Research Article

Open Access

Ioannis Karipidis, Danielle Vienneau, Manuel Habermacher, Micha Köpfli, Mark Brink, Nicole Probst-Hensch, Martin Röösli, and Jean-Marc Wunderli

Reconstruction of historical noise exposure data for environmental epidemiology in Switzerland within the SiRENE project

Abstract: In 2014 the three-year interdisciplinary study SiRENE (Short and Long Term Effects of Traffic Noise Exposure) was launched in Switzerland. The goal of SiRENE is to investigate acute, short- and long-term effects of road, railway and aircraft noise exposure on annoyance, sleep disturbances and cardio-metabolic risk.

The study is based on a detailed Swiss-wide assessment of transportation noise exposure, including diurnal distributions. The exposure analysis comprises current as well as historical exposure calculations for up to 20 years in the past.

We present the major challenges of compiling sufficient data to support a Swiss-wide model for all buildings and including all transport infrastructure as a basis for the subsequent SiRENE sound exposure analysis for the years 2011, 2001 and 1991. The task is particularly challenging for the early years due to poor data quality and/or lack of availability. We address the integration of geo-referenced input datasets from various sources and time periods, the assignment of traffic noise exposure from façade points to dwelling units, as well as the processing of traffic information and statistics. Preliminary results of the noise exposure calculations are presented.

Ioannis Karipidis: Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland
Danielle Vienneau: Swiss Tropical and Public Health Institute, Basel, Switzerland,
and University of Basel, Basel, Switzerland
Manuel Habermacher, Micha Köpfli: n-Sphere AG, Zürich, Switzerland
Mark Brink: Federal Office for the Environment, Bern, Switzerland
Nicole Probst-Hensch, Martin Röösli: Swiss Tropical and Public Health Institute, Basel, Switzerland,
and University of Basel, Basel, Switzerland
Jean-Marc Wunderli: Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

1 Introduction

Transportation noise, largely from road, railway and aircraft traffic, is one of the most widespread sources of environmental stress and discomfort in daily life. Viewed mainly as an urban problem, it impacts a large proportion of the population in Europe. Based on the EU strategic noise maps, covering approximately 20% of the total population in 2010, an estimated 50% of residents in agglomerations with >250,000 inhabitants are exposed to road traffic noise of ≥55 dB Lden [1]. This led European legislation to adopt the European Noise Directive, END [2], which is currently being implemented by the member states [3]. END aims at monitoring and mapping environmental noise, to inform the public and to initiate noise mitigation and abatement actions.

Little is known, however, about how acute and short-term noise effects translate into long-term health consequences. In particular, it is unclear which acoustical characteristics of noise from different transportation sources are most detrimental for human health and wellbeing. To date, research and noise policy has mainly focused on annoyance and metrics capturing average exposure (e.g. Lden, Lnight) [4–6]. Despite certain limitations, for example in communicating noise exposure in a comprehensible way to the public [7], such energy-based exposure measures seem to predict sufficiently well annoyance or disturbance [8]. However their application to forecast the impact of noise on sleep has not met with much success [9–13]. Whereas the probabilities of event-related awakenings and cardiovascular arousals clearly increase with the maximum sound pressure level of noise events (Lmax,

SEL) [4, 14, 15], average noise metrics usually fail to predict sleep disturbances sufficiently [16–18]. Thus, depending on whether the noise source is intermittent (e.g., passing flights or trains) or continuous (e.g., road traffic from a highway), the effects of noise on sleep might be better predicted by the number of noise events and their characteristics [19]. There is, for example, evidence that railway noise at comparable average levels across a night elicits stronger reactions in the sleeping individuals compared to noise from other transportation modes [20]. It has been proposed that the distribution of maximum sound pressure levels and the relatively short rise time of railway noise events are primarily responsible for the increased reaction probability, as compared for example to road traffic noise events. For these reasons, it is essential not only to evaluate the average exposure levels for possible long-term health effects but also investigate more detailed exposure assessment characteristics, in particular the *degree of intermittence* and the *distribution of maximum sound pressure levels*, and also the *diurnal variation of exposure*.

The SiRENE project (Short and Long Term Effects of Transportation Noise Exposure) aims at investigating the health effects of exposure to transportation noise in the Swiss population. We focus on the relationship between noise exposure from individual and combined transportation sources and three main outcomes: annoyance, sleep disturbances and cardio-metabolic risk. Cardio-metabolic morbidity and mortality is investigated, with the aim to derive exposure-response associations for the various transportation noise sources, using data from two on-going Swiss epidemiological studies (SAPALDIA and SNC, see below) dating back to the 1990s. Underpinning and linking these three components is the detailed, nationwide modelling of road, railway and aircraft noise exposure to cohort participants' residential and occupational address.

The SAPALDIA (Swiss Study on Air Pollution and Lung Disease in Adults) Biobank is a large chronic disease cohort initiated in 1991 to investigate the effects of air pollution on respiratory and cardiovascular health in adults [21, 22]. The baseline survey (1991, SAPALDIA 1) included 9,561 subjects residing in eight geographically distinct urban and rural communities across Switzerland. Two follow-up surveys have since been conducted, including 8,047 subjects in 2000 (SAPALDIA 2) and ∼6,000 in 2010-11 (SAPALDIA 3). Over the 20 year period, detailed questionnaire information on lifestyle, sleep problems, noise annoyance, medical history and risk factors as well as blood and DNA samples have been collected and stored. Full residential history has also been compiled over the entire follow-up period, as well as addresses for secondary residence and work place. The database contains exposure relevant information including the building floor level where each participant lives, the orientation of the sleeping room relative to the street, the type and age of the building, and personal window-opening habits. The Swiss National Cohort (SNC) is a national longitudinal research platform which uses a probabilistic linkage of census with mortality records [23]. Participation in the censuses (years 1990, 2000 and 2010) was mandatory and enumeration is near-complete. The database is continuously updated with mortality and migration data, and the fully linked SNC includes an individual record for each person in Switzerland, a household record, and a building record including exact geocodes for the home address. It also contains exposure-relevant information including whether persons live (or lived) on the ground floor or above, type of the housing (e.g. detached house, apartment), and age of the building or date of the last renovation.

The accuracy of geocodes in SAPALDIA and the SNC is essential, directly impacting the accuracy of the noise exposure assessment as a whole. Pilot work in SAPALDIA suggested that annoyance can be used as an internal validation criterion to improve exposure assignment, and that building age is one of the most important modifying factors [24]. Furthermore, the SAPALDIA and SNC cohorts span several decades over which transportation in Europe has shown steady growth [25], altering the soundscape and exposure situation for many residents. Recognizing this spatial and temporal change in noise levels across the population is crucial for the epidemiological analysis, in order to minimize exposure misclassification in the assessment of long-term health effects.

