Bibliographical reference

Zurich Aircraft Noise Index: An Index for the Assessment and Analysis of the Effects of Aircraft Noise on the Population, Beat Schäffer, Georg Thomann, Philipp Huber, Mark Brink, Stefan Plüss and Robert Hofmann, Acta Acustica **vol. 98** (Number 3), 2012, pp. 505-519

DOI
https://doi.org/10.3813/AAA.918533

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 98 (2012) 505 – 519

DOI 10.3813/AAA.918533

Zurich Aircraft Noise Index: An Index for the Assessment and Analysis of the Effects of Aircraft Noise on the Population

Beat Schäffer[1], Georg Thomann[1,2], Philipp Huber[1,3], Mark Brink[4], Stefan Plüss[1], Robert Hofmann[5]

[1] Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory of Acoustics/Noise Control, 8600 Dübendorf, Switzerland. beat.schaeffer@empa.ch
[2] Present address: Amt für Natur und Umwelt Graubünden, 7000 Chur, Switzerland
[3] Present address: Departement Bau, Verkehr und Umwelt, 5001 Aarau, Switzerland
[4] ETH Zurich, D-MTEC Public and Organizational Health, 8092 Zurich, Switzerland
[5] 8304 Wallisellen, Switzerland

Summary

This article reports on the Zurich Aircraft Noise Index (*ZFI*), a noise effect index describing the integral effects of aircraft noise (annoyance and sleep disturbance) on the population in the vicinity of Zurich airport, integrating the considered noise effects to a single number valid for the whole airport. In the year 2007 the *ZFI* became operational as an effect-oriented monitoring tool serving noise abatement policy in the canton of Zurich, Switzerland. During its development, various exposure–response relationships and parameter settings were studied as a basis to establish the official calculation rule. The official calculation rule was then applied to a time series of 12 years, and reasons for changes in the *ZFI* were studied by means of sensitivity analyses, taking into account the air traffic operations and population development around Zurich airport in great detail. The article presents the concept and implementation of the *ZFI*, its development, its application, and insights obtained so far. Based on the obtained results, the potential and limitations of the index to express the number of affected persons, its sensitivity to changes in population figures and air traffic as well as the possibilities to separate different influencing parameters, and the scientific shortcomings of the index are discussed.

PACS no. 43.50.Qp, 43.50 Ba, 43.50.Lj, 43.50.Sr

1. Introduction

Aircraft noise usually covers large areas in the vicinity of airports, affecting millions of people in Europe alone [1]. In Switzerland, for example, 3% (225’000 persons) and 1.3% (95’000) of the population are exposed to aircraft noise levels > 55 dB(A) by day and > 50 dB(A) by night, respectively [2]. Aircraft noise therefore challenges land use planning [3] and causes intensive political (e.g., [4]) and scientific debates.

In order to estimate the impact of aircraft noise on people, noise effect indices have become a popular concept. This article reports on the ‘Zurich Aircraft Noise Index’ (‘Zürcher Fluglärm-Index’, *ZFI*), a noise effect index recently developed for Zurich airport, serving noise abatement policy in the canton of Zurich, Switzerland. The *ZFI* is a single number representing the monitoring value for the number of persons affected by aircraft noise, either by annoyance and/or sleep disturbance. The monitoring value is compared to a guide value. The government of the canton of Zurich takes preventive measures to avoid the guide value to be exceeded.

As outlined in Brink *et al.* [5], noise effect indices describe the integral effect(s) of aircraft noise on the population in the vicinity of airports, integrating all considered noise effects to a single number valid for a whole airport. Of the various noise effects such as hypertension [6] or myocardial infarction [7], the most useful dimensions for effect indices are probably annoyance and sleep disturbance [5]. While many different exposure–response relationships have been established in the past yielding very disparate results [8, 9, 10], no consensus has been reached as to which is the ‘most appropriate’ relationship to establish noise effect indices. But also various other aspects concerning such indices remain yet unsolved [5, 11].

In Switzerland, noise effect indices recently came into political focus. In response to the conflicts between air traffic and population around Zurich airport, the people’s initiative ‘for a realistic airport policy’ was submitted in 2004, demanding the number of movements per year on Zurich airport not to exceed 250’000 and a flight cur-

Received 2 August 2011,
accepted 5 March 2012.

few of 9 hours during the night. The government of the canton of Zurich objected this initiative and submitted a counter-proposal which, as its centrepiece, proposed a guide value limiting the number of highly affected persons, instead of limiting the movements. This centrepiece was denoted as *ZFI*. In November 2007, the initiative was put to referendum, but was rejected by the voters. Instead, the government's counter-proposal was accepted. Based on this plebiscite, the *ZFI* was included in the cantonal law [12, 13]. It became operational as an effect-oriented monitoring tool in the year 2007 [14].

The *ZFI* is not the first noise effect index, but is one realization in a series of several indices (e.g., [15, 16, 17]). While much has been recently discussed [5, 11, 18], available data to study their feasibility are still rare. Here, the *ZFI* is an exception. Various exposure–response relationships and parameter settings were studied as a basis to establish the official calculation rule, and thereafter the *ZFI* was determined for various scenarios, studying also the reasons for its variation by sensitivity analyses. The authors of this article have, to different degrees, been involved in either the development or evaluation of the *ZFI*. In this paper they present the concept and implementation of the *ZFI*, its development, its application, and insights obtained so far.

2. The Zurich Aircraft Noise Index (*ZFI*)

This section describes the concept and the official calculation rule of the *ZFI*, as well as its development. In the development process, scientists as well as representatives of the public administration were involved, as the *ZFI* has a political purpose (cf. section 1). Therefore, discussions, parameter settings and decisions involved scientific as well as political considerations. With the development process not only science- but also policy-driven, the official calculation rule is burdened with some scientific shortcomings as discussed in detail in section 5.2. Below, sections 2.1 to 2.3 describe the concept and the established, legally enforced calculation rule according to [13, 19], together with the sensitivity analysis, by which the *ZFI* has to be determined and analysed to day, with all the strengths and weaknesses they may have. Section 2.4 then gives a historical retrospection on how the official calculation rule was developed and on the most important findings.

2.1. Concept

The *ZFI* is a single number representing a monitoring value for the number of persons affected by aircraft noise around one single airport, either by annoyance and/or sleep disturbance. The monitoring value is compared to a guide value; the government of the canton of Zurich takes preventive measures to avoid the guide value to be exceeded.

To calculate the *ZFI*, the number of highly annoyed persons during the day (*HA*) as well as the number of highly sleep disturbed persons during the night (*HSD*) are determined using exposure–response relationships and summed up. The *ZFI* concept thus sets the basis for a purely mathematical determination of noise effects, the results of which are then used as a monitoring value for a setpoint value comparison.

The concept of the *ZFI* has some important features. Firstly, it aims at limiting the monitoring value, while not primarily restricting the air traffic. Secondly, the dimensions of annoyance and sleep disturbance are combined to a single number of affected persons. Thirdly, double counts are allowed, i.e., a person who is annoyed during the day and also sleep disturbed during the night is counted twice. Finally, the 24 h of a day are strictly divided into the day-time period (06–22 h) for the *HA* and night-time period (22–06 h) for the *HSD*, following the time periods of Swiss legislation (Noise Abatement Ordinance, NAO [20]), ignoring any possible *HA* or *HSD* in the other time period.

