Example of a meteogram with wind vectors at different heights as a function of time.

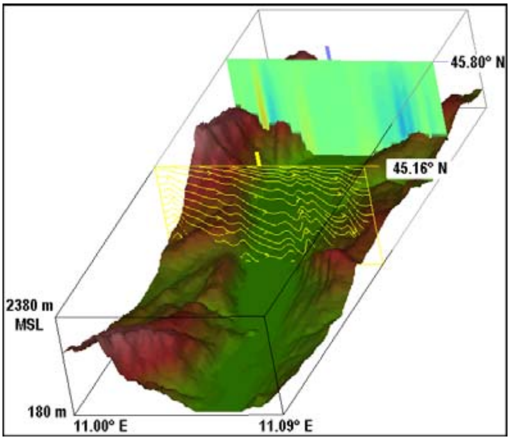

Fig. 3.18 Example of a 3D-representation of the simulated wind speed.

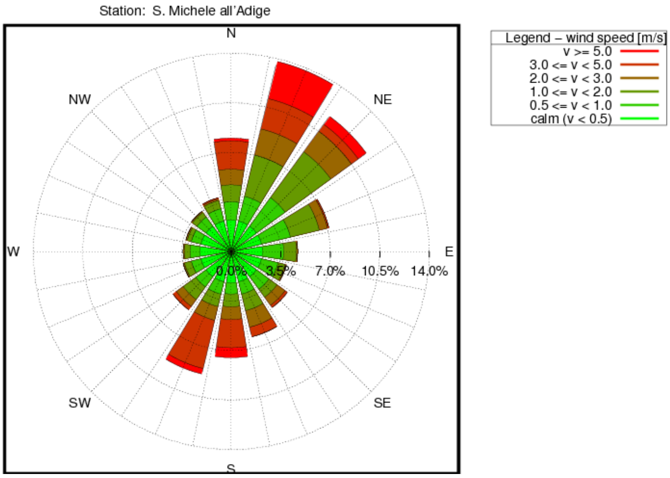

Fig. 3.19 Example of a wind rose (frequencies of directional sectors as function of the wind speed).

4 Air pollution

4.1 Parameters, units, and limits

Clean air is a valuable asset for a sound environment and public health as well as for tourism and recreation. Any additional gases and particles in the air which could cause adverse health effects or damage the environment are regarded as air pollutants. These pollutants mainly come from man-made (anthropogenic) and natural (biogenic and geophysical) near-ground emission or they are formed out of air components (precursors). The first group is called primary pollutants, the latter secondary pollutants. Most of the secondary pollutants are the product of chemical reactions, for example ozone, or ammonium nitrate and sulphate. Nucleation and physical aggregation of small particles are also relevant. The chemical reaction rates strongly depend on the air temperature, the incoming short-wave radiation (photolysis of precursors) and, of course, the concentrations of the precursors. Aggregation processes depend strongly on air temperature and moisture. Some of the pollutants can be odours, other can be toxic. The suspension of particulate matter (PM) in air is usually called aerosol and particles are referred to as aerosol particles.

Here we are not going to take into consideration greenhouse gases which do not take part in the atmospheric chemistry in near-surface air. This shall not imply that the emission of these gases (mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) is not harmful to the environment and human beings. The measurement and regulation of greenhouse gases has been beyond the scope of the ALPNAP project. Furthermore, this section will concentrate on outdoor air pollution only.

Typical examples of primary emitted gaseous pollutants are nitric oxide (NO), carbon monoxide (CO), sulphur dioxide (SO_2), ammonia (NH_3) and many volatile organic compounds (VOCs) like hydrocarbons (HC, e.g. fuel vapour and solvents). NO and VOCs are also emitted from biogenic sources as e.g. from plants and soils. Main secondary gaseous pollutants are ozone (O_3), and peroxyacetyl nitrate (PAN). Nitrogen dioxide (NO_2) is a primary as well as a secondary pollutant. Ozone and PAN, formed from NO_x and VOCs, are the main compounds of photochemical smog.

Apart from the gaseous compounds also particulate matter plays a significant role in air quality. Primary emitted particulate matter of anthropogenic origin comprises among others soot, abrasion from tyres and resuspended particles. Those of natural origin include sea salt, mineral dust, and volcanic ashes. Among the secondarily formed particles the main inorganic compounds are ammonium nitrate (NH_4NO_3) and ammonium sulphate ($[NH_4]_2[SO_2]$) produced from the precursors NH_3, NO_x, and SO_2. Secondary organic aerosols (SOA) can form out of organic gases like isoprene. They are often found on hot summer days above forests (so-called “blue haze”). Man-made sources for primary emitted pollutants are mainly fossil-fuel burning (residential heating, traffic, power stations), waste incineration, land-fills, many industrial processes, and fertiliser application. Natural emission sources include volcanoes, oceans, lightning, and forest fires.

Particulate matter is usually classified by its size into so-called modes. The particles can have sizes from a few nanometres (nano-particles, nucleation mode) to a few micrometres (fine particles, accumulation mode) up to several tens of micrometres (visible dust, coarse mode). For health aspects the classification into classes with a fixed upper bound for the size is very common, because this determines how deep these particles are inhaled into the human lung by breathing. PM10 comprises all particulate matter with a diameter of less than or equal to 10 μm, PM1 all particulate matter with a diameter of less than or equal to 1 µm. Principally, PM1 is more dangerous to human health because it penetrates deeper into the lungs than PM10. A complete characterrisation of particulate pollution also requires a chemical analysis of the particulate matter.

Particle concentrations in the ambient air can be expressed as number concentrations (number of particles unit volume of air; unit: m^{-3}) or as mass concentrations (particle mass per unit volume of air; unit: $\mu g\ m^{-3}$). Both quantities disregard the size of the single particles. Therefore a conversion from number concentrations to mass concentrations and vice versa is only possible if the size spectrum of the particulate matter is known. In terms of number concentration, atmospheric aerosol is dominated by the small particles, whereas in terms of mass concentration, the large particles are most relevant. The accumulation mode has the largest particle surface per volume and thus is most relevant for chemical reactions.

The amount of gases in an atmospheric volume can be either described by a mass concentrations (unit: $ng\ m^{-3}$, $\mu g\ m^{-3}$, etc.) or by a number or volume mixing ratio (unit: ppb or ppbV (parts per billion = molecules per 10^9 air molecules), ppm or ppmV (parts per million), etc.). Conversion between the two units is easily possible if the molecular weight of the gas in question and the pressure of the ambient air are known. Mixing ratios are suitable for the identification of air masses independent of vertical motions in the atmosphere since these concentrations do not depend on atmospheric pressure. Number and mass concentrations change if an air volume is displaced vertically. An approach frequently adopted is to express concentrations not as mass or number per volume of ambient air, but to refer for these concentrations to standard values for pres-

Tab. 4.1 Limit and target values prescribed by the European Union for the protection of human health. Based on EU guidelines 1999/30/EC (SO_2, NO_2, PM10, Pb), 2000/69/EC (benzene, CO), and 2002/3/EC (ozone).

species	limit value	allowed exceedances per year	temporal average
SO_2	350 $\mu g\ m^{-3}$	24	hourly mean
	125 $\mu g\ m^{-3}$	3	daily mean
	20 $\mu g\ m^{-3}$		annual mean/ hibernal mean
benzene	5 $\mu g\ m^{-3}$ (from 01 Jan 2010)		annual mean
CO	10 $mg\ m^{-3}$		8-h mean
NO_2	200 $\mu g\ m^{-3}$ (until 31 Dec 2009)		98 percentile of hourly means during a year
	200 $\mu g\ m^{-3}$ (from 01 Jan 2010)	18	hourly mean
	40 $\mu g\ m^{-3}$ (from 01 Jan 2010)		annual mean
PM10	50 $\mu g\ m^{-3}$ (until 31 Dec 2009)	35	daily mean
	50 $\mu g\ m^{-3}$ (from 01 Jan 2010)	7	daily mean
	40 $\mu g\ m^{-3}$ (until 31 Dec 2009)		annual mean
	20 $\mu g\ m^{-3}$ (from 01 Jan 2010)		annual mean
lead (Pb)	0.5 $\mu g/m^{-3}$		yearly mean
species	**target value**		**temporal average**
ozone (O_3)	120 $\mu g\ m^{-3}$	25 (for 2010) none (long-term)	8-h mean

sure and temperature (namely 20°C and 1013 hPa). Therefore these measures are independent from the actual environmental conditions.

Because of the harmfulness of many pollutants limit values have been introduced by the national governments and the European Union. The limit values required in the European Union by the various Daughter Directives of the European Air Quality Directive 96/62/EC are listed in Tab. 4.1. National regulations may set additional limits and target values, e.g. for the protection of ecosystems. The difficulties to comply with these limit values was one major motivation for the execution of the ALPNAP project and for this publication. The execution of the European Air Quality Framework Directive and its daughter directives must be reported to the EU by each country by producing 1-year average air pollution maps with a spatial resolution of up to 200 m^2 (for so called "micro-environments" as e.g. living areas near industrial zones or main traffic roads).

4.2 Mountain-specific aspects of air pollution

The treatment of air pollution in mountainous terrain is much more difficult than in flat homogeneous terrain. The orographic features of mountainous terrain influence the spatial distribution of emissions and relevant receptors as well as the transport and diffusion, the chemical reactions, and the deposition of the pollutants.

4.2.1 Temporal and spatial distribution of emission sources and receptors

Anthropogenic sources of primary pollutants in the Alpine region are mostly concentrated on the valley floors while biogenic sources (e.g. forests as a source of VOCs) are mainly found on the slopes. Especially traffic routes (motorways and railway tracks), nearly all residential areas, and the industry are concentrated on the valley floors. The problem of the concentration of the emission sources within a small part of the available space is aggravated by the specific meteorological conditions in valleys (see Section 3.1). These conditions cause situations with low dispersion and strong accumulation of pollutants. E.g., at night-time, cold air originating from local radiative cooling and cold air outflow from tributaries, very often covers the valley floor. This leads to a strong reduction of the vertical diffusion of freshly emitted pollutants, especially those emitted in the evening and during the night. If the ground is a snow covered, the air can remain stably stratified throughout the whole day and even for several consecutive days. During the day the lower layers usually become well-mixed but often a persisting inversion in the valley prevents complete vertical mixing.

As already mentioned above most residential areas in the Alpine region are on the valley floors and therefore most of the people live relatively close to main streets, highways and industrial sources. The degree to which people are affected by these near-by emission sources also depends on whether they live up-valley or down-valley of the main emission sources. Usually, under conditions with weak large-scale pressure gradients, up-valley winds prevail during daytime and down-valley winds at night-time. The vertical dilution of emitted pollutants in the well-mixed up-valley wind regime during daytime is much larger than in the stably stratified nocturnal down-valley wind regime. Therefore people living and working down-valley of a strong emission source are much more affected than those living up-valley.

People living or working on the valley slopes are mostly affected by emissions from the valley floor during daytime when upslope winds prevail. At night-time they usually enjoy the benefits of clear air masses flowing down-slope. People living or working on plateaus usually have a good air quality as long as they are above the inversion limiting the valley boundary layer.

4.2.2 Pollutant transport and dispersion

Transport and dispersion of atmospheric pollutants in the Alpine region is severely limited by the orography, because the space available for dispersion is limited by the mountains. Also the atmospheric flow and weather features are dominated by the orography. They can be considerably different from the features found above flat terrain (see also Section 3.1).

Under conditions with weak large-scale pressure gradients, dispersion is mainly possible along the valley axis due to the prevalence of the autochthonous up- and down-valley wind system. If stronger large-scale pressure gradients lead to stronger large-scale winds it depends on the wind direction and the stability of the air in the valley whether these winds penetrate into the valleys and remove the accumulated pollutants. Winds along the valley axis will override the diurnal up- and down-valley wind system and will transport air from or to the forelands. Hence, the polluted air in the valley atmosphere can be substituted by fresh unpolluted air. Winds across the valley axis will in many cases only enter the valley and bring fresh air masses down to the valley floor if the thermal stratification of the air within the valley is not too stable. Stable stratification is most likely in clear nights and over a snow cover. In cold winters this can lead to a system of several inversions, one above the next, within a few hundreds metres of height

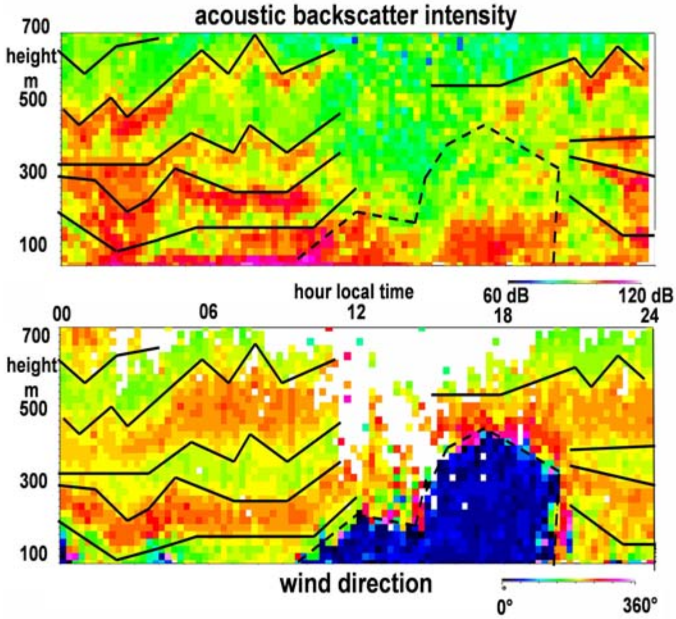

Fig. 4.1 Occurrence of multiple inversions in the Inn valley near Schwaz (SW-NE orientated) from acoustic remote sensing with a Sodar (see Section 3.3.1) on 29 Jan 2006. Cross-sections for one day (horizontal axis) and the first 700 m above ground (vertical axis) are given. Top: acoustic backscatter intensity in dB (red: high, green: low). Inversions are marked by elevated backscatter maxima. Below: horizontal wind direction in degrees (yellow/green: southerly winds, red: southwesterly winds, blue: northeasterly winds).

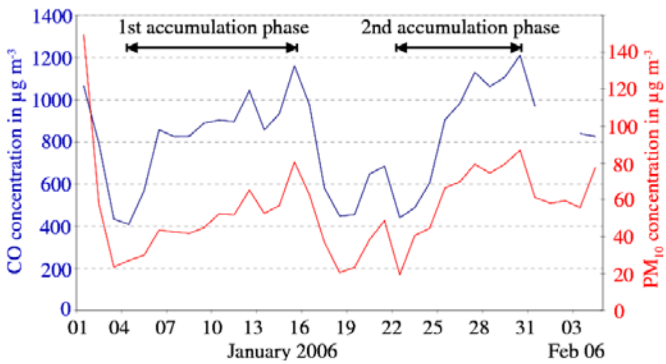

Fig. 4.2 CO (blue curve, left scale) and PM10 (red curve, right scale) concentrations (daily means) in µg/m^3 over 35 days (01 Jan 2006 to 04 Feb 2006) in the Lower Inn valley near Schwaz.

(Fig. 4.1). Channelling of the air flow in valleys and recirculation behind mountains or ridges can lead to strong and persistent horizontal gradients in the wind field.

The diurnally changing up- and down-valley wind systems can sometimes completely prevent the advection of fresh air masses in longer valleys. If this wind system is rather weak – as it often is in winter – or if the valley is long enough, the air within the valley is moved down-valley at night and again up-valley during the next day. Under such weather conditions air pollutants can accumulate in the valley air. Fig. 4.2 shows an example. Two high pressure situations with weak winds (one over 11 days in the first half of the period shown and one over eight days in the second half of the period) both times led to increases in the mean CO concentration from 400 to 1200 µg/m^3 (factor 3) and in the mean PM10 concentration from 20 to 70 µg/m^3 (factor 3.5). For PM10 the period plotted in Fig. 4.2 shows 21 exceedances of the limit value of 50 µg/m^3 (Tab. 4.1), this is more than half the number of presently permitted exceedances per year, and it is three times the number of exceedances per year permitted from 2010 on.

Nocturnal slope winds transport near-surface air masses downward to the valley floor. If there are pollution sources in the nocturnal slope wind layer (e.g. outlets from road tunnels) their emissions will inevitably be transported downward to the valley floor or at least kept in stably stratified air layers in the valley centre. Fortunately, slope wind layers are not very thick (usually they are thinner than 50 m) so that it would be possible to find technical solutions to release the pollutants above of the slope wind layer.

4.2.3 Chemical reactions and aerosol formation

The assessment of chemical and physical formation processes of secondary pollutants in valleys is complicated by the existence of large spatial gradients in the concentrations of the precursors and in the environmental conditions. In places where e.g. two down-valley flows merge or an outflow from a tributary valley enters the main valley, strong horizontal concentration gradients can persist for hours. Likewise, strong temperature and moisture gradients can exist in the valley air for many hours. Also the incoming short-wave radiation, which is important for photochemical processes, exhibits strong horizontal and vertical gradients e.g. due to shadowing by the surrounding mountains and – quite frequently – due to persistent clouds (or fog) in confined areas. All this leads to a low spatial representativeness of local pollution measurements. Simultaneously a high spatial resolution for any numerical modelling effort is required (see Section 4.4).

4.2.4 Routine air pollution data

Air quality networks have primarily been designed to monitor the regulated air pollutants listed in Tab. 4.1 providing hourly or half-hourly mean concentrations. Often monitoring stations are located inside or very close to urban areas. Following EU and national regulations they are classified as traffic, urban, urban background, and rural stations. This has to be taken with some care. Stations very close to major roads are strongly influenced by the emissions of passing traffic. Stations in a distance of a few hundred metres are found in a region with strong change of concentration with distance from the motorway. Urban stations are usually found in larger towns, where local emissions may be important. Roads along slopes or on viaducts are an Alpine-specific problem. A station sufficiently below such a road may never experience really high concentrations as under stable atmospheric conditions because it may be shielded from the source. On the other hand, a station above will receive the pollution only during upwind conditions which are connected to strong dispersion, so that even if close to the road it may not be able to sense the traffic emissions well.

4 Air pollution

The number of monitoring stations along the main Alpine transit corridors is quite variable from region to region. In addition to permanent monitoring, measurement campaigns of limited duration (e.g. a few weeks in different seasons) have been realised, and, sometimes, repeated after longer periods as a compromise between costs for stations and desired spatial density.

Some pollutants, i.e. PM10, have been introduced as mandatory species for monitoring only quite recently and therefore only very few long-term time series and respective analyses are available. In addition to networks run to assess the burden to people, there are also networks for background air pollution. While networks are often operated by regional authorities, background stations are usually operated by national authorities. Such stations are partly located on high mountains.

In Tyrol (Austria) exists a dense air quality measurement network[1]. However, there is generally a lack of "background stations". In particular in the Inn Valley, most stations are on the valley floor and are therefore within 1 km distance to major sources like motorways or urban settlements. Unfortunately, PM10 is not measured at background stations like mountain tops. Additional air quality stations have been run by the BEG (Brenner Eisenbahn Gesellschaft - Brenner Rail Company) in the last couple of years.

In Bavaria (Germany) the state air quality network has no stations along the transalpine traffic corridor in the Inn valley south of Rosenheim. Valley stations only exist in Garmisch-Partenkirchen and Bad Reichenhall[2].

In Italy on the Southern Route of the Brenner corridor the air quality monitoring network usually covers urban areas and is therefore not best suited for directly monitoring the influence of the motorway on air quality. Nevertheless, in the last few years two PM10 monitoring stations have been positioned close to the motorway: one can be found a few kilometers south of Bressanone/Brixen, routinely operated since 2005, and the other close to Egna/Neumarkt starting from the end of 2006[3].

In France, some specificity must be noticed in the Maurienne valley. Due to future infrastructure projects, likely economic and demographic evolutions, and tourist stakes, measurement stations have been installed for monitoring air quality. The first one, running since 1997, is located in St Jean de Maurienne in an urban environment. It is a permanent station. The second one is devoted to traffic pollution and is situated close to the A43. It was set up in St Jean Montdenis in 2000 in order to monitor the consequences of the traffic increase once the Mont Blanc tunnel was reopened. These stations are part of a wide network of stations distributed on the French territory and they are managed by Air-APS, the association in charge of air pollution monitoring in the Savoie department. According to the French law, all the data produced by this association are made public and can be downloaded from their website. One objective reached by the project was to carry out a long term monitoring (May 2000 to Dec 2005), that represents a major source of recent data all along the Maurienne and Chamonix valleys. Upon the measurement campaign eight sites were instrumented with permanent or mobile stations[4].

[1] see for example http://www.tirol.gv.at/themen/umwelt/luft/messnetz
[2] see for exaample http://inters.bayern.de/luebmw/html/tagesbericht.php
[3] see http://www.provincia.bz.it/umweltagentur/ and http://www.appa-agf.net
[4] see also http://www.atmo-rhonealpes.org/site

4.3 Observation methods

This subsection presents available standard and innovative observation methods for air quality.

4.3.1 Instruments and methodologies

Air pollution measurements can be made by in-situ instruments and by remote sensing instruments. In-situ instruments can be placed on different measurement platforms, e.g. on the ground (including lines of measurement sites along the slope of valleys), on masts, on tethered balloons, or on aircrafts. In-situ instruments are in direct contact with the air volume whose pollutant concentrations are to be determined and yield a value representative for the point of measurement. Remote sensing instruments can also be deployed to the abovementioned measurement platforms. An active remote-sensing instrument emits a well-defined electro-magnetic or acoustic signal of a chosen wavelength and measures the backscattered signal from the atmosphere. Passive remote sensing instruments register radiation from the atmosphere without emitting own signals. Most present-day remote sensing instruments are active instruments. The parts of the electro-magnetic and acoustic spectrum which are used for remote sensing of the atmosphere are shown in Fig. 4.3.

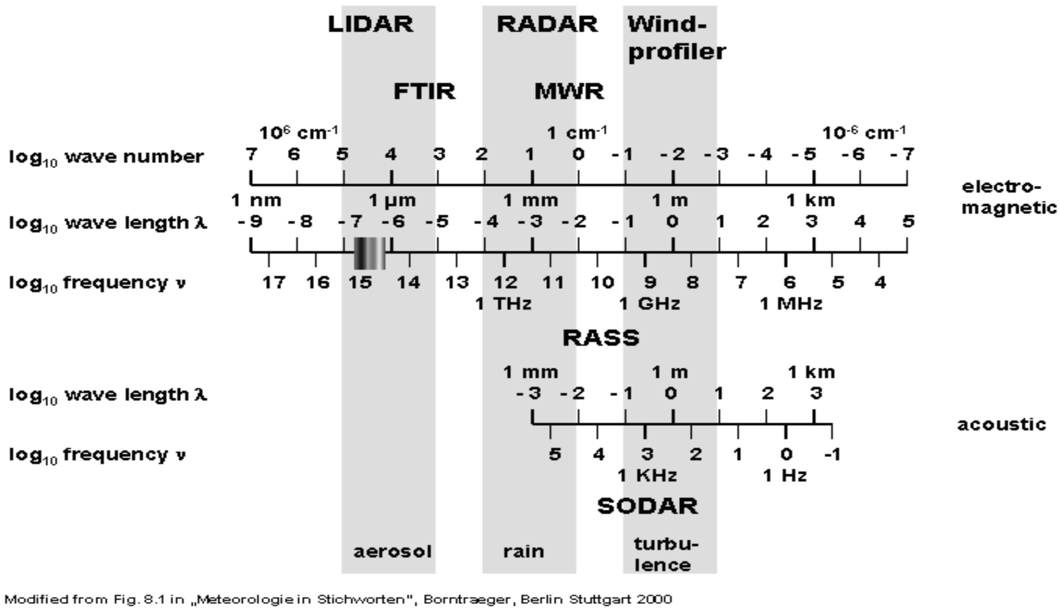

Fig. 4.3 Wavelengths for remote sensing of the atmosphere. The upper bars in the Figure refer to electro-magnetic and optical remote sensing, the lower bar to acoustic remote sensing. The vertical grey bars indicate the three parts of the spectrum which are most favourable for remote sensing of the atmosphere. Air pollution information is mainly yielded from optical instruments (left bar). Adapted from Emeis (2000).

The detection of air pollution can be performed by point, path-averaging or volume-averaging measurement methods. Point measurement methods are in-situ techniques while the path or volume averaging methods are remote sensing techniques. Remote sensing techniques are typically used in two different ways: (a) for line-integrating measurements over several hundreds of metres or even some kilometres (FTIR, DOAS), and (b) for vertical profiling (ceilometer, Lidar). Line-integrating measurements usually operate with an emitter/receiver and a reflector (mono-static method) or with an emitter and a receiver (bi-static method). In both configurations the installations at both ends of the measurement line have to be close to the ground or on building tops or they have to be mounted on masts. Profilers comprise emitter and receiver in one instrument; therefore they are always operated in a mono-static way. In the following in-situ, line-integrating and profiling instruments for air pollution measurements are introduced that can easily be used in mountainous terrain. All these meteorological and air pollution measurement methods can be operated in mobile units, i.e. the systems can be installed in measurement vans or trailers and the data are transmitted via modem or internet.

If data is intended be representative for a certain area or an air volume or if they will be used for model initialisation and evaluation the spatially averaging methods are better adapted to the spatially and temporally averaging numerical models than in-situ methods.

4.3.1.1 In-situ methods

By continuous sampling of ambient air those compounds for which limit values have been set can be detected (CO, NO_2, O_3, PM10, PM2.5, also NO). Up to 50 specific VOCs can be analysed in air samples collected in canisters. Different laboratory instruments like gas chromatography or mass spectrometry including preparatory processes and calibration procedures are necessary to detect specific VOC within these air samples. Depending on the measurement principle used for the in-situ instruments the detection limits are up to 100 ppt and the temporal resolution up to 10 seconds. These instruments are capable to detect one single compound (in the case of NO_x also NO). Automatic or manual calibration procedures have to be performed in intervals between once per day and once per week; again depending on the measurement principle. All instruments can be operated in high altitudes, too. Some PM measurement methods are using a radioactive source with must be declared officially. A weather-proofed housing for the instruments and a heated air inlet must be installed.

Fig. 4.4 In-situ van at Schwaz during the ALPNAP Lower Inn valley campaign.

In-situ measurements of air pollutants like NO, NO_x, CO, O_3 and PM10 can be performed using a mobile measuring platform (in-situ van, Fig. 4.4). The air is sucked in by an inlet tube whose height is about 4.6 m AGL. and is then distributed to the different analysis instruments inside the van. Typical instruments in such a van could be the following in-situ instruments:

NOx Analyser

A 42C Trace Level (42C TL) chemiluminescence analyser can be used to analyse NO and NO_x. The measurement principle is based on the chemical reaction of nitric oxide (NO) with ozone (O_3), whereby NO_2 is formed. The reaction process causes a luminescence which is linearly proportional to the NO concentration. The concentration of NO_x is the result of the sum of NO_2 and NO.

NO_2 passive samplers

Such samplers are low cost devices delivering valuable information about the vertical and horizontal distribution of NO_2. Generally they consist of a sample of micro-porous material (polyethylen) which is covered by a substrate absorbing NO2 (triethanolamin). After the exposition of the samplers over a predefined time period and preprocessing the NO_2 concentration is assessed in the laboratory (ionchromatography). There are standardised regulations for this procedure (e.g. ÖNORM EN ISO 10304-1). Typically, the samples are collected in about weekly intervals, thus the achieved information corresponds to averages (totals) about this period.

Several intercomparison studies investigated the performance of passive samplers in relation to standardised reference methods based on chemoluminescence methods (NUA, 2005; Danninger, 2005; Pfeffer et al, 2006; Spangl et al, 2006). They indicate an overall uncertainty in the order of ±10% (annual data) with a tendency to overestimate the NO_2 concentrations. Analysing twin samples in the laboratory and in the field indicates that most of the uncertainty is related to inappropriate pollution of the filters. Therefore, the time of exposure and the filter characteristics must be adjusted to the local conditions (test measurements). Moreover, parallel measurements of temperature and precipitation are recommended in order to estimate/correct corresponding effects.

During the ALPNAP project passive samplers have been used to monitor the seasonal profile of NO_2 concentrations across the Inn-valley (10 sites at different altitudes).

CO Analyser

The Analyser AL 5001 (Aero Laser GmbH) can be used for in-situ analyses of CO. The technique is based on the resonance fluorescence of electronic transition of CO in the vacuum ultraviolet (VUV, the fourth positive band at 150 nm). Light which comes from a CO resonance lamp is used for excitation. The fluorescence is detected by a VUV-photomultiplier.

O_3 Analyser

The Analyser APOA 350E (Horiba Ltd.) can be used for in-situ measurements of ozone (O_3). The measuring principle of UV absorption guarantees a continuous measurement. The measurement is based on a comparison between a reference gas, without O_3, and the sample gas. Both gases are led into the cell alternating by a magnet valve. The cell is irradiated by a low-pressure mercury vapour lamp with 253.7 nm wave length (UV) and the measurement signal is determined by difference in the unequal absorption.

Measurement of particulate matter by x-ray absorption

In-situ measurements of fine particulate matter (PM10) can be made with an analyser of the type FH 62 IR (Digitel Electronics AG). FH 62 uses the radiometric principle of β-ray absorption with a two-ray-compensation method. At this method a comparative length serves as the reference and the filter band is replaced by a foil. By setting up the difference a high measurement stability is ensured. Air is sucked in through a filter band with a constant flow and the particulate matter is deposited on the filter band. The film of particulate matter, which is built up continuously on the filter band weakens the intensity of the β-ray penetrating through the filter band, which is received in an ionisation chamber. From the reduction in the received signal the concentration of particulate matter is calculated.

Measurement of particulate matter by scattering of light

Particulate matter floating in the air can be measured by light scattering methods. A pump draws air at a known rate (between 1 and 3 litres per minute) through a measurement chamber where it passes through visible laser light. Particles in the air will scatter light in proportion to the particulate load and the scattered light is focused by optics on a laser diode. The intensity of the signal is processed by the measurement electronics yielding calibrated analogue/digital output. Specific corrections are necessary to correct for influences of temperature and humidity on the signal. A sheath system isolates the particles in the chamber to keep the optics clean for improved reliability and maintenance. Laboratory calibration is performed using test samples of particles with defined sizes and optical properties ensuring compliance to standards like ISO 12103 or EN 12341. By discriminating appropriate ranges of the size of particles (scattering intensities) the recorded signals correspond to concentrations of TSP, PM10 or PM2.5, respectively. Field calibration can be performed by parallel filter measurements and analysis of the particle load on the filter and the flow protocol, respectively. Moreover, field intercomparison against primary standards (gravimetric methods) is recommended. The resulting accuracy is in the order of 0.001mg m^{-3}. Critical maintenance of these instruments mainly concerns regular cleaning of the relevant components of the system (optics, filters, inlet tubes) and associated recalibration.

This kind of instrument can be operated in different modes. During ALPNAP for instance, they were used for permanent in situ measurements (yielding continuous records at selected sites), mounted on tethered balloons (yielding vertical profiles of particulate matter) and mobile measurement platforms (yielding pseudo vertical profiles along the valley slopes).

4.3.1.2 Remote sensing methods

Three different optical remote sensing strategies are in use to derive profiles or line averages of atmospheric pollutants: (i) backscatter Lidar (light detection and ranging) systems, which emit light at one frequency , used for the measurement of vertical particulate matter backscatter profiles and cloud heights, (ii) absorption Lidar systems which emit light at two or more frequencies and which employ the differential absorption spectroscopy principle (DAS or DIAL), used for the detection of vertical profiles of gas concentrations like ozone, and (iii) laser absorption techniques (DOAS and FTIR), used to detect path-averaged gaseous concentrations near the ground. Remote sensing methods are non-intrusive and no sampling is necessary. The temporal resolution is in the order of minutes because it has to be integrated over many single measurements. The measurement systems can be operated in high altitudes with some modifications. If the radiation sources are eye-safe no permission is necessary.

Backscatter Lidar systems for vertical profiling of aerosols

The ceilometer is a profiling optical remote sensing instrument. It is a small Lidar with reduced electronics and no evaluation of the Doppler shift of the backscattered signal. It measures the optical attenuated backscatter intensity at 0.855 µm averaged over 15 s. This special wavelength has been chosen because the absorption by water vapour is rather low here. The human eye is not very sensitive to radiation at this wavelength; therefore the instrument is eye-safe and can be operated unattended. The typical vertical range of this instrument is 4 km; the vertical resolution is 7.5 m. The distance of the backscattering volume is determined by the signal travel time. Apart from the very strong backscatter from clouds (that is what the instrument had originally been designed for), fog and precipitation, weaker gradients in the backscatter intensity are mainly determined by the vertical distribution of number and the size spectrum of particles floating in the air. The instrument can be operated unattended in an automated mode. Access to the instrument should be restricted to the public. An installation at a site with a fence or which is guarded is recommended. It needs stationary electricity supply (230 V, 16 A).

Absorption Lidar systems for vertical profiling of gas concentrations

The DAS-LIDAR (Differential Absorption Spectroscopy), also known as DIAL (Differential Absorption LIDAR), works with the emission of two light pulses with slightly different wavelengths. One wavelength is optimally absorbed by the gas to be measured, the other wavelength as little as possible. By this procedure, the influence of absorption by particulate matter, which depends only weakly on the wavelength, can be eliminated. For the detection of ozone UV light between 230 and 280 nm is preferable. The backscattered light intensity is recorded. The less light is received back the larger is the absorption and the concentration of the gas in question. This technique offers a height resolution of about 75 m and a temporal resolution of 1 min. The range is from about 300 m to many kilometres.

Laser absorption techniques for path-averaged gas concentrations

DOAS (Differential Optical Absorption Spectroscopy, suitable for NO, NO_2, O_3, NH_3, benzene and HCHO) and FTIR (Fourier Transform Infrared Spectrometry, suitable for CO, greenhouse gases and tracers like SF_6) are line-integrating open-path spectroscopic absorption methods. They can be operated over distances in the order of several hundreds of metres. These systems are multi-component measurement methods because they analyse the absorption in a larger part of the electromagnetic spectrum. The absorption technique needs a light source at one end of the measurement path and a receiver unit with an analyser at the other end. If a mirror is used emitter and receiver can be mounted side by side. The DOAS light emitter contains a high-pressure xenon lamp which emits visible light. The light rays are reflected by a retro-reflector which is typically mounted about 200 to 250 m away giving an integration path of 400 to 500 m. The chosen path length is a trade-off between received light intensity (sets an upper limit to the path length) and absorbing gases on the path (sets a lower limit to the path length). The detection limits of these instruments are in the order of ppb. A basic calibration with calibration gases is necessary for this method.

4.3.2 Representativeness and measurement strategies

4.3.2.1 Representativeness

The choice between point measurements (e.g. employing an inlet sucking air into an analyzer) or path-averaged measurements (e.g. DOAS or FTIR) depends on the expected local concentration gradients and the purpose of the measurements. In areas with low gradients and outside of narrow valleys point measurements may be sufficient. In highly complex terrain path-averaged (or even volume-averaged measurement by scanning with remote sensing techniques) can be advisable. Averaging techniques must be applied to measurement results that will be used as input for models or for comparison with model results. This is necessary if the spatial resolution of the models does not match the spatial representativeness of the measurements.

In mountainous terrain line-integrating measurements can be made along the valley axis to get values which are typical of a certain section of a valley. Alternatively they can be performed across a valley to get average values at a selected cross-section. In mountainous terrain profilers offer the possibility not only to acquire vertical profiles but also horizontal or slanted profiles from elevated positions.

4.3.2.2 Measurement strategies

Measurements strategies have to be designed in order to catch the spatial and the temporal variation of air pollution simultaneously. While the temporal variation is covered by recording longer time series with sufficient temporal resolution (depending on purpose) different strategies are possible for the spatial variations. In principle three strategies could be employed: (1) measurements at different sites with similar instrumentation; (2) measurements with one set of instruments on a movable platform (e.g. car, tethered balloon, aircraft); (3) remote sensing measurements in a scanning mode from one site. If both noise and air pollution is a problem they should be studied in the same framework. In this case the measurements have to be designed to satisfy both needs.

4.3.2.3 Monitoring and campaigns

Measurement activities are usually part of either long-term monitoring activities or of short-term campaigns. The monitoring of concentration levels according to air quality regulations (see **Tab. 4.1**) or for the purpose of operating traffic limitations (temporal speed limits or part-time traffic bans) are typical monitoring tasks. Instruments are mounted permanently and the data are transmitted directly to the responsible agencies. Often they are evaluated automatically by computer software designed for this purpose.

Among the main monitoring issues are:

- Temporal variation pattern of pollutant concentrations in the ambient air near the surface
- Daily variations in air pollution e.g. due to temporal variations of traffic emissions (10 times higher during the day than during night) and meteorological conditions (e.g. diurnal wind regimes, thermal stratification)
- Spatial variation of air pollution as a function of the distance to the Alpine traffic roads and other main emitters
- Differences in ambient air concentrations between locations near sources and at the slopes
- Surveillance of air quality improvement strategies

The investigation of poorly known air quality or noise situations in certain areas on the other hand requires the execution of short-term measurement campaigns in order to understand the underlying physical and chemical mechanisms. The choice and siting of the instruments must be chosen with respect to the purpose of the campaign. Here, a flexible employment of instruments is recommended (e.g. on mobile units). On-line data transmission is not always necessary; data loggers may be sufficient for many purposes. The interpretation of the data needs scientific expertise.