In the following, we present the noise exposure analysis of SiRENE and the major challenges of this task. We address the integration of geo-referenced input datasets from various sources (infrastructure and building datasets, population data address directories and geocodes of study participants), the processing of traffic information, the noise calculations as well as the assignment of traffic noise exposure characteristics from façade points to dwelling units.

2 Methods

2.1 Overview

According to the overall objective of SiRENE, noise exposure data is required for virtually all residential households in Switzerland - essentially each dwelling of every building. Precondition for the corresponding exposure

assessment is detailed and accurate information about building coordinates and heights as well as the number of floors per building. For each building and floor, façade points are defined for which noise calculations for road, railway and aircraft noise are performed for the years 2011, 2001 and 1991. Due to the three decades of interest in the SiRENE project, represented by three specific years, data compilation and processing of adequate input data is repeated for each year.

The number of dwellings per building can be extracted from census data. The façade points are assigned to dwelling units, allowing for a detailed exposure analysis per unit. Using the census data (GWS 2011), each building record is geocoded and has the number of residents attributed. The same applies for participants of SAPALDIA and SNC cohorts, which are also assigned to distinct dwelling units as part of this noise exposure analysis.
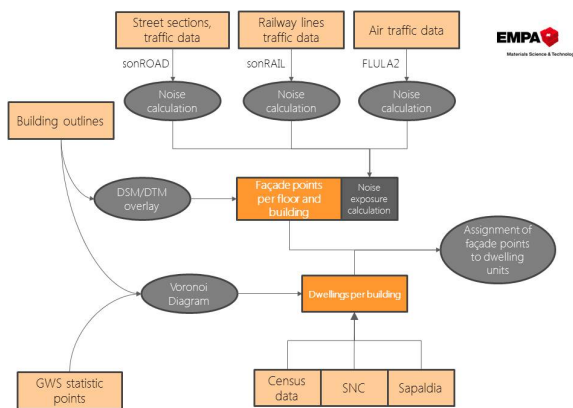

Fig. 1. Flow chart depicting the data processing, from the input data to the exposure analysis. Further information about sonROAD is available in [26], for sonRAIL in [27] and FLULA2 in [28].

In SiRENE we implement a more detailed temporal evaluation of noise exposure than recommended in the Swiss Noise Abatement Ordinance (NAO) [29] to have estimates relevant to the actual sleeping behavior of the population. Time periods in the SiRENE project are: 07:00-19:00 L_{Day}, 19:00-23:00 $L_{Evening}$, 23:00-07:00 L_{Night}. A particular focus is on the late night and early morning hours when a large proportion of the population is still asleep. The night period is thus subdivided into four further partitions: 23:00-01:00, 01:00-05:00, 05:00-06:00, and 06:00-07:00.

Our analysis is based on and closely related to the sonBASE Project [30], the Swiss Noise Geodatabase application. Some of the input data used for SiRENE is already incorporated in sonBASE, such as building outlines and the definition of the façade points. Another main rea-

son for using sonBASE is the pre-calculated attenuations database between emission source and façade points. The following sections present the detailed data processing and methodology for the calculation year 2011, as well as strategies to overcome data availability issues for the calculation years 2001 and 1991.

2.2 Building outlines and definition of façade points

Building outlines from the period 1998 – 2006 are defined in the digital landscape model of Switzerland (1:25,000 VECTOR25) from the Swiss Federal Office of Topography, Swisstopo [31]. VECTOR25 displays connected houses as single buildings. Thus, one building can have several entrances and dwellings. The accuracy of position of the building polygons is in the order of 3 – 8 metres.

The building heights are derived by incorporating information from a digital surface model (DSM) and digital terrain model (DTM) from Swisstopo. The DSM provides three-dimensional information for all artificial and natural obstacles and objects on earth's surface, while the DTM displays solely the natural terrain. The deviation between these two datasets is used to determine the height of the buildings, and subsequently the number of floors. The number of floors is based on an assumed 2.5 to 3.3 metre floor height, with a base height of 1.5 metres.

On the defined buildings we assign façade points. Façade or receiver points represent the 3-D point location at which the incoming transportation noise is calculated. A maximum of 3 façade points, spaced a minimum distance of 5 metres, are specified for each façade and floor of all buildings. We created a total of 54,300,000 façade points, assigned to 1,813,000 buildings throughout Switzerland.

Buildings and façade points for earlier periods are also necessary to calculate noise exposure for 2001 and 1991. The earliest useful digital dataset for buildings in Switzerland was created by Swisstopo in 2004, with data originating from 1996 to 2000. Although this dataset lacks streets and buildings built between 2000 and 2001, it is sufficient for the definition of façade points, dwellings within buildings and the subsequent exposure calculation. The terrain model is the same as used for the analysis 2011, as there is little change assumed. The same buildings dataset created for 2001 is used for 1991, as there is no more accurate data available.

2.3 Definition of dwelling units and assignment of façade points

In a further step, these façade points are assigned to dwelling units within the buildings. The building footprints in VECTOR25, however, do not include separating walls between dwellings. In order to define distinct dwellings, we use geo-coded raster point information about dwelling units, obtained from the building and dwelling statistics (GWS) from the Swiss Federal Statistics Office. These GWS points are located inside each VECTOR25 building. The number of points contained in each VECTOR25 building indicates how many distinct dwellings are contained within. Hence, multiple GWS coordinates can point to the same VECTOR25 building and, given that a building may have more than one floor with an assumed one dwelling per floor, multiple dwellings may be associated with the same GWS coordinates.

The GWS points allowed us to subdivide buildings into dwelling units by creating Voronoi (or Thiessen) polygons in ArcGIS (Figure 2). This approach does not claim to generate a realistic representation of the dwelling units. It is, however, sufficient for delineating the correct number of dwellings per building.

Due to a temporal mismatch between the GWS data (compiled in 2010) and older VECTOR25 data, these two datasets do not necessarily match. For example, if a building was replaced by a new construction, the GWS point might be displayed outside the VECTOR25 building outline. GWS points are thus assigned to the nearest building outline with a threshold distance of 20 metres. All GWS points beyond this threshold are eliminated. A possible solution to this problem could be the generation of a default building around GWS points more than 20 metres from an existing building outline. While this approach fell short of computing capacity and this is a very rare case, we decided to erase these entrance points without substitution.

The number of inhabitants per GWS point is next assigned to the subdivided buildings respectively to individual dwelling units. SNC datasets already contain the number of inhabitants per dwelling and furthermore the floor on which they reside [23].