2.2. Official calculation rule

The official calculation rule, as legally prescribed in [13], was established as follows [19]. The *ZFI* is the sum of the *HA* and *HSD*,

$$ZFI = HA + HSD. \tag{1}$$

The *HA* and *HSD* used in equation (1) are determined for each receiver point i within a specified grid by multiplying the fractions of the highly annoyed ($\%HA_i$) and highly sleep disturbed persons ($\%HSD_i$) by the number of residents ($N_{\mathrm{pop},i}$), and summing them up using equations (2) and (3). Given the spatial resolution of available population data (section 3.3), all calculations are done on a hectare grid (100 m by 100 m).

$$HA = \sum_i HA_i = \sum_i N_{\mathrm{pop},i} \cdot \frac{\%HA_i}{100}, \tag{2}$$

$$HSD = \sum_i HSD_i = \sum_i N_{\mathrm{pop},i} \cdot \frac{\%HSD_i}{100}. \tag{3}$$

The $\%HA_i$ used in equation (2) are determined from the exposure–response relationship by Miedema and Oudshoorn [21], where the acoustic input L_{dn} of the original equation is replaced by the $L^*_{\mathrm{Aeq},16}$, while all other parameters remain unchanged (equation 4). The $L^*_{\mathrm{Aeq},16}$ is the weighted equivalent continuous sound level of the day (06–22 h), determined by charging penalties of 5 dB to the sound levels during the first and last hour of the day (06–07 h and 21–22 h). On average, the $L^*_{\mathrm{Aeq},16}$ closely corresponds to the L_{dn} in the case of Zurich airport (not shown).

$$\%HA_i = \begin{cases} -1.395 \cdot 10^{-4} \cdot (L^*_{\mathrm{Aeq},16,i} - 42)^3 \\ +4.081 \cdot 10^{-2} \cdot (L^*_{\mathrm{Aeq},16,i} - 42)^2 \\ +0.342 \cdot (L^*_{\mathrm{Aeq},16,i} - 42) \le 100\% \\ \qquad \text{for } L^*_{\mathrm{Aeq},16,i} \ge 47\,\mathrm{dB}, \\ 0 \qquad \text{for } L^*_{\mathrm{Aeq},16,i} < 47\,\mathrm{dB}. \end{cases} \tag{4}$$

The determination of the $\%HSD_i$ used in equation (3) is effected in two steps. In a first step, the probability (P)

of an additional awakening reaction (*AWR*, i.e., a change from sleep stages REM or 2–4 to stage 1 or awake [22, 23]) as a function of the maximum sound level (L_{Amax}, time constant slow) of a single aircraft event is estimated from the exposure–response relationship by Basner *et al.* [22, 23],

$$\begin{aligned} P_{AWR} = {} & 1.894 \cdot 10^{-5} \cdot (L_{\text{Amax}} + D)^2 \\ & + 4.008 \cdot 10^{-4} \cdot (L_{\text{Amax}} + D) \\ & - 3.3243 \cdot 10^{-2}, \end{aligned} \qquad (5)$$

where D is the attenuation of the sound level during transmission from the outside to the inside (set to $-15\,\text{dB}$ for tilted windows [24]). In a second step, equation (5) (single event) is applied to complete L_{Amax} frequency distributions (H_i) per hectare point i of the night (22–06 h) to obtain the effect of all aircraft events on sleep (AWR_i), and the result is multiplied by a constant factor of 26 (F_{SD}, see section 2.4.2), to convert the AWR_i into the $\%HSD_i$,

$$\begin{aligned} \%HSD_i &= F_{\text{SD}} \cdot AWR_i \qquad (6) \\ &= F_{\text{SD}} \cdot \begin{cases} \int H_i(L_{\text{Amax}} + D) \\ \quad \cdot P_{AWR}(L_{\text{Amax}} + D)\,\mathrm{d}L_{\text{Amax}} \le 100\% \\ \qquad\qquad \text{for } L_{\text{Aeq},8,i} \ge 37\,\text{dB}, \\ 0 \qquad\qquad \text{for } L_{\text{Aeq},8,i} < 37\,\text{dB}. \end{cases} \end{aligned}$$

where $L_{\text{Aeq},8}$ is the equivalent continuous sound level of the night from 22–06 h.

The calculations are confined to perimeters of $L^*_{\text{Aeq},16} \ge 47\,\text{dB}$ (*HA*; equation 4) and $L_{\text{Aeq},8} \ge 37\,\text{dB}$ (*HSD*; equation 6), corresponding to $\%HA_i \ge 2.7\%$ and approximately to $AWR_i \ge 0.1$ (respectively, $\%HSD_i \ge 2.6\%$).

The resulting *ZFI* monitoring values are compared to the guide value of 47’000, which was determined by a predefined reference scenario [13]. This scenario is based on (i) the number of movements of the year 2000, (ii) the aircraft fleet of the year 2004, (iii) the allocation of movements to the air routes as in 2004; and (iv) the population data of 2000. The reference scenario accounts for the need of Zurich airport to increase the number of movements by using those of the peak year 2000, while it avoids too much developmental freedom by considering the acoustically favourable development in aircraft fleet between 2000 and 2004 (section 3.2). Further, with (iii) it incorporates the changes in the flight regime after 2001 (section 3.2). The population data of the year 2000 was used because no current data was available back then.

Note that the official calculation presented here only accounts for potential active noise reduction measures, as the *HSD* are determined for tilted windows. Passive measures such as sound insulating windows or even just closed windows are not taken into account. Thus the calculation yields a reliable upper limit for noise effects on sleep, as many people will sleep with windows closed, particularly in modern buildings with low-energy standard.

2.3. Sensitivity Analysis

The calculated *ZFI* values (respectively, *HA* and *HSD*) depend on two main parameters, namely, the population (i.e., the number of persons and their spatial distribution within the perimeters) and the air traffic determining the spatial sound immission levels. The air traffic may be subdivided into (i) the number of movements, (ii) the composition of the aircraft fleet and its operation over the different periods of the day and night, (iii) the allocation of the movements to different air routes, and (iv) the flight geometries (horizontal and vertical dispersion). These five parameters (population and four air traffic parameters) mutually affect the *ZFI* to different degrees.

To find out to which degrees the *ZFI* is influenced by these five parameters, their individual contributions to the changes in the *ZFI* between two scenarios A and B may be studied by means of a sensitivity analysis. Separate *ZFI* calculations are performed where one parameter at a time is set to the characteristics of scenario A while the remaining parameters are kept to those of scenario B (*ceteris paribus* method). The differences between the original and new *ZFI* value are attributable to the studied parameters. Thus, for each sensitivity analysis, five separate calculations are performed. The results indicate which parameters contributed by what degree to the changes (ranking). Summing up the five individual differences to obtain the total contribution of all parameters, and comparing the result with the effective difference between the two scenarios shows how well the effects of the parameters can be separated.

2.4. Retrospection: Development of the *ZFI* calculation

Based on the concept described in section 2.1, different possible realizations for the calculation of the *%HA* and *%HSD* used in equations (2) and (3) were tested to establish the official calculation rule described in section 2.2. Since the development of the calculation rule was an iterative process, only the most important results are discussed here.