Monitoring instruments should be properly calibrated before a campaign or monitoring task. In addition, it is advisable to define intercomparison periods at the beginning and the end of the measurement period (in long-lasting campaigns and monitoring also at regular intervals within the period). In measurement campaigns the intercomparison typically requires a simultaneous operation of all instruments used in the campaign at one selected station for a certain time period (36 hours minimum).

4.4 Modelling

Dispersion modelling has proved to be a very effective tool to assess the environmental impact of human activities on air quality. While the number of air quality monitoring stations is obviously limited in mountainous areas, models are able to estimate the airborne pollutant concentrations in a whole computational domain. Only models can give detailed information on the distribution of pollutants with high spatial and temporal resolution. They allow decision-makers to devise a range of scenarios, in which the various processes determining the environmental impact can be easily simulated and changed. Considering the current knowledge of atmospheric physics and chemistry, these models use chemical and physical parameterisations as well as mathematical and numerical techniques to simulate the main processes affecting air pollutants as they are transported and dispersed by atmospheric motions, and as they are formed and destroyed by chemical reactions and photolysis in the atmosphere. Thus, models provide a cost-effective way to analyse pollutant impact over large domains. Models account for the mean features influencing the dispersion such as orography, meteorology, land use and emissions both from nearby sources or from remote sources. They can be used for: (1) determining the maximum allowable emission rates that will meet given air quality standards; (2) evaluating proposed emission control strategies; (3) selecting locations for future sources in order to minimise their environmental impact; (4) planning the control of air pollution episodes; (5) assessing the source-receptor relationships; (6) appropriately locating air quality monitoring stations (Seinfeld, 1975; Zannetti, 1986).

4.4.1 Principle design features

In order to describe the dispersion of pollutants both off-line and online models are operated. Off-line coupled models are based on numerical meteorological models that solely describe the atmospheric flow and weather conditions (Section 3.3) and on chemistry-transport models which solely describe the transport, diffusion and chemical reactions. Both models are coupled by conveying the necessary meteorological information from the meteorological driver model to the chemistry transport model, and operated one after the other. On the other side, online coupled models (mainly Eulerian models) include meteorological and chemistry processes within one code, and exchange information at each time step in both directions. In this section, both off-line and on-line coupling of meteorological models and chemistry transport models will be considered.

The operation of numerical air quality models needs sufficient computational facilities and trained staff. A numerical model starts from a prescribed initial state that can be either a simplified ideal state or a given real situation. The latter case requires the availability of gridded meteorology and air quality data with a certain spatial resolution. During the simulation, numerical models continuously need lateral boundary values. At the surface, emission data define the boundary condition. Emission source information are the geometric type of the emission source, namely point sources (e.g. a single stack), line sources (e.g. a road) or area sources (e.g. a whole village), the emission rates and the type of emitted pollutants (see Chapter 2). During the operation and at the end of a model run sufficient storage facilities are required to save and to further process the model results.

4.4.2 Types of models

Models can be stratified by type, by purpose, and by scale. Some examples will present frequently used models. Some examples will present frequently used models.

4.4.2.1 Model types

Models types are arranged in the following overview in ascending order with respect to their complexity and their capabilities. Statistical models are the simplest ones, online coupled Eulerian chemistry-transport models are the most complex and capable ones.

Statistical models

Statistical models are based on a sufficiently long time series of measured air pollution concentrations (predictands) and observed influencing parameters (predictors). They express an empirical relationship between predictands and predictors. Once established they can be applied to forecast air pollution concentrations from the predictors, e.g. the output of weather forecast models.

Regression models

Regression models express the predictand as an analytical function of a set of possible predictors (multivariate regression). Linear regression models are based on the formula:

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + ... + b_n x_n$$

with:

$\hat{y}$	predictand (forecast pollutant concentration)
b_0	regression constant
b_i	regression parameters
x_i	predictors

Here, relations between predictors and the predictand are linear, but using mathematical transformations of the primary quantities allows for non-linear effects as well. For example, to take into account the fact that concentrations downwind a source are inversely proportional to wind speed and mixing height, one can use the inverse of these parameters in the regression.

To develop this forecasting equation, a historical dataset of possible predictors) and observations y of the desired quantity to forecast is analysed. The relevant predictors are screened from a set of possible ones and their corresponding regression parameters (the b_i in the above equation) are calculated. The regression parameters b_i can be time-dependent or a function of some other variable if sufficient input data for the calculation of the dependence are available. To test and analyse the quality of the resulting forecasting equation, an independent dataset of predictors and observations, not used for developing, has to be used. This kind of regression models are frequently used in meteorological forecasting in combination with outputs from numerical weather prediction models (NWP, e.g. that of ECMWF) in order to derive forecasts for locations or quantities not represented by the NWP models. Herein, following the so called “model output statistics” (MOS) procedure by correlating historical meteorological forecasts with air quality measurements, implies considerations of peculiarities of the used numerical model – like biases or predictabilities for different forecasting time steps. This is not the case using the so-called “Perfect Prog” approach, where time series of meteorological measurements are used to determine the relationship between meteorological parameters and the resulting pollution concentrations. In forecasting mode, however, both methods use NWP outputs as input data (Wilks, 2006).

Neural networks

Neural networks are an increasingly important way of statistically comprising amounts of data (predictors) into a forecast. In contrast to regression models, the single ingoing parameters are not connected with the predictand by a simple analytical function. Instead, there is a so-called hidden layer in which interactions are modelled with many intermediate variables. Therefore, complex and nonlinear interactions can be represented. Another substantial feature of neural networks is that they do not find solutions – here forecasts – from a hard-coded implementation but they are designed to learn and keep on learning as they are run, hence permanently improving their forecast skills (Callan, 2003).

Analytical models

Analytical models are based directly on analytical solutions of simpler equations for physical laws and chemical reaction mechanisms. No discretisation in space and iteration in time is needed.

Gaussian models

Gaussian models are the analytical solution of the dispersion equation for stationary and homogeneous conditions. Then the vertical and the cross-wind distribution of the pollutant emitted from a point source is Gaussian. Variation in time can only be reproduced as a succession of stationary states. Line and area sources can be simulated by a dense array of point sources. These models work best in homogeneous terrain where the assumptions made are more or less fulfilled. Inside of valleys they may be used as long as the Gaussian plume is not impacting the valley sidewalls and the wind and turbulence field is approximately homogenous. In practice this means that they can only be used in larger valleys with a rather flat floor and on distances on the order of the width of the valley floor. In Austria, a modified Gaussian model has been developed that is able to handle the impact of a stack plume on a slope or hill (Kaiser et al., 2005).

Numerical models

Numerical models are based on a numerical solution of differential equations describing transport, diffusion, sources and sinks (budget) of one or more substances for conditions that vary in time and space. Then, the equations can no longer be solved analytically. Discretisation in space (meshes of a numerical grid) and time with discrete time steps is necessary. The length of the time steps is coupled to the mesh size in order to guarantee a stable numerical solution. Finer grids (smaller mesh size) require smaller time steps and thus more calculation steps. The consideration of nonlinear chemical reactions (i.e., reactions with two or more reaction partners whose concentration is not fixed) introduces nonlinear equations and considerably increases the numerical efforts required for the solution. It is important to discern pure transport and diffusion models on one hand, and chemistry-transport models on the other hand.

Box models

Box models are zero-dimensional models (models integrally valid for a given volume of the air, no spatial resolution) which describe chemical reactions but no diffusion (e.g. Emeis et al., 1997). The box model assumes that the air pollutants are homogeneously distributed inside the chosen computation domain (the box), thus considering negligible the advection and diffusion contributions. Box models can be used for well defined air volumes, e.g. in a stagnant valley atmosphere which is topped by an inversion.

Three-dimensional models

Three-dimensional models are models describing physical and possibly chemical processes in a three-dimensional air volume, usually integrated forward in time. They may include interaction with the ground and with precipitation.

– Lagrangian models

  Lagrangian models describe the path and properties of hypothetical particles used as markers or limited volumes of air. They need input for wind and turbulence fields. Three major types of Lagrangian models can be found:

  - *Puff models* are one of the simpler subtypes of a Lagrangian model. They describe the transport of a sequence of puffs (a limited cloud of pollutants released within a short time period from a single source) with the mean wind. During this transport the clouds disperses following a Gaussian distribution. Chemical reactions are not included. The concentrations are calculated by summation over the contributions of all the puffs. Their main advantage is that calculations are relatively fast. However, they cannot deal well with more complicated meteorological conditions and are also not state-of-the-art anymore.
  - *Particle models* are the more advanced subtype of Lagrangian models. They describe the transport and dispersion of fictitious particles released from arbitrary sources. All particles separately undergo transport by the mean wind and dispersion by turbulent fluctuations, possibly also deposition to the ground and wash-out by precipitation. Usually, chemical reactions are not considered, or only with fixed reaction rates. Concentrations are determined on a grid by summation over the particles found inside a given grid cell.

– Eulerian models

  Eulerian models are also called "finite-difference time-domain models" (Section 5.4.1.6). They are grid-cell models, the relevant equations are solved for every grid-cell. Processes taking place on scales smaller than the grid distance (especially turbulent mixing) have to be parameterised, i.e. they have to be expressed by resolved parameters through empirical relationships. Initial and boundary values have to be specified externally for their operation. Eulerian models are based on the numerical solution of the 3D advection-dispersion equation thus, in each grid cell, at each time step, the concentration of the substances of interest is known.

  Offline coupled models are the simpler type of Eulerian chemistry-transport models. They require input from a meteorological simulation (see Section 3.3) such as wind and turbulence fields, temperature, moisture, etc. at certain time intervals (e.g. every hour), and then compute advection and diffusion. Nowadays, these models usually also consider nonlinear chemical reactions schemes.

Online coupled models are an advanced type of Eulerian chemistry-transport models. They integrate meteorological and chemical equations simultaneously, in one code. Here the actual temperature, moisture, wind, and turbulence conditions are available at every time step for the simulation of the chemical reactions. This type needs considerably larger computer resources.

Inverse models

Inverse models compute emission strengths from concentration measurements and backward dispersion modelling with one of the above analytical or numerical models.

Model purposes

Models can also be stratified according to their field of application. This mainly yields the following categories:

– emission models (describing emissions or emission factors, see Section 2.5.2)
– dispersion models, also called transport or advection-diffusion models (mainly for inert substances)
– chemistry-transport models (for chemically reactive substances including the formation of particulate matter)
– deposition models (usually not as stand-alone models, but integrated into dispersion or chemistry-transport models.

Model scales

Especially three-dimensional models can additionally stratified by their scale:

– microscale models, working on the scale of e.g. a street canyon
– mesoscale models, working from the scale of a single valley to the whole Alpine arc
– macroscale models, working from the scale of on continent to the global scale.

4.4.2.2 Grid and nesting

For the application of a numerical model an important choice to be made is the grid resolution of the model. For Eulerian models, this concerns the computational grid, but even in Lagrangian and in complex Gaussian models a grid is needed for the model output. The size of the grid cells determines the spatial resolution of the model results. The decision usually is a trade-off between computer resources (which puts an upper limit to the number of grid cells) and the desired size of the simulation domain and the spatial resolution within this domain. Computation time and storage requirements typically increase with the second or even third power of the grid point number. Also input data (e.g. emission inventories) have to be available in a suitable resolution. State-of-the-art models offer grid nesting strategies in order to zoom in on smaller target areas with high spatial resolution while keeping a larger surrounding domain to provide appropriate boundary conditions of the smaller domain. Using this strategy, smaller simulation domains (so-called nests) with high spatial resolution are inserted (nested) into larger simulation domains with coarser resolution. A hierarchy of even four to five nests is possible. With this strategy only small domains with high spatial resolution and respective input data have to be defined, but still large-scale meteorological information can be used in order to perform meaningful simulations over several days (zoom-in strategy).

If the model is run on all domains simultaneously during one simulation run and information is transmitted in both directions (from the coarser domain to the finer nests and vice versa) this procedure is called two-way nesting. If information is only transferred from the coarser domains to the finer nests, the strategy is called one-way nesting. One-way nesting is advisable only for short integration periods (a few hours), but is needs less computational resources. In a one-way nesting strategy it is possible to run the simulations for the different domains one after the other.

4.4.2.3 Model examples

In the following paragraphs some selected, widely implemented models are described (following the order which has been used for the list of model types above) for illustration purposes.

CALINE

CALINE is a Gaussian line source model designed for the assessment of traffic emissions from roads. The original code was developed by the California Department of Transportation and the U.S. Federal Highway Administration (Benson, 1992). It is based on the Gaussian diffusion equation and employs a mixing zone concept to characterise pollutant dispersion over the roadway. The purpose of the model is to assess air quality impacts near transportation facilities in what is known as the microscale region. Given source strength, meteorology, site geometry, and site characteristics, the model can predict pollutant concentrations for receptors located within a few hundreds meters from the roadway. The model can handle only inert pollutants such as carbon monoxide, or particulate matter (primary, not reacting). In this study it has been adopted in order to perform a comparison with respect to other more complex models and to verify for which applications they are suitable, also considering that the uncertainties in estimating emission factors and traffic volumes are often not negligible. It can model junctions, street canyons, parking lots, bridges and underpasses; CALINE predicts 1-hour mean concentrations and is therefore useful for investigating episodes of high NO_2 and CO concentrations. Hourly meteorological conditions are user-defined, and line source emission rates must be calculated independently by the user, based on vehicle speeds and emission factors (see Chapter 2 for available methodologies). Computation has been optimised by defining a mask inside the domain within the computation is performed: this allows defining a non-regular domain mask following the contour of the valley floor.

Since the original version of the model looked somewhat too rough for a direct application inside a complex Alpine valley, a preprocessor has been specifically developed within the ALPNAP project: it can produce a network of receptor whose position is adapted to the road track, thus defining more accurately the dispersion in the near-field, where higher gradients of concentration may be expected, as clearly depicted in Fig. 4.5. A finer grid of receptors near the source (less than 25 m appeared

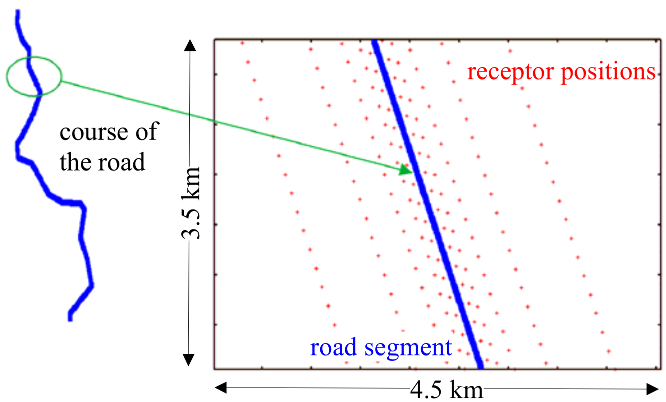

Fig. 4.5 Optimal receptor network distribution in a Gaussian model

to be a good choice) allows in fact a better representation of the highest concentration gradient; far from the source this requisite can be relaxed and the distance between receptors can be higher (up to 100-200 m).

CALPUFF

CALPUFF (Scire et al. 2000) is a Lagrangian puff model. It includes a simple chemistry module to predict downwind concentrations of NO_2 from NO emitted by vehicle exhausts. Emissions are simulated through continuous release of "puffs" whose barycentre is advected by the mean wind field. Turbulent diffusion for a puff is calculated at the start and end of every advection step. Each puff is "frozen" during the advection. The total concentration at a receptor point is then the sum of the contributions of all puffs moving over this receptor point during a chosen time period. In CALPUFF different kinds of emissions can be defined: point, area, line and volume source emissions; both the latter can represent a quasi-one-dimensional source such as a highway. It is then possible to specify the source parameters and emission rates for each time step in the model run. When simulating linear sources CALPUFF is able to consider two important features: the buoyancy-induced dispersion and the initial plume size. CALPUFF also allows the use of stability-dependent minimum turbulence velocities. This option should be selected whenever the velocities otherwise obtained (measured or predicted) are less than the tabulated minimums; default values, which may be varied on the basis of field campaigns, are based on the effective turbulence intensity implied by the Pasquill functions, as prescribed by Briggs (1973). Of course, when detailed wind and turbulence measurements are available, care has to be used to ensure that valid measurements are not superseded by the minimum turbulence values. The linear chemical transformation effects are modelled in a manner consistent with the puff formulation of the CALPUFF model. The CALPUFF chemical module contains four options for dealing with chemical processes: among these the pseudo-first-order chemical reaction mechanism is able to simulate the conversion of SO_2 to SO_4 and NO_x (i.e. NO + NO_2) to NO_3. This mechanism incorporates the temperature dependency on the transformation rates.

SPRAY

SPRAY is a three dimensional Lagrangian particle model originally developed by a joint team (ISAC-CNR, ARIANET of Milan, ARIA of Paris and Università del Piemonte Orientale of Alessandria). The code operates the transport and diffusion of chemically neutral airborne species in complex real conditions (orography, land use heterogeneity, low wind regime) characterized by non-homogeneity in space and time of the main meteorological variables (vertical wind shear, breezes caused by non-uniform terrain) delivered by RAMS (see Section 3.3.3.2) or by other diagnostic and prognostic meteorological models. SPRAY reconstructs the concentration fields determined by point, line, area and volume sources. The behaviour of the airborne pollutants is simulated through "virtual particles" whose mean motion is defined by the local wind and the dispersion is determined by velocities obtained as solution of the Lagrangian stochastic differential equations, able to reproduce the statistical characteristics of the turbulent flow. Different portions of the emitted plumes can therefore experience different atmospheric conditions, allowing more realistic reproductions of complex phenomena (low wind-speed conditions, strong temperature inversions, flow over topography, presence of terrain discontinuities such us land-sea or urban rural). The version adopted for the work presented in Sections 7.3.3 and 7.4.3 uses the most recent developments regarding the formulation of the Langevin stochastic equations and new more efficient methods for the particle time-stepping; this allows the model to perform more efficient complex simulations, taking into account a large number of emissions of several origin. A new algorithm to account for low wind or calm conditions has recently been introduced (Anfossi et al., 2006 and 2007).

GRAL

GRAL is a 3D Lagrangian particle model developed at the Institute for Internal Combustion Engines and Thermodynamics, Technical University Graz, Austria (Öttl et al., 2003a; Öttl et al., 2003b). GRAL uses the flow fields computed by the prognostic wind field model GRAMM (Graz Mesoscale Model, Almbauer et al., 2000; Öttl et al., 2005). The model system uses special algorithms to account for low wind or calm conditions (Öttl et al., 2001; Öttl et al., 2005). The transport and diffusion of PM10 and NO_x are treated as chemically inert. The formation of secondary organic and inorganic PM is not considered.

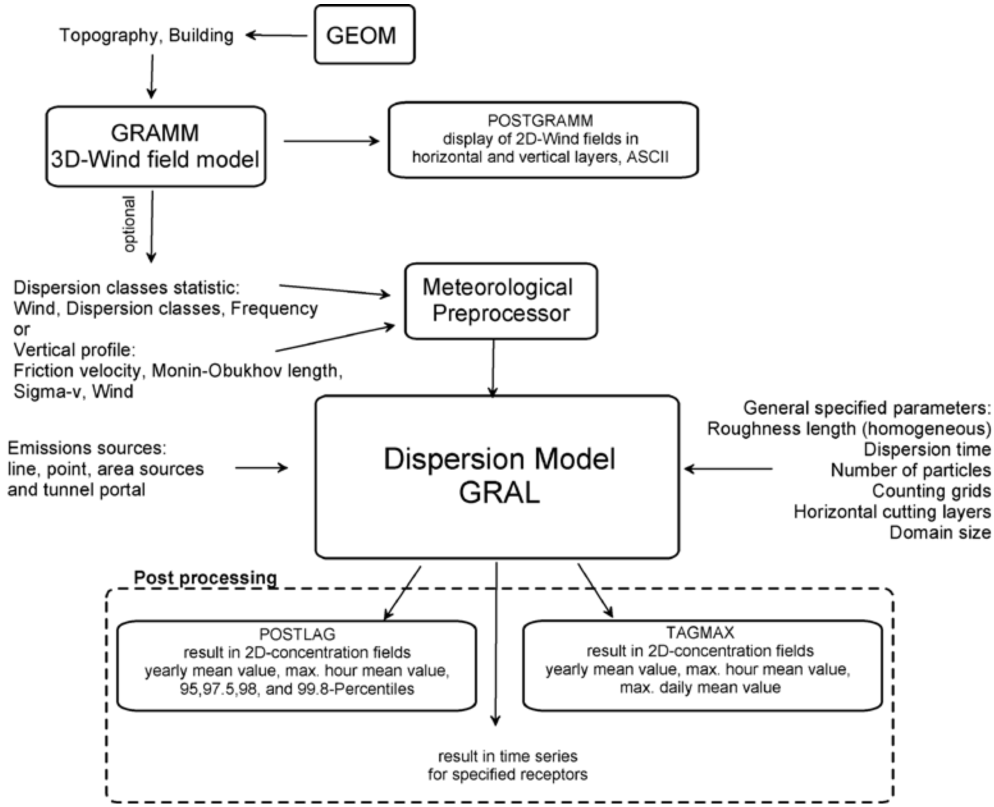

Fig. 4.6 The model system GRAL

Standard applications of GRAL are environmental assessment studies, i.e. the computation of annual mean values for air pollutants like CO, NO_x, NO_2 and PM10.

When using classified meteorological situations a meteorological pre-processor calculates friction velocities, Monin-Obukhov length, standard deviations of the normal components of the wind speed, ensemble average dissipation of turbulent kinetic energy, parameters to take into account flow meandering, skewness and curtosis of vertical wind fluctuations in convective conditions. The pre-processor is based mainly on the works of Golder (1972), Venkatram (1996), Zannetti (1993) and Öttl et al. (2001).

A statistical classification of flow situations is used and steady state simulations with wind field model GRAMM (see Section 3.3.3.2) are run. Thereafter, the corresponding dispersion simulations with GRAL are calculated. Finally, annual means, summer and winter means, maximum daily means, and maximum half hour concentrations are calculated using the TAGMAX post-processing software, see Fig. 4.6.

The NO_x to NO_2 conversion is calculated according to the scheme of Romberg et al., 1996 a simple regression model, based on the results of field measurements, describing the conversion rate as a function of the NO_x concentration only. The scheme only works for annual means and 98-percentiles but not for single hours.

Currently 18 different data sets for tunnel portals, point sources, line sources and built-up areas are used for the model evaluation.

CALGRID

CALGRID is an offline Eulerian photochemical model (Yamartino, et. al., 1989; Scire, et. al., 1999). The model input is fully compatible with CALMET (see Section 3.3.3.1) output. It incorporates the Statewide Air Pollution Research Center (SAPRC) chemical reaction mechanism. Horizontal advection is solved by a finite-difference mass-consistent scheme. The vertical dispersion is simulated through the similarity theory and diffusion coefficients are based on PBL meteorological regimes. A chemical integration solver based on a quasi-steady-state implementation (Hesstvedt et al. 1978) is used. Hourly 3D wind and temperature fields and 2D fields of turbulent quantities (mixing height, Monin-Obukhov length, friction velocity, vertical convective velocity) are taken as input from CALMET. On the other hand, emissions are provided, for each emitted species, as mass per time unit for every grid cell for the area sources and for every stack for point sources. Therefore, boundary and initial concentrations shall be explicitly assigned. Obstacles are not addressed explicitly, but orography at each grid location is taken into account as the meteorological input already accounts for it. Dry deposition is calculated using the values of deposition velocity given for each chemical species, also depending on the resistance models of the ground (i.e. vegetation characteristics, adsorption capacity, etc.). In CALGRID the wet deposition is not yet foreseen.

CAMx

The offline Comprehensive Air quality Model with extensions (CAMx) is a Eulerian photochemical dispersion model that allows for an integrated “one-atmosphere” assessment of gaseous and particulate air pollution over many scales ranging from urban to super-regional. CAMx simulates the emission, dispersion, chemical reaction, and removal of pollutants in the troposphere by solving the pollutant continuity equation for each chemical species on a system of nested three-dimensional grids. The model as well as its documentation (ENVIRON, 2006) is publicly available at the CAMx homepage[5].

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[5] http://www.camx.com

The model is used on the same Lambert conformal nested grids as the meteorological driver MM5 applying two-way nesting. Alternative chemical mechanisms are the Carbon Bond 4 (CBM-IV) mechanism (Gery et al., 1989) with updated isoprene chemistry based on Carter (1996), which is also available including aerosol chemistry, and the SAPRC99 mechanism (Carter, 2000), where the lumping of the hydrocarbons is achieved by combining compounds with similar chemical reactions and similar reactivity to single species. Special features of CAMx are the source apportionment technologies OSAT and PSAT for ozone and for particles, respectively, that allow to calculate information about the origin of the precursors of secondary pollutants.

CAMx has been applied in a number of studies concerning the ozone concentration in Northeast-Austria, in which comparisons with measurements of pollutants showed a good agreement with the model results (e.g. Krüger, 2004). Since several years CAMx is used for an operational ozone forecast of ozone for Northeast-Austria. Meteorological fields from the regional meteorological model ALADIN are used for these calculations (Krüger et al., 2005).

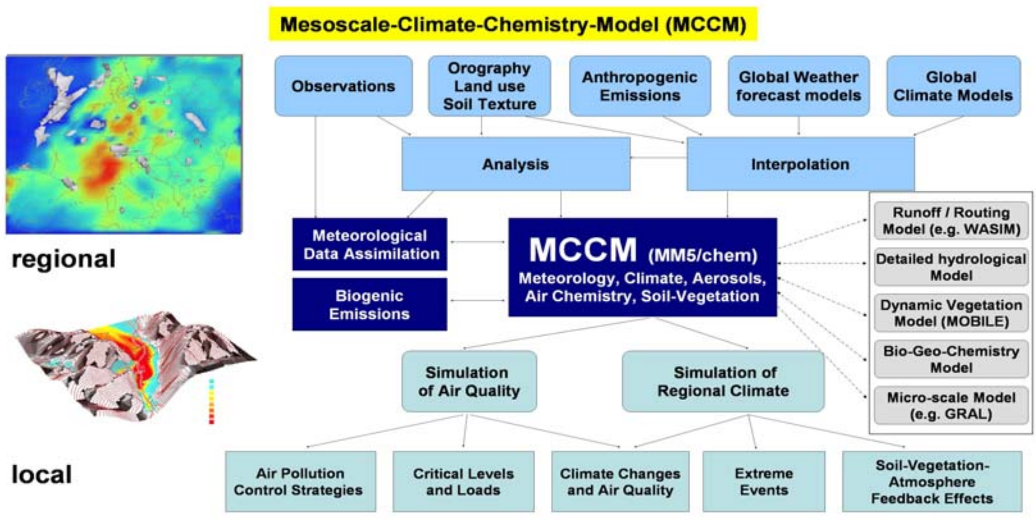


Fig. 4.7 Schematic overview over necessary input for and output from MCCM

MCCM

The online coupled regional Eulerian meteorology-chemistry model MCCM (mesoscale climate chemistry model, Grell et al., 2000) has been developed at the IMK-IFU (see Fig. 4.7). MCCM is based on the non-hydrostatic NCAR/Penn State University mesoscale model MM5[6] (Grell et al., 1994, see Section 3.3.3.2). Like MM5, MCCM supports multiple nesting of domains and can be applied over a spatial scale ranging from the continental scale with domain extensions of several thousand kilometres and resolution of 30 – 100 km down to the regional scale with domains of 100 – 200 km and resolutions of 1 – 5 km.

[6] http://www.mmm.ucar.edu/mm5

MCCM includes several online coupled tropospheric gas phase chemistry modules (RADM, RACM, RACM-MIM; cf. Stockwell et al., 1990, 1997; Geiger et al., 2003), a photolysis module, and a BVOC emission module. Aerosol processes are described with the modal MADE/SORGAM aerosol module (Schell et al., 2001) which considers the single compounds sulphate, nitrate, ammonium, water, and 4 organic compounds.

Anthropogenic emissions of primary pollutants, like NO_x, SO_2, and hydrocarbons, as well as emissions of primary particulate matter have to be supplied either at hourly intervals or as yearly data from gridded emission inventories.

Various validation studies with MCCM have shown its ability to reproduce observed meteorological quantities and pollutant concentrations for different conditions and regions of the earth (Forkel and Knoche, 2006; Grell et al., 2000; Jazcilevich et al., 2003; Forkel et al., 2004; Suppan and Schädler, 2004; Kim and Stockwell, 2007). Recent applications of MCCM at the IMK-IFU include short term studies such as simulations of high pollutant episodes for Mexico City (Forkel et al., 2004), receptor analysis (Suppan and Schädler, 2004) as well as long term climate-chemistry simulations (Forkel and Knoche, 2006), and daily real time forecasts of ozone and particulate matter for Germany.

4.4.3 Benefits and costs

Statistical models can be used for forecasting air quality on a time scale of some hours to several days. They are based on statistical relationships between observed immission levels (called “predictand” in statistical terms) and relevant independent parameters (so called “predictors”) rather than on physical laws. They can be run by local administrations in order to plan short time measures to reduce emissions – e.g. during high pollution episodes. To develop a statistical forecasting model, historical time series of immission measurements and input parameters for the selected location (and air pollution matter) are necessary. These input parameters can be emission estimations, meteorological parameters (observations and forecasts from numerical weather prediction models are also possible), initial levels of pollution, astronomical parameters, etc.

Both Lagrangian and three-dimensional Eulerian models are widely tested and validated, and are considered as powerful tools for describing the turbulent dispersion in the atmosphere. Especially the Eulerian models need large computational resources but, on the other hand, they provide three-dimensional concentration fields that are more reliable than those from statistical and analytical models. This is due to a more detailed description of atmospheric chemistry and of the physical processes responsible for dispersion, surface exchange processes, larger-scale forcing, and the interaction of the flow with the orography, provided the quality and representativeness of the input data is ensured. The large computational needs of Eulerian models are due to the necessity to solve the whole system of equations for each grid point. A doubling of the resolution in each of the three spatial directions (together with the then necessary halving of the time step) means an up to sixteen-fold computational effort. The main differences between Lagrangian and Eulerian models can be summarised as follows:

Lagrangian particle models, since the exact position of the fictitious particles is always known and does not need to be approximated by a grid, can follow the particle motions on all scales. Therefore, they are able to simulate all the phases of dispersion with equal accuracy. However, they cannot solve chemical reactions of second order. Some hybrid solution schemes have been proposed but are still under development. Thus Lagrangian particle models are more appropriate than Eulerian models for the simulation of dispersion in the near-field of emission sources, especially for the dispersion of inert substances. Moreover, Lagrangian puff models cannot deal well with vertically variable wind and are no longer state-of-the-art.

In Eulerian models, the solution is obtained on fixed grid cells (meshes) for both the pollutant concentrations and meteorological variables. On the contrary, in Lagrangian models, the equation is solved in terms of the total derivative in time, while the particle is advected by the mean wind. Eulerian models are able to deal explicitly with chemical reactions, but they have problems in the exact definition of sources, in particular point sources, and in the coverage of the early phase of dispersion processes, because they cannot resolve processes on spatial scales smaller than the grid cells used. On the other hand, Eulerian models are effective in describing the pollutant dispersion when the cloud size is large enough so that the concentrations gradients are resolved well by the grid. Thus Eulerian models are more appropriate than Lagrangian models for the simulation of dispersion in the far-field of emission sources, and for the dispersion of chemically reactive pollutants.

With respect to the various Eulerian chemistry transport models, one has the choice between offline and online coupled models. Offline models need lower computational resources than online models. They allow for fast scenario calculations. However, online models are more accurate because only they guarantee a continuous interchange between the meteorological conditions and the chemical reactions. With today’s computer resources online models are manageable.

4.5 Data evaluation methods

4.5.1 Statistics

Measurements with a high temporal resolution (up to 10 Hz for wind, temperature and some chemical species) and numerical simulation models deliver a vast amount of data. Therefore, in the past decades, a great effort was made by the scientific community in order to develop a common base of measures for the quality and accuracy of measurement and simulation results. A variety of statistical techniques and other type of measures, called data or model evaluation, have been suggested. Some of these techniques consider the correct spatial or temporal location of measured or predicted concentrations; others are based only on the estimate of the maximum values, or the overall concentration distribution. Some of the more commonly used statistical indexes are resumed in, e.g., Hanna et al. (1991), Klug et al. (1992), Mosca et al. (1998a,b), Sachs (1992), and Taylor (2001). Furthermore, methods such as histograms, plots of time series of specific variables (wind speed, temperature, humidity, selected chemical species, etc.), and box-and-whisker plots can be employed

4.5.1.1 Mean values

A first check of simulated values can be made by a comparison of the long-term mean values. They can easily give a hint to systematic errors (biases). The selected observational data have to be representative for the size of the grid cell of the model from which the modelled data are taken. Data chosen from areas with low horizontal gradients (to be diagnosed e.g. from maps, see below) are more likely to fulfil these representativeness requirements than data from areas with high gradients. Mean values are good data for trend analysis.

4.5.1.2 Maps

Maps of selected variables representing an average over a certain period of time (typically 1 hour, 1 day, 1 month or 1 year) can be plotted. They exhibit different features compared to observations which show a snapshot valid at a particular time. The reason for this is the fact that the models reproduce the statistical behaviour of turbulence effects through the employment of parameterisations, but they are not able to simulate the exact time evolution of the turbulent eddies and fluctuations. Therefore the modelled distribution of air pollution concentrations in plumes is generally smoother than the real concentration field at a certain moment. However, if the model output is compared with time-averaged observations where the averaging time is larger than the turbulent time scale, this discrepancy disappears.

The aforementioned fact applies not only to geographical maps but also to vertical cross-sections if simulated data are compared to the results of vertical remote sounding data (e.g. the comparison of aerosol distributions with ceilometer data).

4.5.1.3 Time series

Data obtained for certain locations can be plotted as time series. The comparison of the diurnal or annual course of observed and modelled meteorological or air quality parameters can easily be made from such series. Phase shifts and differences in the amplitude in modelled and observed time series can be analysed from these plots.

Time-height sections are an extended version of time series which display the temporal evolution of simulated or measured vertical profiles of meteorological or air quality parameters. They can be used in similar way like maps (see above).

4.5.1.4 Frequency distribution

Apart from time series and the display of horizontal distributions in maps also the analysis of frequency distributions of meteorological and air quality parameters can give valuable hints on the quality and reliability of simulated results. Statistical parameters (mean, median, shape, etc.) of the distribution of simulated parameters should be comparable to respective distributions of observed parameters. Again the representativeness requirements (see above) have to be fulfilled. If the frequency distribution is known forecasts about extreme values may be possible.

5 Noise

By the term "noise" one usually means an annoying, unexpected and undesired sound of any kind which is often considered to be too loud. Most outdoor noises are due to the human activity such as transport (land, air and sea), industry, construction/demolition (buildings, infrastructures), recreational activities and loudspeakers. What is remarkable is that human noise is often perceived as pollution while the ambient sound of our natural surroundings is usually accepted, even if louder.

According to the Green Paper on Future Noise Policy by the European Commission (1996), the noise situation in the European Union is alarming: *"it has been estimated that around 20 percent of the EU's population or close on 80 million people suffer from noise levels that scientists and health experts consider to be unacceptable, where most people become annoyed, where sleep is disturbed and where adverse health effects are to be feared. An additional 170 million citizens are living in so-called 'grey areas' where the noise levels are such to cause serious annoyance during the daytime"*.

At the beginning of 21st century, environmental noise was, for the first time, addressed multi-disciplinarily. Since then researchers, engineers, sociologists and doctors, as well as town planners, councillors, stakeholders and residents aimed at the common goal of better holistic living conditions in Europe. This chapter aims to present the main tools available to the acoustician to meet this social expectation.

The fundamentals of outdoor noise are firstly addressed with a focus on indicators and regulations. Different propagation processes and the mountain-specific aspects of noise are presented next. The two last sections are dedicated to the discussion of available scientific models (empirical, analytical and numerical) as well as evaluation methods.

5.1 Parameters, units and limits

In this section the main parameters are presented which are used for environmental noise studies, from the fundamental definitions to applied indicators. The most relevant environmental noise limits are also given.

5.1.1 Definition of noise levels

In environmental acoustics, two different types of noise level are used: The sound power level which is an intrinsic value of the sound source, and the sound pressure level as an extrinsic value corresponding to the received level at a microphone membrane or a human eardrum.

The sound power level L_w of a source is given, in decibel (dB), by:

$$L_w = 10 \log_{10}\left(\frac{P}{P_0}\right) \quad (5.1)$$

where P is the sound power of the source, in Watt (W), and P_o the standard reference sound power with $P_o = 10^{-12}$ W.

For line sources (such as roads and railway tracks), one specifies instead a unity sound power level L_W^*, in dB/m which is defined analogously to L_W with P being replaced by P^*, the sound power of the source per unity length in W/m. Thus for a line source of a length x, the total sound power level writes:

$$L_w^* = 10\log_{10}\left(\frac{P^* x}{P_0}\right) \tag{5.2}$$

The sound pressure level (SPL) L_p, predicted or measured at a specific receiver, writes, in dB:

$$L_p = 10\log_{10}\left(\frac{p^2}{p_0{}^2}\right) = 20\log_{10}\left(\frac{p}{p_0}\right) \tag{5.3}$$

where p is the root mean square sound pressure amplitude in Pascal (Pa), and p_0 the standard reference root mean square sound pressure $p_o = 2\cdot 10^{-5}\,\text{Pa}$. L_W and L_p always refer to a given single frequency f or frequency band Δf. The common frequency bands are the octave, 3rd octave and 12th octave bands. The bands are indicated by their (rounded) standard centre frequencies.