The final step is to assign the façade points available in sonBASE to dwelling units (Figure 3). Dwellings typically span buildings, and have more than one facade point. The subsequent epidemiological analysis in SiRENE considers both the highest exposure of each dwelling and also the potential benefit of quiet façades. Since we use Voronoi polygons and existing façade points from sonBASE, there is the possibility that some dwellings are left without a façade point. Dwelling units A and B in Figure 3 contain
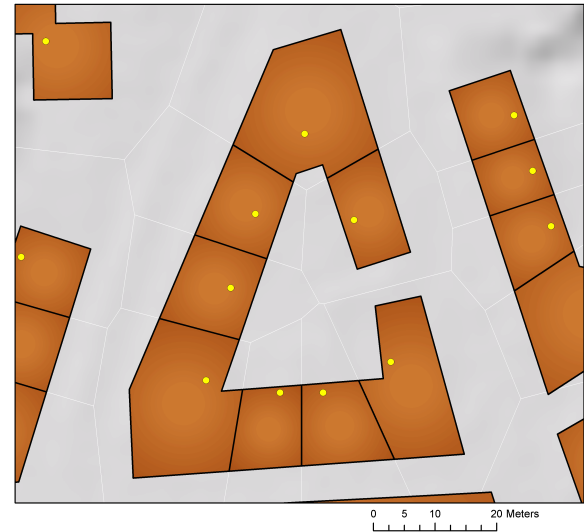

Fig. 2. Buildings and Voronoi polygons to represent dwellings based on the GWS points.
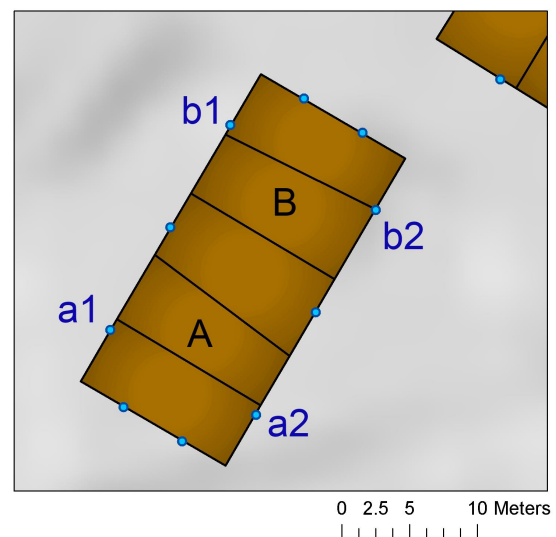

Fig. 3. Façade points and dwelling units within a building showing assignment of the nearest façade point to units with none.

no façade point within their boundaries, thus the closest façade points are assigned (e.g., façade points a1 and a2 are assigned to A; b1 and b2 are assigned to B).

2.4 Data processing and noise calculation

2.4.1 Road traffic

Road traffic noise exposure calculation requires information about the geometry and classification of all streets as

well as detailed traffic statistics, including yearly averages and diurnal variations, for all vehicle categories. Statistics and datasets concerning this information vary in quality and availability, and historical information is often particularly difficult to obtain.

The geometries of all existing roads in Switzerland are based on the sufficiently accurate VECTOR25 street section dataset. We supplement this with further geo-referenced data including:

– slope of each road section,
– road type and width,
– speed limit,
– bridge construction height, and
– traffic statistics.

To obtain the slope of each road section, we projected the VECTOR25 data on the DSM and calculated change in slope. Consequently the road is subdivided into sections corresponding to the changes of slope. Information about the correct height of bridge constructions is derived by manually overlaying VECTOR25 with DSM.

Information about noise barriers was obtained from the Federal Road Office (FEDRO) and the cantonal offices for infrastructure and traffic. The year of construction is available for ∼20% of the noise barriers. Adequate data specifically for the years 2001 and 1991 is not available. State and cantonal expenditures on noise barriers indicate that the large majority of the noise barriers in Switzerland have been built after 2000 (∼85%), hence we assume that if there is no construction date, it did not exist in 1991 or 2001 [32].

By comparing the geo-data with satellite images we controlled and corrected the dataset. False noise barriers, such as bushes and shrubs which were sometimes coded as noise barriers by mistake, were manually deleted. We rendered the surface resolution more precisely by generating a Triangulated Irregular Network (TIN) from a 2 × 2 metre resolution DTM using ArcGIS 3D Analyst. Thus more obstacles such as small hills or slopes, which influence the sound propagation similarly to a noise barrier, could be identified. In the case of missing values for height of the noise barriers, we assumed a default value of 3.5 metres for barriers proximate to highways and 2 metres for all other barriers. In total we incorporated 1,700 noise barriers (with an overall length of 238 km) at cantonal roads and 870 noise barriers (284 km) at national highways. Default height values were assigned to 30% of the barriers at cantonal roads. As there was no information for the barrier heights at national highways, 100% of these barriers were assigned the default height.

Traffic information can be gathered from traffic census monitoring systems. However such data is typically only available for highways and major roads. For Switzerland the federal department of the environment, transport and energy DETEC provides annual statistics that currently cover about 17% of all streets and about 60% of the total traffic volume. In sonBASE, a sophisticated traffic model developed by Arendt Consulting, is implemented [33] that combines this dataset with Swiss federal census data of population and business enterprises to generate traffic information also for the street sections not represented by monitoring stations. Based on assumptions of a distinct traffic behavior between dwellings and enterprises or other targets, the model creates daily average traffic statistics for passenger cars and heavy traffic. The Arendt road traffic model [34, 35] also includes a classification of the road type and the number of lanes. In combination with information about speed limits the specifications for each street section were defined. Due to its high temporal and spatial resolution and traffic statistics from each street category, the model allows for a highly detailed calculation of road traffic noise for the year 2011.

For the past situations we performed a back scaling based on the simulation of 2011. In a first step the street network was adjusted. Comparing the infrastructure of 2011 with 2001 for example this resulted in a reduction of the total street network of 3%. Then available traffic census data was again combined with information on local population density and the number of workplaces for the years 1991 and 2001. After a reevaluation with the Arendt model, scaling factors were derived for each street section.

Finally we performed the traffic noise calculation using the emission model of sonROAD [26] and the propagation model of StL-86 [36].

2.4.2 Railway traffic

Basic geometry for railway tracks is derived from information provided by the Federal Office of Transport (FOT). Supplemental data about the rail system, including the start and end of route sections and the coordinates of switch points, was provided by the Swiss Federal Railways (SBB). SBB also provided detailed information dating back to the 1970s about the year of construction, x-y-coordinates and height of noise barriers. Datasets contained information about a total of 2,055 noise barriers with an overall length of 244 km.