2.4.1. Exposure–response relationships

In total, four exposure–response relationships for the *%HA* and five for the *%HSD* were tested. Table I lists the functions as well as their origin. The exposure–response functions for the *%HA* are denoted as $f_{\text{d1}} - f_{\text{d4}}$ in the following account (index ‘*d*’ for day). They use an equivalent continuous sound level as input and yield the *%HA* as output (Table I). The exposure–response functions for the *%HSD* ($f_{\text{n1}} - f_{\text{n5}}$; index ‘*n*’ for night) either use an equivalent continuous sound level or an L_{Amax} of a single aircraft event as input, and either yield the *%HSD*, the maximum number of behavioural awakenings (n_{max}, i.e., awakenings followed by an action such as pressing a button) or the probability of an *AWR* (Table I).

As $f_{\text{n2}} - f_{\text{n5}}$ do not directly yield the *%HSD*, the latter are estimated from the respective outputs in a subsequent step (see section 2.4.2). This is a fundamental difference

Table I. Exposure–response relationships $f_{\mathrm{d1}} - f_{\mathrm{d4}}$ for the day (06–22 h) for the fractions of the highly annoyed persons (*%HA*) as a function of the equivalent continuous sound level of the day ($L_{\mathrm{Aeq,16}}$) or the day-night level (L_{dn}), and $f_{\mathrm{n1}} - f_{\mathrm{n5}}$ for the night (22–06 h) for the fractions of the highly sleep disturbed persons (*%HSD*), the maximum number of behavioural awakenings (n_{max}) or the probability of an additional awakening reaction (P_{AWR}) as a function of the night level (L_{n}) or the maximum sound level of a single aircraft event (L_{Amax}). out = outdoor sound level, in = indoor sound level.

Time		Output	Input	Description and Reference
day	f_{d1}	*%HA*	$L_{\mathrm{Aeq,16}}$ (out)	‘New Zurich Formula’ by Oliva (internal report [25]), published as Figure 4 in [26]. Re-evaluation of data from a noise study (‘Lärmstudie 90’) by Oliva [27].
	f_{d2}	*%HA*	$L_{\mathrm{Aeq,16}}$ (out)	Exponential curve approach by Oliva (internal report [28]). Re-evaluation of data from a noise study (‘Lärmstudie 90’) by Oliva [27].
	f_{d3}	*%HA*	L_{dn} (out)	EU standard curve by Miedema and Oudshoorn [21].
	f_{d4}	*%HA*	$L_{\mathrm{Aeq,16}}$ (out)	Sigmoidal curve approach by Hofmann (internal report [29]), purely mathematical function developed for this study.
night	f_{n1}	*%HSD*	L_{n} (out)	Self-reported sleep disturbance in EC position paper [30].
	f_{n2}	n_{max}	L_{n} (in)	Review study by Passchier-Vermeer in EC position paper [30].
	f_{n3}	P_{AWR}	L_{Amax} (in)	Field study by Basner *et al.* [22, 23].
	f_{n4}	P_{AWR}	L_{Amax} (in)	Laboratory study by Basner *et al.* [22].
	f_{n5}	P_{AWR}	L_{Amax} (out)	Loudness approach by Hofmann (internal report [29]), purely mathematical function developed for this study.

to the functions f_{n1} and $f_{\mathrm{d1}} - f_{\mathrm{d4}}$. While the latter directly link an acoustic measure to a conscious negative judgement, the functions $f_{\mathrm{n2}} - f_{\mathrm{n5}}$ yield behavioural reactions (n_{max} and *AWR*) from which the *%HSD*, i.e., again a conscious negative judgement similar to the *%HA*, are estimated by means of a ‘calibration’, be it a function or a constant, which generally is not 1, but an unknown quantity that first has to be defined. Thus, the *%HSD* differ from the *%HA* insofar as the latter are directly related to the judgment of noise affected residents, while the *%HSD* are to a large part related to the judgment of scientists.

2.4.2. Parameter settings

For the development of the *ZFI* calculation, some of the exposure–response functions (Table I) were modified, and corresponding parameter settings were established as follows.

Firstly, for the *%HA* ($f_{\mathrm{d1}} - f_{\mathrm{d4}}$), the equivalent continuous sound level of the day from 06–22 h ($L_{\mathrm{Aeq,16}}$; see also section 2.4.3) was used as acoustic input, as it is determined for Zurich airport on a yearly basis according to NAO [20]. The original equation of f_{d3} was therefore modified (section 2.2).

Secondly, for the *%HSD* ($f_{\mathrm{n1}} - f_{\mathrm{n5}}$), the $L_{\mathrm{Aeq,8}}$ or the frequency distributions of the L_{Amax} of the night from 22–06 h were used as acoustic inputs, as they, like the $L_{\mathrm{Aeq,16}}$, are annually determined. Thus, the L_{n} used in f_{n1} and f_{n2} was replaced by the $L_{\mathrm{Aeq,8}}$. As the functions $f_{\mathrm{n3}} - f_{\mathrm{n5}}$ estimate the effect of a single aircraft event on sleep, they were applied to complete L_{Amax} frequency distributions, and the effect of all aircraft events on sleep (*AWR*) was obtained by summing them up.

Thirdly, the acoustic inputs correspond to either outdoor or indoor sound levels (Table I). As the aircraft noise calculations (cf. section 3.2) yield outdoor levels, they were converted to indoor levels where applicable (i.e., for $f_{\mathrm{n2}} - f_{\mathrm{n4}}$), using a sound level attenuation (cf. section 2.2) set to −15 dB for tilted windows [24].

Fourthly, the $n_{\mathrm{max}}(f_{\mathrm{n2}})$ and *AWR* ($f_{\mathrm{n3}} - f_{\mathrm{n5}}$) were multiplied by a constant factor (F_{SD}; SD = ‘strong disturbance’) to convert them into the dimension of *%HSD* used in equation (3). This assumes a linear relation between n_{max} or *AWR* and disturbance. The factor F_{SD} is defined as

$$F_{\mathrm{SD}} = 100 \cdot \frac{r_{\mathrm{pop},HSD}}{r_{\mathrm{crit}} \cdot n_{\mathrm{null}}}, \tag{7}$$

where $r_{\mathrm{pop},HSD}$ is the fraction of the population characterizing itself as highly sleep disturbed, r_{crit} is the critical fraction of sleep reactions to aircraft noise, and n_{null} is the average number of spontaneous *AWR* or n_{max} per night occurring without any noise event. With the latter being 24 for *AWR* [22] and 1.6 for n_{max} [30], the critical number of reactions set to 4% of the spontaneous reactions ($r_{\mathrm{crit}} = 0.04$), and assuming 25% of the population to feel highly sleep disturbed for $r_{\mathrm{crit}} \cdot n_{\mathrm{null}}$ ($r_{\mathrm{pop}} = 0.25$, corresponding to the 25% often used to determine exposure limits [31, 32]) one obtains $F_{\mathrm{SD}} = 26$ for *AWR* and $F_{\mathrm{SD}} = 391$ for n_{max}. (Note that different values for F_{SD} were tested, but as F_{SD} simply scales the n_{max} or *AWR*, only the results based on the final values are discussed here.)

Finally, the calcultions were confined to certain perimeters for the day and the night. Perimeters are necessary [5], as considering too large areas in the calculations would result in the *ZFI* reacting very sluggishly to changes in the population or air traffic. Here, the perimeters were acoustically defined as the areas enclosed by $L_{\mathrm{Aeq,16}} = 47$ dB for the day (*HA*) (exception: $L_{\mathrm{Aeq,16}} = 54$ dB for f_{d1}: Figure 1) and $L_{\mathrm{Aeq,8}} = 37$ dB for the night (*HSD*).