In practice it is often necessary to use time-averaged sound levels which describe a long-term situation rather than a single event (sound peaks). In this case an energy-equivalent average of the time-dependent sound (power or pressure) level $L(t)$ over a given time period is used. It is called the equivalent continuous sound pressure level, noted $L_{eq,T}$. It is defined as:

$$L_{eq,T} = 10\log_{10}\left(\frac{1}{T}\int_{t_1}^{t_2}\frac{p^2(t)}{p_0^2}dt\right) \approx 10\log_{10}\left(\frac{1}{T}\sum_{t\in T}10^{\frac{L(t)}{10}}\delta t\right) \tag{5.4}$$

where $p(t)$ is the instantaneous sound pressure amplitude in Pascal, $T = t_2 - t_1$ is the total integration period and δt is the sampling time period of typically 1 s

5.1.2 The A-weighting

In order to provide frequency-integrated values of the sound power or pressure level, one uses weighting curves to integrate the acoustical energy over a large frequency range. Among the five curves used in noise engineering (noted by A, B, C, D and Z), one applies the A-weighting one for assessing the noise impact of roads, railways and industries. The A-weighting reflects the sensitivity of the human ear to the audible frequency range. It emphasizes sound levels between 1 and 5 kHz and reduces them below and above this range (see Fig. 5.1).

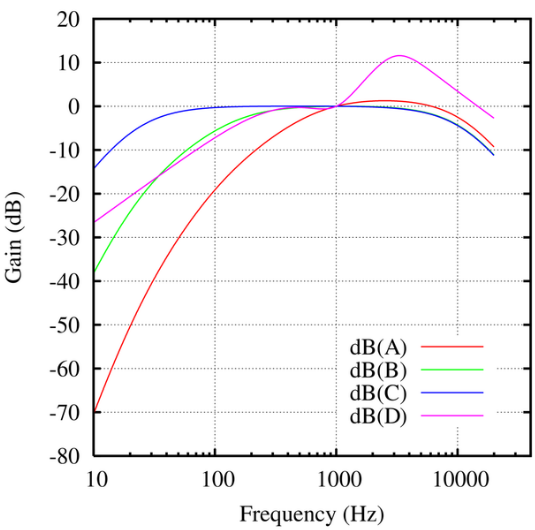


Fig. 5.1 A, B, C and D-weightings in dB as a function of frequency.

A-weighted sound levels are often indicated by dB(A). The global A-level L_A is calculated from the non-weighted levels $L_{\Delta f,i}$ of the frequency band $L_{\Delta f,i}$ as follows:

$$L_A = 10\log_{10}\left(\sum_i 10^{\frac{L_{\Delta f,i}+w_{A,i}}{10}}\right) \tag{5.5}$$

where $w_{A,i}$ is the discrete A-weighting correction of the *i-th* frequency band. The frequency weighting can be applied to both the source power level and the sound pressure level.

For road and railway noise, the integration is usually achieved using six octave bands with the standard band centre frequencies 125, 250, 500, 1000, 2000, 4000 Hz, or 18 3^{rd}-octave bands with the standard band centre frequencies 100, 125, 160, 200, 250, 315, 400, 500, 630, 800,1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000 Hz. The new European harmonised noise prediction model (Harmonoise Technical Report D18, 2004) even foresees 27 3^{rd}-octave bands ranging from 25 Hz to 10 kHz.

Applying the frequency weighting to the time average sound level $L_{eq,T}$ one gets the equivalent continuous A-weighted sound pressure level (during a period T), noted $L_{eq,T}$. It represents the basic environmental noise indicator. T is usually a period of several hours (e.g. daytime, evening, night).

Another useful indicator for the acoustic characterisation of passing trains is the $L_{Amax,T}$ which represents the maximum value of a L_{Aeq}(t) time series within a period T .

Tab. 5.1 presents a few typical values of L_{Aeq} corresponding to real situations

Tab.5.1 Some typical values of L_{Aeq} in dB(A)

Situation	L_{Aeq}	Situation	L_{Aeq}
desert / breathing	15	2×2 lane motorway, 200 m away	60
quiet farmland / wind in trees	20	animated street	70
sleeping room	30	2×3 lane motorway, 10 m away	80
murmur, 2 m away	40	High speed train at 300 km/h, 25 m away ($L_{Aeq,Tp}$, T_p being the passing duration)	90

5.1.3 Environmental noise indicators

Noise outdoors is generally characterized by specific indicators. These descriptors are of three types: energy-based, statistical and dynamic.

5.1.3.1 Long-term noise indicators

Most of environmental noise studies are achieved by predicting or measuring energy-based noise indicators. The most commonly used indicator is the A-weighted energy-equivalent continuous sound pressure level L_{Aeq} which is obtained by combining Eqs. 5.4 and 5.5. This indicator is often determined for specific long-term periods T (in Eq. 5.4) such as “day” (e.g. 07 h – 19 h), “evening” (e.g. 19 h – 23 h) and “night” (e.g. 23 h – 07 h). “Long-term” means here that the level is characteristic of a mean full year.

Combinations of $L_{Aeq,T}$ of different periods are also of common use in order to obtain a global value related to a global annoyance. The European noise indicator L_{den} (day-evening-night level) is defined as:

$$L_{den} = 10\log_{10}\left(\frac{1}{24}\left(12\times10^{\frac{L_{day}}{10}} + 4\times10^{\frac{L_{evening}+5}{10}} + 8\times10^{\frac{L_{night}+10}{10}}\right)\right) \quad (5.6)$$

where L_{day} is the A-weighted long-term average sound level determined over all the day periods of a year, $L_{evening}$ is the A-weighted long-term average sound level determined over all the evening periods of a year, and L_{night} is the A-weighted long-term average sound level determined across all the night periods of a year. The weighting factors 12, 4 and 8 refer to the duration of the respective periods. To express the relevance of the three periods for the annoyance (sensibility to noise depending on daytime) and audibility (decrease of masking during evening and night) the evening level is raised by 5 dB and the night level by 10 dB.

The maximum A-weighted sound pressure level $L_{A,max}$ determined over a given period or event (e.g. passing train), is sometimes used.

5.1.3.2 Statistical noise indicators

For the characterisation of non-steady noises (such as traffic noise in city centres) it is convenient to derive percentile levels L_n or L_{An} which represent the level exceeded for *n %* of the time during a given period. The most common percentile levels are:

- L_1 (exceeded in only 1 % of the time) to characterise outstanding noise (also called “peak level”),
- L_{50} (exceeded in 50 % of the time) to represent the median level,
- L_{90} (exceeded in 90 % of the time) to quantify the background noise level (also called “ambient level”).

Also combinations of percentile levels have been defined such as the noise pollution level

$LNP \approx L_{Aeq} + (L_{10} - L_{90})$ and the traffic noise index $TNI = L_{10} + 4\ (L_{10} - L_{90}) - 30$ dB; however their use remains limited.

5.1.3.3 Dynamic noise indicators

Dynamic noise indicators give the opportunity to quantify several temporal characteristics of urban noise. Most of them are calculated upon the A-weighted instantaneous (1 second) sound pressure level $L_{Aeq,}$1s. The main temporal sound characteristics addressed are:

- The *Sound Rhythm*, evaluated from the calculation of the amplitude modulation of a series of $L_{Aeq,1s}$ over a given period. This modulation is obtained by applying a spectral decomposition (usually by a Fast Fourier Transform; FFT) of these short-time levels. The rhythm is said to be pure when the modulation spectrum energy is concentrated to one peak (e.g. the sound occurs every 10 minutes), whereas it is rough when the energy is spread over a wide range of time intervals.
- The *Sound Roughness*, assessed from the statistical distribution of the $\delta L_{Aeq,1s}$ (instantaneous levels difference from one second to another). The roughness is high for a wide distribution whereas it is low for a narrow one. One often considers that for a given L_{Aeq} the degree of annoyance due to noise is proportional to its sound roughness.

- The *Noisiness*, quantified from the number and the mean duration of noisy events when a series of $L_{Aeq,1s}$ exceeds a fixed threshold, e.g. 70 dB(A).
- The *Quietness*, quantified from the number and the mean duration of quiet events when a series of $L_{Aeq,1s}$ does not exceed a fixed threshold, e.g. 55 dB(A)

5.1.3.4 Regulations and limits

The key international standards recommended for environmental noise purposes are summarised below:

- ISO 1996-1: 2003. “Acoustics – Description, measurement and assessment of environmental noise –Part 1: Basic quantities and assessment procedures”. It defines the basic quantities to be used for the description of noise in community environments and describes basic assessment procedures.
- ISO 1996-2: 2006. “Acoustics – Description, assessment and measurement of environmental noise – Part2: determination of environmental noise levels”. It describes how sound pressure levels can be determined by direct measurement, through the extrapolation of measurement results by means of calculation, or exclusively by calculation, intended as a basis for assessing environmental noise.
- ISO 9613-1: 1993. “Acoustics – Description, assessment and measurement of environmental noise – Part 1: Calculation of the absorption of sound by the atmosphere”. It specifies an analytical method of calculating the attenuation of sound as a result of atmospheric absorption for a variety of meteorological conditions.
- ISO 9613-2: 1996. “Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation”. It describes a method for calculating the attenuation of sound during propagation outdoors in order to predict the levels of environmental noise at a distance from a variety of sources. The method predicts the equivalent continuous A-weighted sound pressure level under meteorological conditions.
- The European Directive 2002/49/EC relating to the assessment and management of environmental noise (shortly: Environmental Noise Directive – END) was published on 25 June 2002. The aims of the Environmental Noise Directive are:

The determination of exposure to environmental noise through strategic noise mapping,

- the development and use of methods of assessment common to the Member States,
- the dissemination to the public of information on environmental noise and its effects,
- the adoption of action plans based upon noise-mapping results, preventing and reducing environmental noise where necessary and preserving environmental noise quality and
- the development of community measures to reduce noise emitted by the major sources, in particular road and rail vehicles, infrastructure, aircraft, outdoor and industrial equipment.

Two main indicators shall be evaluated through strategic noise maps:

- The L_{den} (day-evening-night level, see Eq. 5.6) which is a global annoyance indicator,
- The L_{night} which is the A-weighted long-term average sound level determined across all the night periods (typically 8 hours long) of a year and which is linked the annoyance at night.

For the largest agglomerations (airports as well as road and railway infrastructures) the first set of strategic noise maps should be published in mid 2007, followed by associated action plans in mid 2008. The process will be renewed and extended to smaller agglomerations and infrastructures (2012 – 2013), and repeated every 5 years afterwards.

It has to be noted that in parallel to the European and international standards and recommendations, many countries have their own standards with specific national regulations which may deviate from the aforementioned ones.

5.2 Mountain-specific aspects of noise

Transport-related noise in mountainous areas distinguishes from noise in typical flat terrain by three major effects:

- distribution of source and receivers: the topography restricts the area suited for transport routes and settlements. Traffic and villages concentrate along valleys and the average distance between noise sources and recipients is often short.
- sound propagation: ground and atmospheric propagation effects are strongly modified by the irregular terrain.
- sensitivity: mountains are often used as recreation areas where noise is especially annoying.

It has to be noted that the terms “flat terrain” and “mountainous terrain” are generalised. Firstly, there is a rather smooth transition from “flat” over “gentle” to “mountainous” terrain. Secondly, specific topographical features are found both in flat and mountainous terrain. Extended water surfaces (bights, lakes), for instance, have distinctive consequences for the distribution of traffic sources and residential areas and modify the propagation effects.

The following subsections address the specific aspects of transport noise in the Alps. Most of these aspects also apply to other mountainous areas and highlands in Europe.

5.2.1 Temporal and spatial distribution of emissions and receivers

To avoid expensive artificial constructions (long viaducts or tunnels) most of the major transport routes (road and rail) were built on the floor or sometimes the side slopes of the major Alpine valleys. Most residential areas in the Alpine region are found along the valleys. Transit routes which often stay away from settlements in flat areas, transect the housing areas very closely.

As residents and tourists wish to have spectacular panorama views, exquisite housing areas and tourist resorts are often built on elevated estates above the valley floor. However, with respect to noise such exposed positions can be a disadvantage. This situation is elucidated in Section 5.4.3.2.

Bridges are much more frequent in mountains than in non-hilly areas. Noise emissions from bridges are problematic due to the following effects: (1) the source is elevated and the sound can propagate without ground attenuation. (2) The rolling noise can be amplified by expansion gaps across the roadway or resonances with the bridge construction (e.g. old steel railway bridges). Noise from viaducts is therefore especially addressed in Section 5.4.3.1.

Since the number of suitable corridors for mountain crossings is limited, a high number of vehicles and trains concentrate along neuralgic transport axes where the nearby living population is exposed to excess noise and air pollution. In many valleys of the Alps even all types of transport infrastructures are bundled in parallel: motorways, secondary roads and railway lines. In this case the emissions of all these routes add up.

The transit traffic adds to the originating and terminating traffic which is not only caused by the domestic population but also by the enhanced tourist traffic to and from the respective attractions in the Alps. While the local traffic follows the usual daily/weekly cycle of rush hours on week days, the seasonally strong tourist traffic concentrates on weekends and partly fills the gap in traffic flow which is normally expected on weekends. The long-distance transit traffic, above all the freight traffic, is more or less equally distributed unless where special regulations are effective such as night-time or Sunday bans.

5.2.2 Propagation processes

5.2.2.1 General noise propagation

Before the specific sound propagation processes found in mountainous areas are described, the general processes are elucidated which are also responsible for the sound propagation in flat terrain. For further information we refer to review articles by Embleton (1996) and Sutherland and Daigle (1997).

Concept of sound rays

Sound rays are defined analogously to light rays. They describe an imaginary path along which a certain wave form feature travels through the carrying medium. In outdoor sound propagation the medium is the atmosphere. In a homogeneous atmosphere the rays are straight, while they are curved in an inhomogeneous atmosphere (see “refraction”). The rays are kinked at reflecting surfaces (ground, obstacles) according to the specular law of reflection. One or several sound rays connect a single sound source (point source) and a single receiver.

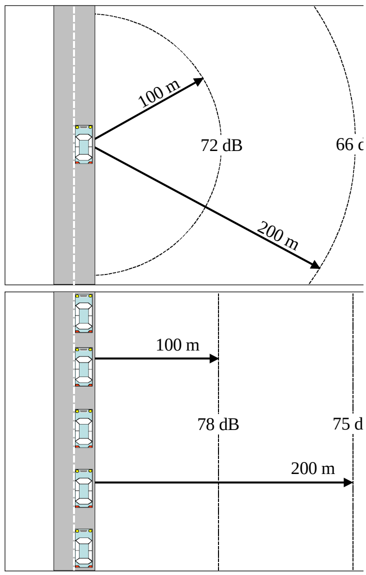


Fig. 5.2 Schematic view of the consequences of geometrical spreading. Top: point source, bottom: line source.

Geometrical spreading

Sound which is emitted from a near-ground source spreads into the half space above plane ground. With increasing distance from the source the sound energy is distributed into a growing volume of air and the sound intensity is thus diluted. For a single point source (e.g. a car) this leads to a 6 dB decrease of the instantaneous sound level for each doubling of the distance (see upper panel of Fig. 5.2). For a moving single point source (e.g. a moving car) the time-integrated sound exposure level decreases by only 3 dB for each doubling of the distance from the route of the moving source. The same 3 dB increase per doubling of the distance holds true for multiple sources on an elongated route (line source). Provided the traffic is constant and dense the 3 dB decrease applies to both the instantaneous sound level and the time-integrated sound exposure level (see lower panel of Fig. 5.2).

Atmospheric absorption

A certain portion of the sound energy dissipates as the sound waves propagate through the atmosphere. The degree of atmospheric absorption depends on the air pressure, the air temperature and the humidity. High frequency waves are much more attenuated than low frequency waves. Typical values of the absorption coefficient are 0.01 – 0.1 dB per 100 m for 100 Hz waves, 0.1 – 1 dB per

100 m for 1 kHz waves, and about 10 dB per 100 m for 10 kHz waves. An acknowledged procedure to calculate the atmospheric absorption of sound is given by the international standard ISO 9613-1 (International Organization of Standardization, 1993).

Reflection and ground attenuation

Sound waves are reflected at the ground and at the surface of obstacles (e.g. buildings, noise barriers), see Fig. 5.3. At the receiver the reflected wave superimposes the directly arriving wave. Because the travel distances of the reflected and direct sound are not equal, the waves are out of phase. Depending on the phase shift constructive or destructive interference occurs. For perfectly reflecting surfaces and a coherent source this leads to a doubling of the sound amplitude (phase shift 0°, 360°, etc.) or a complete cancellation (phase shift 180°, 540°, etc.), respectively.

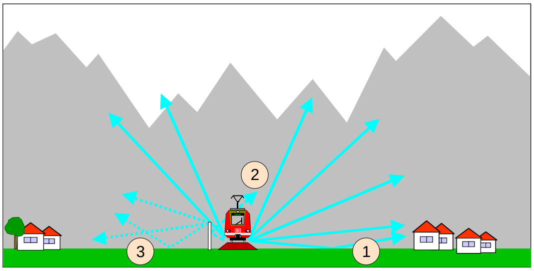


Fig. 5.3 Reflection at the ground ① and at a noise barrier②. Broken sound rays show the diffracted sound behind a barrier ③.

The reflection is specular, i.e. the angle of incidence equals the angle of reflection, if the surface of the reflecting surface is smooth. Rough surfaces lead to scattered reflection. Acoustically hard surfaces with high acoustical impedance (wave resistance) reflect almost all sound energy while acoustically soft surfaces partly absorb the sound energy. Natural porous types of ground (soil, sand, snow) are typically soft, i.e. the acoustical impedance is low. Moreover, a part of the sound energy penetrates into the ground and is reflected backwards to the atmosphere with a phase shift. This phase shift approaches 180° as the angle of incidence is low (grazing incidence). In this case the superimposition of the direct and reflected leads to a partial cancellation of the sound waves even though the travel distances do not much differ. This effect is referred to as ground attenuation. It is strongest for sound propagation from near ground sources to near ground receivers.

Diffraction

Diffraction sheds some sound energy into the regions shaded by obstacles (e.g. buildings, noise barriers); see Fig. 5.3. The degree of diffraction and thus the noise protection efficiency of obstacles depend on the geometry of the diffraction edge, e.g. the top of a noise barrier. Diffracted sound propagates like the direct one and can be reflected at the ground or at further obstacles.

Scattering

Sound is scattered at randomly distributed inhomogeneities (turbulent density and wind fluctuations) in the atmosphere. Forward and backward scattering dominates but some sound energy is also scattered in lateral direction such that additional sound energy may enter acoustically shaded areas. In addition, scattering lowers the phase correlation and decreases the importance of interference effects if direct and reflected sound superimpose. Scattering can also occur at rough reflecting surfaces if the roughness elements are of similar size or smaller than the wave length.

Refraction

Sound waves are refracted if the propagation speed is not uniform. The speed of the sound relative to the air is mainly determined by the air temperature and typically varies between 325 m/s (for

-10 °C) and 350 m/s (for 30 °C). The sound speed relative to the ground is additionally determined by the wind.

downward refraction

If the mean temperature increases with height (called “temperature inversion” or simply “inversion) as it is normally the case during clear nights, horizontally propagating sound waves (from near-ground sources to near-ground receivers) are refracted downward since the wave fronts move slower near the ground than aloft. As a consequence the sound rays are bent towards the ground repeatedly, thus resulting to *multiple reflections* (Fig. 5.4). A long-range audibility is often the consequence, above all if the sound propagates over acoustically hard, i.e. non-absorbing, ground. The sound level can be *increased* by 3 to 6 dB as compared to non-refracted propagation.

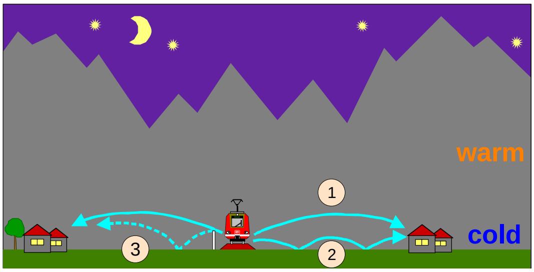


Fig. 5.4 Schematic view of sound rays in an inversion layer (night) with downward refraction ①, multiple reflection ②, and diffraction behind a noise barrier ③.

upward refraction

During sunny days when the mean temperature usually decreases with height, the opposite occurs, i.e. the sound waves are refracted upwards and the sound rays of horizontal propagation are bent away from the ground (Fig. 5.5). Beyond the point where the limiting ray touches the ground, sound rays cannot reach a ground based receiver anymore. This marks the beginning of the so called *refractive shadow zone*. Sound wave can only enter this zone by diffraction (creeping wave along the surface) or scattering from higher altitudes. The sound level in the shadow zone can be *reduced* by up to 25 dB compared to non-refracted propagation.

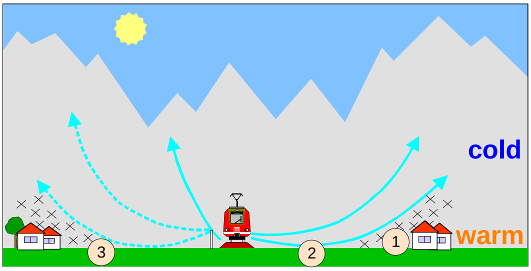


Fig. 5.5 Schematic view of sound rays in a layer with vertical temperature lapse (day) with upward refraction and the formation of a refractive shadow zone (×) ①, the limiting ray ②, and diffraction behind a noise barrier ③.

wind effects

If the sound propagates through a moving atmosphere the speed of the sound relative to the ground is not only determined by the sound speed relative to the air but also by the wind that carries the waves. The fact that the mean wind speed in the boundary layer always increases with height, has the following consequences (Fig. 5.6). If the sound propagates with the wind the wave fronts are slower near

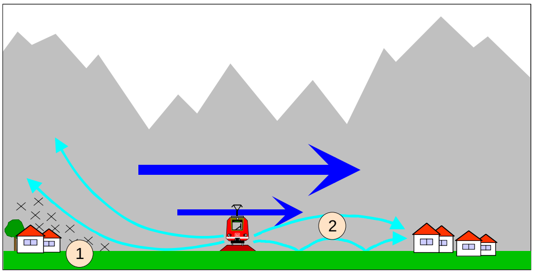


Fig. 5.6 Schematic view of sound rays in a layer with vertically increasing wind speed. Upward refraction and a refractive shadow zone ① occur in the direction of upwind propagation, while downward refractions and multiple reflection ② occur in the direction of downwind propagation.

the ground than aloft. On the contrary, they are faster close to the ground than aloft if the sound propagates against the wind. Therefore, downwind propagation leads to downward refraction (like in a calm atmosphere with temperature increasing with height, i.e. in an inversion layer) and upwind sound propagation leads to upward refraction (like in a calm atmosphere with temperature decreasing with height). The acoustical consequences of wind-induced refraction for ground-to-ground propagation (multiple reflections at the ground, formation of an acoustical shadow zone) are the same as for temperature-induced refraction.

combined temperature and wind effects

Over flat terrain only vertical variations of the mean temperature and the mean wind play a role. They determine the vertical gradient of the sound speed relative to the air and the vertical gradient of the wind speed component in the direction of sound propagation. Both can be added to form the *vertical gradient of the effective speed of sound*. This quantity is the decisive parameter for refraction in outdoor sound propagation.

The refraction effect is most pronounced for sound propagation from near-ground sources to near-ground receivers. Slant-wise propagation (e.g. from elevated sources like aircraft or to elevated receivers like the upper floors of tall buildings) is much less affected.

5.2.2.2 Noise propagation in mountainous areas

In mountainous areas the nature of the aforementioned propagation effects is different from that in flat areas. This is caused by the presence of the irregular topography and the reaction of the atmosphere to the topographical forcing. The relevant meteorological processes in mountainous terrain are explained in Section 3.1. The following paragraphs refers to the aspects of sound propagation as explained in Section 5.2.2.1 and points to the differences that occur in mountains, especially in Alpine valleys.

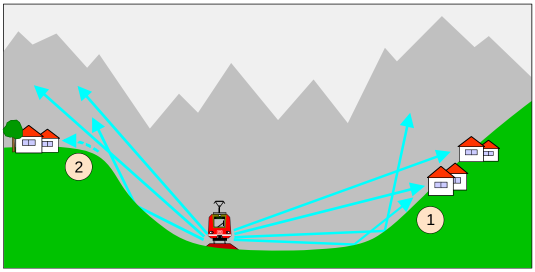


Fig. 5.7 Sound rays in a non-refracting valley atmosphere with reflection at a convex terrain shape ① and diffraction behind a slope edge ②.

Geometrical spreading

Sound that is emitted from a near-ground source spreads into the half space above plane ground. If the same sound is emitted near the bottom of a valley, the air space is reduced by the side slopes of the valley. Hence, the same sound energy is received by a smaller volume of air and the sound energy density (= sound intensity) is thus enhanced (Fig. 5.7). This is sometimes called *amphitheatre effect* because the tribune of an amphitheatre also reduces the propagation volume. A typical amphitheatre view is shown in Fig. 5.8. As a consequence the specific geometry of a valley generally

Fig. 5.8 Alpine valley with a motorway on a viaduct (Brenner route near Steinach/Austria) and an artificial head microphone in the foreground. Photo: P.Lercher.

tends to amplify the received sound level. In reality however, a general statement is not possible due to the reflection at the ground and the ground attenuation which largely depend on the shape of the terrain and the properties of the ground.

Atmospheric absorption

The effect of atmospheric absorption is principally independent of the topography. However, the meteorological conditions (temperature and humidity distribution) in an Alpine valley often deviate from those in the plains and may modify the local absorption coefficients.

Reflection and ground attenuation

If source and receiver are both placed on the valley-bottom the situation is similar to that in a plain. However, the situation is quite different if either the source or the receiver is placed on an elevated position. In this case the directly connecting sound rays do not graze over the ground but have a rather large distance from the ground. Even if the valley profile admits the superimposition of direct and reflected sound at the receiver, the ground attenuation is much less pronounced because the angle of incidence is larger than for near ground propagation. Therefore, bottom-to-slope or slope-to-bottom propagation normally results in higher sound levels at the same horizontal (projected) distance from the source even though the slant propagation path is longer.

Another characteristic of mountainous areas is the possible presence of snow at wintertime. The snow acoustically acts as a layer of fibrous material covering the ground. Attenuation is high (mainly for the high frequency sound) if this layer is sufficiently thick and fresh. The ground effect is estimated through its acoustic surface impedance. The later can be calculated from Delany and Bazley's ground model (Delany and Bazley, 1970; see also Section 5.4.1.1) with an air flow resistivity between 3 (very fresh snow) and 30 kPa s m^{-2} (old snow). However, as noticed before, the sound attenuation occurs only if the sound propagation is somewhat grazing on a quite long distance (several hundreds metres) which does not occur so often in mountainous areas due to the curved valley geometry.

Diffraction

In structured terrain diffraction does not only occur behind obstacles, but also behind convex terrain features such as the top of slopes or hills. Diffraction is one effect that transports sound energy to places on plateaus above a valley that do not have a line-in-sight connection to a source situated on the valley-bottom.

Scattering

The principle effects of sound scattering due to atmospheric turbulence do not depend on the topography. However, the Alpine topography strongly modifies the generation of atmospheric turbulence and changes its spatial and temporal distribution, its strength, and its frequency of occurrence.

Refraction

Refraction generally plays a minor role for oblique bottom-to-slope or slope-to-bottom propagation, i.e. for propagation paths that are not parallel to the underlying ground. As in flat terrain ground-to-ground propagation (e.g. on the valley bottom or parallel to a slope) can be also strongly affected by refraction. The importance of sound refraction in mountainous areas is largely determined by the specific meteorological effects that are inherent to structured terrain. This has various consequences to the sound propagation and the noise impact.

Even in situations with a large-scale flow across the valley, the wind in the valley is often *guided* or *channelled* by the side slopes and blows along the valley rather than slantwise or perpendicular to the valley axis. More complex flow situations are found near the mouth of tributary valleys. This means that the variability of sound levels due to wind induced refraction is less effective for propagation perpendicular to the valley axis.

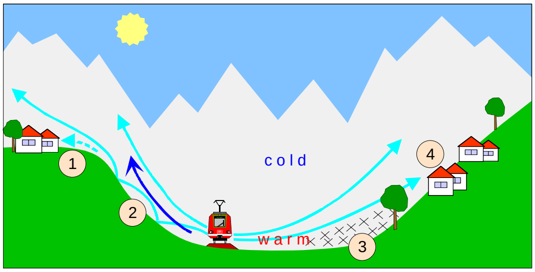


Fig. 5.9 Propagation features during a clear-sky day with diffraction and upward refraction behind the top of slope ①, downwind-upslope propagation in a upslope wind layer ②, upward refraction and formation of a shadow zone (×) due to temperature lapse ③, and direct sound incidence on the slope ④.

The frequency of *temperature inversions* is enhanced in deep valleys because cold air layers cannot be easily removed by the mixing with large-scale currents. Particularly in winter time the side slopes and adjacent mountains prevent the bottom of the valley from solar radiation such that nocturnal inversion layers cannot be heated away. This gives rise to rather frequent situations of downward refraction and long-range audibility.

In the vicinity of high-pressure weather systems with reduced cloudiness and weak large-scale wind flow *local* or *regional autochthonous wind systems* do frequently form. They are caused by differential heating or cooling of the near-ground air and the elevated layers of air at the same altitude.

Two major thermally induced wind systems are known (see also Section 3.1): mountain-valley winds and slope winds.

Mountain-valley (in-valley / out-valley) wind systems reach far up into the valley atmosphere. Hence, they are deeper than the acoustically relevant layer and the common refraction rule for upwind/downwind propagation applies (see Section 5.4.3.2). As a consequence downward refraction with high audibility occurs for down-valley propagation during out-valley flow (usually in the night and morning hours) and for up-valley propagation during in-valley flow (usually in the afternoon and early evening hours). Upward refraction with the formation of acoustical shadows and thus limited audibility occurs during the opposite situations.

During clear-sky days with heated air, the formation of a refractive shadow zone with reduced noise level occurs on the valley bottom in a sufficient distance from the source (Fig. 5.9). However, elevated dwellings do not benefit from the shadow zone since sound can arrive there despite of their upward directed curvature. If the sound propagates upwards along a slope with upslope wind a downward refraction may result as a net effect and multiple ground reflection is the consequence. In this case the diffraction behind the upper edge of the valley is supported by the downward refraction such that settlements on the elevated plateau are exposed to extra sound.

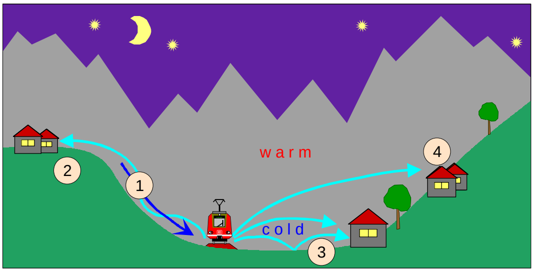


Fig. 5.10 Propagation features during a clear-sky night with upslope propagation in a downslope wind layer ①, diffraction and downward refraction behind the top of slope ②, downward refraction and multiple reflection due to a nocturnal inversion ③, and direct sound incidence on the slope ④.

However, downslope winds and drainage flows have a particular acoustical property as they are so shallow that a wind speed maximum is found in only a few metres above ground, that is, within the layer through which sound rays usually connect source and receivers. The existence of a wind speed maximum means that the vertical wind gradient below and above the level of maximum wind speed changes its sign and therefore the direction of refraction also changes from upward to downward and vice versa. If sound propagates in upslope direction in the presence of a downslope wind, the sound rays are bent upwards below the wind maximum and return downwards above. When the re-enter the layer below the maximum they are again refracted upwards and so on. As a consequence an *acoustical duct* can form which carries the sound without geometrical spreading up the slope. This may lead to a noise enhancement even though the sound propagates in upwind direction (Fig. 5.10).

Forests

Defrance and Barrière (2002) have shown that traffic noise propagation through a strip of trees (at least 100 m wide) is affected by two major phenomena:

- the typical ground effect due to the presence of humus. This brings about a change in the absorption due the specific soil porosity. Compared to a standard plain covered with farmland in homogeneous atmospheric conditions, noise attenuation due to the humus is usually less around 500 Hz but higher elsewhere.
- the meteorological effects due to a quasi cancellation of wind speed and air temperature gradients under the canopy. The consequence is that in the case of downward sound propagation conditions e.g. temperature inversion at night) leading to a maximum noise at the receiver (see Section 5.2.2), the presence of a wide strip of trees along a road or a railway track will transform this climatic situation into a quasi-homogeneous one, meaning less noise immission.

The effects of sound diffusion by trunks and foliages appear at 2 kHz, increasing afterwards with higher frequencies. However, in terms of long-term L_{Aeq}, these effects remain small compared to both ground and meteorological ones.

5.3 Observation methods

5.3.1 Instruments and methodologies

5.3.1.1 Standard sound level meters

Sound level meters measure the instantaneous sound pressure level (Fig. 5.11). They are commonly used in noise pollutions studies for the quantification of almost any noise, but especially for industrial, traffic and aircraft noise. The current international standard for sound level meter performance is IEC 61672 : 2003. The standard mandates the inclusion of an "A"-frequency-weighting filter and also describes other frequency weightings of "C" and "Z" (zero) frequency weightings (see Section 5.1.2). The older "B" and "D" frequency-weightings are now obsolete and are no longer described in the standard.

Fig. 5.11 Sound level meter (Norsonic 121) during the ALPNAP field campaign in the Lower Inn valley (Photo: M.Kästner).

The standard sound level meter must have a time-constant of integration, referred to as time-weighting. Three of these time-weightings have been standardised, "S" (1 s) for "Slow", "F" (0.125 s) for "Fast" and "I" (0.035 s) for "Impulse".

Sound level meters are divided into two classes. The two classes have the same design centre goals but the tolerances differ. "Class 1" instruments have a wider frequency range and a tighter tolerance than a similar, lower cost, "Class 2" unit. This applies to both the sound level meter itself as well as the associated calibrator. Most national standards permit the use of "*at least a Class 2 instrument*" and for many measurements, there is little practical point in using a Class 1 unit; these are best employed for research and law enforcement. New in the standard IEC 61672 is a minimum 60 dB linear span requirement and no frequency-weighting, with a general tightening of limit tolerances, as well as the inclusion of measurement uncertainty in the testing regime. This makes is unlikely that a sound level meter designed to the older 60651 and 60804 standards will meet the requirements of IEC 61672: 2003.

Many commercial instruments have integrated analysers which apply Fourier decomposition. It allows to analyse the noise frequency spectrum. Also time averaging processors which allow the calculation of energy-equivalent continuous noise levels over selectable periods are normal features of these instruments.

5.3.1.2 Binaural measurements

While standard noise level meters allow for a monaural recording of noise, it is more convenient to measure the binaural signal for psychoacoustic evaluations. In this case an artificial head is used which basically consists of two microphone that are installed in the "ears" of the model of a human head (Fig. 5.12). The binaural signal enables the determination of the direction from which the noise is arriving at the receiver. The difference in arrival time and sound pressure amplitude between both microphones is used to determine the directivity.

Fig. 5.12 Artificial head microphone for binaural noise measurements. Photo: P. Lercher.

5.3.2 Representativity and measurement strategies

Stationary noise monitoring networks are limited to neuralgic points and around airports. Normally, traffic noise is measured during temporary surveys and at distinct locations. Outside villages it is advisable to measure the noise synchronously with meteorological parameters. This is important to allow the evaluation of meteorological effects and to exclude spurious measurement values caused by wind noise. The latter is important in the case of unattended measurements.

The European Environmental Noise Directive (END, see Section 5.1.3.4) defines a standard level for noise predictions (noise mapping) of 4 m above ground. Noise measurements according to the END must not be installed below 1.5 m above ground. The height of 1.5 m is representative of the audition of human beings outdoors. The height of 4 m is representative of sound at the façades of buildings. Sometimes noise measurements are performed directly at the ground on a acoustically hard, i.e. perfectly reflecting plate to exclude the possible effect of interference of directly inciding sound waves and sound waves that were previously reflected at the ground. However, this observation method is not representative for the sound perceived by human beings.

The measurement strategy depends on the purpose of the measurement. For the documentation of events (e.g. after complaints) it is mostly sufficient to measure only at one location over a period that is long enough to encounter the problematic situation. For comparison studies synchronous measurements at several locations are necessary. In the support of process studies that aim at certain propagation effects, systematic measurements are necessary.

Prototype and maybe exemplary field campaigns were performed during the European project HARMONOISE to gain data for model validation near traffic routes (motorways and railway lines). Two campaigns were accomplished in hilly terrain. In these campaigns five or more acoustical measurement stations were aligned nearly perpendicular to the traffic route. One of the stations was erected in a close distance (25 m) from the source to monitor the source level. This is possible since propagation effects can be largely excluded at this distance. The remaining stations were placed up to a distance of more than 1000 m from the traffic infrastructure. The microphones were installed on masts at 4 m above ground. In addition to the acoustical sensors the masts were also equipped with meteorological instruments for wind, temperature and humidity. Near one mast an additional ultrasonic anemometer (see Section 3.2.2.2) was located to measure the turbulent fluxes of momentum and heat. The later enable the estimation of the vertical wind and temperature profiles through empirical flux-profile relationships (see Heimann et al., 2007).