SBB provided the aggregated daily traffic for 2011 for each of the main train types, including actual driving speed. The diurnal variation of railway traffic, which is cru-

cial information for the subsequent exposure calculation, is also available and will be incorporated. Historical data of railway traffic statistics will be incorporated as soon as it will be available. However it already became apparent that traffic information will not be on hand for all railway lines, especially not for the year 1991. For these railway lines, where historical data is not available, a back-scaling will be performed using global scaling parameters for passenger and freight trains.

The traffic statistics are based on a classification system with 9 different train types including intercity trains, commuter trains and freight trains. The composition of these trains is varied for each year of calculation, representing the rolling stock in use during this period. Of great importance on the resulting noise exposure level is thus the noise remediation program for rolling stock which has been conducted in Switzerland since 2000. In this program the braking systems of all Swiss vehicles with cast-iron brakes are replaced with braking blocks made of composite material, resulting in a noise reduction of up to 10 dB(A) [37].

The emission of railway noise is calculated with the recently developed calculation model sonRAIL [38]. An essential part of the model is the emission data base, which has been developed based on an extensive measurement campaign and contains emission data for the major track constructions and rolling stock types used in Switzerland.

The corresponding propagation model [27] however has so far not been applied for sonBASE. As a propagation calculation for entire Switzerland was not possible within the given time frame, an attenuation database of calculations with the previous Swiss railway noise model SEMI-BEL [39] was used instead.

2.4.3 Air traffic

The nature and level of detail for air traffic data is entirely different to that for road and rail. Ongoing radar monitoring of each single aircraft movement for the main airports Zurich, Geneva and Basel provide a high level of detail, including exact event times and the actual flown flight tracks. Combined with traffic statistics delivered by the airports, each radar track can be assigned to a specific aircraft type. The main runways infrastructure at Swiss airports did not change since 1991. The radar data we used contains information about the x-y- and z-axis in time steps of approximately 4 seconds, from which the actual flown speed is deduced.

The aircraft noise calculation is performed with FLULA2 [28, 40], which includes a sound source database with information about sound directivity patterns of almost every conventional aircraft type operated in Switzerland. The sound source database is based on measurements of real traffic, distinguishing landings and take-offs. FLULA2 performs a time-step simulation of individual flights and yields maximum noise levels ($L_{A,max}$) and sound exposure levels (L_{AE}) as results.

The acoustical footprint of an aircraft is the noise exposure, on average, created by a certain aircraft type on a specific route, calculated for a receiver grid with a constant height of 4 metres above terrain. The average is based on a sufficiently large number of aircraft of the same type flying the specified route. By assuming that the existing air routes remain unchanged, acoustical footprints can be taken from other years if radar data is not available. In FLULA2 these acoustical footprints can be imposed with an assumed air traffic volume to calculate the air traffic noise exposure for the survey years where radar data is missing [41].

Radar data for Zurich, the largest Swiss airport, is available for each survey year at an hourly resolution, with information about aircraft types and the flown air routes. For Geneva, the second largest Swiss airport, data availability is analogue only for the calculation year 2011. Radar data is not available for the years 2001 and 1991. For the exposure calculation of 2001 and 1991 traffic statistics including the fleet mix, from the Federal Office of Civil Aviation (FOCA), will be used with available acoustical footprints dating from the year 2000.

Yearly calculations for Basel airport have always been conducted in France, so data availability is limited. We therefore use data derived from a calculation made by Empa in 2001, based on highly detailed traffic statistics for this year, and 1999 footprints. Due to the lack of information, these footprints are also assumed for the exposure calculations for 2011 and 1991. For 2011 and 1991 traffic statistics from FOCA are used.

Military airfields are not taken into account with the exception of Payerne, as Payerne is of great importance for SAPALDIA. Information about military aircraft operations is generally poor. Radar data is not accessible, thus solely idealized flight paths are used. The aircraft types and the number of flights are known. However the hours of operation are only accessible in very generalized way, differentiating morning, afternoon and evening flights.

Small airfields used for private and business aviation are not taken into account as there is no reliable data available.

3 Results

Key interim results for the ongoing SiRENE noise exposure analysis are presented below.

3.1 Improvement in sound propagation calculation using topography

As already mentioned in section 2.4.1 topography is represented more precisely for the actual calculations compared to the sonBASE 2006 and previous versions. Figure 4 and Figure 5 show as an example a section of a highway close to Geneva, where the highway is embedded in a cutting before entering a tunnel. As a consequence of the rough resolution of the terrain model DHM25 of swisstopo used for sonBASE 2006 no noticeable reduction of the source takes place and sound seems to propagate freely resulting in the levels as depicted in Figure 4. With the refined topography the basin situation is represented more accurately, yielding a prominent barrier attenuation and consequently significantly lower exposure levels in the vicinity of the source, as shown in Figure 5. It can be concluded that a more detailed representation of topography results in major increase of the accuracy of the resulting exposure analysis.
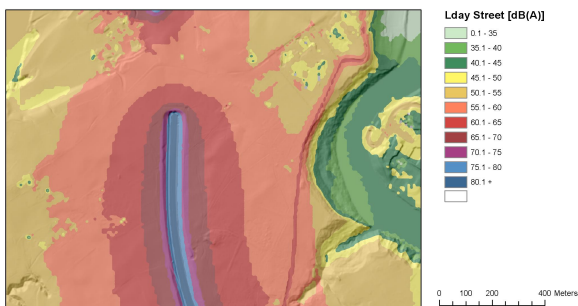

Fig. 4. Sound propagation and topography in sonBASE 2006 based on the terrain model DHM25 of swisstopo, calculated for a height of 4 m above terrain.