Figure 1 compares the final equations (after parameter settings) of functions $f_{\mathrm{d1}} - f_{\mathrm{d4}}$ and $f_{\mathrm{n1}} - f_{\mathrm{n5}}$. In order to display $f_{\mathrm{n1}} - f_{\mathrm{n5}}$ in the same graph, the $L_{\mathrm{Aeq,8}}$ of f_{n1} and f_{n2} was converted to L_{Amax} (for the graph only). As Figure 1 shows, the functions yield very disparate results.

2.4.3. Penalties for early and late hours of the day

While the major part of the *HA* determination described in section 2.4.2 was based on the $L_{\mathrm{Aeq},16}$, discussion was also raised about increased sensitivity of early and late daytime hours. Responding to this, penalties of 5 or 10 dB for the sound levels of the first (06–07 h) and/or of 5 dB for the sound levels of the last hour of the day (21–22 h) were tested and found to increase the resulting *HA* by 1–51%, depending on the exposure–response function, penalty and scenario. Accounting for these effects was therefore decided to be essential, and in the official calculation rule (section 2.2), the sound levels of the first and last hour of the day are charged with penalties of 5 dB each to obtain the $L^*_{\mathrm{Aeq},16}$. The $L^*_{\mathrm{Aeq},16}$ and $L_{\mathrm{Aeq},16}$ may locally distinctly differ in the case of Zurich airport, as the flight regime strongly varies over the day, e.g., due to restrictions to the air traffic over south German territory during early and late daytime hours.

The results obtained during development of the *ZFI* calculation are therefore based on the $L_{\mathrm{Aeq},16}$, while those of the official calculation rule use the $L^*_{\mathrm{Aeq},16}$ as input.

2.4.4. Insights

For the development of the *ZFI* calculation, 14 air traffic scenarios were tested, using population census data of the year 2000. These scenarios are not further discussed, as their main purpose was to yield the data basis to test different exposure–response functions. Figure 2 shows the scatter of calculated *ZFI* values obtained with the studied exposure–response functions. The functions yield very disparate absolute values, with ratios of maximum to minimum values of 2.2–3.0 for the *HA* and 7.6–8.7 for the *HSD*. For the *HA*, the function f_{d1} yields the smallest values due to the restrictive calculation perimeter ($L_{\mathrm{Aeq},16} \geq$ 54 dB instead of 47 dB, section 2.4.2), and f_{d2}, which was derived from data of the same study, yields only slightly larger values. In contrast, f_{d3} and f_{d4} yield substantially larger values. For the *HSD*, f_{n1}, f_{n3} and f_{n5} give similar results, while f_{n2} and in particular also f_{n4} yield substantially larger values. Nevertheless, the resulting values are mostly highly correlated ($r = 0.916$–0.999, $P < 0.0001$ for the *HA* and $r = 0803$–0.997, $P < 0.01$–0.0001 for the *HSD*, cf. Figure 2). While correlations do not consider that the results obtained with the different functions deviate from the 1:1 line (cf. Figure 2), with differences generally large and strongly varying with number of affected persons (or underlying sound levels), the results may be quite reliably converted into one another, e.g., by doing regression for nonuniform differences (details see [33]).

Depending on the functions used to determine the *HA* and *HSD*, very disparate *ZFI* values result. Combining the minimum ($f_{\mathrm{d1}}, f_{\mathrm{n5}}$) and maximum ($f_{\mathrm{d4}}, f_{\mathrm{n4}}$) values for the *HA* and *HSD* (Figure 2) yields a wide range of *ZFI* values differing by factors of 3.1–5.0. While scattering more than the *HA* and *HSD* values (not shown), the maximum and minimum *ZFI* values are still moderately correlated to each other ($r = 0.763$, $P < 0.002$).

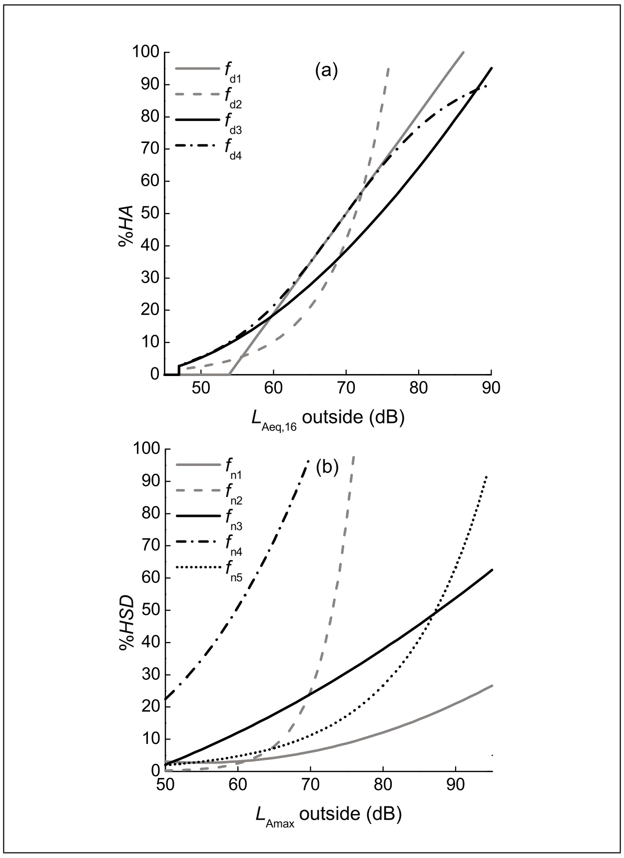

Figure 1. Exposure-response relationships for the fractions of (a) the highly annoyed persons ($f_{\mathrm{d1}} - f_{\mathrm{d4}}$ for *%HA*) as a function of the equivalent continuous sound level of the day ($L_{\mathrm{Aeq},16}$) and (b) the highly sleep disturbed persons ($f_{\mathrm{n1}} - f_{\mathrm{n5}}$ for *%HSD*) as a function of the maximum sound level (L_{Amax}). The relationships displayed for the *%HSD* assume 20 flight events. Details see Table I and text.

Given the primary aim of the *ZFI* to compare scenarios, especially with regard to the question whether a scenario complies with the guide value, it is thus not critical which function to choose, because the results, while very different in absolute numbers, are highly correlated. Based on these insights, the functions f_{d3} and f_{n3} were chosen for the official calculation rule (section 2.2), as the former is one of the well established relationships sometimes referred to as 'EU standard curves' (e.g., [34]), while the latter was derived from an extensive field study [22, 23] and should thus reliably represent real conditions.