During ALPNAP noise measurements were performed in the Lower Inn valley (for the results see Section 7.1). The strategy of this campaign was to ensure a coordinated and synchronous observation of meteorology, air pollution concentration end noise levels in a certain cross-section of the valley. Measurement instruments were therefore place on the bottom of the valley and at an adjacent slope position.

5.4 Modelling

5.4.1 Types of models

Two families of models are usually employed for outdoor noise predictions. The first gathers methods based on a geometrical approach of the sound propagation. The principle is that sound is assumed to propagate along acoustical paths (empirical, ray and beam models). The models are then called analytical methods since they do not imply the numerical integration of a function. The second family is concerned with numerical approaches usually involving the resolution of more complex equations (Boundary-Element-Model or BEM, Parabolic-Equation or PE, and Euler-type or FDTD models). A few other numerical approaches have been developed but show strong limitations to handle complex situations (Fast Field Programme or FFP, Gaussian beam models). In the following sections, the principles of these models with their limits, advantages and shortcomings, are presented.

Commercially available models mostly belong to the first model family. The respective software is user-friendly and compatible with standard data interfaces, e.g. Geographical Information Systems (GIS). The models of the second family have specific abilities to study or assess complex situations which cannot be tackled with the 1st-family models. However, they require well-trained staff to be operated. These types of models are usually owned by research centres, universities or some consulting bureaus that can be commissioned for model studies.

5.4.1.1 Empirical models

Many empirical formulations have been developed in order to predict specific outdoor noise effects. As for the ground effect, the ISO-9613-2: 1992 method proposes a set of empirical formula based on measurements of elevated industrial noise sources. These expressions are function of the propagation distance, the source and receiver heights as well as the ground type. However each of these parameters has a limited range of validity. An extension to situations outside this range (for example for more absorbing ground or a very low source height) is not possible.

Other models are semi-empirical. An example is the acoustic impedance model for porous materials developed by Delany and Bazley (1970). It is often used to parameterise the effect of outdoor grounds and asphalt surfaces on the base of the flow resistivity (common unit: kPa s m^{-2}) of porous ground. Concerning noise barrier abatement effects, the well-known Maekawa attenuation curve (Maekawa, 1968) is actually a compromise between Fresnel theory of diffraction and scale model measurements results. For the same purpose Kurze and Anderson (1971) used both experimental data and Keller's theory of diffraction (see next section) in order to develop their semi-empirical formulae of noise barrier attenuation. However these two approaches are limited to rigid straight barriers.

Advantages: All these empirical models are very fast algorithms. They are often used together with a ray tracing algorithm. They can handle standard basic situation but not too complex ones.

Shortcomings: The main restriction is the impossibility to extend the applicability of each model out of its range (type of ground or type absorbing material, propagation distance, characteristic heights, shapes). It is mainly due to the fact that the various physical effects are taken into account all together (absorption, turbulence, diffraction, meteorological effects…). Another limitation is the accuracy of the noise predictions which should be considered with care.

5.4.1.2 Ray and beam models

The ray model is a Lagrangian description of sound propagation. It traces the wave surface points as they move. The acoustic ray is actually the projection of given points of a wave surface. For such a so-called geometrical method, the main hypothesis is that the medium varies slowly meaning that the wavelength should be small compared to the characteristic scale of the medium. In other words, the ray model is a high frequency approach and often fails in the low frequency range.

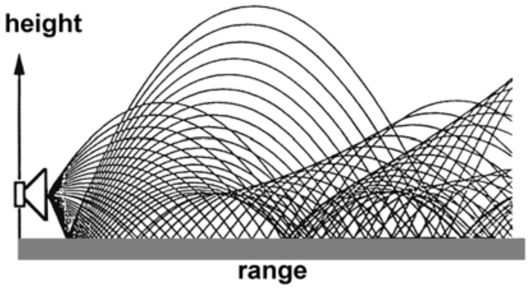


Fig. 5.13 Ray tracing from a monopole sound source above ground in the case of a positive vertical sound speed gradient (downward refraction).

The first step in such a method is to determine the paths of the rays, applying step by step either the Snell's law or the characteristics method. Fig. 5.13 shows an example of ray tracing in the case of a positive vertical sound speed gradient. The sound pressure can be calculated along a path using Blokhintzev's theory (1946). However in these geometrical methods, the calculation of the sound pressure level attached to one ray is generally obtained by subtracting the acoustic attenuations due to the main physical phenomena encountered during propagation of sound along the ray or beam from the source sound power level. The main physical phenomena are:

- the geometrical divergence,
- the atmospheric absorption,
- the diffraction effects,
- the ground effects,
- the effects of reflection and multi-reflections.

The atmospheric absorption can be determined from the standard ISO 9613-1 model. The attenuation due to diffraction can be evaluated using Keller's (1962) geometrical theory of diffraction or preferably the unified theory of diffraction later developed by Kouyoumjan and Pathak (1974). The ground effect may be evaluated by Chien and Soroka's (1980) asymptotic formulae. On a complex path with one or more diffraction and several ground effect zones, one usually applies a heuristic association of several separate asymptotic solutions (Defrance and Gabillet, 1999). Meteorological effects can be taken into account in a simplified way by linearising the sound speed profiles (van Maercke, 2007). The beam approach is actually an extension of the ray theory where each of the polyhedral beams is defined by a series of individual rays.

Advantages: The ray model is a fast algorithm. It is able to handle very complex geometries in an approximate way. It is suited to sound propagation in dense urban areas as well as uneven terrains. Two and three-dimensional simulations are possible. Another positive point is that it opens a didactic view to wave phenomena and also gives the opportunity to explain physics to non-specialists in a rather simple, understandable way.
Shortcomings: The two main limitations of the model are: the low frequency range where the calculations usually fail; and a number of approximations that make it difficult to apply it to more complex geometries such as ground impedance discontinuities, reflection and diffraction on small obstacles, or complex noise barriers. The presence of caustics in downward refraction, i.e. zones where rays of the same tube cross in one point, lead to an unrealistic infinite sound pressure. Shadow zones generated in upward refraction cause false results.

5.4.1.3 Boundary-element models (BEM)

The Boundary Element Method is a numerical technique developed in the early 1960s, based on the older theory of boundary integral equations. These methods have been intensively discussed in the literature (for instance Ciskowski and Brebbia, 1994). In unbounded situations, the BEM has been found to be more appropriate than other well-known numerical tool, e.g. the Finite-Element Method, since it requires only boundary, instead of a domain discretisation. In fact, since the propagation domain does not have to be meshed, the BEM allows to reduce the dimension of the problem by one and the acoustic field everywhere in the medium is then solely determined by the radiation of the boundaries.

Two families of Boundary Element Methods can be distinguished: direct and indirect formulations. An advantage of the indirect formulation over the direct one is that, in the case of simply boundary conditions, the acoustic field can be represented by only one simple- or double-layer potential. In any case, both formulations depend on the Green's function of the problem, that is, an elementary solution of the Helmholtz equation satisfying the Sommerfeld condition and certain boundary conditions. The more information the Green's function accounts for, the smaller the integration domain of the corresponding integral formulation.

This model is a frequency domain approach and exists in 2D (coherent line source) and 3D (point source) versions. For 2½D simulations of propagation from a point source or incoherent line source in a 3D environment with the geometry kept constant in the 3rd dimension, Duhamel (1996) has shown that it is possible to obtain the pressure field by simply post-processing 2D results via a Fourier-type integration. One application is the study of the diffraction by road barrier caps depending on the source type (Jean et al., 1999).

Advantages: The BEM is one of the most powerful reference models dedicated to sound propagation over complex geometries in a homogeneous atmosphere. It can take into account any boundary shape with a given surface impedances. It has been widely used for the assessment of complex noise barriers such as crownings (Defrance and Jean, 2003), vented covers (Defrance et al., 2004) and low height protections (Baulac et al., 2006).

Shortcomings: The two main restrictions are the calculation time and the negligence of meteorological effects. The BEM is a finite element approach, meaning that the boundary needs to be meshed in segments according to the considered sound frequency. The higher the frequency the smaller the segments on which the pressure function has to be estimated. Thus the BEM is not a high frequency method and calculations over 5 kHz need important processing time. In the same way, the length of the boundary is limited but an infinite impedance ground can be included without extra processing time (source-image method).

5.4.1.4 Parabolic equation models (PE)

The Parabolic Equation is an approximate form of the wave equation. The PE method was introduced at the beginning of the 1940ies to solve problems in electromagnetic wave propagation. Later it was used in underwater acoustics. Gilbert and White (1989) adapted the PE method to atmospheric acoustics. The sound field of a point source in a refracting atmosphere above a ground surface is calculated. Sound propagation can be calculated in a range-dependent environment: the sound speed profiles and the ground impedance may vary along the propagation path. The atmosphere may also be turbulent. Diffraction by simple straight noise barriers can be accounted for with a Kirchhoff approach.

There are many PE methods (Crank-Nicholson, Generalized Terrain, Split-step Padé or Green's function PE). Most of these PE methods are described in Salomons (2001). Even if PE is a one-way propagating method (no backscattering) recent works by Aballéa and Defrance (2007) have shown the possibility to take into account reflections by finite impedance noise barriers. Other research carried out in the frame of the European project HARMONOISE has shown the efficiency of coupling the Boundary Element Method with the Parabolic Equation (Defrance et al., 2007) in order to take advantage of both of them: propagating in a complex geometry in the vicinity of the source (BEM) and then in an open area on a long range with range-dependant sound speed profiles and ground impedances (PE).

Advantages: The Parabolic Equation is an efficient model well-suited for long-range sound propagation over an almost flat terrain with complex range-dependant sound speed profiles. Two and three-dimensional simulations are possible. Turbulence may be taken into account.

Shortcomings: The main restriction of the PE is its spatial zone of validity within a small angle (maximum of 40° up and down a horizontal line from the source). The processing time depends on the considered frequency and range. It can be a limiting factor for high frequencies and/or long ranges. Some implementations of the PE (such as the GF-PE) are less stable than other when meteorological profiles become rough. PE models take into account only simple diffraction obstacles (straight barrier or rectangular building) and are difficult to handle uneven ground situations.

5.4.1.5 Lagrangian sound particle model

Sound particle models are ray-based procedures. They resemble the Lagrangian air pollution dispersion models (see Section 4.4.2.1). A realization of such a type of models which is capable of mountain effects was published by Heimann and Groß (1999). This model considers complex terrain and meteorological fields which are consistent with the terrain. The publication shows how this model can be coupled to the results of a meteorological mesoscale model (see Section 3.3) and how it can be applied to an idealized narrow valley under slope-wind conditions (see Section 3.1). This specific model realization is briefly described in the following.

In the model some thousands of sound particles are released at the source into prescribed directions. Each sound particle carries a fraction of the total sound energy (individual amplitude) according to the sound power of the source and its directivity. The particles move with the speed of sound relative to the wind. The direction of travel is changed according to the local refraction where the gradients of the sound speed and the wind are determined at each particle position by interpolation of the background meteorological field. The trajectories of the particles therefore coincide with the sound rays (see Section 5.4.1.2). For each frequency (wave length) the individual amplitude and phase is known at each position. During propagation the individual amplitude is reduced due to atmospheric absorption. If a sound particle hits the ground it is reflected. During reflection the individual amplitude changes and the phase is shifted according to the angle of incidence and the ground impedance. The later is parameterized from the prescribed ground resistivity using the method of Delany and Bazley (1970), see Section 5.4.1.1.

In predefined receiver volumes inside the model domain the number of passing particles is counted. For each frequency the individual amplitudes are added where the respective phase is considered. Diffraction is simulated by splitting the sound particles and distributing the individual amplitude to several new particles. The new particles continue the travel into the shaded area along diffracted rays. The model calculates the noise frequency spectrum at each receiver element. Weighted (e.g. A-weighted) noise levels can be derived.

Advantages: The sound particle model is a rather fast algorithm. Nevertheless, it is still more expensive than empirical models as described in Section 5.4.1.1. It is suited to sound propagation over a long range. Two and three-dimensional simulations are possible. Complex terrain shapes, inhomogeneous ground properties, inhomogeneous wind fields (three components), temperature and humidity fields can be considered.

Shortcomings: Since the sound particles follow sound rays the solution is most exact for high frequency sound. The diffraction process is simplified. However, frequency effects can be considered for diffraction. The computational effort grows with increasing domain size because of the longer travel time and the fact that a higher number of particles is necessary. It also grows with the number of frequencies involved. The consideration of obstacles (e.g. buildings or barriers) is principally possible, however difficult to realize.

5.4.1.6 Eulerian time-domain sound propagation models

Linearised Euler finite-difference time-domain models (LE or FDTD models) work like dynamic meteorological models as described in Section 3.3. Prognostic equations for the sound particle velocity (three components) and the sound pressure are integrated in time on a numerical grid. The equations consider the meteorological field as a constant background. A specific realization which considers non-plane ground by means of transformed coordinates is published by Heimann and Karle (2006). This specific model realization is briefly described in the following. Alternative realizations are for example Van Renterghem and Botteldooren (2007) or Wilson et al. (2007).

The source is implemented either as an initial condition (pulse source) or by an internal boundary condition (continuous source). In the first case the sound pressure is disturbed near the source at the beginning of the simulation. As a consequence a solitary pressure wave travels away from the source. The integration is terminated after the complete sound energy has left the model domain. The time-evolution of the sound pressure is recorded at the receiver points. Subsequent Fourier analysis is applied to determine the amplitude and frequency spectrum. In the second case harmonic or arbitrary oscillations are continuously excited at the source. The integration is terminated when a steady state is achieved inside the model domain. The effective amplitude of the travelling sound waves is determined at the receiver points by averaging the square of the sound pressure over the longest wave period.

Ground effects (reflection) are considered by a ground layer in which the equations are modified according to the ground model of Zwikker and Kosten (1949) adapted by Salomons et al. (2002). Uneven terrain is simulated by the implementation of a terrain-following coordinate system. Totally reflecting obstacles can be simulated by setting the particle velocity to zero at the surface of the obstacles.

At present, Euler-type finite-difference time-domain models are most appropriate to simulate the effect of complex geometries in the vicinity of the source (e.g. the effect of noise barriers in wind, noise in street canyons, etc.). Nevertheless, 2D simulations for the lower frequency range (< 500 Hz) are possible over a range of a few hundred of metres. 3D simulations are limited to the immediate vicinity (about 25 m) of a source.

Advantages: Euler-type finite-difference time-domain models provide straight-forward solutions of refraction, diffraction and reflection processes. Also scattering at turbulence can be simulated by underlying changing turbulence realizations which are superimposed to the background meteorological field. Simulations are possible in two and three dimensions. Uneven terrain and arbitrary obstacle geometries can be considered.
Shortcomings: Euler-type finite-difference time-domain models have a very high computational demand since the full domain has to be meshed and the numerical grid interval must be in the order of 1/10 of the wave length. This means that a grid interval of about 3 cm is necessary for the simulation of a 1 kHz wave. Depending on the desired range the number of grid point can rise to a number which is no longer feasible even by high-performance computers. Atmospheric absorption cannot be directly simulated.

5.4.1.7 Other numerical models

Other interesting numerical approaches have been developed during the past decades. Two of them are briefly presented hereafter for information. However they are characterized by a number of limitations which make them difficult to apply in complex situations such as mountainous valleys.

Fast Field program (FFP)

The FFP allows the acoustic pressure field due to a point source in a layered atmosphere above a flat homogeneous ground to be calculated. It has been originally developed in underwater acoustics (DiNapoli and Daevenport, 1980) and adapted later to the propagation in the atmosphere (Nijs and Wapenaar, 1990). It is basically a numerical implementation of the integral transform technique for horizontally stratified media where the field solution can be described as a spectral integral of solutions to the height separated wave equation, with the use of a Fast Fourier Transform (FFT). Compared to the Parabolic Equation, the FFP shows many disadvantages: calculations fail if source and receiver have the same height above ground, the ground cannot be discontinuous, sound speed profiles are not described through continuous functions and the diffraction effects cannot be accounted for.

Gaussian beam model

This model requires first to launch rays from the sound source and then to solve the propagation equation in the vicinity of each ray, leading to a solution in the form of a Gaussian beam (Blokhintzev, 1946; Cerveny et al., 1982). The pressure at the receiver is finally obtained by summing the contribution of all beams passing close to the receiver. This solution is uniform anywhere and solves the problem of caustics. Moreover this method is less sensible to the exact details of the medium since the Gaussian beams method achieves a local average. Furthermore it is not necessary to find the rays which intercept exactly the receiver bringing about a reduction of calculation time. However this method is not suited for the calculation of diffraction by barriers and topography, and the ground effects should be handle with great care.

5.4.2 Benefits and costs

The various types of models which are available in outdoor acoustics cover nearly all relevant effects of sound propagation. However, there is no model that can be used as a universal tool. Many models are highly specialised to certain processes and effects. A few models are capable of more effects, but suffer from high computational demands which limit their use in practice.

In many cases, especially in long-term noise assessments and short distances, empirical models are sufficient. They are particularly suited for noise mapping with extended lines sources and a large receiver area. This type of models is therefore used in prediction standards (ISO 9613-2, the intermediate methods of the Environmental Noise Directive, see Section 5.1.3.4).

Nevertheless, special effects, above all those addressed in Section 5.2.2.2, may lead to substantial deviations from the assumptions underlying the empirical models. In this case more sophisticated models should be used to assess the consequences of the negligence of these effects. These models can be applied either under real or idealised conditions, i.e. for selected case studies or more principle studies, respectively (see also Section 5.5). The use of the models described in Sections 5.4.1.2 to 5.4.1.7 requires the knowledge of experts who know about the accuracy and limitations of the respective models and who have the experience in setting up appropriate simulations strategies. Moreover, the computational demand of these models can be very high and may require the access to high performance computers.

In many cases it can be less expensive to use a numerical model to find indications for the solution of existing problems than to make experiments in the real world. Models can be used already in the planning phase to find optimal solutions that can be realised later, e.g. specific noise abatement measures in a certain topographical situations. For instance it is easily possible to perform several simulations in which one parameter (e.g. the height of a noise barrier) is systematically changed. Comparisons between the results of such simulations can be evaluated to quantify the expected effects.

More detailed and generally valid information about benefit and costs cannot be given here because of the variety of imaginable problems. The advice of noise propagation model experts is strongly recommended.

5.4.3 Idealized model studies of typical noise problems in mountains

Advanced sound propagation models are used to study special topographical and meteorological effects. Like in laboratory experiments, idealized simulations allow to isolate distinct causes and their effects. Real cases are normally exposed to a variety of synchronously occurring influences such that an isolation of the causes is often not possible. In the following two subsections it is demonstrated how noise propagation models, partly coupled with precursory meteorological simulations, can be applied to study the effects of roadside installations on the ambient noise immission. The first study deals with the influence of edge barriers and central gaps of a road viaduct. The second one investigates the efficiency of noise barriers near a slope with its characteristic meteorological phenomena. Both situations are often found in the Alps although the geometric dimensions vary from place to place and may be different from the assumptions that were met here.

5.4.3.1 Noise emission from viaducts

Many viaducts are built in the Alps, most of them for motorways. The way the sound grazes the asphalt surface from the low and high traffic sources up to the road railing, and how it then diffracts towards dwellings is a complex mechanism. The standard approaches are suited to plain situations but fail in predicting finely sound behaviour for such geometries.

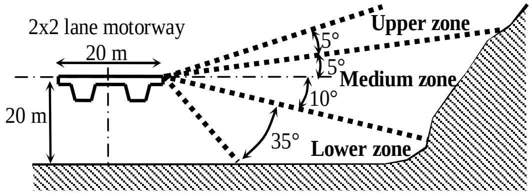


Fig. 5.14 Definition of the three receiving zones

Fig. 5.15a Geometry of the platform with the absorbing 1 m high edge barrier

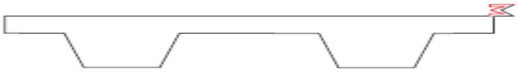


Fig. 5.15b Geometry of the platform with the absorbing sigma-shaped 1 m high edge barrier

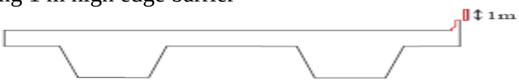


Fig. 5.15c Geometry of the platform with a 2 m barrier having a horizontal slit

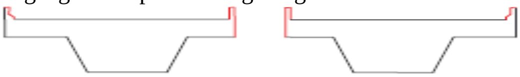


Fig. 5.15d Geometry of the platform with a gap and 1 m high barriers at edges

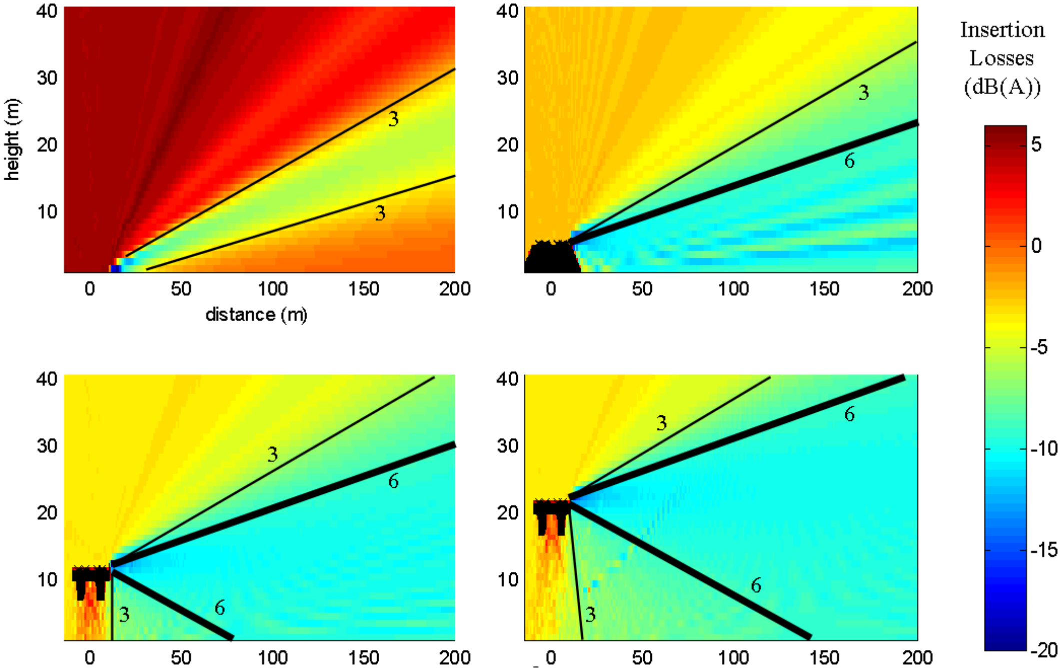


Fig 5.16 Efficiencies in dB(A) of a 1 m high absorbing barrier constructed at the right edge of the road platform, as a function of its elevation. From top left to bottom right: 0 m (natural terrain level), 5 m (embankment), 10 and 20 m high (viaducts).

One gives hereafter the trends of noise emission from viaducts as a function of both their geometry and the receiver location. The 2D-BEM model is used since meteorological effects can be neglected for the short propagation. This assumption makes sense since the viaduct considered here is sufficiently high (20 m) and the ground effect is not affected by refraction. In order to summarize the major trends obtained from simulations, one considers three receiving zones (lower, medium and upper) defined from the position of the right platform edge (see Fig. 5.14).

Effect of the platform elevation

The question addressed here is: what is the difference from the sound receiver point of view between a zero-elevation motorway (plain situation) and a motorway on an elevated viaduct? If one stands on a flat terrain 100 m away from the motorway, the average received noise will be maximum when the elevation is around 5 m and minimum for an elevated viaduct (5 to 10 dB(A) less). In the case of a receiver 1.50 m above the road platform level (i.e. receiver on a slope ground for the viaduct cases) 100 m away from the motorway, the maximum sound level is observed for the elevated platform when the minimum occurs for a zero-elevation road (3 to 10 dB(A) less depending on the meteorological conditions).

Effect of a 1 m high barrier at the edge

Fig. 5.15a shows the noise attenuation results due to an absorbing 1 m high barrier at the edge of the platform (geometry in Fig.GeoViad1). For a plain situation, the effect of the 1 m high barrier is weak. In the case of a viaduct, the effect is sensitive with a maximum attenuation in the medium zone (up to 10 dB(A) improvement). However the effect remains limited in the lower zone.

Effect of the complex shape of the barrier

In order to improve the efficiency of the 1 m high barrier in the lower zone of a 20 m viaduct, one may carry out a shape optimisation. For instance, for the case of a sigma-shaped 1 m high barrier (as described in Fig. 5.15b), the extra attenuation calculated compared to the case of the straight barrier (as described in Fig. 5.16) is between 3 and 6 dB(A) in this lower zone.

Effect of a mid-height horizontal slit along the edge barrier

A horizontal slit of about 20 cm is often encountered on the Alpine viaduct barriers. The reason is that the lowest part (usually a concrete 1 m high barrier) stands for security when the upper part (usually a 1 to 2 m high Plexiglas panel) is used as a wind screen. The BEM calculations show that the presence of a 20 cm slit at the mid-height of a 2 m high straight barrier (geometry in Fig. 5.15c) does not lead to any sensible noise gain in the three receiving zones.

Effect of a central gap in the platform

The viaduct is sometimes made of two parallel platforms separated by a few metres wide gap. The presence of this void brings about an important increase of the received noise level (6 to 15 dB(A)) in the zone located just below the viaduct. In the lower, medium and upper zones, the impact of the gap remains small in the order of a few dB(A).This degradation can be cancelled by the addition of complementary absorbing barriers at the two gap edges (as shown in Fig.5.15d).

5.4.3.2 Efficiency of noise barriers near slopes and plateaus

The following two-dimensional model study demonstrates how the efficiency of road-side noise barriers is influenced by a nearby slope with slope winds. A traffic source (motorway) is located on the bottom of a valley while housing areas are found on the slope or on an elevated plateau. For simplicity the slope between the valley-bottom and the plateau is uniformly inclined. Only the transition from bottom to slope and from slope to the plateau is assumed to be smoothly curved.

The model study comprises several experiments (Fig. 5.17) with three different plateau heights (h_p= 40, 80 and 120 m) and two source positions (10 and 100 m away from the foot of slope).

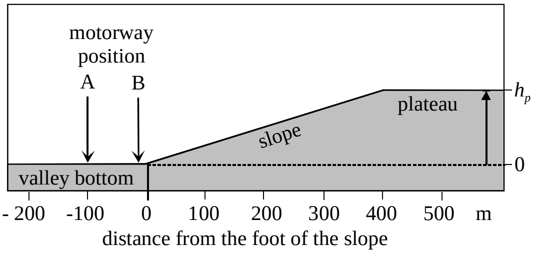


Fig. 5.17 Geometry of the investigated situation.

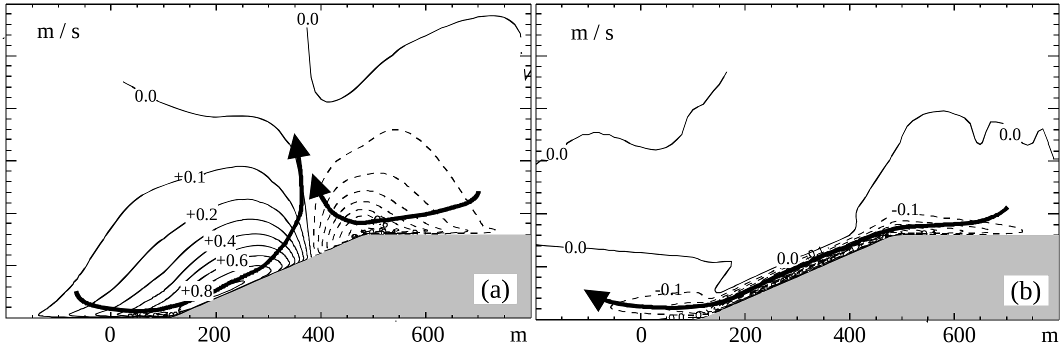


Fig. 5.18 Simulation with a meteorological mesoscale model of a heated slope layerwith upslope winds (a) and a cooled slope layer (b) with downslope winds The vertical scale is stretched by a factor of 2.

Results of the meteorological simulations are shown in Fig. 5.18 for the case with an 80 m high plateau. Panel (a) presents the results for a heated slope which is faced towards the sun (e.g. a westward facing slope in the late afternoon). The heated air above the slope induces an upslope current. It extends from the foot area of the slope over the lower 2/3 of the slope where it separates from the surface. Panel (b) of Fig. 5.18 shows the results for a cooled slope which is representative of the early evening hours (1 hour after sunset). An inversion layer has formed which extends up to 80 to 100 m above the level of the valley-bottom. A downslope wind is induced which penetrates about 100 m into the bottom area of the valley.

Acoustical simulations were performed with the Euler-type finite-difference time-domain model as described in Section 5.4.1.6 (Heimann and Karle, 2006). The simulated transmission loss due to the road-side noise barriers (barrier insertion loss) is visualized in Fig. 5.19 for all considered situations. The higher the insertion loss the more is the noise reduced by the barriers. A negative insertion loss means an amplification of the sound level due to the inserted noise barriers.

Relative to plane ground (black curve) the insertion loss is reduced on the slope and the plateau in most cases, in particular if the motorway is located close to the foot of the slope (position B) and for steep slope angles. In these cases the barriers even lead to a slightly enhanced noise level on the upper part of the slope (negative insertion loss). The barrier effect depends on the meteorological situation and on the steepness of the slope. It is rather independent of the receiver position on the slope. The barriers are most efficient for a flat slope under nocturnal meteorological conditions (inversion and downslope wind). On the other hand, the barriers can even cause an amplification of the noise level (by up to 1.5 dB), mainly on the upper parts of steep slopes and during day-time or under isothermal and calm conditions.

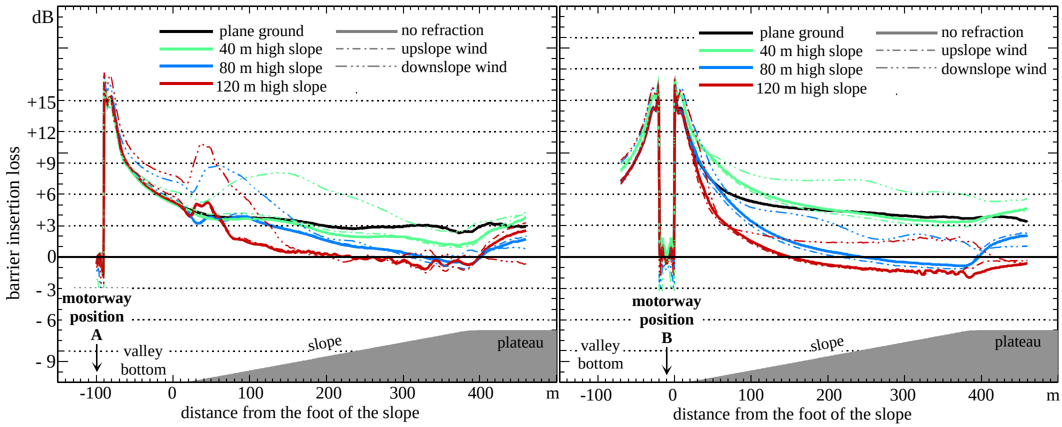


Fig. 5.19 Simulated barrier insertion loss at 1.5 m above ground for all of the considered situations. Left panel: motorway position A, right panel: motorway position B. The line styles and colours are explained in the left panel. The slope profile is indicated by the grey shade on the bottom of each panel.

5.5 Evaluation methods

Acoustical studies are carried out at different space scales and precision scales and thus can be divided in three different types of representation:

The use of one type of representation or another mainly depends on the aim of the acoustical study but is also function of the data and the tools or software owned.

5.5.1 Idealised process studies

Idealised process studies aim at acoustical simulations with a very high precision to study the effect of special processes which seem to be of importance. They cannot be carried out with commercial standard software tools since the methods implemented in those tools are normally not adapted to the specific requirements of the considered processes. The idealised process studies therefore necessitate numerical methods adapted to the respective problems like complex geometries, complex meteorological effects or the combinations of both. Since these methods are often time consuming their use needs a careful planning. To keep the computational effort and consequent costs within reasonable limits it is often necessary to apply the model in a 2D configuration, i.e. in a vertical cross-section. If meteorological factors are relevant, the acoustical model should be coupled with a precursory meteorological simulation which provides the pertinent temperature, humidity and wind fields.

5.5.2 Real case studies

It is sometimes interesting to study the reasons for observed phenomena, e.g. reported high noise levels which occur under certain circumstances. Such real events can be realistically simulated with numerical sound propagation models, for instance to study the causes of the phenomena and to find ways for a mitigation, e.g. by the modification of noise abatement measures. If meteorological factors are involved but have not been measured, it is expedient to couple the acoustical model with a precursory meteorological simulation which provides the respective temperature, humidity and wind fields.

5.5.3 Impact studies

The case study is an intermediate type of representation between idealized process studies and noise mapping; intermediate in terms of scale but not in terms of importance. This type of representation is used for acoustical studies evaluating the impact of the integration of a new infrastructure (or of a modification implying changes in noise levels of an existing infrastructure). Those case studies are mostly carried out with commercialized soft-ware; as a consequence they are based on 3D-ray tracing methods and cannot evaluate all configurations in comparison with idealized process studies (approximations have to be done to evaluate complex phenomena). This type of representation is strongly dependant on European or national standards.

5.5.4 Large scale noise mapping

Noise mapping concerns very large scale areas, i.e. multiple propagation paths over a long range. For instance, it is the type of representation required by the European directive 2002/49/EC as a prerequisite for noise abatement action plans. The aim is to evaluate the population exposure and the global noise impact rather than to make exact forecasts of the noise level. The required precision level is therefore low, for the input data and the model output as well. Acoustical simulations can be carried out with simplified numerical methods; software dedicated to this kind of representation can be found.

5.6 Soundscape and non-acoustic factors

The assessment of effects on quality of life, annoyance, and health of transport noise at the community level is less straightforward than e.g. for the worksite or for other more closed acoustic spaces or products emitting noise. Many factors beyond the single average A-weighted noise indicator $L_{A,eq}$ in influence the reaction of a community to transport noise. Only about 10 to 20 % of the variance in the community annoyance reactions is attributable to basic acoustic indicators (L_{den}, L_{night}) used in regulations. For more severe health effects it is even much less.

To improve environmental and health impact assessment especially at the local and regional level the consideration of factors which contribute further to the variance explanation of community reactions (about one third) is necessary (Job, 1988; Job, 1991; Fields, 1993; Flindell and Stallen, 1999; Guski, 1999; Miedema and Vos, 1999 and 2004; Lercher, 1996 and 2007a). Job and Hatfield (2001a,b) have coined the terms “Soundscape”, “Enviroscape” and “Psychscape” to classify the most important factors in a comprehensible way. The application of this knowledge is especially important when deviations from the typical exposure-effect relationships occur.

5.6.1 The ambient soundscape

General acoustic aspects: the ambient acoustical environment in which the target noise occurs can influence the reaction to it. For instance, certain background noise can reduce reaction to a particular noise due to masking. In average practice this seems not often to be the case as a comprehensive meta-analysis of 32 field studies failed to find an effect on source specific annoyance (Fields 1998). However, on a local scale this may observed more often if it is properly investigated (see Section 7.1.6). On the other hand the reaction to combined noise sources appears not to follow always an arithmetic summation rule (Schulte-Fortkamp et al., 1996; Job and Hatfield, 2001a,b; Nilsson, 2001; Lercher, 2007b; Öhrström et al. 2007). The perceived loudness of the individual source and the duration of exposure to it were of critical importance in an experimental study (Nilsson, 2001). For a demonstration of a combined source analysis in the ALPNAP investigations see Section 7.1.6 and 7.4.3. To handle the issue of combined noise exposure - as both „exposure intensity“ related psycho-physical models and "perceptual models" did not yield satisfactory results – Miedema (2004a,b) proposed – related to similar attempts by Vos (1992) and DELTA (1995) – the so called "annoyance equivalents model" and showed a theoretical proof of this approach. However, the requirements are strong (independence among others) and seem often difficult to meet in practice in order to be generally applied, as Schomer (2005) has pointed out.

Using a "neighbourhood noisiness indicator" Klæboe et al. (2003, 2006) could demonstrate that in standard noise mapping annoyance reductions due to shielding apartments are likely to be overestimated, while the impacts of noise reduction at the source are likely to be underestimated. For about 30 % of the dwellings an adjustment by at least 3 dB(A) of the noise exposure values had to be made. While these results could be repeated in a second study the alternative "quiet side" indicator did not show a significant reduction in annoyance as hypothesized (Klæboe, 2007).

Specific acoustic aspects: Psychoacoustic research has shown how loudness of single sound sources can be underestimated or how differences in loudness between several sources are overestimated by the use of the A-weighted sound level in dB(A) as criterion metric. In industrial practice these known weaknesses of the A-weighting scheme have been counteracted by giving penalties for tonal components or impulsive sounds. The development of further psychoacoustic assessment criteria – like sharpness, roughness, fluctuation strength and the introduction of binaural measurements complex sounds environments can be further analysed and intervention measures more specifically tailored to reduce the most annoying frequencies of the individual sound spectra. Unfortunately, this analytical potential has been almost exclusively utilized for consumer and industrial products or for closed spatial units such as cars, trains, air planes, and workplaces. Applications within in the field of community annoyance remain rare exceptions. In analogy to the penalties for more annoying sources Schomer et al. (2001) have recently proposed an approximate method ("loudness-level weighting") that is easier to implement for environmental noise assessment. Further insight is provided in the specific soundscape literature (Lercher and Schulte-Fortkamp, 2003; Schulte-Fortkamp and Dubois, 2006; Zhang and Kang, 2007).