3.2 Calculation at facade points

The exposure calculation was performed on 54,3 million façade points of 1,8 million buildings of the VECTOR25 dataset. As an example, Figure 6 shows an excerpt of a noise map including the exposure at façade points for road traffic for the period of 06:00-18:00 (L_{Day}).
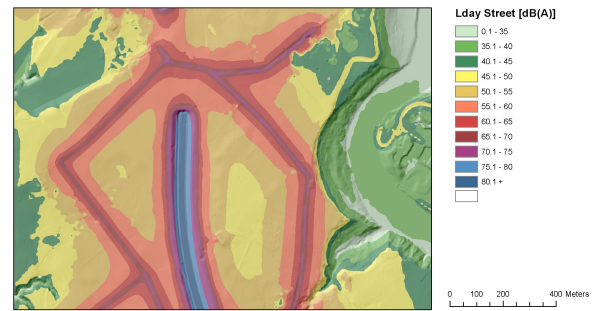

Fig. 5. Sound propagation and topography in sonBASE 2010 based on the terrain model swissALTI3D of swisstopo with a 2 × 2 meter resolution.
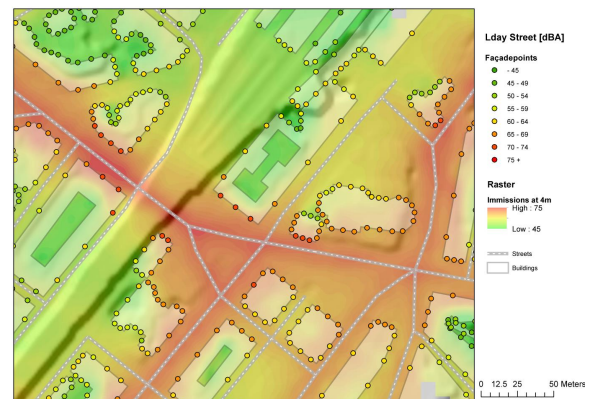

Fig. 6. Noise map and exposure at façade points of road traffic for the period of 06:00-18:00 (L_{Day}).

Exposure results can be broken down to single buildings, allowing the analysis of distinct buildings or areas of interest. Calculation results of a detached house parallel to a street with no reflections from surrounding buildings are shown in Figure 7. Of each building side, the façade point with the highest exposure is represented. As can be seen, the levels vary substantially for the different façades. This illustrates the importance of the orientation of dwelling units as discussed in section 2.3.

3.3 Statistical analysis for the year 2011

A total of 7,9 million inhabitants, which represent the entire Swiss population, were assigned to buildings and subsequently to distinct dwellings and façade points. For our preliminary results we assigned the inhabitants to the façade point with the highest L_{eq} value, taking into account a potential overestimation of the true exposure as rooms like sleeping and living rooms are likely to be oriented toward less noisy façades. Figure 8 shows histograms of exposure of the Swiss population, in noise ex-
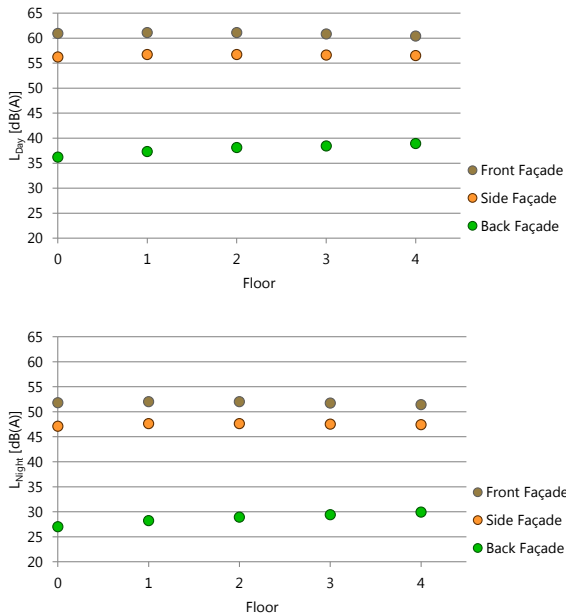
Fig. 7. Road traffic noise exposure at façade points for a single building for the period of 06:00-18:00 (L_{Day}) and 22:00-06:00 (L_{Night}).
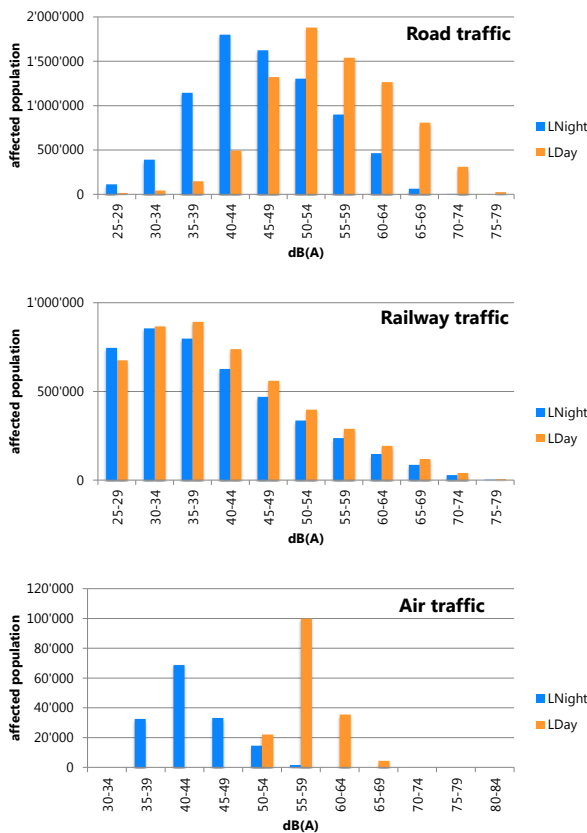

Fig. 8. Distribution of the Swiss population exposure to road, railway and air traffic noise, L_{Night} and L_{Day}, classification in 5 dB(A) steps for the year 2011.

posure categories in 5 dB(A) steps, respectively for L_{Day} and L_{Night} for the year 2011. The figures depict clearly the shift from lower to higher exposure levels during the day relative to the night period for road and air traffic noise. In the case of railway noise this shift is not present, although the overall exposure is slightly lower during the night period.
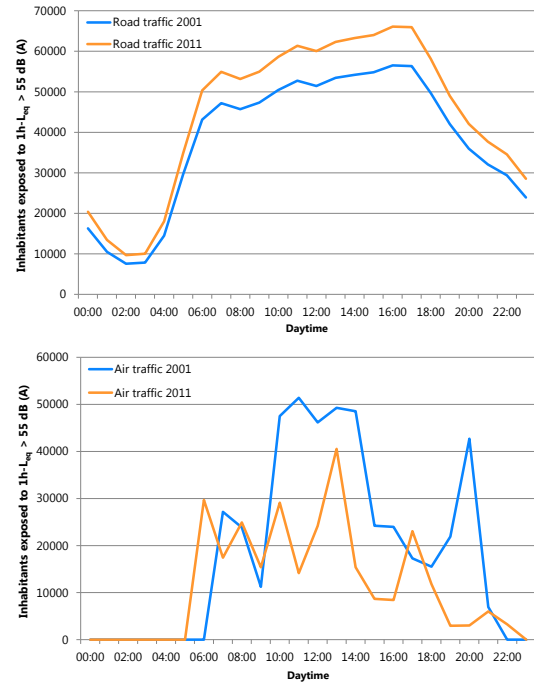

Fig. 9. Number of affected inhabitants by road and air traffic noise (1h-L_{eq}) >55 dB (A) for an area of 35 km^2 south of Zurich airport.