2.5. Calculation uncertainties

The standard uncertainties of the estimated *HA*, *HSD* and *ZFI* values result from uncertainties of the aircraft noise calculations and of the fitting parameters of the exposure–response functions. For sound levels relevant according to NAO [20], the standard uncertainties of calculated L_{Aeq} values obtained from the simulation model FLULA2 (see below) range from 0.6 dB(A) for the day to 1.0 dB(A) or more for the night for 'real' (past time) scenarios [35]. They are larger (up to about double) for larger distances from frequented air routes and therefore for lower sound

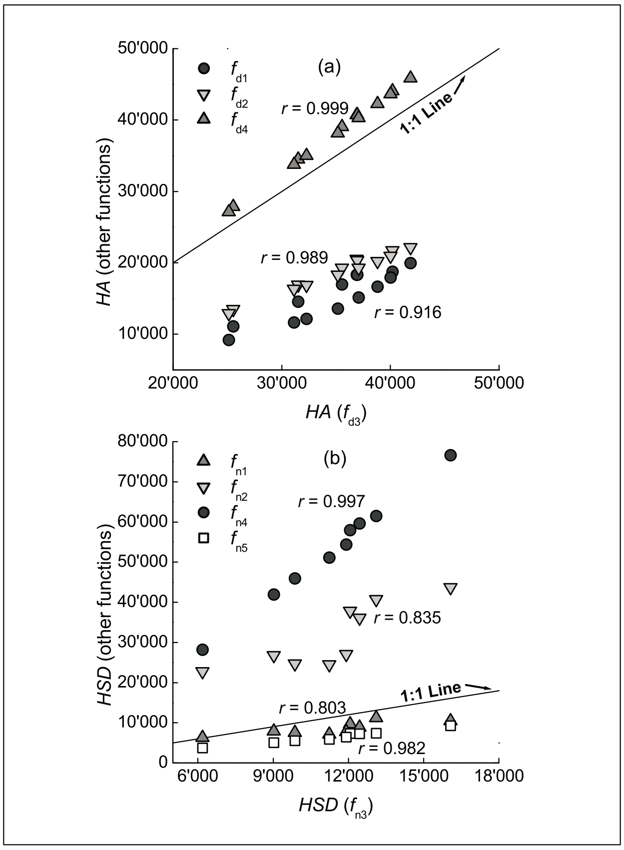

Figure 2. Scatter diagrams of the results obtained with different exposure–response relationships for (a) the highly annoyed (*HA*) (f_{d1}, f_{d2}, f_{d4} vs. f_{d3}) and (b) the highly sleep disturbed persons (*HSD*) (f_{n1}, f_{n2}, f_{n4}, f_{n5} vs. f_{n3}).

levels as still relevant for the *ZFI*, as well as for prognoses. The uncertainties of the fitting parameters strongly depend on the function. The total uncertainties, while difficult to determine, will add up to 10–35% for the *HA*, 40% for the *HSD* [19], and, accordingly, 10–30% for the *ZFI*. While these figures seem rather large, the *ZFI* is well suited as a tool to compare scenarios (including comparison to the guide value), as in comparisons the relevant uncertainty decreases to about 10% [19].

3. Input data, scenarios, and calculations

3.1. *ZFI* scenarios

The calculations according to the official calculation rule were done for (i) the reference scenario, (ii) the time series of 1998–2009 using the population data of the year 2000, showing the influence of changes in air traffic on the *ZFI*, and (iii) the time series of 2000 and 2005–2009 using the population data of the respective years, revealing the mutual effects of changes in air traffic and population growth.

In addition, eight sensitivity analyses were performed in total, studying short-term changes between two subsequent years as well as long term changes between recent years and the year 2000 or the reference scenario. Below, some of these results illustrate the information to be gained by the sensitivity analysis.

3.2. Aircraft noise exposure

Aircraft noise calculations were made with the simulation program FLULA2 [36, 37]. In short, FLULA2 considers (i) the sound source data (source intensity and directivity patterns) of individual aircraft [38], (ii) the statistics of movements per aircraft type, air route and period of day, (iii) the detailed flight geometries determined from radar data (several 10’000 flight paths per calculation), and (iv) the topography (terrain only).

For the calculation of the *HA*, the *HSD* and the *ZFI*, the $L^{*}_{\mathrm{Aeq,16}}$ (or $L_{\mathrm{Aeq,16}}$: section 2.4) of the average day (06–22 h), and the $L_{\mathrm{Aeq,8}}$ as well as the L_{Amax} frequency distributions of the average night (22–06 h) were determined. In the calculations, large aircraft only are considered, with maximum take-off weights $> 8'618$ kg according to NAO [20], in agreement with Annex 16, Volume I of ICAO [39]. Small aircraft ($\leq 8'618$ kg) are omitted in the calculation as at Zurich airport their contribution to the overall sound levels is small. In the aircraft noise modelling (years 1998–2009), 51–58 reference aircraft types on 14–20 departure routes and 4–14 approach routes were taken into account per year. An illustration of the current air routes is given in [40]. The allocation of the movements to the air routes strongly varies over the years. In particular, three air routes (X16, Y16, Z16) passing over densely populated areas south of the airport were only used for two months in 2000 during construction work on the airport (5th Expansion Project), and the flight regime, i.e., the allocation of movements to different air routes, strongly changed between 2001 and 2002 due to restrictions in air traffic over south German territory during early and late daytime hours. In 2003–2004, an important change in aircraft fleet took place when the Swiss International Airlines Company replaced the MD11 by the less noisy A340-300.

As Figure 3 shows, the number of movements strongly changed over the years. Accordingly, also the calculation perimeters for the *HA* and the *HSD* strongly varied in shape (not shown) as well as in area (Figure 4a). The area depends on the number of movements, but also on the allocation of the movements to air routes and on the aircraft fleet. The latter two also determine the shape of the perimeters.

3.3. Population

Population census data was available on a hectare grid-for the years 2000 and 2005–2009. As Figure 4b shows, the population within the calculation perimeters of the respective years decreased between 2000 and 2005 by 29% (day) and 24% (night), steadily increased from 2005–2008, and slightly decreased again between 2008 and 2009 to reach final values of 80% (day) and 100% (night) of the year 2000 (= 100%). The decreases from 2000–2005 and 2008–2009 were evoked by shrinking perimeters (Figure 4a), while the increase from 2005–2008 was caused by expanding areas, but in particular also by population

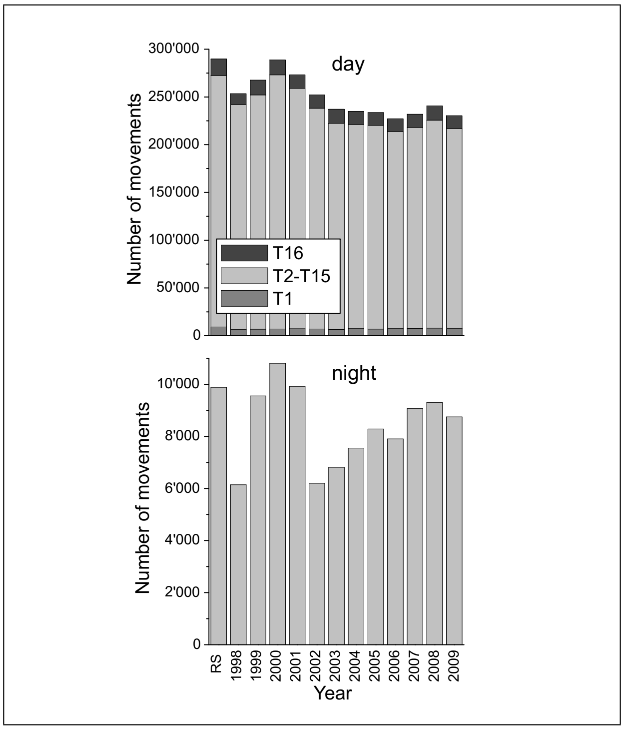

Figure 3. Number of movements of large aircraft (maximum take-off weight > 8′618 kg) on Zurich airport during the day (06–22 h, top) and the night (22–06 h, bottom) for the reference scenario (RS) and the years 1998–2009. The day is subdivided into the first (T1, 06–07 h) and last hour of the day (T16, 21–22 h), and the remaining hours (T2-T15, 07–21 h). Note the different scales of the two figures.