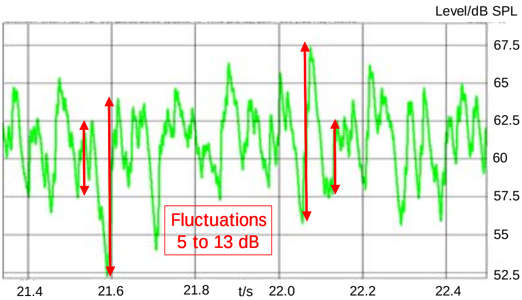


Fig. 5.20 Fast low frequency level fluctuation (level vs time with 0.01s integration time) of truck noise measured at 530 m from the motorway at a slope location. Made visible by low pass filtering.

Nevertheless, in case of deviations in annoyance from standard curves it seems necessary to make more frequent use of advanced psychoacoustic measurement and analysis techniques. In the following paragraphs examples of its use for the detection of typical noise pattern on the slopes of alpine valleys are presented.

Case 1: The impact of low frequencies of diesel engines from trucks and personal cars are strongly underestimated by the A-weighting scheme. Furthermore, the typical 1-second sampling of classical acoustical equipment limits the assessment of its impulsiveness. With binaural measurement equipment and a higher sampling resolution which is adapted to the human ear the low frequency content of truck noise can be better analysed at more distant sites. Through the application of a low pass filter and the higher time resolution Fig. 5.20 makes the fast fluctuation of a distant truck noise visible which would be wrongly labelled as "continuous noise" with classical low resolution methods. Such specific exposure pattern can be responsible for the more "arousing" feature against a lower background level at the slopes (around 25 – 35 dB(A)). At least the typical 10 dB(A) criterion required to lead to potential arousals in humans is met.

Case 2: A further analysis (Fig. 5.21) shows tonal components of truck traffic at several frequencies (vertical axis: between 300 Hz to 1 kHz) at even larger distances. Against the overall lower background noise they appear more pronounced at 1250 m from the source than at 250 m. The low frequencies appear again very prominent between 50 and 100 Hz.

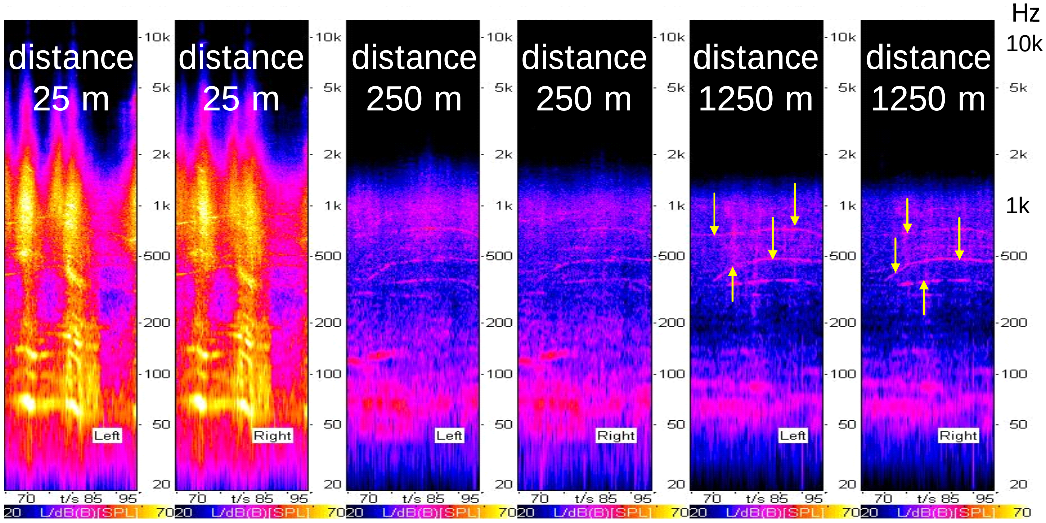


Fig. 5.21 Tonal components of truck noise measured simultaneously at 3 distances from the motorway (slope location at 1250 m). Tonal features indicated by yellow arrows The spectral sound intensity is indicated by the colours (blue is low).

5.6.2 The Enviroscape

Under this umbrella the non-noise features of the source (vibration, air pollution) or the physical environment (orography, housing etc.) where the respondents live are subsumed (Tab. 5.2).

Many of these factors have shown to influence noise annoyance reactions. However, not for all variables is unequivocal evidence available (Job, 1991; Fields, 1993; Lercher, 1996; Miedema and Vos, 1999; Miedema and Vos, 2003; Lercher and Schulte-Fortkamp, 2003; Miedema et al., 2005; Lercher, 2007a). The strong context dependence of many of these variables makes it difficult to generalize the observed results from individual studies to other areas. A qualitative assessment of the evidence of these variables is provided elsewhere (Lercher, 1996; Miedema and Vos, 2003). Some analyses concerning these factors from the ALPNAP health study are outlined in Section 6.2.

Tab. 5.2 Selected examples of contextual factors potentially influencing response to noise.

Climate	**Geography/Architecture**	**Environment**	**Social ecology**	**Culture**
Cold, hot or moderate	Nature/topography: flat, hilly, valley, lake, sea	Vibration, air pollution/odours	Land use: residential/mixed	Habits and life style
Seasonality	Area layout: the built environment	Visual appearance	Neighbourhood relationships	Meaning of living
Prevailing winds	Housing: type of house, Common green, garden	Density, room design	Infrastructure, Safety	Meaning of place

Source: Lercher (2007a)

As environmental noise acts as a chronic ambient stressor these ambient factors (which can by themselves influence health) are often entirely confounded with the noise experience. A study in the Netherlands found a high clustering of other environmental risks with noise exposure at local levels while risks due to radiation or chemical substances were more evenly distributed across the country (Pruppers et al., 1998). Neglecting these factors in the framework of an EHIA could result in wrong assessments at regional levels.

Note some of these factors of the enviroscape are entirely confound also with factors from the psychscape. E.g. expectations regarding the quality of living or the meaning of place is clearly not only determined by land use or group experience within the community but also from personal characteristics such as home ownership or duration of living.

5.6.3 The Psychscape

As Stallen (1999) pointed out: “noise annoyance is phenomenon of mind and mood”. These factors do not comprise only psychological person characteristics such as noise sensitivity or attitudes towards the source for which is strong evidence of stronger reactions toward noise or other environmental exposures. Moreover, they include socio-demographic characteristics which may often be strongly linked with factors from the enviroscape and therefore the specific evidence is more difficult to separate and varies also from region to region. Eventually, these factors are strongly influenced by actions or non-actions of the responsible agencies (Green and Fidell, 1991; Flindell and Stallen, 1999; Fidell, 1999).

The psychscape addresses factors such as trust (“misfeasance”) and recognition of impacts by authorities and traffic management agencies, issues of compensation and social and economic benefits, accessibility of information, perceived control, fear of health effects etc (Langdon, 1987; Job, 1991; Lercher, 1996; Flindell and Witter, 1999; Guski, 1999; Miedema and Vos, 1999 and 2004).

Although some factors (like noise sensitivity) are not subject to possible interventions, however, other negative factors (like misfeasance) are strongly dependent on administrative procedures, the amount and style of communication and information with the concerned population and its involvement. Therefore, neglecting these factors can lead to wrong impact assessments, distrust, litigation and costly reassessments (Staples, 1996 and 1997). Or as Staples (1997) expressed it boldly: “do we want only modelling exposure or understand the effects”.

6 Impact assessment

6.1 Introduction

After almost a century of uncontrolled industrial and traffic development, quality of life and the "sustainability" of development turn out to be of major concern in most of the "advanced" countries. The last decades have seen the birth of a new discipline dedicated to the study of environmental impact from the increasing human activities. Under the pressure of scientists, people, and non-governmental organisations, politicians have become aware that this exponential expansion strongly modifies the environment, and that the effects of human activities on environment must be at the heart of any space-related projects. Many themes are covered by the notion of "environment" and most of them are interdependent or strongly related (air quality and climate, noise, vibrations, water quality, waste treatment, landscape, cultural heritage, agriculture, etc.). Assessing these interactions requires a systemic approach, but for the sake of simplicity these subjects are generally addressed separately. The scientific knowledge in all these domains has recently made considerable progress. The challenge is now to bring together the expertise from the different fields to help decision-makers, technical actors, and people to understand environmental issues. One of the goals of the ALPNAP project is to explain how advanced scientific methods of predicting noise and air pollutions, including meteorology as a base, can contribute to a better understanding of environmental impacts in mountainous areas, and especially of impacts on human health. From the previous paragraphs indeed, it is clear that nowadays the most used (and probably abused) expression is "Environmental Impact", while so far no specific and extensive studies about the health of citizens of the Alpine region are available, whereas there is an increasing interest within the population about the effects of mobility, infrastructure development etc. on human health. An underlying issue of this general concern is to find relevant indicators for the complex physical phenomena and their impacts on health in a comprehensive and synthetic way for actors in the Alpine space who are not specialists in the respective fields. This is a key motivation why the main focus of the present report is devoted to the health impact assessment and focussing only some spots to the more general issue of impacts on the environment.

A comprehensive summary of the actual "health" status of the Alps is also contained in the "Report on the State of the Alps" (2007), including data, information and analysis on sustainability, social and economic aspects in the alpine region. In this document the challenge to combine mobility and accessibility with the preservation of the Alpine environment and the quality of life of the population living in the Alps is described.

The large number of studies dedicated to impact assessment methods might be confusing, particularly as national practices are mixed with international recommendations. However, real efforts have been made at the European scale to propose harmonised methodology and indicators. For instance, in 2004 WHO published the results of a pilot study about the feasibility and applicability of uniform health indicators for European countries (WHO, 2004). Consensus between countries is still difficult to find and decisions are often delayed because of experts' disagreement or national interests. However, a common methodology has been adopted, for example, by the EC for noise exposure in directive 2002/49/EC (END), requiring member states to provide strategic noise maps, based on the common indicators (L_{den} and L_{night}). The need for uniform environmental evaluation procedures is particularly clear as land and transport planning must be considered at the European scale. One key issue is the difficulty to compare impacts of different kinds. Evaluation of external costs is now widely used to aggregate such effects as accidents, congestion, noise, air pollution, climate change, or deterioration of nature and landscape. Each impact is converted into a monetary unit, and compared or added to the others. The method is very useful to estimate benefits and drawbacks of the variants of a project on a larger scale; however the final output only gives a macroscopic and economic view of the situation with no possibility, for instance, to show the spatial distribution of impacts.

Environmental Impact Assessment (EIA) is a key tool which aims at assessing the consequences of possible interventions and, in particular, to weigh relevant evidences on positive and negative effects, including monitoring procedures, reviewing the impact of policies after they have been implemented and estimating costs and benefits of proposed measures.

In the European Union, Environmental Impact Assessments are currently regulated by two directives: the SEA Directive 2001/42/EC for Strategic Environmental Assessments (SEA) and the previous EIA Directive 85/337/EC for Environmental Impact Assessments (EIA).

The EIA directive demands: “Member States shall adopt all measures necessary to ensure that, before consent is given, projects likely to have significant effects on the environment by virtue, inter alia, of their nature, size or location are made subject to a requirement for development consent and an assessment with regard to their effects”. It specifies which project categories shall be made subject to an EIA, which procedure shall be followed and the content of the assessment.

An EIA procedure has a project-specific nature and usually, a final decision (approval) needs to available before construction work starts. It ensures that environmental consequences of projects are identified and assessed before authorisation is given. The public can give its opinion and results are taken into account in the authorisation procedure. The public is informed of the decision. Remembering EIA procedures, one is dealing with detailed and localized decisions, related to the extent of the project and to the adoption of measures to mitigate, rather than prevent, environmental impacts.

The SEA directive (DG TREN, 1999) embeds environmental considerations into a broader policy context, above the project level, at plans and programmes tiers, to have some influence on the decision-making process. In general policy, plan and programme can be defined respectively as:

- a guidance rationalising the course of a government action, for instance the development of a High Capacity Rail line (HCR) to promote the shift of goods traffic from road to rail;
- a linked set of proposed actions together with a time frame to implement a policy, e.g. where and when to construct the HCR line;
- a set of projects that specify the geographical and temporal design criteria of the plan objectives, for instance, the proposal to develop a HCR track to connect two or more cities by a given year.

In short, a SEA

- allows for a wider consideration of impacts and alternatives as compared to an EIA;
- plays as a pro-active tool and can thus be used to support the formulation of strategic action for sustainable development;
- allows for a systematic and effective consideration of the environment at higher tiers of decision-making;
- entails more consultation and participation of the public.

The SEA may therefore influence decisions on need, mode and location of transport infrastructure projects and, subsequently, the scope of single project EIAs. An important feature of a SEA is that it allows evaluation of impacts of the transport flows on a region or a country and associated effects. In this context, a SEA relies on appropriate forecast methods. Two examples may be clarifying what this means: the construction of a new high-capacity rail (HCR) line and the construction of new road infrastructure. A new HCR line and the consequent shift of heavy vehicles from road to rail contribute to mitigation of road congestion and reduce air pollution. Conversely, the increased attraction capacity generated by new road infrastructure may lead to creating bottlenecks that are not foreseeable at project level. Finally, cumulative effects of different single impacts can most readily be appreciated at the SEA level.

This Chapter will present and briefly discuss the different issues relevant for understanding how noise and air pollution affect human health. Moreover different methods available for collecting health information as well as for quantifying – and comparing – the impacts of noise and air pollution are addressed.

6.2 Health and well-being

The increase in life expectancy in post-industrial societies has shifted the interest in health policy towards prevention of morbidity at early stages. The influence of the environment on health status gains importance as the potential exposure time increases and genetic influences decrease with a prolonged lifespan ("survivors"). Furthermore, an increase of potentially susceptible individuals (people with allergic dispositions, mental health problems etc.) to environmental effects is observed. Therefore, WHO-EU ministerial conferences on "environment and health" have recognised the need to evaluate the "environmental burden" of disease (WHO, 2004a). The transport environment has been shown to contribute in various ways to decrements in health and triggering and progression of disease (Dora, 1999; Dora and Raccioppi, 2003). Sensitive areas as defined in the Alpine Convention are believed to be specifically vulnerable to the effects of transport (Lercher, 1998; Lercher, 2007a). However, they have neither received sufficient attention in research nor from the health, environment and transport administrations.

The following paragraphs summarise the concepts and main results obtained in investigations carried out in the Lower Inn Valley by the Medical University of Innsbruck.

The underlying concept of this investigation is important to the understanding of this chapter.

The potential effects of transport on health have to be studied with regard to a broad scale of potential outcomes (the morbidity pyramid: well-being to specific disease, medication and death). Here, more attention is also directed to the lower part of the pyramid to detect early effects which are amenable to prevention. As the focus of public health has gradually shifted from life expectancy to health expectancy (WHO, 2001), a similar situation has developed in environmental health impact assessment. Health impact assessment is no longer predominantly involved in mortality risks or loss of life expectancy, but rather deals with aspects of the health related quality of life in a broad sense (de Hollander et al., 2003). This necessary shift in emphasis is driven mainly by a policy change towards the precautionary principle and sustainability (EC, 2007).

The potential health effects of transport are considered to come from both *direct* and more often *indirect* pathways via vulnerability factors and imposed additional stress (Fig. 6.1).

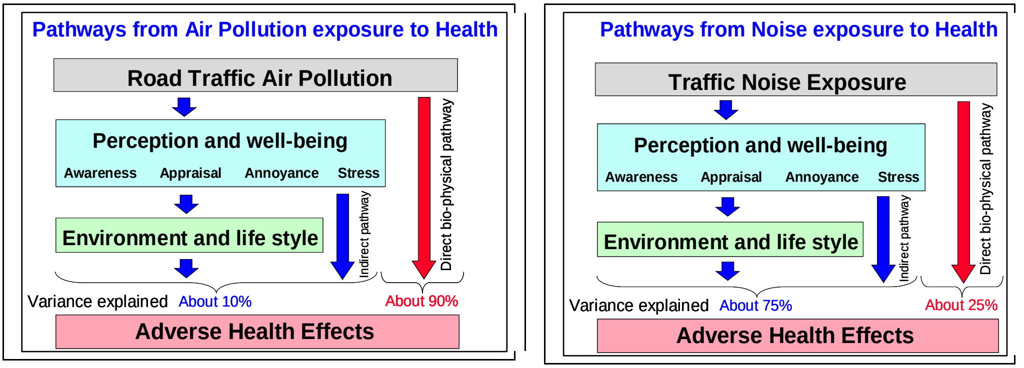


Fig. 6.1 Direct vs. indirect pathways from air pollution (left graph) and noise pollution (right graph) to adverse health effects in transport health research (percentages given for noise apply to annoyance as indicator of effects). Source: Lercher (2007 b).

In this investigation, many of the analyses are therefore directed at the interplay between environment, life style, dispositions and health, and they intend to demonstrate the public health importance of these interactions.

The results of these analyses can be taken to calculate "disability-adjusted life years" (DALYs) or "quality adjusted life years (QUALYs) which enable economists and administrators to compare the observed health effects with other external determinants on health such as life style, occupational and social risks (unemployment, social cohesion etc.) in a region (see similar examples in Staatsen et al., 2006; Lercher and Botteldooren, 2006).

6.2.1 Well-being and satisfaction with life

Quality of life (QoL), subjective well-being (SWB), and satisfaction with life concepts are increasingly used in the social and economic sciences to measure the quality of living and social welfare, as the limits of economic growth and its social and ecological impact are recognised. QoL is a multi-dimensional concept that encompasses – besides traditional material conditions of living – the subjective perception of the social and environmental quality of living, well-being and health (Lindström 1992; Rogerson 1995; Diener and Suh 1997; Sen 1999; Veenhoven 1999; Pacione 2003; van Kamp et al., 2003).

In environmental health impact assessment, the measurement of the "health-related environmental quality" (HREQ) is of primary interest. This means that the assessment of the *person-environment-health relationship* is at the core of this task. Why is this assessment so important? Several studies during the last decade have shown that large differences in health exist between different areas and that these differences can not be easily attributed to differences in material living. Rather they need to be explained by complex interactions between the environment, the social circumstances and the population (Balfour and Kaplan, 2002; Diez-Roux, 2005).

6.2.1.1 Empirical data from the area of investigation (based on phone surveys)

The following two tables (Tab. 6.1 and 6.2) compare the results of the "Eurobarometer" questions (Eurobarometer 43.1 BIS), which were identically applied already in an earlier phone survey completed in 1998 (TEL-EHIA 98) in the same area and the current phone survey for the ALPNAP health study (TEL-ALPNAP 06). Tab. 6.1 shows a rather high satisfaction with several qualities of the social and physical environment and this satisfaction remained remarkable stable between the two points in time.

Tab. 6.1 Very and fairly satisfied with ... in your area. A comparison TEL-EHIA 98 – TEL-ALPNAP 06

Highly satisfied with ...	**TEL-EHIA 98**	**TEL-ALPNAP 06**
Attractiveness of the area	84%	85%
Housing quality	87%	86%
Recreation possibilities in the area	82%	80%
General safety in the area	89%	88%
Neighbourhood support	81%	81%

TEL-EHIA 98: For the environmental health impact assessment (EHIA) of the new rail track 15 April to July 1998
TEL-ALPNAP 06: May to July 2006, 4+5 from a 5-point scale

Tab. 6.2 Very much/quite a lot of reasons to complain about … in your area. A comparison TEL-EHIA 98 – TEL-ALPNAP 06

Reasons to complain about ...	**TEL-EHIA 98**	**TEL-ALPNAP 06**
Amount of traffic	32%	62%
Noise	29%	45%
Air pollution	21%	45%
Landscape destruction	14%	24%
Odours	13%	19%
Industry	9%	11%
Waste disposal	6%	9%

TEL-EHIA 98: For the environmental health impact assessment (EHIA) of the new rail track 15 April to July 1998
TEL-ALPNAP 06: May to July 2006, 4+5 from a 5-point scale

Contrasting with this general satisfaction, complaints about traffic-related items were found with high percentages. Even more worrying is the substantial change of those items within eight years while the control items “industry” and “waste disposal” remain within their range. This may come as a surprise or seem as a paradox, when these results are compared with those in the previous table. It is, however, known from other studies that residents who have a superior environment are reacting stronger to changes in their environment threatening this “advantage”. The stronger increase in complaints about air pollution may reflect the increase in political and media attention since the labelling of this area as an air pollution remediation area (“Sanierungsgebiet”). The fact that the strongest complaints are made about the amount of traffic may indicate awareness of increasing traffic jams during recent years.

Tab. 6.3 Emotions towards traffic … most of the time/always. Comparison TEL-EHIA 98–TEL-ALPNAP 06

Emotions and experiences ...	**TEL-EHIA 98**	**TEL-ALPNAP 06**
Anger over traffic	34%	31%
Feeling helpless about traffic	24%	30%
Fear of traffic jams	14%	24%
Quality of life restrictions by traffic	n.a.	17%
Loss of property value	n.a.	15%
Mobility restrictions by traffic	n.a.	8%

TEL-EHIA 98: For the EHIA of the new rail track15 April to July 1998: yes vs no
TEL-ALPNAP 06: May to July 2006 4+5 from a 5-point frequency scale

The results presented in Tab. 6.3 support the interpretation as increasing awareness of traffic-induced restrictions. Feelings of helplessness and fear of traffic jams rose significantly and 8 % even see mobility restrictions by the traffic in the area "very often".

Although the degree of anger did not increase, the strong trend towards helplessness and fear does not indicate a healthy and sustainable development in this area.

6.2.1.2 Exposure-effect relationships

To date, there are no reliable exposure-effect curves available as QoL and satisfaction scales have rarely been used in a standardised manner in environmental health impact studies. There is also criticism concerning the use of single items. Although single-item questions are important to obtain specific information (see Tabs. 6.1, 6.2 and 6.3) the reliability is assumed to be more dependent on the specific wording and its interpretation in various segments of the population than in multi-item instruments where the larger number of questions may counterbalance this effect. Furthermore, such subjective information needs to be supplemented by subjective or objective data of the environment where the person actually lives. It is only then possible to determine whether increased reactions are caused by increases in exposure or whether the increase in reactions is caused by people reacting stronger to the same exposure. Most of the “fast” public opinion surveys lack this necessary link.

One way to overcome the problem of single indicators is to use a multi-criteria instrument which integrates several aspects of life domains that contribute to well-being, QoL and satisfaction into one indicator. This cumulative indicator can then be related to subjective or objective measures of the environment (like noise or air pollution). It will also better reflect the overall environmental impact on a persons life situation than focussing on the health related impacts alone The conclusions obtained by such a procedure are more valid than single item QoL information without relation to the environment.

In this study the “quality of life” indicator is constructed on the basis of several questions from the health study’s phone questionnaire (see interim report on the ALPNAP website). This implies that the answers to these multiple questions will have to be aggregated to obtain an overall assessment. This aggregation can be done using fuzzy integrals (Verkeyn et al., 2003, Botteldooren et al., 2006). The weights used at each step of the aggregation to the specific domain measured are shown in Tab. 6.4. Health was given the strongest weight.

Tab. 6.4 Weights used for questions assigned to the main life domains in the aggregation of survey results to the QoL indicator

Life domain	stressors	basic needs	social life	work	health
Weight for QoL	0.6	0.8	0.8	0.8	1

The overall satisfaction with life was measured with Diener’s satisfaction scale, widely used in global satisfaction surveys (Diener et al., 1985). It is very important to check against satisfaction because differences in satisfaction with life between communities can unduly determine the QoL results. In this case only small differences in satisfaction with life were observed between communities. This supports the interpretation that the observed larger differences in QoL between communities are unbiased by overall satisfaction with life.

In a next step it should be tested whether these perceived reductions in QoL are related to indicators of traffic experience or measured exposure. The reported reason to complain about noise and air pollution (from the Eurobarometer questions) is a good indicator of affectedness and is therefore related to the multi-criteria QoL indicator. The results show a similar linear decline in QoL with both air pollution and noise.

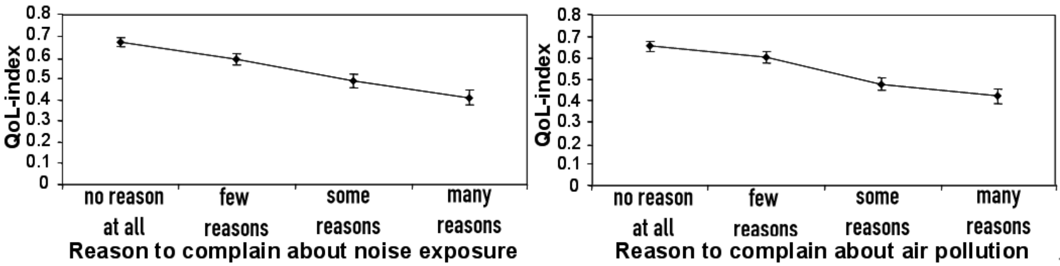


Fig. 6.2 Reasons to complain about noise (left) or air pollution (right) and quality of life (QoL)

6.2.1.3 Comparison with European surveys

The choice of questions from the Eurobarometer (EB) has the advantage of being able to compare with national and international figures. The actual comparison of environmental concerns shows a diverging picture (Tab. 6.5**)**. There are obviously much fewer problems with waste disposal and also there is still less perception of landscape distraction in the lower Inn valley. However, complaints about the amount of traffic and noise pollution are substantially higher, while complaints about air pollution are only slightly above the EB values. The percentages for the Austrian Eurobarometer (EB 1999: AT) match those of the European countries. A comparison with the results from the 1998 survey (Tab. 6.2) shows the percentages with the traffic indicators still below the 1999/95 figures of the EU-countries. The strong concerns with traffic related exposures are warning signs that the development of the traffic situation in this area is far from sustainable.

Tab. 6.5 Very much/quite a lot of "reasons to complain about …" in your area. A comparison EB 1999 – ALPNAP 06

Reasons to complain about ...	TEL–ALPNAP 06	EB 1999: AT	EB 1999/95: EU
Amount of traffic	62%	n.a.	51%
Noise	45%	32%	31%
Air pollution	45%	n.a.	41%
Landscape destruction	24%	32%	35%
Odours	19%	n.a.	n.a.
Industry	11%	n.a.	n.a.
Waste disposal	9%	35%	35%

Eurobarometer 1999 or 1995 (last available data with the same phrasing)
n.a.: not available
EB 1999/95:EU: all 15 countries EB 1999: AT: results for Austria

6.2.2 Annoyance due to traffic exposure

6.2.2.1 Conceptual foundation of annoyance

Measurements of air pollution and noise levels are important basic inputs for an EHIA. However, the measurements alone are not sufficient to fully understand the regional affectedness by traffic exposure. Whereas it is reasonable to base policy decisions related to air pollution on measured pollutant values only (because the effect follows toxicological principles) this procedure would be unacceptable for noise pollution. Noise is perceived subjectively (although measurable by physical instruments) and effects are following the general stress response (WHO, 2000). Therefore, a simple effect measure ("annoyance") was introduced that should express the amount of stress (or dissatisfaction) people experience when exposed to sounds from traffic sources. Standard questions for the measurement of annoyance were developed (Fields et al., 2001) and are described in the interim report (ALPNAP website). More recently, annoyance measures are used in air pollution epidemiology as supplemental information. These studies demonstrate increasing annoyance with increasing air pollution at exposure levels typical for European cities (Lercher, 1992; Weiland et al., 1994; Lercher et al., 1995; Forsberg et al., 1997; Klaeboe et al., 2000; Oglesby et al., 2000; Rotko et al., 2002; Heinrich et al., 2005; Jacquemin et al., 2007).However, common exposure-effect curves are not yet available and their usefulness is not yet established (Brody and Zahran, 2007). These investigations have, however, demonstrated that people can detect poor air quality at concentrations well below limits set in current guidelines for outdoor air pollution, and annoyance studies should have a place in air-quality monitoring (Forsberg et al., 1997).

In noise pollution administration, the examination of noise-annoyance curves is recommended in the EU since the release of the Environmental Noise Directive (END) in 2002 ("dose-effect relations should be used to assess the effect of noise on populations"). Normative noise-annoyance curves have been established separately for aircraft, road traffic and rail noise based on large data bases (Miedema and Oudshoorn, 2001; Miedema and Vos, 2004) and included in the END as a kind of reference data.

These normative noise-annoyance curves represent an average response of people towards noise exposure and serve reasonably well as a first step. On average, the physical measure (L_{eq}, L_{den}) accounts for about 10 – 20 % of the observed annoyance reaction, and an additional 40 – 60 % can be explained by personal, situational, and community variables. While the variance explained by personal, attitudinal and situational factors is well understood (Job, 1988; Fields, 1993; Miedema and Vos, 1999; Lercher, 1996; Miedema and Vos, 2003) substantial community differences remain unexplained (Fields, 1990; Gjestland, 1998; Lercher, 1998; Breugelmans, 2005; Klaboe et al., 2005; Lercher and Botteldooren ,2006). In a meta-analysis of 26 surveys (Fields, Ehrlich, Zador, 2000), the mean difference in annoyance found in these communities corresponds to the equivalent of a 7 dB(A) difference. This is the reason why more recent literature (van Kempen et al., 2005; Lercher and Botteldooren, 2006; Staatsen et al., 2007) recommends adopting a more cautious local approach ("if surveys and local risk estimations are available, their use is preferred to the use of the 'normative' exposure-response curves"). Van Kempen et al. (2005) is a rich source about the currently available exposure-effect curves for EHIA.

6.2.2.2 Measurement of annoyance

The effect of noise exposure on annoyance is expressed in a standardised form as the percentage of highly annoyed individuals (% HA). This convention has been introduced in order to be less dependent on personal, situational or other external factors in the judgement of annoyance. Since the threshold for % HA is based on a five-point numeric scale, and other scales may have been used, formulas are available (in Miedema and Oudshoorn, 2001) to normalise other common scales in use (4-, 7-, 10 or 11-point scales). These formulas were developed to establish the normative curves. As any "normalization" inherently runs the risk of distorting the actual relationship to some extent, cautious use is necessary.

6.2.2.3 Prevalence of annoyance

In the lower Inn valley (Tab. 6.6) the percentage “highly annoyed” (HA) remained constant over time for road traffic noise, while the percentage HA from particles and soot increased significantly. Higher media coverage and public awareness of the health effects of particles may have contributed to this increase (compare with Tab 6.2: area complaints). On the other hand, the percentage HA from exhaust gases remains at about the same level. Notably, both, the percentage HA from rail noise and from rail vibrations are significantly smaller in 2006 than in 1998. Several rail noise abatement measures have been implemented since 1998.

Tab. 6.6 Extremely and very annoyed by … in and around your home (last 12 months). A comparison TEL-UVP 98 – TEL–ALPNAP 06

Annoyed by ...	TEL–EHIA 98	TEL–ALPNAP 06
Road traffic noise	22 %	22 (41) %
Road traffic vibrations	7 %	3 (8) %
Rail noise	20 %	12 (25) %
Rail vibrations	9 %	3 (6) %
Odours from exhaust gases	13 %	11 (25) %
Particles and soot from road traffic	14 %	21 (38) %

TEL-EHIA 98: For EHIA of the new rail track 15 April to July 1998 4+5 vs (3+4+5)
TEL-ALPNAP 06: May to July 2006 3+4 from a 4-point scale

6.2.2.4 Exposure-effect relationships

Noise modelling

To investigate the importance of accurate noise modelling for standard exposure-effect relationships, noise modelling in the ALPNAP health study included two-three noise models. The first model used is MITHRA-SIG, an implementation of the French standard method NMPB by CSTB, the second model is BASS3 an implementation of ISO 9613 by INTEC-University of Gent. In addition INTEC carried out modelling of motorway noise, based on the HARMONOISE/IMAGINE model, a candidate for future European harmonisation (Van Maercke et al., 2007). In all of the above simulations, the Harmonoise/Imagine source model for road traffic noise is used. Railway traffic emission is based on analyses of measurements close to the source.

Effect relationships and comparison with standard curves: highly annoyed by all sources (L_{den} based)

In Fig. 6.3 below a side-by-side comparison is made with the noise-annoyance relationship for motorway and railway sound levels: a comparison between the types of sound modelling used and a comparison between the actual noise-annoyance relationship in this area with the standard exposure-effect curve as provided by the Environmental Noise Directive (END). For motorway noise, sound modelling with MITHRA-SIG shows reasonable agreement with the standard curve, except for an underestimation at higher sound levels. The BASS3-ISO and HARMONOISE/IMAGINE types of modelling show a substantial departure from the MITHRA-SIG modelling. Around 65

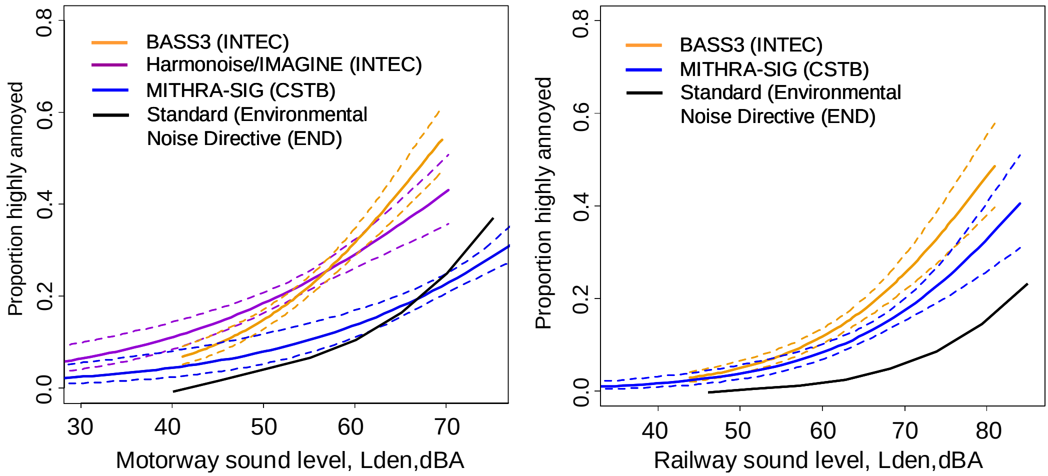


Fig. 6.3 Exposure effect relationships: highly annoyed by motorway (left) and railway (right) main road sound exposure by different noise modelling procedures compared with the standard curve (Environmental Noise Directive). Dashed lines indicate 95% confidence intervals.

dB(A), one can find a difference in the highly annoyed of more than 10 %. For railway noise, both sound models lead to a significant departure from the standard curve.

Both types of modelling lead to a surprisingly consistent picture with respect to noise exposure from the main road. Here, an even stronger departure from the standard curve (END) is observed. At 60 dB(A), the underestimation of the percentage of highly annoyed would be more than 25 %. An additional note is necessary here: the even stronger departure from the standard curve is likely to reflect an increase in the exposure to traffic which bypasses the motorway due to the introduction of restrictions for trucks, a new toll on the motorway and increasing traffic jams.

All sources show general annoyance levels exceeding those predicted by the standard curve provided by the END. Different noise calculation routines also lead to differences in the results. Nevertheless a clear overall picture of changes in exposure-effect relationships emerges:

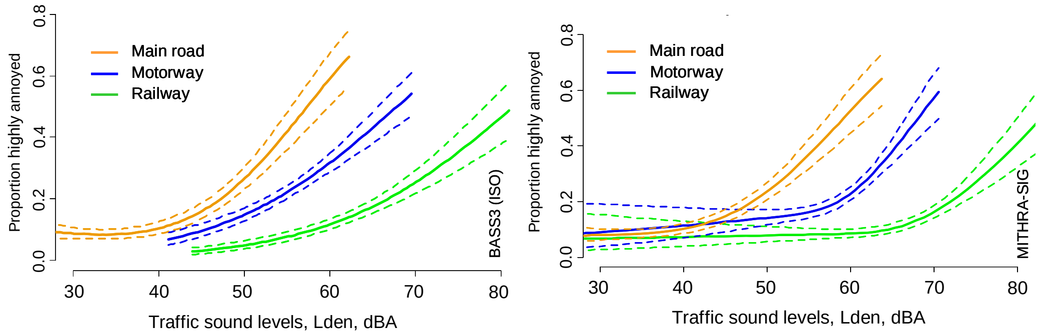


Fig. 6.4 A comparison of source related exposure effect relationships for highly annoyed by noise propagation method (ISO left and MITHRA right). Dashed lines are 95 % confidence intervals.

The strongest increase of annoyance with sound levels is found for main roads, followed by motorways and rails, if sound levels are determined with the BASS3-ISO and MITHRA-SIG noise models. The respective curves level off earlier with the BASS3-ISO calculations than with MITHRA-SIG (Fig. 6.4).

To assess the effect size and the origin of these differences between BASS3-ISO and MITHRA-SIG with respect to the number of people highly annoyed, above or below a certain level, the noise mapping results were stratified by region. Two statistical techniques were applied. First, a cumulative distribution is used to explore the effect of region on the noise distribution (see Fig. 6.5). The cumulative distribution plots demonstrate well how the population distribution of sound levels is pushed towards higher values (especially in the case of MITHRA-SIG).