3.4 Comparison of noise exposure 2001 and 2011

Figure 9 yields a comparison of the number of people exposed to 1h-Leq levels above 55 dB(A) for road and air traffic in the course of the day for the years 2001 and 2011. The calculation was performed for an area south of the Zurich international airport of 7 × 5 km. The area was inhabited by 103'727 persons in 2001 and 115'145 in 2011. Primarily as a consequence of population growth a general increase of the number of affected people can be seen for road traffic, which is to a large extent independent of the time of the day.

The situation for air traffic differs substantially from road traffic. First an overall decrease of the number of af-

fected people can be seen. This decrease of overall air traffic noise at Zurich airport has also been stated by other investigations [42]. Second it is interesting to see how much the temporal pattern varies between the two years, indicating the great operational variability of the airport as a consequence of its three runways with differing orientation.

4 Discussion

4.1 Noise exposure assessment for environmental health studies

Accurate assessment of exposure is an essential component of any epidemiological study aiming at elucidating the exposure-response relationships. Noise models which are used for regulatory strategic noise maps (i.e. in accordance with the END) only reproduce long-term equivalent continuous sound level and do not meet the needs of SiRENE. We thus present a novel approach for calculating a highly detailed, nation-wide assessment of (individual) noise exposure. In addition to average exposure levels the potential health effects of other noise characteristics including distribution of maximum sound pressure levels, number of events, and the diurnal variation are studied as well.

Typically the exposure assessment in socio-acoustic surveys or epidemiological studies on the cardio-metabolic effects of transportation noise is based on the gridded (mapped) output from these models [43–47], while only a few use the calculation results assigned to the home address and distinct dwellings [48–50]. To our knowledge, none have considered the additional noise characteristics we compute for SiRENE in epidemiological research on long term effects. Furthermore, except for Huss et al. [47] which was also conducted in Switzerland, none of these examples have been conducted on a nation-wide basis.

4.2 Uncertainty of the exposure analysis

The quality of SiRENE's exposure-response analyses and risk assessments depends strongly on the reliability and credibility of the input data and the models used for the exposure calculations. As nationwide exposure data cannot be taken from measurements, models have to be used to provide a realistic representation of the exposure situation. Models as such pose a potential risk of failing to depict reality sufficiently. With respect to epidemiological

studies, therefore, systematic errors are more significant than stochastic uncertainties. Validation results of all calculation models used in SiRENE have been published before. In combination with the uncertainties of input parameters, such as the traffic modeling or the accuracy of geo-referenced data, a combined standard uncertainty of 2.7 dB for daytime road traffic noise calculations and 3.1 dB for nighttime calculations can be deduced. The resulting overall uncertainty of the A-weighted equivalent continuous sound level ($L_{A,eq}$) calculations of railway noise with sonRAIL remains below 2.5 dB for day and night [51]. Given the real fleet mix of aircraft and the corresponding noise source data, the remaining standard uncertainties of the aircraft noise calculation software FLULA2 add up to 0.5 dB for daytime calculations and 1.0 dB for nighttime calculations [28, 52]. Detailed information about this topic has been previously published [30, 51, 52].

On the noise exposure assessment side, achievements of SiRENE include compiling and refining data about existing buildings and traffic infrastructure and integrating their true spatial position and dimensions in the subsequent exposure calculations. By not only using existing standard models, but additionally refining and combining them with other sources, we created the most sophisticated model of the current situation in Switzerland with respect to noise. Shortcomings deriving from the temporal mismatch of input data, as described in section 2.3, have to be taken into account. However, there is no systemic error emerging from this issue and the absolute error has been kept to a minimum.

The quality of input data regarding traffic statistics has essential influence on the accuracy of the subsequent noise exposure analysis. In contrast to railway and air traffic, statistics for road traffic were taken from a model. The Arendt model used for the road traffic statistics has proved to be relatively precise in its modelling, with a weighted deviation of 4.6% from real traffic [34], which translates into an insignificant variation of +0.2 to −0.2 dB(A).

4.3 Challenges related to historical noise exposure estimation

Data quality and availability improved markedly over the past 20 years, leading to the current situation where a large variety of often high quality information is available. Although the datasets representing the present situation cannot be used without corrections and processing, the 2011 information is by far more reliable compared to datasets available from 2001 or 1991. This particularly ap-

plies to the geo-referenced data such as buildings, streets and railway lines, and statistics on traffic and population.

One of the main objectives of SiRENE is to depict the temporal variation in noise exposure of the Swiss population from 1991 to 2011 and to assess the long-term health effects of noise. Thus, noise calculations representing the past years have to be performed as similar as possible to those done with the state-of-the-art models available for the current situation in 2011. As pointed out in the methods, this led to a variety of challenges mainly related to data availability.

Through our overall approach, we solved many of these problems. The solutions rely mainly on certain simplifications, as the required datasets for the years of interest are simply not available. This includes road, railway and air traffic statistics of 1991, leading to larger uncertainties for this particular year. The uncertainty, however, is expected to be lowest for major sources such as highways, major railways and national airports. Thus, the identification of highly exposed buildings will be more accurate than in the low exposure range. The impact of this exposure assessment error on the epidemiological results will be addressed by sensitivity analyses and simulation studies.

4.4 Conclusions and impact of SiRENE on further surveys

It is well recognized that noise exposure from transportation is one of the most widespread sources of environmental stress, especially in densely populated areas such as those in Europe and mega-cities outside of Europe. Based on population noise exposure derived from the strategic noise maps through END, the annual burden of environmental noise in Western Europe is an estimated loss of 1 – 1.6 million healthy life-years [1]. As demonstrated in a recent special issue on noise, development of a common methodological framework under END for noise assessment in Europe is ongoing [53]. Improvements to the strategic noise maps in future will no doubt help to improve calculation of disease burden. Equally important, however, is the derivation of reliable exposure-response relationships based on large population studies. To support this particular type of research, more refined exposure models for a broader range of metrics are needed compared to the outputs for strategic noise modeling.

A key aspect of our exposure assessment is the evaluation of noise in three-dimensions. This allows us to link exposures to individuals based on the floor of their particular dwelling. Also, given that we estimate exposures for the entire Swiss population our subsequent exposure database can be used for other studies besides SiRENE.

References

[1] WHO, 2011. Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe. ed. L.B. Fritschi, Lex; Kim, Rokho; Schwela, Dietrich; Kephalopolous, Stelios and Place. World Health, Copenhagen.