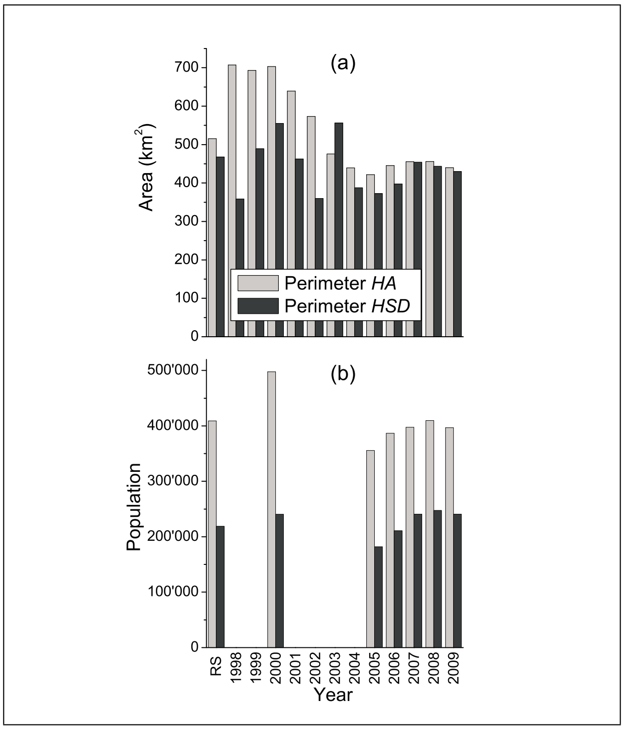

Figure 4. Calculation perimeters. (a) Areas of the perimeters used for the calculation of the highly annoyed (perimeter *HA*) and highly sleep disturbed persons (perimeter *HSD*) for the reference scenario (RS) and the years 1998–2009. (b) Population of the RS and the years 2000 and 2005–2009 in the calculation perimeters of the respective years.

growth. In fact, within the perimeters of 2009, the population grew continually from 2000–2009, and by 2009 it was 13% (day) and 15% (night) larger than in 2000. The pronounced increases are caused by disproportional population growth in the vicinity of Zurich airport, as the area is attractive for residents (e.g., favourable job situation). During the same time period, the population grew only by 9% within the whole canton of Zurich, but by 18% within 14 municipalities in the close vicinity of the airport.

3.4. Number of affected persons according to Swiss federal legislation

'Affected persons' are fundamentally differently defined by the *ZFI* concept and by NAO [20] (for details see [32]). Exposure limits of NAO [20] are usually set such that at the so-called 'impact thresholds', not more than 25% of the population are highly annoyed [32, 41]. Thus, even below the exposure limits a considerable fraction of the population is affected by aircraft noise. In contrast, the *ZFI* concept also considers a large part of this fraction, accounting for populated areas exposed to aircraft noise well below the exposure limits. On the other hand, in areas where the exposure limits of NAO are exceeded, only the fraction of people that is (highly) affected by aircraft noise is effectively accounted for by the *ZFI*, while the whole population is counted in the quantifications according to NAO [20], thus overestimating the noise impact on the population. Finally, NAO [20], in contrast to the *ZFI*, does not allow for double counts.

To study the comparability of these two quantifications, the number of residents in areas where the impact thresholds are exceeded were determined, separately for (i) the day, (ii) the night, and (iii) in total (envelope of the day and the night). The results were compared with the *ZFI* approach, namely, (i) with the *HA*, (ii) with the *HSD* and (iii) with the *ZFI*. Calculations were done for the years 1998–2009, using population data of the year 2000.

4. Results

4.1. Official calculation rule

4.1.1. *ZFI* Mapping

Figure 5 shows the spatial distribution of the *ZFI* around Zurich airport, exemplarily for the year 2008. Similar maps apply to the other years, and to the *HA* and *HSD* alone (not shown). As expected, the population of areas in the vicinity of the airport and close to highly frequented air routes (e.g., approach route P28 east of runway 28) is particularly affected, as the exposure to aircraft noise is pronounced there. In fact, while 104–137 municipalities lay within one or both calculation perimeters of the years 2000 and 2005–2009, 10 municipalities in the vicinity of the airport accounted for as much as 52–60% of the total

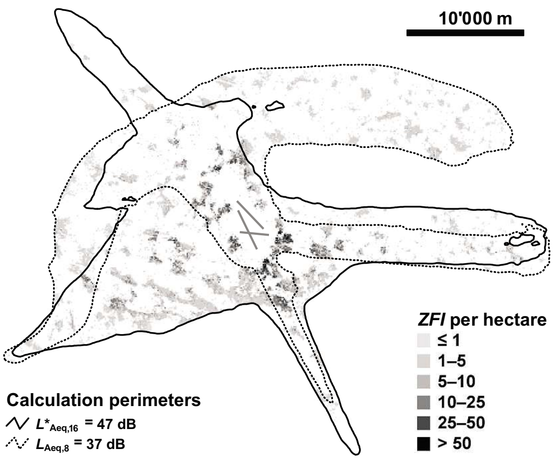

Figure 5. *ZFI* mapping. The Zurich Aircraft Noise Index (*ZFI*) around Zurich airport for the year 2008. The areas with affected people are delimited by the calculation perimeters for the highly annoyed ($L^*_{\mathrm{Aeq},16} = 47$ dB) and the highly sleep disturbed persons ($L_{\mathrm{Aeq},8} = 37$ dB). Areas within both perimeters allow for double counts (see text).

ZFI (sum of all *ZFI* values per hectare). However, also areas with moderate aircraft noise levels far away from the airport, which still lie within the perimeters, considerably contributed to the *ZFI*.

4.1.2. *ZFI* time series

Figure 6a shows the *HA*, *HSD* and *ZFI* of the reference scenario and of the years 1998–2009 (population data of 2000). The reference scenario yields a *ZFI* value of 47’450 persons, based on which the guide value of 47’000 was established. As Figure 6a shows, the *ZFI* strongly varies over the years, which is caused by changes in the air traffic parameters (e.g., number of movements: Figure 3; see also section 4.2). Reaching its maximum in 2000, the *ZFI* exceeded the guide value in 1999–2001, but complied with it thereafter. However, Figure 6a ignores changes in the population since 2000, although the latter will affect the results.

Air traffic and population changes were therefore both accounted for in a next step. Figure 6b shows the *HA*, *HSD* and *ZFI* of the reference scenario and of the years 2000 and 2005–2009, based on the population of the respective years. Note that these are the official *ZFI* values according to legislation [13]. Between 2000 and 2005, the *ZFI* strongly decreased by one third. Thereafter, it steadily increased from 2005–2008. In 2008, the *ZFI* exceeded the guide value by more than 2’000 persons. From 2008–2009 the *ZFI* again decreased to just below the guide value. To the changes in the *ZFI* from 2005–2009, particularly the pronounced changes in the *HSD* contributed, while the *HA* varied only moderately. The official *ZFI* values of 2005–2009 are distinctly larger (Figure 6b) than those not accounting for population growth (Figure 6a).