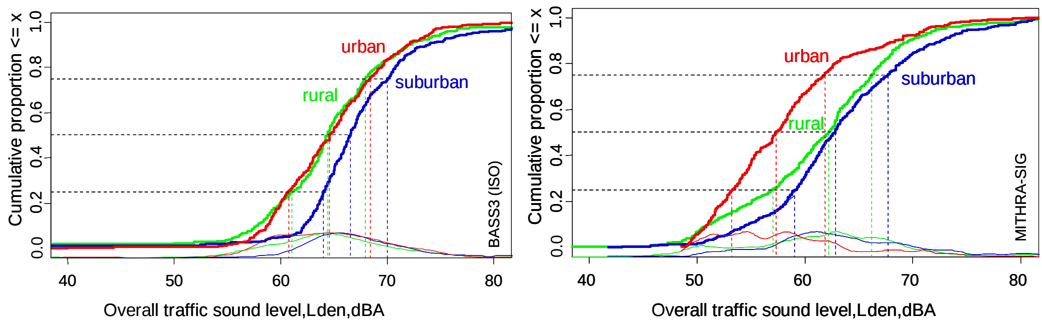


Fig. 6.5 Cumulative distribution of sound levels by sub-region displaying three percentiles (25th, 50th,75th).

This probably leads to both an underestimation of lower as well as higher sound values – excluding the “middle” area. On the other hand the BASS3-ISO mapping by INTEC seems to yield lower sound levels in the urban areas (a difference of 5 dB(A) at the median).

In a second step, two cut-off points, >70 dB(A) and <55 dB(A), were used to illustrate the size of the ”mapping effect” on the prevalence of highly annoyed (see Fig. 6.6).

This rather strong effect of biasing the estimated population fraction above or below a defined sound level can clearly be observed. The effect is much larger, when you view the prevalence below 55 dB(A) compared to above 70 dB(A). This is not

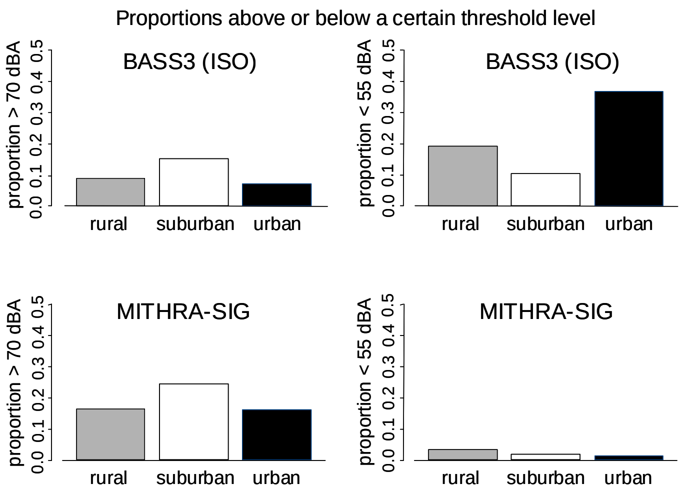


Fig. 6.6 Proportions of sound levels above 70 dB(A) (left side) and below 55 dB(A) (right side) by region subtype and type of sound level calculation (BASS3-ISO upper graphs, MITHRA-SIG lower graphs)

surprising as the accuracy of noise mapping is known to be lower at lower sound exposure. This is an important practical observation which has to be considered when "quiet areas" is assessed in the framework of the END.

Effect relationships: highly annoyed by traffic sources during night

The effect indicator "annoyance during night" has been introduced recently (Miedema 2004) in analogy to the "general annoyance" methodology. It seemed necessary to obtain more information about reactions during night time in the fore field of insomnia. Physiologically, the night time is a time of increased susceptibility (about 15 dB(A) lower threshold to be aroused). This is the reason for the application of a night time penalty. Therefore, it is critical to evaluate night time annoyance separately from sleep disturbance. Currently, however, no data are available for comparison and only limited data exist to judge whether this additional indicator adds to our knowledge about the area.

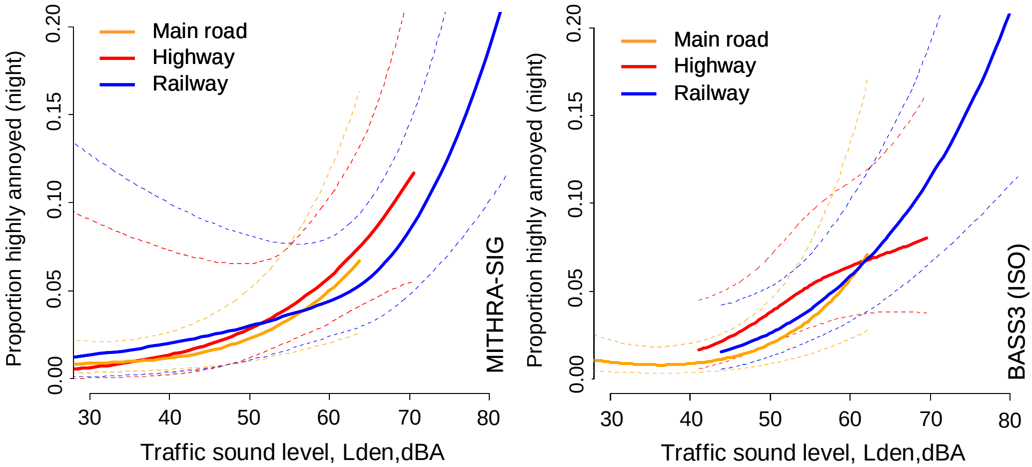


Fig. 6.7 Exposure effect relationship: highly annoyed during night by traffic source and sound calculation technique (BASS3-ISO left, MITHRA-SIG right). Dashed lines indicate 95 % confidence intervals.

From Fig. 6.7 it is evident that curves for all sources follow very much the same pattern up to 65 dB(A). At higher levels, only the railway is left and shows a strong increase in the number of people reporting to be highly annoyed. This observation questions the practice in many European countries of applying a 5 dB(A) "rail bonus" (Möhler et al., 2000). No indication of a "rail bonus" is evident in this area, where the nightly noise exposure is strongly dominated by rail noise. This confirms the conclusion of the EHIA in 1998, that no rail bonus was evident beyond 55 dB(A) in the general annoyance curve (Lercher et al., 1999).

As for the noise mapping: reasonable congruence for night annoyance can be observed when motorway and main road curves are compared.

A direct comparison of the railway noise modelling for night annoyance (Fig. 6.8 left) also reveals a reasonable agreement for rail. Using L_{night} (the recommended sound indicator for disturbances of sleep in the END) does not change the conclusions (Fig. 6.8 right). This can be attributed to the fact that the day/night difference in this area does not comply with the recommended 10 dB(A) (which equals the penalty in L_{den}). Therefore, the penalty given for this departure is already included in the L_{den} measure and the L_{night} does not provide any additional information.

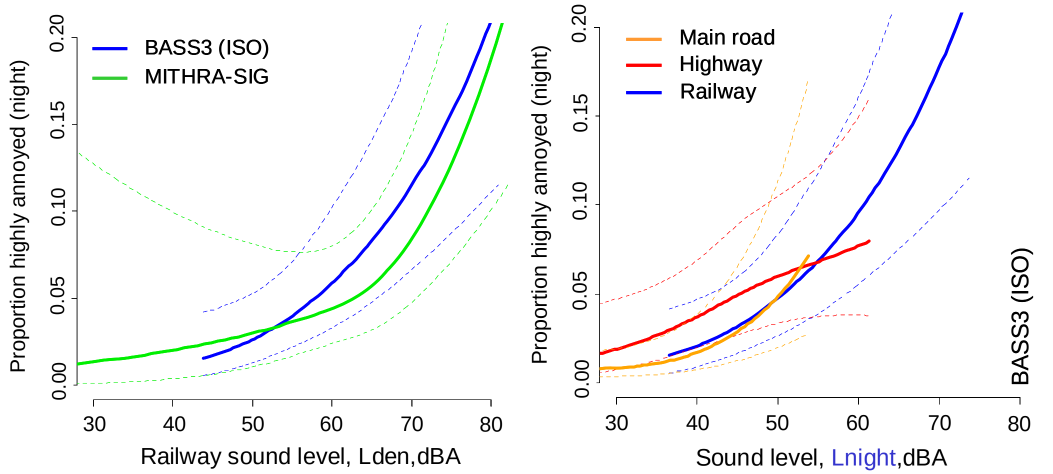


Fig. 6.8 left**:** Proportion highly annoyed during night by railway sound levels and noise mapping technique (BASS3-ISO vs MITHRA-SIG); right**:** Proportion highly annoyed during night by L_{night} for three traffic noise sources (BASS3-ISO modelling). Dashed lines indicate 95 % confidence intervals.

Comparison with standard curves

Miedema has published a position paper for the European Commission's "Working Group on Health and Socio-Economic Aspects" concerning the relationships for self-reported sleep disturbance (Miedema, 2004). This paper contains equations for exposure-effect relationships based on analyses of 15 data sets with more than 12,000 individual observations of exposure-response combinations from twelve field studies (Fig. 6.9**,** upper left). The curves are based on L_{night} as sound level indicator (outside, most exposed facade). The wording used in the ALPNAP health study is compatible with most of the wording used in the underlying studies of this meta-analysis.

A comparison with the ALPNAP data gives the following results. The comparison for motorway (Fig. 6.9**,** upper right) shows a consistent deviation of both noise modelling types towards higher annoyance already at lower levels and a stronger slope increase around 55 dB(A). The main road exhibits the most significant departure from the standard curve (Fig. 6.9**,** lower left) and follows with the behaviour already seen in general annoyance curve. Likewise, the railway effect curve (Fig. 6.9**,** lower right) starts earlier and the BASS3-ISO noise mapping shows a stronger slope up to 55 dB(A) and joins MITHRA-SIG noise mapping only at higher levels of sound exposure. In comparison with the standard, the MITHRA curve follows in parallel about 5 percentage points above this curve and levels off stronger between 65 and 75 dB(A). This corresponds to an increase of more than 10 % highly annoyed within 10 dB(A).

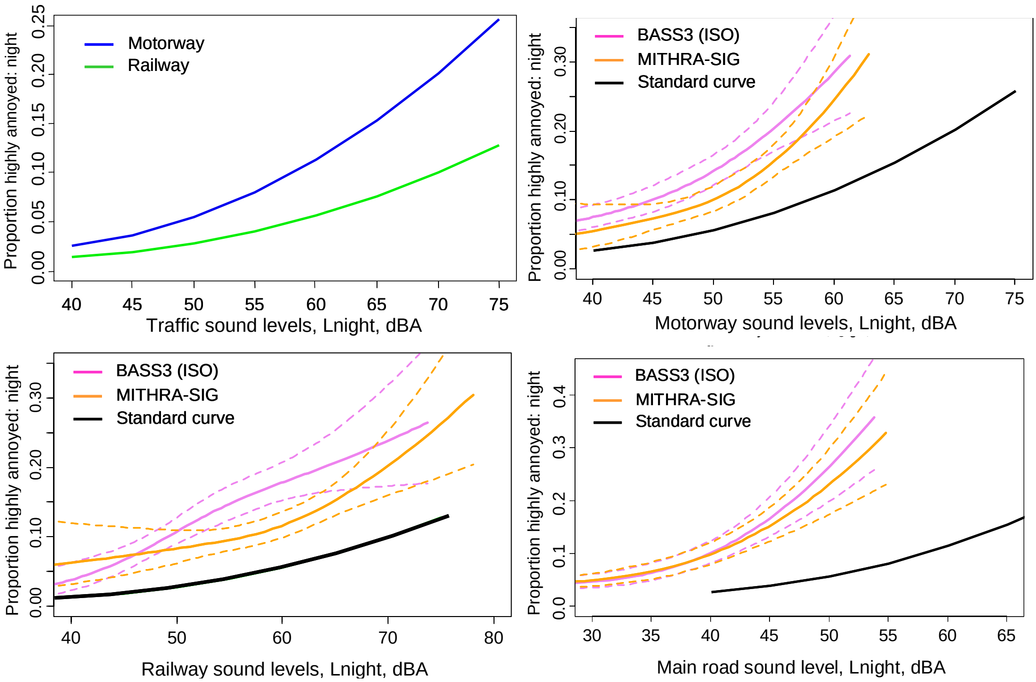


Fig. 6.9 Upper left: Proportion highly annoyed by motor- and railway sound levels (standard curves by Miedema, 2004); upper right: Proportion highly annoyed by motorway sound levels: a comparison of BASS3-ISO and MITHRA-SIG modelling with the standard curve by Miedema, 2004); lower left: Proportion highly annoyed by main road sound levels: a comparison of BASS3-ISO and MITHRA-SIG modelling with the standard curve by Miedema (2004); lower right: Proportion highly annoyed by railway sound levels: a comparison of BASS3-ISO and MITHRA-SIG modelling with the standard curve by Miedema (2004).

6.2.3 Sleep disturbance due to traffic exposure

6.2.3.1 Traffic noise and sleep

Traffic noise is clearly an unwanted environmental component of a sleeping room. Due to its obvious direct pathway, noise-induced sleep disturbance is among the best-investigated effects of noise (Vallet et al., 1983; Griefahn, 1991; Pearsons et al., 1995; Kageyama et al., 1997; Maschke et al., 1997; Griefahn et al., 2000; Miedema et al., 2003; HCN, 2004; Kawada, 2005; Passchier-Vermeer et al., 2005; Griefahn, 2007). What is often neglected: the overt disturbance effect of noise on sleep is only one (the most visible) part of a multifaceted problem. Cardiovascular and neuroendocrine effects silently take place without notice. Impaired glucose tolerance, activation of the sympathetic nervous system, increased blood pressure and inflammatory activity has been found in short term sleep deprivation studies (Spiegel et al., 1999; Kato et al., 2000; Meier-Ewert et al., 2004). Whereas the awakenings tend to disappear after some time of nightly noise exposure, unfortunately, the cardiovascular and endocrine responses do not habituate (Vallet et al., 1983; Muzet and Ehrhart, 1980; Di Nisi et al., 1990; Carter, 1996; Kuroiwa et al., 2002; WHO, 2007). The troubling and still unanswered question here is whether in the long run the “residual” chronic response (e.g. 3 to 5 more heart beats/minute or higher cortisol excretion in urine) poses a significant health risk.

6.2.3.2 Public health importance and assessment

It is now well established that noise exposure induces a series of co-called *primary* (short term effects) and *secondary* or "after" effects such as fatigue, changes in mood, impairment of performance and possibly an increase in accident rates (Berglund et al., 2000; HCN, 2004; Kawada, 2005; Passchier-Vermeer et al., 2005). Clear relationships between noise exposure and sleep disturbance are established only for immediate effects. Whether primary or secondary effects are able to contribute to the incidence of other diseases (long-term or *tertiary effects*) is still an open question.

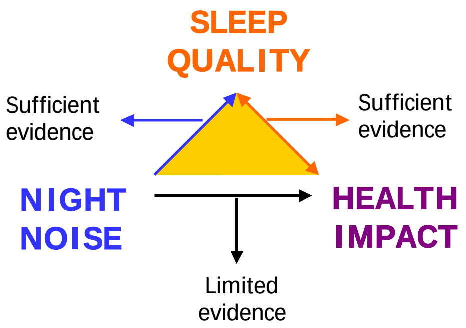


Fig. 6.10 The relationships between noise, sleep and health and their evidence: while noise can impair sleep and poor health can affect sleep it is not clear whether a direct causal pathway exists between noise exposure

The major obstacle to verifying this causal pathway is that sleep disturbance is a common symptom and often a sign of an underlying disease ("reverse causation"). Thus, not every noise-induced sleep disturbance may lead to disease, although shortened sleep time is associated with higher body mass index (Shigeta et al., 2001; Reilly et al., 2005; Singh et al., 2005), accident proneness (Valent et al., 2001) and increased mortality (Kripke et al., 2002; Patel et al., 2004; Tamakoshi and Ohno, 2004).

However, for the public health perspective, the causality is not the issue here: the more people develop diseases which lead to impaired sleep the more likely they are affected and disturbed by nighttime noise exposure. An increase in sleep quality has been observed after a decrease of 10 dB(A) of the external exposure to road traffic noise (Jurriens et al., 1983). Acoustic insulation in the home, however, has not shown to be as effective as expected (Passchier-Vermeer, 2004). This is a troubling fact which points to the need to place main abatement strategies at the source and not at the point of the receiver.

Most of the observed immediate ("direct") effects can only be studied with special equipment in smaller groups and such studies are therefore not well suited for health impact assessment.

For this purpose – in analogy to the annoyance assessment – simple questionnaire items were proposed to monitor long-term sleep disturbance induced by noise in the community. The possible link between disturbed sleep and long-term effects on specific health outcomes (depression, cardio-vascular disease) is not the main goal here. It is nearly impossible to establish this link to these diseases (except in long-term studies) as most of these illnesses show sleep problems as secondary effects or as precursors of disease. Insomnia is also caused by other medical conditions or problems related to the sleeping environment (snoring partners, indoor climate etc.). It should not be forgotten that up to one third of the adult population experience sleep disturbance to some degree during their life time (Hossein and Shapiro, 2002; Ohayon and Partinen, 2002)

However, questionnaire studies on sleep and sleep medication can establish whether sleep disturbance is associated with exposure to noise at the home location (Miedema et al., 2003; Miedema 2004; Passchier-Vermeer, 2004). There is no doubt that noise interferes with sleep and the induced decrement in sleep quality is a sufficiently strong criterion for a health effect, as the relationship between insomnia (based on DSM-IV-criteria) and health-related life quality (measured by SF-36 or similar instruments) is well established (Chevalier et al., 1999; Zammit et al. 1999; Hajak, 2001).

In the ALPNAP health study three assessment strategies were applied.

– In a format similar to that for general annoyance we asked distinctly for annoyance during night (see Chapter 6.4.2.2) by the main traffic sources rail, motorway, or main road.
– Additionally, five questions were asked *without reference to noise* on a 5-point frequency scale ("how often?"): falling asleep, awakening, problems in falling asleep again, earlier awakenings, and feeling tired after sleep). This method is recommended (Barker and Tarnopolsky, 1978) to determine the unbiased noise-induced fraction of sleep disturbance.
– Again *without reference to noise* the sleep medication prevalence was obtained. A positive answer should indicate a more serious insomnia problem.

6.2.3.3 Prevalence of sleep disturbance in the area

In this area the most frequent sleep problems reported are awakening during night (21 %), and feeling tired after sleep (21 %). Falling back to sleep after awakening (14 %) and difficulties falling asleep (13 %) are less common (Tab. 6.7). The comparison with other more recent surveys in noise-exposed areas in Tyrol shows high agreement with the most prevalent sleep problems. The data are even consistent with Japanese studies using the same wording. They also found that frequent awakening is the most prevalent symptom and quantitatively related to exposure, while falling asleep is least prevalent among reported sleep disturbances (Kageyama and Kabuto, 1993). However, in a large study with women only, falling asleep was the most prevalent sleep problem (Kageyama et al., 1997). Note: situational aspects (residential layout relative to the traffic sources) and other contextual factors can lead to a substantial distortion of the main effect of traffic noise on sleep pattern.

Tab. 6.7 Sleep problems occurring several times per week or always (4+5 from a 5-point frequency scale). Results of the ALPNAP health survey are compared with other surveys in the same (1998) and a closeby alpine valley*)

TYPE OF PROBLEM	BBT 04 INT 2004	BBT 04 TEL 2004	TEL–ALPNAP 2006	INT–EHIA 98 N=807
Falling asleep	11.8%	11.3%	13%	15.3%
Frequent awakenings	20.8%	17.6%	21%	25.2%
Re-falling asleep	15.1%	11.8%	14%	17.9%
Early awakenings	14.0%	13.9%	16%	17.3%
Tiredness after sleep	17.7%	20.5%	21%	21.6%

*) INT-EHIA 98: Interview study Inntal 1998, BBT 04 INT: Interview study Wipptal 2004, BBT 04 TEL: phone study Wipptal 2004, TEL – ALPNAP 06: phone study Inntal 2006

6.2.3.4 Exposure-effect relationships: sleep medication

The analyses have shown that a direct effect of traffic noise exposure on sleep medication is difficult to detect as health status, age and other vulnerabilities (trauma history, noise sensitivity) play such an important role. In this study a significant direct effect can be observed only for the indicator "overall noise level" (total noise level) – which is independent of the noise mapping model applied (Fig. 6.11, upper left). Traffic noise is, however, a highly significant contributor to medication use, when health differentials (dispositions, vulnerabilities and underlying health status) are considered. Below, this is illustrated for health and psycho-trauma history as strongly moderating factors (Figs. 6.11**,** upper right, lower left and lower right).

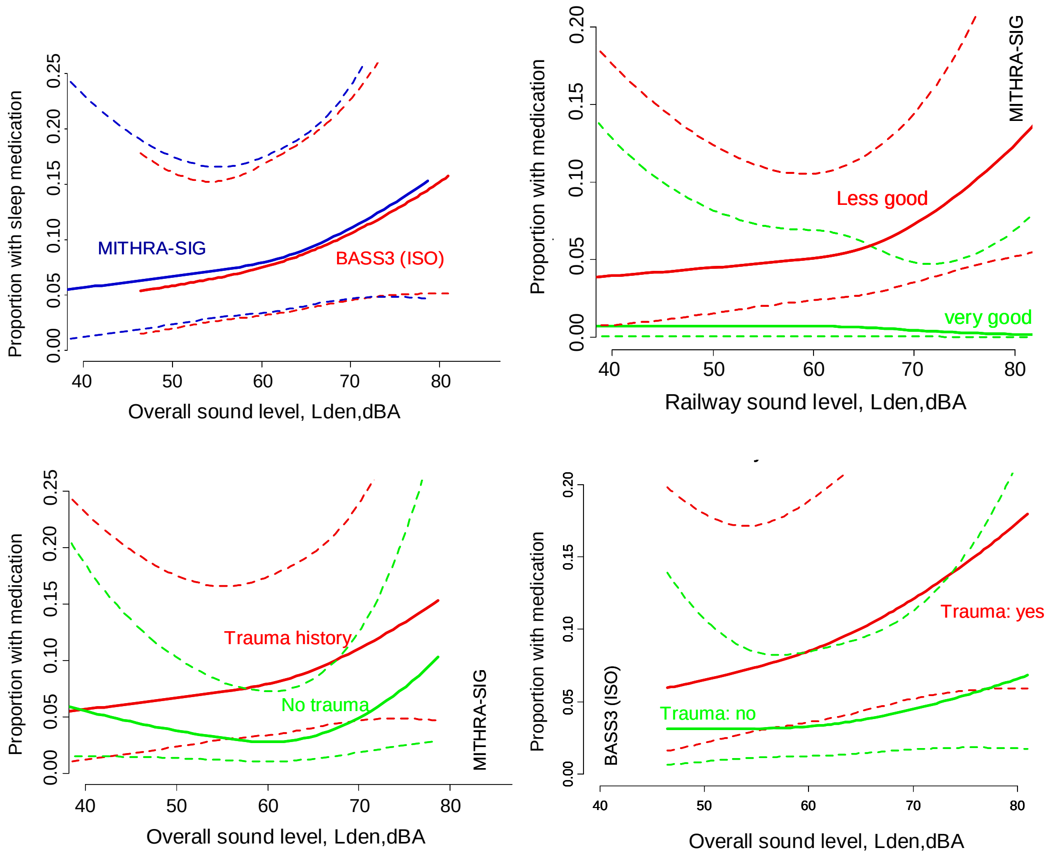


Fig. 6.11 Upper left: Proportion with sleep medication and overall sound level by mapping method; upper right: Proportion with sleep medication and railway sound level by level of health status, MITHRA-SIG; lower left: Proportion with sleep medication and overall sound level by psycho-trauma history, MITHRA-SIG; lower right: proportion with sleep medication and overall sound level by psycho-trauma history, BASS3-ISO.

Further Figures (Fig. 6.12**,** left and right**)** show the moderating effect for railway and main road noise, when you consider trauma history separately. Both models do miss statistical significance: railway: odds ratio 1.50 (95 % CI 0.95 to 2.35) for an increase from 60 to 70 dB(A); main road: odds ratio 1.41 (95 % CI 0.83 to 2.37) for an increase from 50 to 60 dB(A). Nevertheless – on the population level there may be an true impact due to the large number of people with trauma history.

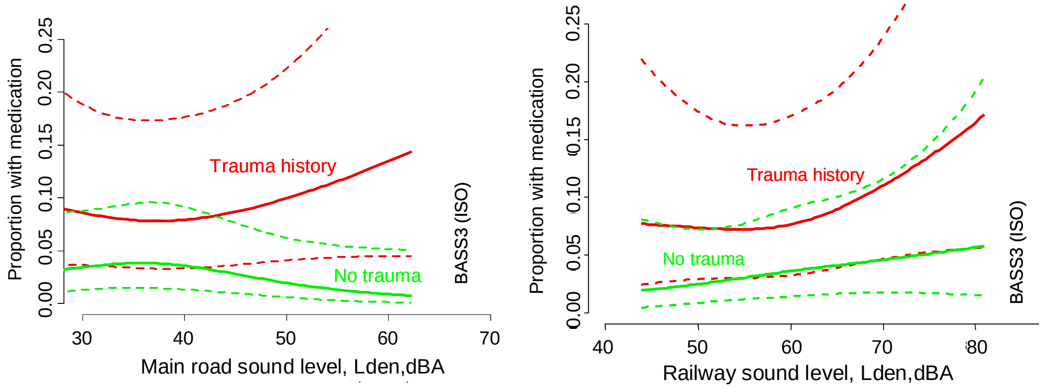


Fig. 6.12 Proportion with sleep medication and sound level main road (left) and railroad (right) by psycho-trauma history (all with BASS3 noise mapping)

6.2.4 General health and traffic exposure

6.2.4.1 Reported health status

Obtaining self-reported health estimates on a numeric scale from one to five (like school grades in some countries) is a relatively easy task and reveals information beyond that provided by objective measures. This has been known since a landmark study (Maddox and Douglas, 1973) found that about a third of its sample perceived their health as being much better or much worse than a physician's objective rating. Based on this study, Mossey and Shapiro (1982) examined both people's self-rated health and physicians' reports and whether or not each person died within the next six years. It turned out that those who rated their health as poor had a three times greater risk of dying and self-rated health was a more powerful predictor of mortality than the physician's objective measures. In the mean time, many more studies were conducted and found strong support for the association between self-rated health status, mortality and morbidity, even when other objective indicators of health status were considered (Idler and Benyamini, 1997; Strawbridge and Wallhagen, 1999; Goldberg et al., 2001; Mackenbach et al., 2002; Singh-Manoux et al., 2005; Chen et al., 2007; Singh-Manoux et al., 2007).

Further studies have also demonstrated a relationship with later functional abilities (Idler and Kasl, 1995) which is of special importance in an aging society, where a large percentage of the population is beyond age 65. Only recently, poor self-reported health was found to be related to immunological parameters (cytokines) and again self-rated health was an independent and more robust predictor of cytokine levels than physician-rated health (Lekander et al., 2004). Therefore, self-rated health is now established as a valid and stable predictor for future health and is used widely in national surveys, Eurobarometer and micro census studies. It is, however, not yet much used in environmental health impact studies in spite of its easy handling.

6.2.4.2 Prevalence and importance of public health

In the ALPNAP health survey, 63 % indicate a good or very good health status (see Tab. 6.8) which is slightly less than what was found in the Tyrolean micro census from 1999. Typically, up to one third exhibit a poor health status and the other two-third report a good or very good health status. It seems from our results that we may have attracted slightly more people with chronic illness (see Table below) than in the other surveys.

Tab. 6.8 Basic health indicators. Results of the ALPNAP health survey are compared with other surveys in the same (1998) and a close by Alpine valley +)

INDICATOR	TEL–EHIA 98	INT–EHIA 98	TEL–BBT 04	TEL–ALPNAP 06
Health status: very good	39%	21%	27%	28%
Health status: good	37%	43%	40%	35%
Health status: less than good*)	24%	35%	33%	37%
Chronic illness+)	17%	19%	19%	27%

*) 3+4+5 of a 5-point scale, +) yes/no question

+) TEL-EHIA 98: phone study Inntal 1998, INT-EHIA 98: Interview study Inntal 1998, TEL-BBT 04: phone study Wipptal 2004, TEL – ALPNAP 06: phone study Inntal 2006

6.2.4.3 Exposure-effect relationships

To evaluate whether traffic exposure (noise or air pollution or both) is related to self-reported health, a multivariate logistic regression model adjusting for basic co-variates (age, sex, education, noise sensitivity, area) was utilised. The regression results are stratified by education, as this factor is the second-most important contributor to this model. The results (Fig. 6.13) for motorway noise show a significant increase in the prevalence of persons with poorer health and also a decrease in population prevalence with very good health when the sound level is increased.

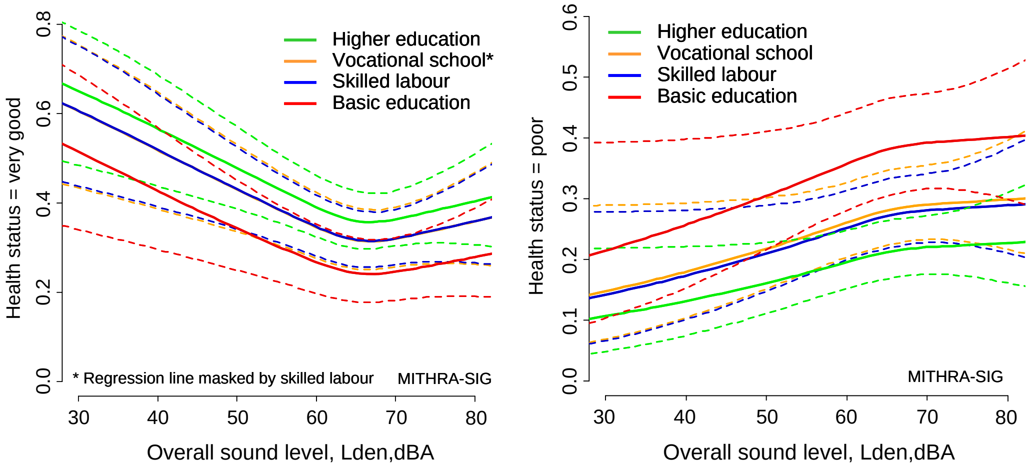


Fig. 6.13 Proportion with very good (left) and poor (right) health status and overall sound level by educational status (MITHRA-SIG modelling)

In order to evaluate whether air pollution has a similar effect, a model without and with an adjustment for a specific noise indicator was built.

The results show a small non-significant trend for an increase in poor health with higher level of particulate pollution (Fig. 6.14, left). However, when an adjustment for overall noise exposure is made, the air pollution effect disappears completely (Fig. 6.14, right). Hence, at higher noise levels, 65 versus 45 dB(A), the proportion of persons with poor health is higher, independent of the level of air pollution.

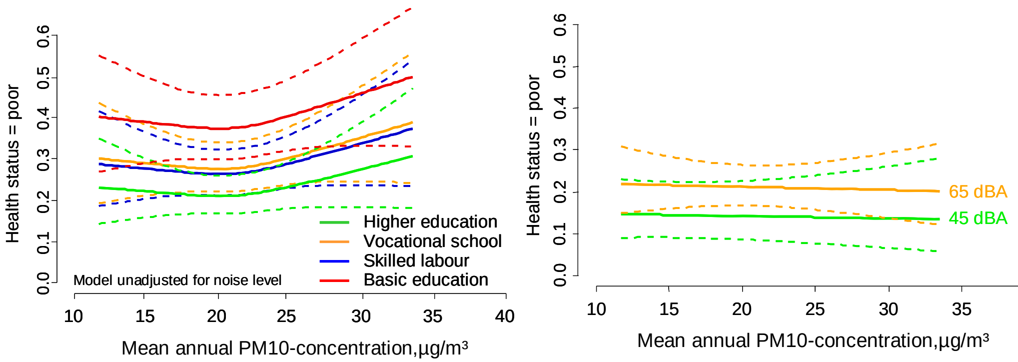


Fig. 6.14 Proportion with poor health status by education and mean annual PM10 concentration (left) and stratified by high versus low overall noise exposure (right). PM10 modelling by TU Graz.

6.2.5 Respiratory illness and allergy

6.2.5.1 Respiratory illness

Diseases of the airways are common and costly and include different conditions such as asthma, chronic obstructive pulmonary disease (COPD), bronchitis, emphysema and bronchiectasis. Their specific diagnosis is often inaccurate because appropriate measurements are not made and the definitions of the conditions are still imprecise (Hargreave and Parameswaran, 2005). Currently, it is thought that asthma, bronchitis and COPD are only different variants of airway disease. Symptoms such as chest tightness, wheezing, dyspnoea, cough and sputum production can occur in all conditions. Chronic bronchitis can be characterised by airway inflammation with airflow limitation during these episodes, while COPD shows chronic airflow limitation and acute severe airflow limitation is pathognomic for asthma.

Tab. 6.9 Respiratory and allergic illness. A comparison between the ALPNAP health survey and an identical survey in 1998 during an environmental health impact assessment (EHIA)

Disease INDICATOR ...	TEL–EHIA 98	TEL–ALPNAP 06
Allergic rhinitis (last 12 months)	7%	11%
Asthma (last 12 months)	1%	4%
Chronic bronchitis (last 12 months)	3%	7%

TEL-EHIA 98: phone survey during EHIA of the new rail track, 15 April to July 1998
TEL-ALPNAP 06: phone survey Inntal, May to July 2006

As the above-mentioned symptoms are more unspecific signs common to all conditions (which may have different etiology) it seems reasonable to use a questionnaire approach to obtain the prevalence of chronic bronchitis and asthma based on physicians' diagnosis. Asthma is handled here under the rubric "allergic illness" due to its allergic component and association with other allergic diseases such as rhinitis and atopy which may also indicate different pathways to disease. The prevalence of these diagnoses in this area is provided in Tab. 6.9.

The results can be interpreted in several ways. They can indicate that physicians are more aware of these conditions or that our study has attracted more sick people than in 1998. It can also indicate a real increase in these conditions in this area. Probably, it is a mix of all as there are arguments for all three explanations. Neither can it be proven by this study design. Higher health costs do apply to two of the three explanations.

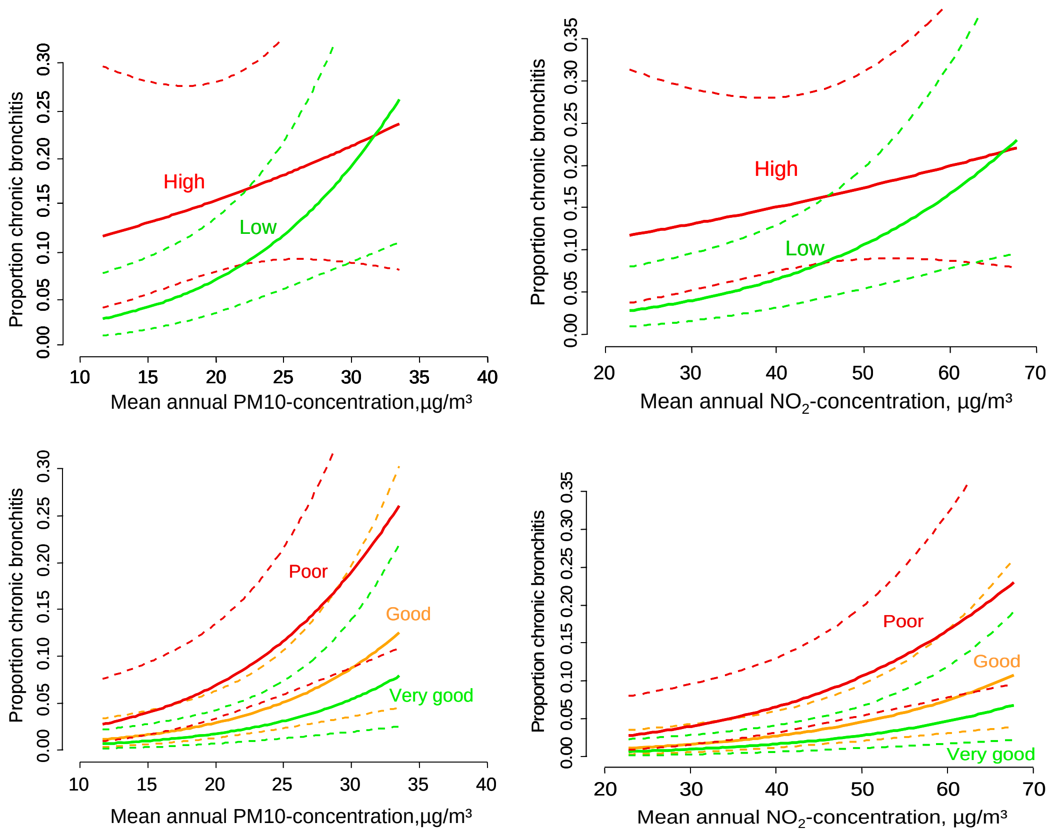


Fig. 6.15 Upper left: Proportion with chronic bronchitis and mean annual PM10 concentration by vulnerability; upper right: proportion with chronic bronchitis and mean annual NO_2 concentration by vulnerability;

6.2.5.2 Chronic bronchitis and air pollution

Earlier research in the 1970s has shown that high levels of particles were related to a higher prevalence of chronic bronchitis (Holland and Reid, 1979). More recent studies have demonstrated that acute exacerbations of chronic obstructive pulmonary disease (COPD), chronic bronchitis or emphysema are associated with short-term exposure to air pollution. Only a small number of recent studies evaluated the association of air pollution with chronic pulmonary disease. Most of these studies used symptoms or hospital admissions of bronchitis (Anto et al., 2001; Karakatsani et al., 2003; Schikowski et al., 2005; Sunyer et al., 2006).