[2] 2002. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 Relating to the Assessment and Management of Environmental Noise.

[3] Curcuruto, S., R. Silvaggio, R. Amodio, L. De Rinaldis, E. Mazzocchi, F. Sacchetti, and M. Stortini, 2012. HUSH project contribution to environmental noise directive implementation and revision, focusing on noise management and public information tools. in 41st International Congress and Exposition on Noise Control Engineering 2012, INTER-NOISE 2012.

[4] WHO, 2009. Night Noise Guideline for Europe. World Health Organization.

[5] Miedema, H.M.E., W. Passchier-Vermeer, and H. Vos, 2003. Elements for a position paper on night-time transportation noise and sleep disturbance. ISBN-90-6743-981-9. TNO.

[6] Asdrubali, F., S. Schiavoni, F. D'Alessandro, C. Schenone, and I. Pittaluga, 2012. Innovative aspects in noise mapping and dissemination activities within life+ "NADIA" project. in 19th International Congress on Sound and Vibration 2012, ICSV 2012.

[7] Ribeiro, C., Anselme, C., Mietlicki, F., Vincent, B., Da Silva, R., Gaudibert, P., 2013. At the heart of Harmonica project: the Common Noise Index (CNI), in 42nd International Congress and Exposition on Noise Control Engineering, Internoise 2013: Innsbruck. p. 10.

[8] Blatter, K., P. Graw, M. Münch, V. Knoblauch, A. Wirz-Justice, and C. Cajochen, 2006. Gender and age differences in psychomotor vigilance performance under differential sleep pressure conditions. Behavioural Brain Research 168, 312-317.

[9] Frey, S., S. Balu, S. Greusing, N. Rothen, and C. Cajochen, 2009. Consequences of the Timing of Menarche on Female Adolescent Sleep Phase Preference. PLoS ONE 4.

[10] Brink, M., P. Lercher, A. Eisenmann, and C. Schierz, 2008. Influence of slope of rise and event order of aircraft noise events on high resolution actimetry parameters. Somnologie -

Schlafforschung und Schlafmedizin 12, 118-128.

[11] Griefahn, B., A. Schuemer-Kohrs, R. Schuemer, U. Moehler, and P. Mehnert, 2000. Physiological, subjective, and behavioural responses during sleep to noise from rail and road traffic. Noise Health 3, 59-71.

[12] de Coensel, B. and A.L. Brown, 2012. Modeling road traffic noise using distributions for vehicle sound power level, in internoise 2012, New York: New York.

[13] Brown, A.L., 2013. Issues in the measurement of sleep-related noise events in road traffic streams, in Acoustics 2013: Victor Harbor, Australia. p. 1-5.

[14] Finegold, L.S. and e. al., 1994. Community Annoyance and Sleep Disturbance: Updated Criteria for Assessment of the Impacts of General Transportation Noise on People. Noise Control Engineering Journal 42, 25-30.

[15] Miedema, H.M.E. and H. Vos, 1998. Exposure-response relationships for transportation noise. Acoustical Society of America 104, 3432-3445.

[16] Birchler-Pedross, A., C.M. Schröder, M. Münch, V. Knoblauch, K. Blatter, C. Schnitzler-Sack, A. Wirz-Justice, and C. Cajochen, 2009. Subjective well-being is modulated by circadian phase, sleep pressure, age, and gender. Journal of Biological Rhythms 24, 232-242.

[17] Cajochen, C., C. Jud, M. Münch, S. Kobialka, A. Wirz-Justice, and U. Albrecht, 2006. Evening exposure to blue light stimulates the expression of the clock gene PER2 in humans. European Journal of Neuroscience 23, 1082-1086.

[18] Späti, J., M. Münch, K. Blatter, V. Knoblauch, L.A. Jones, and C. Cajochen, 2009. Impact of age, sleep pressure and circadian phase on time-of-day estimates. Behavioural Brain Research 201, 48-52.

[19] Schmidt, C., F. Collette, Y. Leclercq, V. Sterpenich, G. Vandewalle, P. Berthomier, C. Berthomier, C. Phillips, G. Tinguely, A. Darsaud, S. Gais, M. Schabus, M. Desseilles, T.T. Dang-Vu, E. Salmon, E. Balteau, C. Degueldre, A. Luxen, P. Maquet, C. Cajochen, and P. Peigneux, 2009. Homeostatic sleep pressure and responses to sustained attention in the suprachiasmatic area. Science 324, 516-519.

[20] Münch, M., S. Kobialka, R. Steiner, P. Oelhafen, A. Wirz-Justice, and C. Cajochen, 2006. Wavelength-dependent effects of evening light exposure on sleep architecture and sleep EEG power density in men. American Journal of Physiology - Regulatory Integrative and Comparative Physiology 290, R1421-R1428.

[21] Ackermann-Liebrich, U., B. Kuna-Dibbert, N. Probst-Hensch, C. Schindler, D. Dietrich, E. Stutz, L. Bayer-Oglesby, F. Baum, O. Brändli, M. Brutsche, S. Downs, D. Keidel, M. Gerbase, M. Imboden, R. Keller, B. Knöpfli, N. Künzli, L. Nicod, M. Pons, P. Staedele, J.-M. Tschopp, J.-P. Zellweger, and P. Leuenberger, 2005. Follow-up of the Swiss Cohort Study on Air Pollution and Lung Diseases in Adults (SAPALDIA 2) 1991–2003: methods and characterization of participants. Sozial- und Präventivmedizin 50, 245-263.

[22] Downs, S.H., C. Schindler, L.J. Liu, D. Keidel, L. Bayer-Oglesby, M.H. Brutsche, M.W. Gerbase, R. Keller, N. Kunzli, P. Leuenberger, N.M. Probst-Hensch, J.M. Tschopp, J.P. Zellweger, T. Rochat, J. Schwartz, and U. Ackermann-Liebrich, 2007. Reduced exposure to PM10 and attenuated age-related decline in lung function. The New England Journal of Medicine 357, 2338-47.

[23] Bopp, M., A. Spoerri, M. Zwahlen, F. Gutzwiller, F. Paccaud, C. Braun-Fahrländer, A. Rougemont, and M. Egger, 2009. Cohort profile: The Swiss National Cohort - A longitudinal study of 6.8 million people. International Journal of Epidemiology 38, 379-384.

[24] Vienneau, D., N. Probst-Hensch, J. Wunderli, B. Struchen, E. Fischer, and M. Röösli, 2012. Epidemiological Noise Exposure Assessment - A Pilot Study. 00.0066.PZ / L142-2822. Federal Office for Environment.