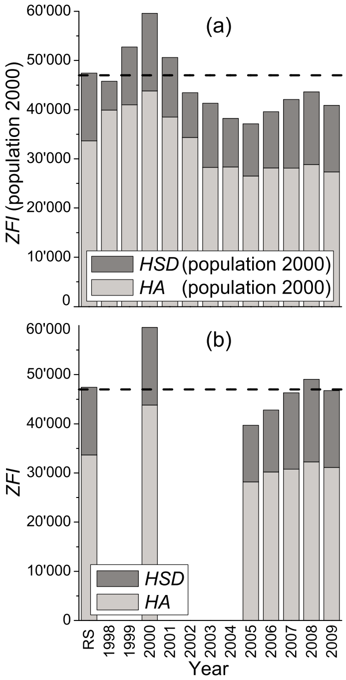

Figure 6. *ZFI* time series. (a) Combination of the number of highly annoyed (*HA*) and highly sleep disturbed persons (*HSD*) to the Zurich Aircraft Noise Index ($ZFI = HA + HSD$) for the reference scenario (RS) and the years 1998–2009, based on the population data of 2000. (b) *HA*, *HSD* and *ZFI* of the RS and the years 2000 and 2005–2009, based on the population data of the respective years. Bold dashed line: guide value of 47’000 persons. RS and year 2000 of (b) are taken from (a).

4.2. Sensitivity analysis

4.2.1. Quantifications

In a first step, the influence of the population growth and air traffic as a whole on the *ZFI* was studied. Figure 7 shows the relative changes in the *HA*, *HSD* and *ZFI* between the reference scenario (= 100%) and the years 2000 and 2005–2009 as caused by the changes in the population (differences in the *HA*, *HSD* and *ZFI* between Figures 6b and 6a) and air traffic (remaining difference to obtain the total difference in Figure 6b between the reference scenario and the respective year). The *ZFI* of the year 2000 was 26% larger than the *ZFI* of the reference scenario, which is exclusively attributable to the air traffic (same population data: section 2.2). For the day of the subsequent years 2005–2009, the population growth was more than compensated by the advantageous development in the air traffic parameters (i.e., reducing the *HA*) compared to the reference scenario. For the night, in contrast, the same is true only for 2005 and 2006. In the other years, the air traffic either did not compensate the population growth (2009) or even contributed to the increasing *HSD* values (2007–2008). In its sum (*ZFI*), the air traffic more than compensated the population growth, except for the year 2008. In fact, if only the population, but not the air traffic had changed compared to the reference scenario,

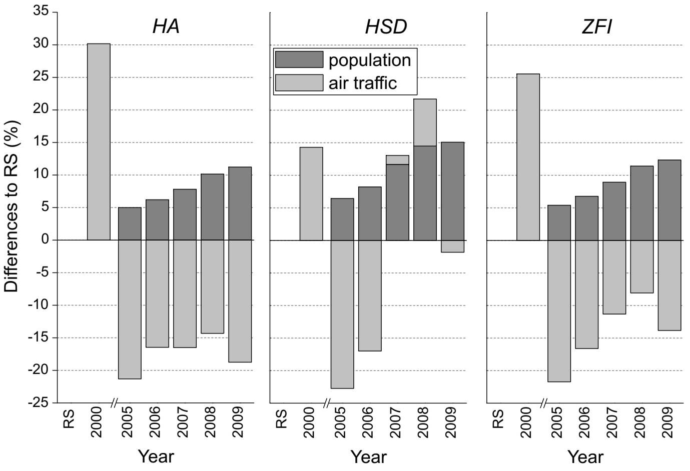

Figure 7. Influence of the changes in the population and air traffic around Zurich airport between the reference scenario (RS) and the years 2000 and 2005–2009 on the Zurich Aircraft Noise Index (*ZFI*): differences (percentages relative to the values of the RS) in the highly annoyed (*HA*, left) and highly sleep disturbed persons (*HSD*, middle), and the *ZFI* (right).

the *ZFI* would have continually increased by 14% to more than 54'000 in 2009.

In a second step, the four air traffic parameters were separately analysed for their influence on the *ZFI*. While the parameters were found to affect the *ZFI* between two scenarios to different degrees, depending on their respective changes, several general features of the parameters, as well as of the sensitivity analysis in general, were found. Firstly, decreasing and increasing population and number of movements always (by necessity) decrease and increase, respectively, the values of *HA*, *HSD* and *ZFI*. For example, the population growth between the reference scenario and 2007 increased the *ZFI* by 9% (Figure 7), while the decreasing number of movements reduced the *ZFI* by 20% in the same period. Secondly, the aircraft fleet will generally reduce the *ZFI* if development goes towards a less noisy fleet (as long as the number of aircraft movements does not change at the same time, an inherent assumption of the *ceteris paribus* method). Accordingly, the changes in the aircraft fleet after 2000 were found to strongly reduce the *HA* by 20–26% and thus the *ZFI* by 15–17% between 2000 and 2007–2009 (year 2000 = 100%). Thirdly, the allocation of movements to different air routes and the flight geometries affect the *ZFI* by determining whether densely or weakly populated areas are passed. For example, an additional calculation of the year 2000, proportionally relocating the movements on routes X16, Y16 and Z16 (section 3.2) to the remaining routes, revealed that this scenario would have yielded a 7% smaller *ZFI* value (55'381) than it effectively was (59'580). Fourthly, different parameters may partly compensate each other, and their extent may differ for the *HA* and the *HSD*. Finally, the effects of different parameters are not completely separable. For example, the aircraft fleet and flight geometries (containing information on flight performance) are strongly interrelated. While an aircraft fleet developing towards a less noisy fleet should decrease the *ZFI*, the opposite was observed for the *HSD* in the sensitivity analyses of the years 2007–2009 vs. 2000: Replacing the MD11 (noisy, but strong climb performance) by the A340-300 (less noisy, but poor climb performance) (section 3.2) on average decreased the distances between the aircraft and population, and thus increased the sound immission.

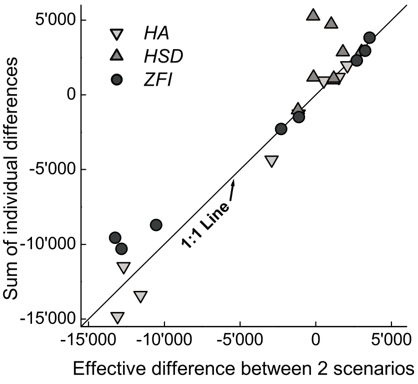

Figure 8. Sum of the individual differences of the five influencing parameters as obtained by 8 separate sensitivity analyses vs. effective differences between the scenarios in the highly annoyed (*HA*) and highly sleep disturbed persons (*HSD*), and the Zurich Aircraft Noise Index (*ZFI*).

As the effects cannot be completely separated, the sum of the individual differences of the parameters will not exactly add up to the effective difference between two scenarios (Figure 8). While the differences mostly closely correspond to each other, deviations do occur, particularly for effective differences close to 0, as small differences may not efficiently be separated.