The analyses in the ALPNAP health study applied several regression models to evaluate the contribution of traffic-related air pollution (see Fig. 6.15). Health status and self-reported sensitivity to pollutants show the strongest association with chronic bronchitis. Therefore, the exposure-effect curves are stratified by these two “sensitivity” variables. The proportion of chronic bronchitis increases significantly with increasing exposure at the home location (as indicated by either air pollution indicator).

6.2.5.3 Allergic illness

Currently, there is weak evidence concerning the contribution of air pollution to diseases with allergic components. Whereas there is sufficient evidence about the possible contribution to the exacerbation of some of these illnesses conflicting results are obtained for the linkage between air pollution and allergic symptoms and illnesses like asthma, allergic rhinitis, atopic dermatitis, wheezing and allergic sensitization (Heinrich and Wichmann, 2004).

In the ALPNAP health study no association could be observed in our models using the same air pollution indicators either with *asthma* or with *allergic rhinitis.* This is in accordance with the existing literature and seems to imply a different pathway to the occurrence of these diseases. Note, this study has not evaluated acute effects or worsening of these conditions.

6.2.6 Mental health

6.2.6.1 Prevalence and public health importance

Mental health embraces a larger group of mental and behavioural disorders which are defined by clinical classification systems (ICD-10, DSM-4).

From large-scale surveys it is estimated that during their entire lifetime, more than 25% of individuals develop one or more mental or behavioural disorders. Psychological problems are the most common reason for work inability in the age group 15 to 44 years. Mental health disorders are the second-most frequent reason for early retirement in Austria with a strong increase since the mid-1980s. From the burden of disease study (WHO, 2001) it is estimated that in terms of disability-adjusted life years (DALY) about 12 % of all years lived with disability are due to mental health disorders.

Depression is a major contributor to this group with lifetime prevalence between 10 and 20 %. At any point in time (12-month period prevalence) during adulthood, up to 10 % experience an episode of depression. Anti-depressive medications are third in terms of cost after cardiovascular and stomach medications for the health care system.

The relationship between noise exposure and psychological disease is not fully established (Kryter, 1990; Halpern, 1995; Belojevic and Jakovlevic, 1997; Stansfeld et al., 2000; Stansfeld and Matheson, 2003; Niemann et al., 2005). It is, however, well known that noise sensitivity increases in people with depression (Stansfeld, 1992). Given the large public health importance of depression today it is assumed that people with mental health problems suffer non-proportionally from traffic noise exposure. There are also some studies of the effects of air pollution on mood. These studies only investigated day-to-day variations in mood (Evans, 1988; Bullinger, 1989; Evans, 1994). No long-term studies are available.

6.2.6.2 Indicators

The health study used “depression diagnosis” by a physician and “prescribed medications due to nervous diseases” as indicators. The prevalence of this area is in Tab. 6.10.

Tab. 6.10 Mental health disorders (past 12 months). A comparison between the ALPNAP health survey and an identical survey in 1998 during an environmental health impact assessment (EHIA)

Disease INDICATOR ...	TEL–EHIA 98	TEL–ALPNAP 06
Depression (physician diagnosis)	6 %	8 %
Nervous disease medication (physician prescription)	n.a.	9 %

TEL-EHIA 98: phone survey during EHIA of the new rail track, 15 April to July 1998
TEL-ALPNAP 06: ALPNAP phone survey, May to July 2006

6.2.6.3 Exposure-effect relationships

The regression models are adjusted for age, sex, education, noise sensitivity, health status, psychological trauma experience and overall noise annoyance.

Overall, significant associations with noise exposure were seen only in people with poor health status (not shown), psychological trauma experience (Fig. 6.16) or higher noise sensitivity (not shown). Interestingly, noise exposure from main roads did reveal the strongest associations.

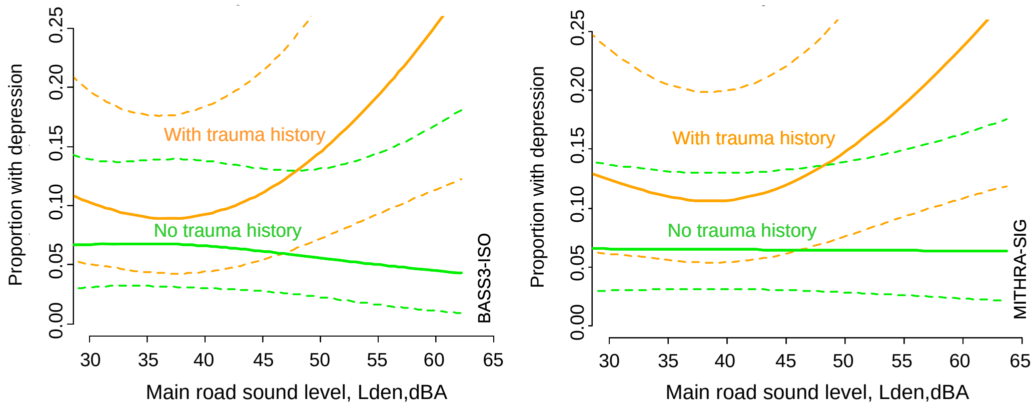


Fig. 6.16 Proportion with depression and main road sound level by psycho-trauma history and noise mapping procedure (BASS3-ISO left and MITHRA-SIG right).

6.2.7 Cardiovascular health and traffic exposure

For a long time cardiovascular diseases, including hypertension, myocardial infarction (MI), angina pectoris and other ischemic heart diseases (IHD), were studied in noise epidemiology as severe health outcome of long-term noise exposure. A recent review considered the scientific evidence now as sufficient for a valid public-health-relevant association between traffic noise and IHD whereas for blood pressure and hypertension the evidence is not yet sufficiently established (Babisch 2006).

Over the last 15 years, evidence has accumulated that short-term particle air pollution is a significant contributor to cardiopulmonary mortality and morbidity. Less strong evidence is available for long-term effects. Some recent studies show an association between traffic exposure and myocardial infarction. The interpretation of these studies is less clear.

Since noise and air pollution co-exist and are highly correlated, long-term effects on cardiovascular health seen in noise and air pollution studies could be confounded. Additionally, in air pollution studies, the associations found with particles are confounded with NO_2 exposure which accompanies road-traffic related air pollution. Furthermore, socio-economic factors associated with poorer health and higher exposure to traffic related pollution may lead to spurious associations between any exposure and health.

Since IHD is a major cause of premature death and hypertension as a prevalent and important risk factor for IHD and stroke both indicators (noise and PM) should always be included to assess the health impact.

6.2.7.1 Public Health importance and prevalence

Cardiovascular disease (CVD) remains the leading cause of death in OECD countries and hypertension and hyperlipidemia are the most common and medically treatable risk factors for CVD. Therefore, costs for medications used to treat CVD, hypertension and hyperlipidemia are the leading expense for the health care system. Hypertension medication is the most costly treatment. For the main health care provider in Tyrol who covers 80 % of the population the cost is nearly 40,000 € per day. From the most recent environmental burden of disease study (WHO, 2007), it is estimated that noise exposure contributes about 3 % to the disability-adjusted life year (DALY) of IHD in Europe. This conservative estimate takes into account the possible overlap between the effects of noise and air pollution on IHD. The contribution of air pollution to CVD seems to come more from the acute effect of high pollution episodes, while the estimated noise effect is attributed to long-term exposure. Methodological differences may also play a role here: it is much easier to detect population impacts of acute air pollution episodes whereas long-term impacts (noise and air pollution) are harder to detect. There is still controversy going on about the relative contribution of noise and air pollution (WHO, 2007). The simple reason is: till now none of the existing, published studies in both fields of epidemiology have been adjusted for the respective other exposure. In this study both air pollution and noise exposure are available at each home location and accounted for in the regression models.

Tab. 6.11 Cardiovascular disorders and treatment (past 12 months). A comparison between the ALPNAP health survey and an identical survey in 1998 during an environmental health impact assessment (EHIA)

Disease INDICATOR ...	TEL–EHIA 98	TEL–ALPNAP 06
Hypertension (physician diagnosis)	9%	17.4%
Angina pectoris (physician diagnosis)		2.4%
Myocardial infarction (physician diagnosis)	1%	0.5%
Hypertension (physician prescription)		17.8%
Heart disease (physician prescription)		4.5%

TEL-EHIA 98: phone survey during EHIA of the new rail track, 15 April to July 1998
TEL-ALPNAP 06: ALPNAP phone survey, May to July 2006

The prevalence (Tab. 6.11) of hypertension and heart disease (respectively, its treatment) is somewhat lower than the average in the European Union (Wolf-Maier et al. 2003).

6.2.7.2 Exposure-effect relationships

Hypertension diagnosis

Overall sound levels were not identified as predictors of hypertension. As family history of hypertension is a strong dispositional factor for later hypertension, separate regression models for this important vulnerability were run. However, motorway noise exposure was the only source leading to a significant relationship with hypertension among persons having a family history (Fig. 6.17) show the results of two regression models with different noise propagation models). No contribution was made by any of the air pollution indicators (PM10 and NO_2).

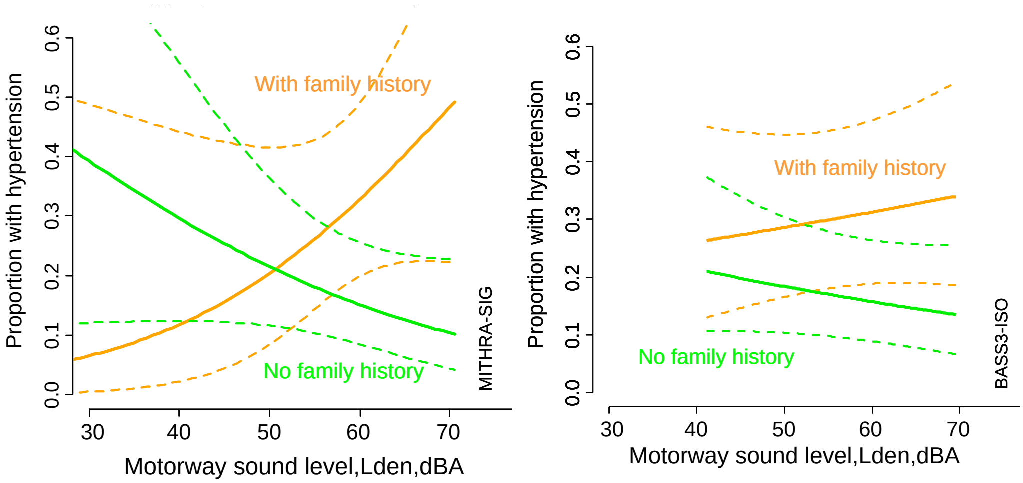


Fig. 6.17 Proportion with hypertension and motorway sound level by disposition (family history of hypertension) and noise mapping procedure (MITHRA-SIG left and BASS3-ISO right.

This means, people with a predisposition are at risk of developing hypertension with increasing noise exposure from the motorway. At lower levels of exposure the confidence limits are rather wide which overemphasises the downward slope for people without family history. The results of the right figure are not significant – although there is only a similar trend which is reassuring. However, this points to a certain degree of dependence of the type of noise modelling and to other factors (measured or omitted) that may modify the relationship.

Note: without considering the interaction between sound level and disposition (Fig. 6.17) you would see a zero relationship.

The public health importance of this finding is notable, as 41 % of the sampled population know about a family history for hypertension in at least one parent, 2 % in two parents.

Hypertension medication

Similar regression models were run with respect to antihypertensive medication and do confirm the findings found with the diagnosis indicator (Fig. 6.18). The relationship with both exposure estimates is also more similar with respect to the significance levels obtained.

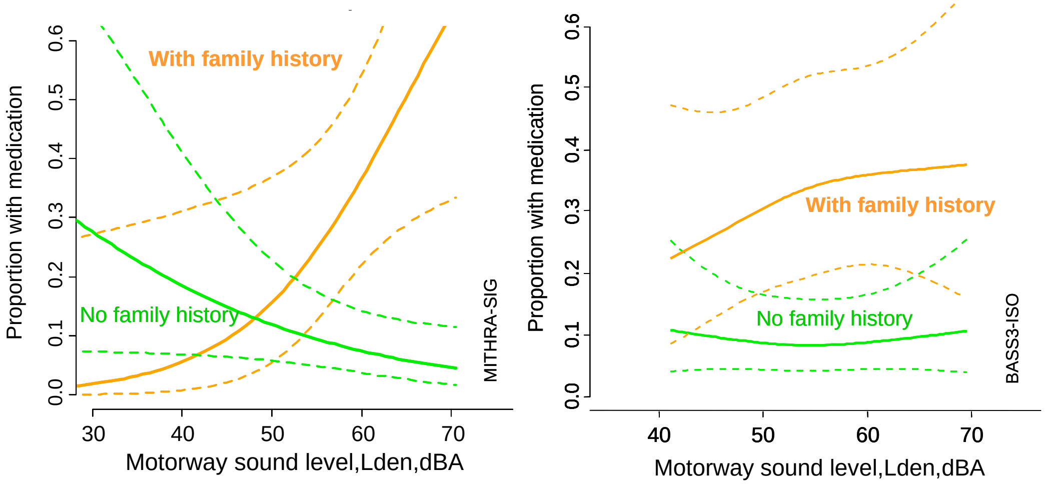


Fig. 6.18 Proportion with hypertension medication and motorway sound level by disposition (family history of hypertension) and noise mapping procedure (MITHRA-SIG left and BASS3-ISO right).

Ischemic heart disease (angina pectoris and myocardial infarction)

The low prevalence of CVD in the Tyrol area makes it difficult to establish a valid relationship with noise and air pollution as the statistical power is very low. The largest power was available for the indicator "angina pectoris ever". This health endpoint was subjected to an adjusted multiple logistic regression model. The exposure-effect curve (Fig. 6.19) shows a statistical trend which is not significant. However, it is evident that the curve only starts to level off around 60 dB(A) and then shows a stronger increase in those having hypertension (left graph) or a strong anger reaction (right graph) towards traffic. Again, this underlines the importance of disease modifiers for detecting effects of noise on health. Air pollution was not a significant parameter in the adjusted models.

As the regional health study is not able to produce a reliable regional exposure-effect curve due to the low number of people with the respective diseases (MI or AP), a comparison is made with the exposure-effect curve of Babisch (2005) as a general guide for risk assessment (see Fig. 6.20). Also this curve has a 95 % confidence interval which is wide and does not imply statistical significance. However, the public health importance is given for risk assessment.

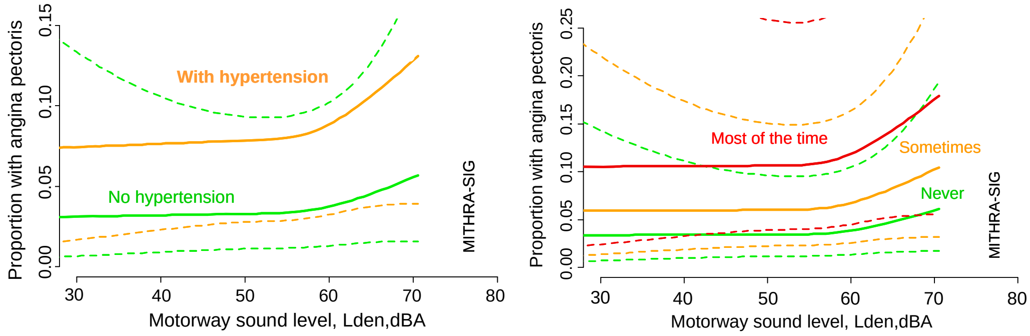


Fig. 6.19 Proportion with angina pectoris and motorway sound level by hypertension (left) and anger reaction to traffic (right) using the same method of noise mapping (MITHRA-SIG).

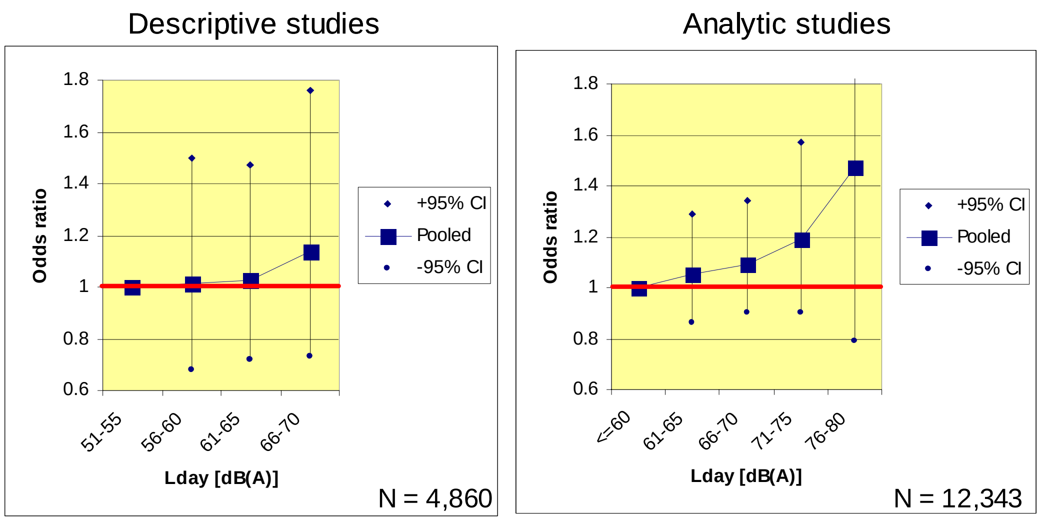


Fig. 6.20 Exposure-effect curve for road traffic noise and risk of myocardial infarction: Meta-analysis from Babisch 2005

The point of levelling off from zero risk at approx. 60 dB(A) is very similar to the results of the ALPNAP health study where the calculated increase in the odds ratio is

from 55 to 65 dB(A): OR= 1.36 (95% Confidence interval 0.81 to 2.30)
from 60 to 70 dB(A): OR= 1.52 (95% Confidence interval 0.72 to 3.21)

The spread of the odds ratio is not much worse in the ALPNAP health study, even though the study size is much smaller (N = 1643). This shows that a more thorough adjustment performed in smaller studies has a certain advantage.

No increase in risk of angina pectoris was observed with rail and main road noise exposure.

6.3 Methods of observations at regional level

It has to be stressed at the beginning of this chapter that impact assessment must include both accurate exposure and health outcome assessment. Whereas exposure assessment guidelines and standards are often clearly defined (see Chapters 2, 3, 4, 5) the choice of health outcomes and the methods applied in environmental impact assessment are less standardised. This is mainly due to the fact that standardised clinical methods are not easily transferred to the field of environmental health (not sensitive enough to detect effects or not applicable to field conditions). Therefore, many investigators have created their own instruments and often insufficient information is available on the validity and reliability of these measurements (Rosen and Olsen 2006). However, great efforts have been made and are still under way to create appropriate intruments and to improve the standardisation and validity of assessments (SF-36, ISAAC, KINDL,WHO-QoL, WHO-QoL-brev). Nevertheless, in smaller scale impact assessments adaptations have to be made to available instruments to allow regional contextual factors to properly be taken into account. These adaptations especially concern the QoL-issue and the behavioural aspects. The available instruments usually target an urban population and do not meet the requirements for assessing Alpine populations. These are often characterised by a scattered residential living pattern between larger urban agglomerations and rural areas.

6.3.1 Existing health data from disease surveillance systems

Routinely collected health data (vital statistics, hospital admissions, special disease registries such as cancer and myocardial infarction, health insurance data) suffer from several restrictions that limit their use in smaller scale assessments of the health impacts of transport systems in sparsely populated Alpine valleys:

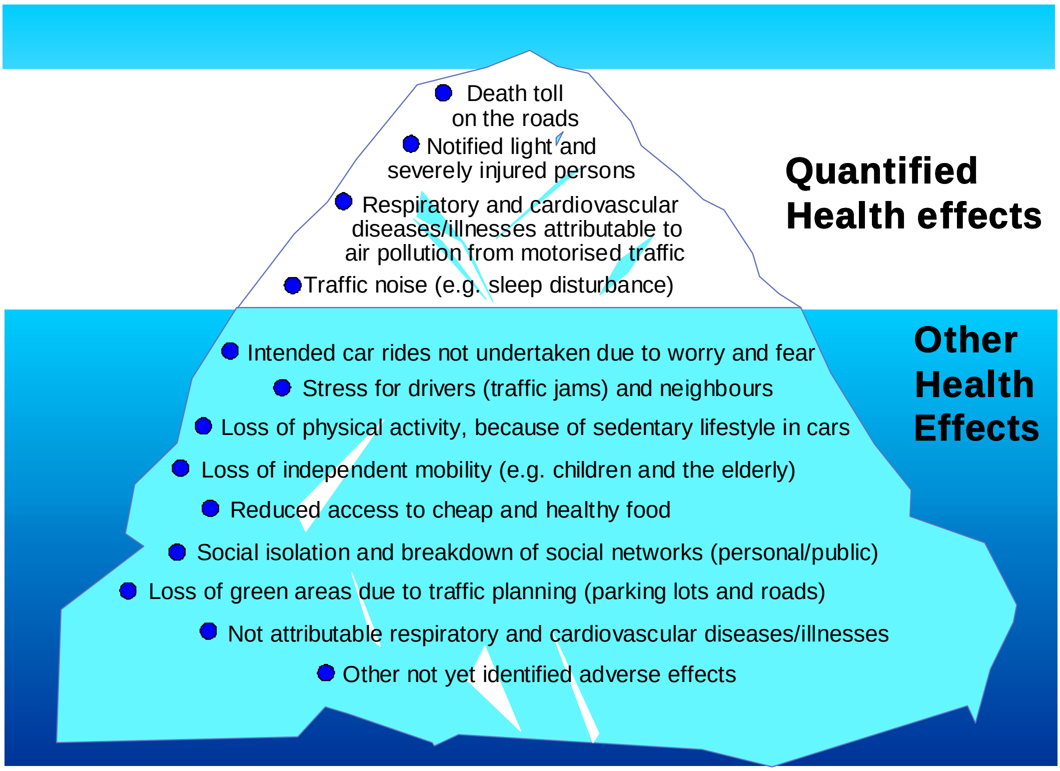
- a lack of detail on a smaller geographic scale (community level) and the fixed linkage to administrative units (neither traffic exposures nor health effects follow these artificial units)
- a lack of information regarding small-geographic-area contextual variables for these aggregated data and the consecutive limits for proper adjustments (chances for “ecologic bias”)
- omission of less severe health outcome (mostly only mortality data are available)
- population sizes are usually too small to obtain reliable statistical findings for severe health indicators (such as lung cancer) between selected subsets of the area of investigation (e.g. distance to transport routes).
- small population sizes limit the analysis of gradients (e.g. health outcomes by distance to transport routes)
- limited access to morbidity data bases such as doctor’s diagnoses and medication data collected by the health insurance system due to privacy restrictions and the lack of standardised data collection

Micro censuses provide individual data. However, in principle they suffer from the same limitations with respect to the resolution/representativeness at smaller scale. The sample sizes are too small to be representative of geographical units smaller than “county”, “federal state” or “provincial” level.

To some extent improvements in the provision of low level health information could be made through the establishment of doctor based surveillance systems. To date, these systems have been utilised only for notifiable diseases. Recently, several proposals have been put forward to link public health data with existing environmental data in order to monitor environmental health (EPHT by CDC 2004). Ritz et al. (2005) caution that in most countries new laws are necessary to allow automatic linkage and that formal linkage of data is not the only approach required for an effective EPHT program.

Over the last 5 years the WHO has developed The Environment and Health Information System (EHIS) which is a pilot study. It forms part of the methodology proposed for a pan-European EHIS (WHO, 2004). This report provides some insight into effective methods for integrating information from environmental monitoring and health surveillance. The report also demonstrates the limitations of routinely collected data and outlines the need for strengthening cooperation between international agencies and the member states in this area.

Gathering of health information necessary for the early detection of “unhealthy” or non-sustainable situations in transport risk assessment requires the use of special surveys. Fig. 6.21 illustrates why a risk assessment which only includes outcomes from the upper part of the morbidity pyramid (“the iceberg model”) runs the risk of being a serious underestimate (BMA ,1999; De Hollander et al., 2000). However, overestimates of health effects are also possible, when related factors buffer the exposure.



Source: Road transport and health (British Medical Association)

Fig. 6.21 The “iceberg” model of quantified adverse health effects

The results obtained from the ALPNAP health study (see Section 6.2) demonstrate clear deviations from "standard" risk assessment curves for the effects of traffic noise. Alternative exposure effect curves could be established for special health indicators profiting from rich information on effect modifiers. Such additional information is seldom available in classical risk assessment which spends most efforts on exposure modelling and uses health outcome information from studies not conducted in the local context. In their review, Joffe and Mindell (2002) already stated: "the evidence base and the methods have to be improved to serve both local and general needs in public health and policy". And Staples (1997) brought it to the point: "do we want modelling of exposure or understanding effects".

6.3.2 Surveys

Specific health and QoL surveys provide broadly based representative information for monitoring trends in health and its relationships to the larger environment. They also provide information on the relative importance of environmental factors over time. Therefore, large national surveys were established during the last few decades in many countries (Bellach et al., 1998; Seifert et al., 2000; Becker et al., 2005) and at the supranational level (Eurobarometer, LARES study of WHO) concerned with health, quality of life (QoL) and the environment (Bonnefoy et al. 2003, Fahey et al., 2004; EC, 2005). An early example (Annest et al., 1983) is the monitoring of a decrease in blood lead concentrations in children after the reduction of lead content in gasoline in the USA (1976-1980). The International Study of Asthma and Allergies in Childhood (ISAAC) has provided evidence for large differences in prevalence and incidence of asthma and allergies (east-west difference in Europe) and the associated factors (Leonardi et al., 2002; Weiland et al. 2004). SCARPOL and SAPALDIA are two Swiss studies which monitored the associations between respiratory and allergic diseases and symptoms with air pollution over years (Braun-Fahrländer et al., 1997; Zemp et al., 1999; Braun-Fahrländer et al., 2004). These show no further increase in asthma and hay fever in Swiss adults. Neuberger et al. (2002) and Bayer-Oglesby et al. (2005) could demonstrate an improvement in lung function of children who experienced a decrease in air pollution exposure over time. The LARES-study did show several significant associations between annoyance from traffic noise and reported diseases (Niemann et al., 2005). However, due to the cross-sectional nature of this and other studies this does not necessarily mean that the associations are causal.

It is a general belief that environmental health surveys provide useful information to the political administration which can be used in risk assessment (Künzli et al., 2000; Maynard, 2001; Babisch, 2006) and risk communication (Schreiber et al. 2001) with the general public to enhance the understanding of environmental decision making (e.g. traffic restrictions) in the course of action plans required by law (air and noise pollution).

Specifically planned health surveys have established advantages and share disadvantages common in empirical research. The ideal survey does not exist. Choices have to be made at each step from planning to reporting (Galobardes, 2002). This is not the place to fully outline these steps and their consequences. The respective decisions may depend on scientific, logistic and practical reasons or financial constraints. The reasons for the choices should be recorded, since often the eventually implemented survey deviates from the plans outlined in the proposal. The most important decisions are at the following steps:

- define a clear objective
- find the proper target population for the objective
- choose the adequate sampling strategy

- choose the type and style of information gathering fitting with the objective
- obtain contextual information
- apply ethical principles and respect privacy
- data management and quality control
- use appropriate analysis techniques and reporting

6.3.2.1 Type of surveys

Mail questionnaires, phone surveys and face-to face surveys are the most commonly used survey technique. Often a mix of methods is necessary because each method has its advantages and disadvantages (see Tab. 6.12). Recently, also internet based surveys are also being employed. However, older and non-technically oriented people are disadvantaged by this survey method, which favours substantial selection paired with very low control over data collection. However, the low costs and the large sample sizes achievable within a short time may render the Internet option as useful for pilot studies.

Table 6.12 Possibilities and limits of the most common survey approaches

Assessment criteria	mail questionnaire	phone questionnaire	face-to-face
Possible sample size	very large	large	medium
Privacy and anonymity	high	high	low to medium
Anticipated participation*	low to medium	medium to high	medium
Control about data collection	very low	high (with CATI)	high (with CAPI)
Interviewer effects	none	medium	medium to high
Maximum possible interview duration	15-20 min	15-20 min	60 min
Possible complexity of questions	low	low	medium to high
Costs	low	medium to high	high (with CAPI)

* large differences between European regions Source: Potthoff and Eller 2000 adapted

CATI (computer assisted telephone interviewing), CAPI (computer assisted personal interviewing)

Often it is useful to combine larger mail or phone surveys with a more intensive face-to face survey to get representative data and also more complex information about the topic. The participation rates differ widely across Europe, e.g. in the recent HYENA study (effects of aircraft and road noise exposure on hypertension) participation ranged from 30 % (Germany) to 78 % (Sweden).

6.3.2.2 The use of questionnaires

Questionnaires provide an efficient means of gathering subjective and objective information about the respondent and the environment she/he is living in. Therefore, most epidemiologic studies apply questionnaires to get information about the key exposure (61 %), the key outcome (34 %) and almost all (97 %) use it to obtain information on important covariates and control for confounding (Rosen and Olsen 2006). Furthermore, the predictive power of questionnaire information on health has been shown to be rather reliable and comparable to expert assessments (Ferraro and Su 2000) – sometimes even better (see also Section 6.2.4**;** literature on health status). Nevertheless, the proper use of questionnaires is essential. Small changes in design, wording, item positioning, mode of administration, interviewer training can introduce measurement error which compromises the achievable results (Oppenheim, 1992; Sapsford, 1999; Taylor et al., 2006; Meyer et al., 2006). In recent years several authors (Wilcox, 1999; Schilling, 2006; Rosen and Olsen, 2006) have made a quest for making existing questionnaires available in order to improve questionnaires. These authors have asked funding agencies to require investigators to publish the applied questionnaires on websites accessible to all for further development and assessment of validity. This proposal seems especially important for surveys at small regional level since most instruments used in these studies are not published in peer reviewed journals but only in the grey literature.

6.3.2.3 The implementation of medical examinations

It makes sense to complement questionnaire information with objective measurements of indicators of physical health. These medical examinations are usually conducted in conjunction with face-to face surveys. Many possible choices are available at different body levels (organs, systems) and should be selected according to the objective of the assessment.

6.3.2.4 Sampling and power

In a regional context (alpine valley) with highly variable population density and its relation to traffic lines simple random sampling will mostly lead to uneven distributions in the exposure categories. It is therefore desirable to use sampling strategies which stratify the exposure (Jarup et al., 2005). As the propagation of noise and air pollution does not follow the same principles and mapping of the exposure is usually not available stratified sampling within certain distances to major traffic lines (based on literature evidence of effects) can be used. Due to the complex valley topography (bottom and slopes) it may still be necessary to supplement the initial sample with a differentiating second sampling (“two stage”) on extended distances (see description of the sampling in the health study in the ALPNAP interim report on the website). Such a strategy can help you to achieve a reasonable balanced exposure contrast and to counterbalance the sampling frame undercoverage.

In environmental epidemiology studies in small areas it is especially important to assure whether the power to detect significant changes or relationships is sufficient (Elliott et al., 1996; Wakefield and Elliott, 1999). As the health risks involved with air or noise pollution are small compared to strong risk factors such as smoking, larger samples are required to detect these risks. Therefore, the task how to improve power (using more prevalent outcomes, using continuous outcomes etc.) is a necessary and important reasoning for any small-scale survey.

6.3.2.5 Non-Sampling errors

Measurement error, non-response (unit and item non-response) and sampling frame undercoverage are the main enemies that further undermine the power of the study by introducing additional variability in the assessments (Korn and Graubard, 1999). Unit non-response can be treated by appropriate substitution of sampling units (Demarest et al., 2007). Item non-response can be minimised through thoughtful design (Smith, 2002; Boynton and Greenhalgh, 2004), consideration of the “checklist misconception-effect” (Meyer et al., 2006) and appropriate dealing with sensitive questions. Measurement error can only be minimised by careful training and supervision of interviewers and good explanations given to the respondents about the intent and content of the questions.

6.3.2.6 Exposure assessment

It is most important to obtain high quality complementary information on traffic exposures (see specific chapters in this report). The exposure information for each persons' residential location can then be linked to the selected health outcomes, QoL and behavioural information at the individual level by means of geographical information systems (GIS).

6.3.3 Environmental indices-based method

In the previous paragraphs very detailed methodologies, based on field studies, have been presented. It demonstrates, among others, the interest to establish specific dose-response curves, since well-being and health impacts are the consequences of interactions between many parameters linked to the local inhabitants, and their environment. It also points out that those responses are likely to evolve, and only give an instant picture of a situation. These conclusions may appear frustrating whereas transport projects or policies are decided many years before they are actually carried out, and because the level of data required to accurately estimate human responses to environmental pressures is very high. Moreover the possibility to compare indicators from one area to another is also of great interest, especially when dealing with evaluations of transport policies in corridors because the impacts of a local decision may have an effect on a larger scale.

Alternative methodologies, based on environmental indicators or indices can be applied, considering that the level or availability of local data may vary. The motivations for proposing the following methodology are:

- to provide decisional and technical actors with "understandable" or "graspable" integrated information about complex physical phenomena such are air pollution and noise and their effects on exposed population
- to have the possibility to "superpose" / "add" different environmental impacts (air and noise but not only!), keeping a certain level of disaggregated data at the same time
- to be able to localize impacts of transport scenarios at relevant scales
- to provide non-specialists with a decision-tool

The present work does not intend to provide future users with a "turn-key" tool, but it aims at proposing a "methodological skeleton" when having to deal with environmental pressure of different kind (e.g. air and noise).

6.3.3.1 Environmental Indicators, Indices

The last few years have seen a multiplication of environmental indicators and indices. This fact renders the public concern about environmental stakes, and the decisions makers' need for synthetic tools helping policies formulation. Among these indicators, air quality indices, ecological foot print (EF), are maybe the most popular, but almost all environmental (ecosystems, water, well-being, health, urban development, waste, etc.) have been translated into indicators (OECD, 2002).

Before going any further, it seems useful to recall what indicators, indices, and parameters mean. OECD (1993) proposed the following definitions:

Before going further, it seems useful to recall what indicators, indices, or parameters mean. OECD (1993) proposed the following definitions:

– **Indicators**: a parameter, or a value derived from parameters, which points to provide information about, describe the state of a phenomenon/environment/area, with a significance extending beyond that directly associated with a parameter value.
– **Index**: a set of aggregated weighted parameters or indicators
– **Parameters**: a property that is measured or observed.

These definitions help to clarify the meaning of commonly used terms, and introduce the notion of "aggregation" underlining the distinction between indicators and indices. In the chain of transformation, parameters are considered as raw data chosen to describe a specific phenomenon. Indicators are generally the result of a first (mathematical) operation aiming at making more understandable base parameters. For instance, sound pressure level (L_p) is derived from the temporal integra-

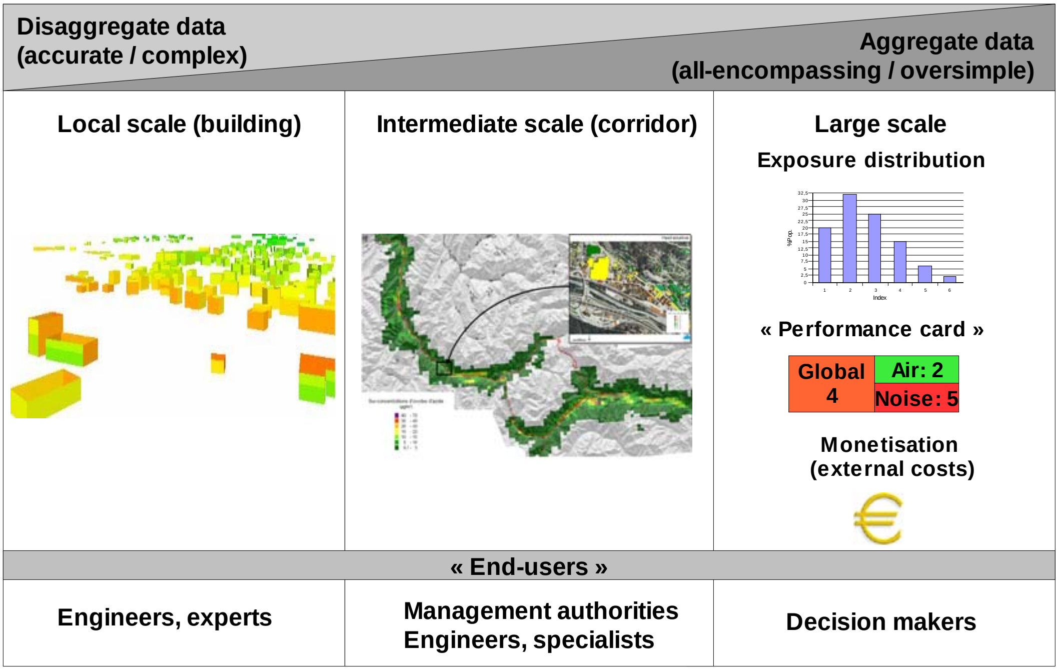


Fig 6.22 The three-scale approach according to users.

tion of acoustic intensity on a given period, using a log-scale to manage data that cover a large range of values. Moreover, the log-scale was historically utilized to account for the fact that some of our senses operate in a logarithmic fashion. Sometimes, external information is used to enhance comprehension. The A-weighted operation (see Section 5.1.2) or the way the L_{den} indicator account for day-evening-night exposure, are good examples of how to introduce human perception of sound and annoyance. At a higher level, indices are used to identify or hightlight particular trend or condition, generally in reference to standard values of indicators or parameters. Indices are often dimensionless number, and/or associated with qualitative judgments for easier interpretation. The OECD's definition suggests that indices are derived from aggregation operations. Three types of aggregation are listed: spatial, temporal, and thematic aggregations. The computation of air pollution indices (*API*), for instance, involves all three kinds of aggregation: global indices may account for measurements obtained from different monitoring stations (spatial); API are representative of hourly, or daily integrated concentrations of pollutants (temporal); several types of pollutants are used to quantify atmospheric pollution (thematic).