[25] Mantzos L., C.P., Kouvaritakis N., Zeka-Pschou M., 2003. European Energy and Transport Trends to 2030, O.f.O.P.o.t.E. Communities, Editor. European Commission.

[26] Heutschi, K., 2004. SonRoad: New Swiss road traffic noise model. Acta Acustica United with Acustica 90, 548-554.

[27] Wunderli, J.M., 2012. sonRAIL - from the scientific model to an application in practice, in Euronoise: Prague.

[28] Empa, 2010. FLULA2, Ein Verfahren zur Berechnung und Darstellung der Fluglärmbelastung. Technische Programm-Dokumentation. Version 4. Eidgenössische Materialprüfungs- und Forschungsanstalt (Empa), Abteilung Akustik / Lärmminderung, Dübendorf.

[29] NAO, 1986. Lärmschutz-Verordnung (LSV) vom 15. Dezember 1986 (Stand am 1. August 2010) (Noise Abatement Ordinance (NAO) from 15 December 1986 (Effective 1 August 2010)). SR 814.41.

[30] BAFU, 2009. SonBase - die GIS-Lärmdatenbank der Schweiz. Grundlagen, in Umwelt-Wissen. Bundesamt für Umwelt: Bern. p. 61.

[31] Swisstopo, 2007. VECTOR 25. Das digitale Landschaftsmodell der Schweiz. Bundesamt für Landestopografie, Wabern. 31.

[32] H., C.L.I.K.L.-F.N.P., 2007. Sanierung Strassenlärm. Stand und Perspektiven: Dezember 2006. Bundesamt für Umwelt: Bern. p. 50.

[33] Arendt. Verkehrsaufkommen flächendeckend ermitteln. 2009 [cited 01.04.2014]; Available from: http://arendt.ch/objects/websitedownload/53/download/VM_Flyer_d.pdf.

[34] 2010. Nationales Personenverkehrsmodell des UVEK, Basismodell 2005, B.f. Raumentwicklung, Editor. Bundesamt für Raumentwicklung.

[35] 2010. Nationales Personenverkehrsmodell des UVEK, Referenzzustand 2030, B.f. Raumentwicklung, Editor. Bundesamt für Raumentwicklung.

[36] BAFU, 1987. Computermodell zur Berechnung von Strassenlärm, Teil 1, Bedienungsanleitung zum Computerprogramm StL-86, in Schriftenreihe Umweltschutz. Bundesamt für Umweltschutz: Bern. p. 47.

[37] 2013. Monitoring Eisenbahnlärm. Bundesamt für Verkehr: Bern.

[38] Thron, T. and M. Hecht, 2010. The sonRAIL emission model for railway noise in Switzerland. Acta Acustica United with Acustica 96, 873 - 883.

[39] FOEN, 1990. SEMIBEL: Schweizerisches Emissions- und Immissionsmodell für die Berechnung von Eisenbahnlaerm. ed. S.F.O.f.t. Environment. Swiss Federal Office for the Environment.

[40] Pietrzco, J.S. and R.F. Hofmann, 1988. Prediction of A-weighted aircraft noise based on measured directivity patterns. Applied Acoustics 23, 29-44.

[41] Schäffer, B., R. Bütikofer, S. Plüss, and G. Thomann, 2011. Aircraft noise: Accounting for changes in air traffic with time of

day. Journal of the Acoustical Society of America 129, 185-199.

[42] Bissegger, M., 2013. Noise Management in the light of airport developement, in 42nd International Congress and Exposition on Noise Control Engineering, Internoise 2013: Innsbruck. p. 7.

[43] Andrew, W., L. Junenette, I. Jonathan, S. Melly, and F. Dominici, 2013. Residential exposure to aircraft noise and hospital admissions for cardiovascular diseases: Multi-airport retrospective study. BMJ (Online) 347.

[44] Anna, L., M. Blangiardo, L. Fortunato, S. Floud, K. De Hoogh, D. Fecht, R.E. Ghosh, H.E. Laszlo, C. Pearson, L. Beale, S. Beevers, J. Gulliver, N. Best, S. Richardson, and P. Elliott, 2013. Aircraft noise and cardiovascular disease near Heathrow airport in London: Small area study. BMJ (Online) 347.

[45] Beelen, R., G. Hoek, D. Houthuijs, P.A. Van Den Brandt, R.A. Goldbohm, P. Fischer, L.J. Schouten, B. Armstrong, and B. Brunekreef, 2009. The joint association of air pollution and noise from road traffic with cardiovascular mortality in a cohort study. Occupational and Environmental Medicine 66, 243-250.

[46] Gan, W.Q., H.W. Davies, M. Koehoorn, and M. Brauer, 2012. Association of long-term exposure to community noise and traffic-related air pollution with coronary heart disease mortality. American Journal of Epidemiology 175, 898-906.

[47] Huss, A., A. Spoerri, M. Egger, and M. Röösli, 2010. Aircraft noise, air pollution, and mortality from myocardial infarction. Epidemiology 21, 829-836.

[48] Selander, J., M.E. Nilsson, G. Bluhm, M. Rosenlund, M. Lindqvist, G. Nise, and G. Pershagen, 2009. Long-term exposure to road traffic noise and myocardial infarction. Epidemiology 20, 272-279.

[49] Sřrensen, M., Z.J. Andersen, R.B. Nordsborg, T. Becker, A. TjЖnneland, K. Overvad, and O. Raaschou-Nielsen, 2013. Long-term exposure to road traffic noise and incident diabetes: A cohort study. Environmental Health Perspectives 121, 217-222.

[50] Sřrensen, M., Z.J. Andersen, R.B. Nordsborg, S.S. Jensen, K.G. Lillelund, R. Beelen, E.B. Schmidt, A. Tjřnneland, K. Overvad, and O. Raaschou-Nielsen, 2012. Road traffic noise and incident myocardial infarction: A prospective cohort study. PLoS ONE 7.

[51] Thron, T. and M. Hecht, 2010. The sonRAIL emission model for railway noise in Switzerland. Acta Acustica united with Acustica 96, 873-883.

[52] Schäffer, B., S. Plüss, and G. Thomann, 2014. Estimating the model-specific uncertainty of aircraft noise calculations. Applied Acoustics 84, 58-72.

[53] Kephalopoulos, S., M. Paviotti, F. Anfosso-Lédée, D. Van Maercke, S. Shilton, and N. Jones, 2014. Advances in the development of common noise assessment methods in Europe: The CNOSSOS-EU framework for strategic environmental noise mapping. Science of The Total Environment 482–483, 400-410.