The aggregation operation is necessarily synonymous with loss of information. For that reason the process and output must be adapted to the final use or user. Fig. 6.22 illustrates the spatial aggregation process as it was defined in the ALPNAP project. Three spatial scales of representation have finally been kept in order to adapt indices or indicators to different final target users. It is clear that the level of detail should decrease with the technical profile of the user. The goal was also to preserve the tree structure of data to be able to analyse the sensibility of the method and for instance to evaluate the effect of local measures on a larger geographic scale.

In Tabs. 6.13 and 6.14, raw data used during the ALPNAP project, as well as indicators or indices are classified according to the three scales of representation. Even if some of these are specific to the project, an environmental consultant will recognize the main categories of information commonly used in impact surveys. This table is practical to insure transparency of the aggregation process, keeping traces of the assumptions made at each level and possibly helping to go further into the interpretation of high level indicators or indices.

In this process, GIS is revealed to be a tool of great interest for managing data and indicators at different spatial or temporal scales, assisting the transparency objective, and assuring coherency between themes.

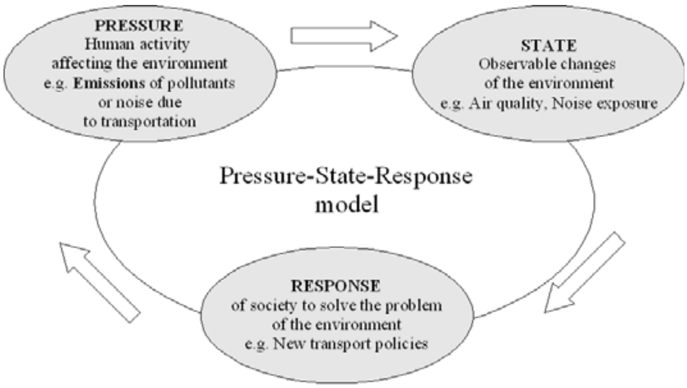


Fig. 6.23 Illustration of the Pressure-State-Response-Model

Aggregation requires a certain level of care to be relevant. As pointed out in the OECD report (1993) the use of the PSR (Pressure-State-Response) model (see Fig. 6.23 can be very useful to develop indicators or indices in a consistent manner. The model relies on the principle of cause-effect relationship, linking human activities to the environmental impacts, and helps to organize monitoring, and decision-making indicators following a reference chart.

Hence, three types of indicators are associated to the three steps of the analysis:

Pressure indicators estimate the anthropic actions having potential negative effects on the environment. In the context of the ALPNAP project it refers to emissions of pollutants, and noise from land transport origin.

State indicators are introduced to inform about environment conditions, quality of life or health of exposed populations (e.g. concentrations of pollutants, noise levels).

Response indicators allow quantification of human actions engaged in reducing pressure (e.g. noise abatement measures, traffic regulation, tax policy, etc.). Therefore, when proposing indices based on the aggregation of indicators, one should take care that these indicators are of the same kind.

Tab. 6.13 Data used for impact assessment at local, intermediate and large scales.

Raw data		Local scale	Intermediate scale	Large scale
Meteorology		Measurements from stations (static and mobile): wind, temperature gradient,…	Fields of meteorological variables (wind, temperature, ...)	
Topography		Detailed GIS data (see Chapter 2), characteristics of tunnels, viaducts, 3D maps, digital elevation models with horizontal resolution 1 to 10 m	Topographic 3D or 2D maps Orthophotographic maps, digital elevation models with horizontal resolution of about 100 m (e.g., SRTM data)	
Land cover		Detailed information on artificial, agricultural, forests, industrial, protected areas, soils' nature, in GIS format	Gridded land-use data from inventories such as CORINNE or USGS	
Population		Distribution of population in buildings, demographic data, occupancy, opinion surveys data	Gridded population data sets, population per adminstrative unit (community or below)	
Traffic		Number of vehicles per category and infrastructures as a function of time	Traffic flow rates averaged over days of the week, months	
Noise	Emission	Individual noise emission characteristic of vehicles Characteristics of road pavements (noise Levels)		
	Immission	Simulated noise levels per source, Measurements, opinion surveys	Isophones per sources	
Air pollution	Emission	Individual source	Mapping of emissions (mobile and static sources)	
	Immission	Concentrations of pollutants (high resolution data from modelling) - Concentrations of pollutants from mobile or static stations	Integrated data mapping	
Health		Epidemiological studies	Dose-response functions	

Response indicators allow to quantify human actions engaged to reduce pressure (e.g. noise abatement measures, traffic regulation, tax policy, etc.). Therefore, when proposing indices based on the aggregation of indicators, one should take care that these indicators are of the same kind.

The ALPNAP project has constituted a rare opportunity to obtain high quality data about air pollution and noise in two corridors of the Alps, considered by Alpine inhabitants as the main pressures. “Responses” to land transport pressure may affect these pressures and environmental conditions in a different way, considering for instance modal shift policies.

In the following paragraphs, an example of index method is proposed, with the purpose of simultaneously estimating the effects of both pollutions. Firstly, possible air and noise indices are presented, and finally an aggregation method is suggested. The methodology is not Alpine specific. It can be applied to others areas and should provide a basis for intercomparisons at national or European scales.

Tab. 6.14 Indicators used for impact assessment at local, intermediate and large scales.

Indicators/Indices		**Local scale**	**Intermediate scale**	**Large scale**
Meteorology				
Topography				
Land cover				
Population		Accurate distribution of populations in buildings (if available?)	Population density distributed in built-up area	
Noise	Emission	Comparison to reference pavement, classification of road pavements	Emission sources noise mapping (optional)	
	Immission	Integrated and weighted noise levels (L_{den}, L_{night}) on buildings facades.	Annoyance indicator per sources, and aggregated (railway+road)	- Mean noise exposure indices (population or surface weighted) - Distribution of population according to the indexes - External cost due to noise effects
Air pollution	Emission		Mapping of air pollutants emissions per pollutants	
	Immission	Air pollution indices at measurement stations	Air pollution indices (NO_2, PM10, NO_2+PM10) simulated results, Exposure indices (crossing indexes with populations)	- Mean air exposure indices (population or surface weighted) - Distribution of population according to the indexes - External cost due to air pollution effects
Aggregate indicators				- Aggregate noise+air indicator - External costs (monetisation)

6.3.3.2 Air Pollution Index

Facing the growing awareness of environmental issues, most of the European countries found it necessary to communicate on atmospheric pollution. The complexity of physical and chemical phenomena (the number of pollutants having very different origins and effects) has generally led to public communication based on indices. In 2000, forty air quality indices were in use throughout the world and not less than thirteen in Europe alone (Garcia, 2002). However, there is no real consensus between countries on these indices, sometimes even several indices are in use in the same country. Moreover, indices are very hard to compare with each others, due to the different choices of pollutants, aggregation methods (spatial and temporal) and different scales of representation (number and limits of classes). Nevertheless, the scales and interval categories are, for EC countries, largely inspired by the series of European directives on atmospheric pollution (see Section 4.1).

Index based communication is not a generality. Hence some European countries (e.g. Greece, Denmark, Austria) prefer to directly inform their citizens on concentrations or/and when limit values or alert thresholds are exceeded. For the others who choose to use indices, those are generally estimated from the monitoring of NO_2, NO or NO_x, PM_{10}, SO_2, ground level O_3, and CO concentrations. Often, a sub-index is defined for each pollutant, and a global index is determined using a maximal criteria.

The number of categories used to convert concentrations into a single integer number varies from one country to another (4 in Canada for AQUI, 10 for French ATMO, 6 for Swiss *IPC*, 7 for German LuQx). Fewer categories probably simplify the message since the result is roughly: "air pollution is low, moderate, bad or very bad. However, the index would lack in sensitivity for comparing evolution or transport scenarios.

Indices adopted by Cercl'Air the Swiss society of air protection officers, are based on three pollutants (see Tab. 6.15). Depending on the situation, the global (maximum index among the three sub-indices) or adapted (index computed from the most relevant pollutants) is used. Another particularity is the introduction of short term (*IPC*) and long term (*IPL*) indices. For NO_2 and PM_{10}, *IPC* is computed from daily average concentrations whereas *IPL* is derived from annual mean values. *IPL* is obtained by reference to annual limit values, and different weights are given to each pollutant (0.6 for particulates, 0.3 for nitrogen dioxide, 0.1 for ozone).

Tab. 6.15 Definition of the Swiss IPC short term air pollution index (Cercl'Air, 2005).

	Description	PM10 (μg/m^3)	NO_2(μg/m^3)	O_3(μg/m^3)
1	Very low	0-10	0-10	0-50
2	Low	11-20	11-30	51-100
3	Pronounced	21-50	31-80	101-120
4	Moderate	51-75	81-120	121-180
5	High	76-100	121-160	180-240
6	Very high	>100	>160	>240

In order to illustrate the air and noise aggregation method proposed, the *IPC* index was retained in the ALPNAP project. The number of categories (6) is small enough to have a "graspable" scale, and large enough to observe the effect of transport related measures. As only NO_x and PM_{10} pollutants (representative of local land transport pollution) were studied, the air pollution index (*API*) computed, does not include ozone contribution.

Obtaining long term exposure values was beyond the scope of the project, but the methodology can easily be extended to account for annual based indices, for instance using *IPL*.

6.3.3.3 Noise index

As recalled, annoyance plays a key role in the evaluation of noise impact on exposed population. It is admitted that noise levels resulting from land transport infrastructures are generally below 80 dB(A) and therefore not responsible for short term health diseases. Linking objective indicators such as noise levels, to the highly subjective feeling that annoyance is, has led to the proposal of several noise indicators or "indices" in the literature (Langdon, 1968; Marquis Favre, 2002; Lambert, 2002). Noise indices are generally combinations of other noise indicators or parameters, and are closer to "indicators" as defined previously, and from our knowledge, there is no equivalent of air pollution index in the acoustic domain. This is probably due to the fact that API have been introduced for communicating about pollution subjected to potentially important daily or hourly variations, involving short term and long term health impacts, whereas annoyance is considered as a more long term consequence of exposure.

An important step has been made at the European level to harmonize noise indicators. The Directive 2002/49/EC (END) imposes the use of L_{den} and L_n (see Section 5.1.3.1 for definition) in the scope of the strategic noise mapping of all main European roads, railways, airports and urban agglomerations. At the moment, no consensus has been officially found to explicitly combine exposures produced by different kinds of sources. The strategic noise maps consist of separate maps for each source. It is possible to superimpose these maps, but no aggregation method is recommended.

As multi-exposure, and the study of modal shift scenarios is a central question when studying Alpine crossings, an example of noise index combining both road and railway sources is proposed in the following. This index, named *NPI* (noise pollution index) is based on the use of dose-responses curves and an aggregation method proposed by Miedema, discussed within the European working group on dose/effect relationships (EC, 2002).

The annoyance equivalents model suggested by Miedema is inspired by methods used in toxicology to estimate the effect of mixtures with different chemical compounds, for instance in the field of health effects of air pollution (toxicological reference values). According to this procedure, a reference source is chosen and the noise levels produced by the others types of sources are converted in equivalent levels that would produce the same annoyance level as the reference source.

The formulae established by Miedema for computing annoyance levels from noise levels for roads and railways are written:

$$A_{road} = 2.22\, L_{den,road} - 107 \tag{1}$$

$$A_{rail} = 2.10\, L_{den,rail} - 110.1 \tag{2}$$

From these two equations, the equivalent railway noise level (road reference) gives:

$$L_{den,rail} = (A_{rail} + 107.0)/2.22 = (2.10\, L_{den,rail} - 3.1)/2.22 \tag{3}$$

The total "equivalent" noise level produced by, for instance, a road and a railway can now be calculated using the energy summation principle as both noise levels refer to the same kind of source (road):

$$L_{den,eq,road+rail} = 10\,\lg(10^{L_{den,road}/10} + 10^{L_{den,rail}/10}) \tag{4}$$

Finally, the total percentage of people, annoyed (lightly, moderately, or highly) is calculated using Miedema's polynomial interpolation functions. For example, the percentage of "annoyed people" due to road infrastructure is given by:

$$\%A = f(L_{den}) = 1.795 \cdot 10^{-4}\,(L_{den} - 37)^3 + 2.220 \cdot 10^{-2}\,(L_{den} - 37)^2 + 0.5353\,(L_{den} - 37) \tag{5}$$

Then the %A due to road plus railway is computed using:

$$\%A_{road+rail} = f(L_{den,eq,road+rail}) \tag{6}$$

Tab. 6.16 illustrates this procedure for noise levels between 45 and 75 dB considering road and railway exposure:

Tab. 6.16 %*A* due to simultaneous exposure to road and railway sources.

	$L_{den,railway}$ (dB)						
$L_{den,road}$ (dB)	45	50	55	60	65	70	75
45	7.2	9.2	13.0	18.7	26.1	35.3	46.2
50	11.6	12.7	15.2	19.8	26.6	35.5	46.3
55	17.8	18.3	19.6	22.6	28.0	36.1	46.5
60	25.8	26.0	26.5	28.0	31.5	37.9	47.3
65	35.5	35.6	35.8	36.4	38.2	42.1	49.4
70	47.1	47.1	47.2	47.5	48.2	50.1	54.5
75	60.7	60.7	60.7	60.8	61.1	61.8	63.9

The next step consists in converting this multi-exposure indicator into an index. Noticing that *%A* reaches a maximum of 63.9 % for highest noise level, a six-step closed scale is determined by normalising the percentage of annoyed people (*%A*) exposed to road plus railway sources by a factor 10:

$$\%A_{road+rail} = f(L_{den,eq,road+rail}) \qquad (7)$$

The result is rounded to the nearest integer number, and limited at 1 as a minimum, and 6 as a maximum. Tab. 6.17 gives an example of a calculation of the *NPI* index obtained from Tab. 6.18. Of course the *NPI* can be computed for intermediate values of noise levels using equation (7). Miedema's dose-response functions should only be used between 45 and 75 dB. The *NPI* can however be computed for lower and higher levels but users must keep in mind that it will be limited by construction to 1 below 45 dB and 6 above 75 dB.

Remark: Because *%HA* does not overestimate noise effects, it is generally preferred to *%A* by psycho-acousticians. However, we chose to use *%A* for aggregation because the variations of the polynomial function for low levels gives more sensitivity to the index. Moreover the *NPI* classes are better distributed.

Tab. 6.17 *NPI* due to simultaneous exposure to road and railway sources

	$L_{den\text{-}railway}$ (dB)						
$L_{den\text{-}road}$ (dB)	45	50	55	60	65	70	75
45	1	1	1	2	3	4	5
50	1	1	2	2	3	4	5
55	2	2	2	2	3	4	5
60	3	3	3	3	3	4	5
65	4	4	4	4	4	4	5
70	5	5	5	5	5	5	5
75	6	6	6	6	6	6	6

Tab. 6.18 Interpretation of the *NPI* values

NPI value	Exposure to noise
1	Very low
2	Low
3	Moderate
4	Pronounced
5	High
6	Very high

According to the definition *NPI* is a state index as it derives directly from state indicators. It should be viewed as a complement to the strategic noise maps displaying exposure per source. It can be used to represent multi-sources exposure on a large-scale map, and gives intermediate information between noise levels defined at local scale (buildings) and macroscopic indicators derived from monetisation for instance. As such it is not adapted to detailed impact surveys but dedicated more to the spatial analysis of environmental stakes from the acoustical point of view.

The index can be used for characterising local (dwellings) exposure but it is more adapted to visualizing hotspots or locating preserved areas in large corridors, through condensed information. Considering this kind of large scale representation, *NPI* can be computed using isophones curves (L_{den} or L_n), with a step of 1 dB obtained for each type of sources. A grid of 1×1 km² or less is used to display the indicators. Due to possible/probable variations of the NPI inside each grid cell, the mean value weighted by areas is estimated.

Air-noise thematic aggregation: exposure index

Aggregating indices or indicators of diverse themes is a tricky exercise because condensing information of different kind can lead to misinterpretations if not correctly explained.

It must first be underlined that here, the aim is not to provide future users with a metric that would quantitatively measure the effect of transport policies on health or quality of life. The two sub-indices defined for air and noise (*API* and *NPI*) do not quantify the same sort of effects, the first one being related to health effects, and the second one to annoyance. The Exposure Index (*EI*) presented in this paragraph should provide a picture of the state of the environment highlighting areas or populations under conditions of multi-exposure. As *API* and *NPI*, the *EI* index can be evaluated for large-scale geographical analysis.

Two alternative aggregation processes are presented below, but the methodology is still open and should be put to the test outside the ALPNAP project before validation.

First alternative: weights method

Having specified both *API* and *NPI* indices and defined a common scale of representation, a "natural" method to aggregate both indices is to weight them. The *EI* is written as:

$$EI = W_{air} \times API + W_{noise} \times NPI, \quad \text{with } W_{air} + W_{noise} = 1 \qquad (8)$$

Note that the Swiss *IPL* discussed in Section 6.3.3.2 is a good illustration of this aggregation method.

Following this definition *EI* varies, of course, in the same scale as *API* and *NPI*.

The weights are determined to give relative importance to both pollution concerns, the difficulty lying in their choices.

Field surveys, as presented in Section 6.3, can be a clue to determine these choices. For instance the answers obtained by asking the people in the Brennero/Brenner corridor the question: "what are the reasons to complain about?" reveal that air and noise pollutions are ranked at the same level of importance. On the one hand, the interest of this approach is that local specificities and concerns can be accounted for; on the other hand there is a risk of losing the inter-comparability property of the index.

Another example, giving a more universal approach, is the use of the ratio between external costs (e.g. using UIC, 2006). In this case more weight should be given to air pollution (0.8 vs. 0.2 for noise).

Second alternative: maximalist function method

This second method is directly inspired from the way some air pollution indices are built. In this case the *EI* is simply given by:

$$EI = \max(API, NPI) \qquad (9)$$

Weakness: the dominant index can mask the variations of the other and therefore limit the sensitivity of the *EI*. This for instance is the case with air pollution indices including ozone that dominate during summer. The solution to this well-known problem is to keep sub-indices information and communicate date that is partially disaggregated.

6.3.4 Health indexes

6.3.4.1 Exposure assessment

The first step in assessing health risk of transport-related air pollution is the evaluation of the population exposure to air pollutant concentrations. Starting from the emission scenario (traffic flow, traffic composition, emission factors – see Chapter 2) and meteorological data (see Chapter 3), the air pollutant concentrations can be modelled using air quality dispersion models (see Chapter 4). The use of exposure-response functions subsequently allows quantification of the health effects and their distribution on the investigated area.

This kind of exposure assessment can be applied to evaluate the effects of the macro-pollutants emitted by road transport, such as PM and NO_2. In fact people are exposed to these pollutants exclusively by means of inhalation. For assessing exposure to toxic and persistent atmospheric pollutants multiple pathways impacts must be considered. All possible routes by which contaminants enter the body of an exposed person must be taken into account – inhalation, ingestion of food or drink, ingestion of soil and adsorption through skin – because such patterns directly affect the magnitude of exposure to substances present in different indoor and outdoor environments. In this case the assessment of exposure needs to combine information regarding soil pollutants deposition, use of the soil, and modality of permanence of the subjects in different exposure places.

A synthetic decisional indicator of the populations' exposure is represented by the percentage of the population living in areas with specified levels of pollution. These pollution concentration levels depend on the substances and have to be defined as a function of the health effects and of the air quality standards rules.

6.3.4.2 Methodologies for health impact assessment

The available methodologies to assess the impact from traffic-related air pollution are different according to whether the pollutant is a toxic and persistent micro-pollutant or a non-persistent macro-pollutant (Fig. 6.24). In the first case the approach may follow US EPA methodology for the health-risk assessment, whereas for the macro-pollutant maps and indicators of the exposed population and dose-response functions may be adopted.

Some toxic substances contained in traffic exhausts, like various organic compounds (polycyclic aromatic hydrocarbons, benzene, dioxins) and heavy metals, even if emitted in small amounts, having a long lifetime, tend to accumulate in the environment and induce severe effects. The methodology to assess the impact on air and on vegetation and water bodies (the latter due to run-off effect) is analogous to the one described for the health impact of persistent atmospheric polluting substances; however it is necessary to point out that for some of these substances in the case of the motor vehicles little data exist for emission factors.

The amount of particulate matter containing toxic substances which reaches water bodies due to run-off is estimated on the basis of the atmospheric deposition. Passage trough the biological chain up to the human being is a function of a bioconcentration depending on the intermediate receptors (OEHHA, 2003). This also shows that same source, in this case the traffic, can have an impact on health and the environment through different pathways.

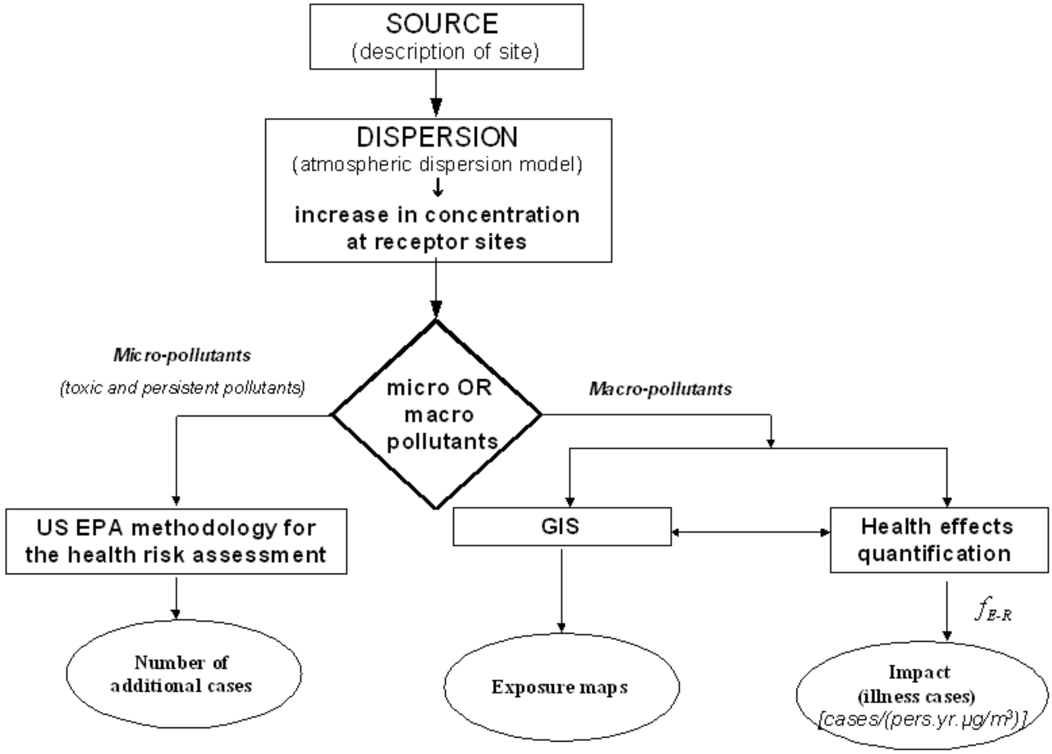


Fig.6.24 General representation of the methodology needed for assessing the impact of pollutants

A non-negligible contribution of pollutants following different impact pathways is given by the re-suspension and wash-out of the particulate matter deposited on the roadways. The phenomenon can depend on many factors such as the state of pavement on the street, the intensity and the type of traffic, the street maintenance and meteorological factors. Conversely, the pathway leading the contamination to human being obviously depends on population density and soil coverage. General emission factors to assess impact on population living near traffic sources are available in literature (e.g. Legret et al., 1999).

The *exposure-response* or *dose-response* functions, provided by epidemiological and toxicological studies, are used for the quantification of health impacts. These functions are generally assumed to be linear in the common range of human exposure; since no other consolidated indication is nowadays coming from epidemiological studies. Moreover, at the present state of the art, there is still a lack of evidence for thresholds at current ambient concentrations (European Commission DGXII, 1999); in other words a null response is considered to be referred to no exposition. Exposure-response function are generally written in the form

$$R = E \cdot K$$

where R (response) is the impact; E is the exposure or dose; K is the relative risk for macro-pollutants, or cancer potency factor for toxic and persistent pollutants.

For micro-pollutant emissions the multiple exposure pathways must be considered. For this reason Toxic and persistent micro-pollutants are substances which remain in the environment for many years after the emission. These substances can migrate from one environmental compartment to the other (i.e. from the atmosphere to the soil and to the water); hence the methodology of estimation is inspired by the US EPA methodology for health risk assessment and considers multiple exposure pathways.

The calculation program consists of three sections:

(1) Calculation of concentration in the soil
(2) Calculation of exposure
  - inhalation exposure
  - dermal contact exposure
    - soil ingestion exposure
    - diet exposure
(3) Calculation of risk
  - individual risk
  - global risk

The model adopted for the evaluations presented in Section 7.2.3 adopts the results of an air quality dispersion model and a detailed territorial analysis of the impact zone as input, to assess, on the basis of parameters related to the characteristics of the pollutants and the examined population, the exposure to the pollutants and the associated risk. The computed doses have to be integrated over the exposure duration, which covers the lifetime (assumed an average value of 70 years) and the time spent in the area.

With respect to traffic, the greatest concern is particulate matter and nitrogen oxides (which are macro-pollutants) and the examples reported in Chapter 7 refer to them.

Epidemiological studies

Epidemiological and toxicological studies over the past decade confirm that outdoor air pollution is associated with negative effects on public health: it is a contributing cause of morbidity and mortality. Road transport is, and will most likely remain in the next decades, a significant contributor to ambient air pollution (Filliger et al., 1999). Evidence from epidemiology and toxicology indicates that transport-related air pollution affects a number of health outcomes, including mortality, non-allergic respiratory morbidity, allergic illness and symptoms (such as asthma), cardiovascular morbidity, cancer, pregnancy, birth outcomes and male fertility. Transport-related air pollution increases the risk of death, particularly from cardiopulmonary causes, and of non-allergic respiratory symptoms and disease. While laboratory studies indicate that transport-related air pollution may increase the risk of developing an allergy and can exacerbate symptoms, particularly in susceptible subgroups, the evidence from population studies that supports this conclusion is inconsistent (WHO, 2005). The major pollutants that are considered as indicators of road transport emissions are fine particulate matter (PM10, PM2.5 and black carbon), ozone and nitrogen dioxide. PM and ozone are principally associated with increased risks of mortality and respiratory morbidity, while nitrogen dioxide, PM and ozone are linked to allergic responses. Other indicators of exposure to transport-related air pollution, such as residence near or distance to major roads and, in part, self-reported traffic intensity at a residence, were associated with several adverse health outcomes. It is difficult to investigate the adverse health effects of air pollution from a specific source, such as transport, because the air-pollution mixture experienced by subjects in most epidemiological studies is generated by a variety of sources. (Künzli et al., 1999; Ciccone et al., 1998) To reduce this problem, some studies have concentrated on the components emitted by transport sources, although, in most cases, other processes may also generate them.

Moreover, the health effects of air pollution may be related to short-term and to long-term exposure: the epidemiological studies are divided between "time series studies" that investigate short term effects of exposure, and "cohort studies" that focus on long-term exposure. Epidemiological studies on the adverse effects of air pollution on health, most frequently use mortality as an indicator, providing information about the dose-response relationships between air pollutant concentration and related health effects. The major epidemiological studies of international interest, to which the health risk analysis discussed in Chapter 7.1.6 has been referred to, are:

- APHEA I (1992) and II (2001), two studies on the effect of air pollution on human health in 15 European cities;
- NMMAPS (2000), a study on morbidity and mortality caused by air pollution in 20 US cities;
- MISA I and II, two analysis on short term effect of air pollution, involving Italian cities;
- "The six cities study" (Dockery et al., 1993), a cohort study involving 8000 people in six US cities over an observation period of about 15 years;
- "The American cancer society study" (Pope et al., 1995 and 2002), a cohort study involving 1,2 million people of 50 US cities over an observation period of 16 years;
- "The seventh-day Adventists study" (Abbey et al., 1999), a cohort study in California on a time span of 15 years;

These studies provide exposure-response functions that are necessary to evaluate the impacts on exposed population in terms of number of deaths.

Dose-effect relationships

As already mentioned, by means of GIS tools, the population living near an investigated traffic corridor can be combined with the air pollution concentrations. After that, crossing population data at the same spatial resolution as the output of a dispersion model, maps of the distribution of exposed population may be easily obtained. The subsequent use of exposure-response functions permits quantification the health effects and their spatial distribution. Exposure to ambient air with a high particulate matter (PM) concentration for some hours induces transitory mild pulmonary inflammatory reactions in healthy people. Long-term exposure to heavy ambient PM concentrations may lead to a marked reduction in life expectancy. The reduction in life expectancy is primarily due to an increased cardio-pulmonary and lung cancer mortality. Increases are likely in respiratory symptoms and reduced lung function in children, and chronic obstructive pulmonary disease and reduced lung function in adults. Sulphate and organic matter are the two main contributors to the average PM10 and PM2.5 mass concentrations in urban areas. Because of its complexity and the importance of particle size in determining exposure and human dose, numerous terms are used to describe particulate matter. Some are derived from sampling and/or analytic methods, while others consist of physiological and epidemiological studies. Concentrations of PM that are somewhat higher than those common in ambient air in urban areas, are necessary to induce toxic effects after very short-term clinical experimental studies. (Abbey et al., 1995; Pope et al., 2002; MISA, 2004; Wordley et al., 1997).

A synthetic decisional indicator of the population exposure is represented by the percentage of the population living in areas with specified levels of pollution. These pollution concentration levels depend on the substances and have to be defined as a function of the health effects and of the air quality standards rules. The population exposure to a pollutant is defined as the product of the population number and the concentration of the pollutant, and can be displayed on a map as shown in the example of Fig. 6.25.

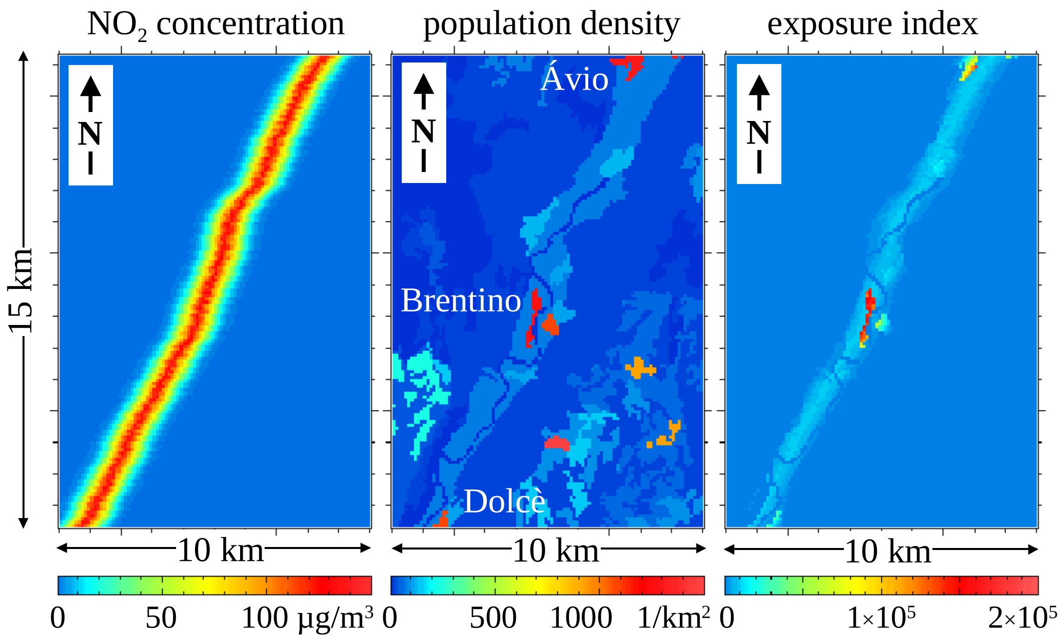


Fig. 6.25 Maps illustrating the combination of the calculated distribution of the pollutant concentration (µg/m^3) (left) and the distribution of the population living in the interested area (centre) to obtain the population exposure (right). The example is related to the Brenner Target Area 3 (see Section 7.2).

Such maps give a quick overview of the areas with elevated population exposure. Furthermore, in order to quantify the impact on the population, two parameters are usually chosen: the hospital admissions and the years of life lost (YOLL). The assessment of the effect on the exposed population has been determined adopting the so-called "ExternE" approach (European Commission DGXII, 1999), which associates every substance an exposure-response (*E*-*R*) function, and then a monetary value to yield the quantified impact. The functions were derived from epidemiological studies and are given in the following form:

Impact = $A \times \Delta C \times P$.

where: A is the parameter function which depends on the substances and on the receptor type (e.g. children, adults, etc.), ΔC (in µg/m³) is the concentration increase due to the examined emission source, and P (in inhabitants/km²) is the exposed population number.

The adopted approach is the one proposed by the ExternE methodology, which was first developed with the aim of assessing externalities of power plants and then extended to transport by the ExternE Transport Project (Bickel et al., 1997). This methodology was applied in various study cases in different European countries, giving a wide overview of site-specific results. The technologies taken into account cover passenger and goods transport by road, rail, and waterway transport. The conclusion of the study is that carcinogens, which were expected to play an important role due to their high specific toxicity, proved to be of much lower importance compared to the fine particles.

In order to further quantify the impact two parameters have been chosen: the “hospital admissions” and the “years of life lost” (YOLL). In the ALPNAP project different exposure-response functions have been analysed, while four expressions have been chosen (Tab. 6.19), in which the results are a function of the total population and not of specific categories (adult, children, asthma adults, etc.), since such detailed population data are not available.

Tab. 6.19 E-R functions for hospital admissions (Dab et al., 1996) and years of life lost (Pope et al., 2002)

	Hospital Admissions	**YOLL**
PM10	$cases = 0.2 \cdot 10^{-5} \cdot \Delta C \cdot P$	$cases = 39 \cdot 10^{-5} \cdot \Delta C \cdot P$
NO_2	$cases = 0.1 \cdot 10^{-5} \cdot \Delta C \cdot P$	$cases = 19.5 \cdot 10^{-5} \cdot \Delta C \cdot P$

Those function are based on a linear dose-effect relationship hypothesis; more accurate and significant response curves would need extensive epidemiological, which are not presently consolidated. The simplification has to be adopted carefully, and results should be intended as the indication of an order of magnitude. Moreover, it has to be noticed that adopting highly detailed (and complicated) functions while only poor input data on population habits and epidemiological data are available, would not introduce any amelioration in terms of final results.

Because of its complexity and the importance of particle size in determining exposure and human dose, numerous terms are used to describe particulate matter. Some are derived from sampling and/or analytic methods; others consist of physiological and epidemiological studies. Exposure to concentrated ambient air particles for some hours induced transient, mild pulmonary inflammatory reactions in healthy people. Long-term exposure to current ambient PM concentrations may lead to a marked reduction in life expectancy. The reduction in life expectancy is primarily due to an increased cardio-pulmonary and lung cancer mortality. Increases are likely in lower respiratory symptoms and reduced lung function in children, and chronic obstructive pulmonary disease and reduced lung function in adults.

The increase in mortality is mostly related to increased cardiovascular mortality for fine particles. On the other hand total suspended particulate is not significantly associated with mortality. The effect estimates remained largely unchanged even after taking spatial auto-correlation into account. Another concern was about the role of SO_2. Inclusion of SO_2 in multi-pollutant models decreased PM effect estimates considerably in the re-analysis, suggesting that there was an additional role for SO_2 or for pollutants spatially co-varying with it.

6.3.4.3 Monetisation

When dealing with different types of impacts produced by different sources, i.e. air pollution and noise as done in the ALPNAP Project, it is necessary to find suitable indexes to compare or even to combine these impacts. As an example the “monetisation” – defined as the action to monetise, i.e. to assess in terms of monetary value – may be introduced as such an index. This particular type of index has the obvious advantage of directly comparing the impacts with real costs and benefits which are, by their nature, expressed in terms of money.

Of course it has to be adopted with extreme caution, since dealing with the value of human life is a very delicate (whenever applicable) issue and in that sense the monetisation approach taken as an absolute method alone would give misleading indications. Moreover available methods need careful adaptation in order to monetise environmental and health impacts, as they may oversimplify the problem's description and cannot take into account all the complex interactions affecting human health.

The monetisation concept, has been widely adopted on the externalities of energy production (ExternE project). It has also been applied to assess the external costs of transport (Bickel et al., 1997).

However it also seems to be useful for a comparison of sources and/or possible mitigation strategies provided a suitable expression of impacts in monetary units is available. In the present case, where health impacts from road noise and air pollution are considered, we recall for example that it is possible to quantify the monetary values of one year of sleep disturbance or chronic bronchitis. The damage value of contaminated air is monetised in order to obtain the so called “total monetised value” of the cost of the illness. This cost can also be interpreted as an indicator of the willingness to accept compensation for the whole population. Indeed the cost of illness is built up by two components, namely the costs for reducing health impact (hospitalisation costs) and the hidden ones arising, for example, from absence from work due to illness itself. Finally, we can state that the monetisation concept may be used for assessing the willingness of a population to accept compensation for the health impact of an infrastructure.