4.2.2. Consequences of surpassing the guide value

As the cantonal government has to prevent the guide value from being exceeded ([12, 13]; section 2.1), the results of the sensitivity analysis may help to identify adequate preventive measures. According to these results, measures to reduce the *ZFI* should particularly concentrate on the night (*HSD*, cf. Figure 7). One should mainly focus on the population (namely, land use planning) and on the allocation of

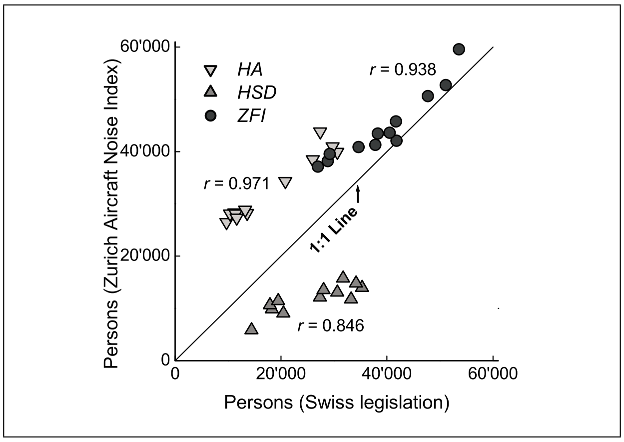

Figure 9. Scatter diagram of highly annoyed (*HA*) and highly sleep disturbed persons (*HSD*), and Zurich Aircraft Noise Index (*ZFI*) vs. number of persons exposed to sound immissions exceeding the impact thresholds of Swiss legislation [20] of the day, the night, and in total, respectively.

the movements to air routes as well as on the flight geometries. Aircraft fleet and number of movements, in contrast, are economically driven factors which are difficult to influence. While the air traffic could in principle be restricted for certain times of the day, it would be impractical if not impossible for Zurich as a hub airport not to operate in the (sensitive) early morning and late daytime/early nighttime hours. For the identification of particularly advantageous air routes affecting a minimum of people, noise effect maps (Figure 5) may be of help. Partly based on these findings, the Office of Transport of the canton of Zurich worked out a concept of measures to reduce the *ZFI* [42].

4.3. Comparison: *ZFI* vs. Swiss federal legislation

Similar to the results of different exposure–response relationships (section 2.4.4), also the quantifications according to NAO [20] yield results that are quite closely correlated to those obtained with the official *ZFI* calculation rule ($r = 0.846$–0.971, $P < 0.001$–0.0001: Figure 9). While the *HA* are larger by a factor of 1.30–2.72 and the *HSD* smaller by a factor 0.35–0.59 than the respective number of persons according to NAO, the *ZFI* values closely correspond to those according to NAO (factor 1.01–1.38) (Figure 9). However, while the numbers of the two quantifications are closely correlated to each other, they comprise different persons from different areas exposed to considerably different sound levels.

5. Discussion

This paper reports on the *ZFI*, a noise effect index developed for Zurich airport and included in the cantonal legislation [13]. Various exposure–response functions and parameter settings were tested as a basis to establish the official calculation rule [19]. With the latter, the *ZFI* was determined for a time series of 12 years based on very detailed and reliable acoustic and population data, and reasons for its variations were studied. While noise effect indices have been critically discussed recently [5, 11, 18], the authors are not aware of a comparably detailed report of such an index in the literature.

5.1. Comparability of results from different exposure–response functions

While the tested exposure–response functions yield very different absolute *HA*, *HSD* and *ZFI* values, their results are strongly correlated (Figure 2). Interestingly, even the quantifications according to NAO [20], though based on a quite different calculation approach, yield results that are closely correlated to the *ZFI* values (Figure 9). However, the latter rather indicates that summing up the number of persons to a single value may alleviate differences between different calculation procedures to some degree.

The 'exact' (unknown) absolute values of *HA*, *HSD* and *ZFI* are very difficult, if not impossible to estimate, as they are afflicted with great uncertainty (section 2.5). Besides, various effects may not or only grossly be modelled. For example, aircraft noise calculations do not account for local effects such as reflections or shielding, which may affect results [43]. Furthermore, the aggregated population data (hectare grid) do not consider specific housing conditions, over-reactions of annoyance due to step changes in aircraft noise exposure (e.g., [44, 45]) remain unaccounted for, and only average reactions of sleep to aircraft noise events are considered, although they strongly depend on sleep duration, on the slope of rise of events, and on the noise-free time between events (e.g., [46]). Particularly ignoring over-reactions may strongly affect the results. People voluntarily moving to areas close to an airport will be more 'noise resistant' than people involuntarily exposed to 'new' noise due to changes in flight regime. However, applying several exposure–response functions for different areas around an airport to account for differing situations would be impractical, if not impossible. Finally, only aircraft noise is considered. Particularly in areas far away from the airport, the (calculated) aircraft noise may lie well below the background noise, inducing errors in the *HA* or *HSD* calculation [47]. However, as the *ZFI* was essentially designed as a tool to compare scenarios (in particular to the guide value), the absolute *HA*, *HSD* and *ZFI* values are not of utmost importance, and consequently, as the different functions yield highly correlated results, their choice is not crucial. Thus, it would be reasonable to determine the relative monitoring values in percentage of the guide value, instead of absolute (but uncertain) numbers. The guide value would then be set to 100%, and the monitoring value would adopt values $\leq$ 100% if complying with the guide value and > 100% if exceeding it.

The pivotal point for accomplishing the aims of the *ZFI* concept is to use the functions consistently. Once a guide value has been established with an aircraft noise model and exposure–response functions, the monitoring values must be determined in exactly the same way. For example, using f_{d4} instead of f_{d3} for the *HA* would have yielded a guide value of ~50'000 instead of 47'000, and comparing the official *ZFI* values (Figure 6b) with this larger guide value would lead to wrong decisions. However, even when using the functions consistently, one may not completely exclude a certain dependency of results and/or decisions on the chosen functions due to their quite disparate curve progressions (Figure 1). In addition, it may become inevitable to modify the calculation rule and thus also the guide value from time to time, be it because the exposure–response functions become outdated (cf. section 5.2.2) or because the aircraft noise calculation model has to be updated.

5.2. Official calculation rule

5.2.1. Advantages of the *ZFI* concept

The *ZFI* concept has strong features. Firstly, the (single number) *ZFI* monitoring value representing the integral effects on the population allows for simple comparisons between scenarios, and to decide whether measures have to be taken, by comparing it to the guide value. Secondly, it considers the population even in areas with sound immissions well below the exposure limits of NAO [20], which usually remain unaccounted for. The *ZFI* (as other noise effect indices) may therefore complement legal exposure limits [5]. Here, however, a fundamental difference between the *ZFI* concept and NAO [20] must be kept in mind: The NAO is the basis for a legal assessment of a situation, in particular for the claim of individuals against responsible(s) for the noise. In contrast, the *ZFI* concept is a political tool for the assessment of the general situation around the airport, which contains a certain ethics in the sense that noise relieve in densely populated areas is more valuable than the disadvantages of noise augmentation in weakly populated areas. Thirdly, the *ZFI* monitors the development of the number of affected persons, instead of purely acoustic measures such as the L_{Aeq} or L_{dn} which are of importance only in areas where people live. Fourthly, it reacts sensitively to changes between scenarios (Figures 6 and 7). Fifthly, the reasons for variations in the *ZFI* may be studied by sensitivity analysis, and the spatial distribution of the *ZFI* can be displayed in noise effect maps (Figure 5) to identify areas of increased *ZFI*. Both help to find out how/where the *ZFI* and thus the number of persons affected by aircraft noise may be most effectively reduced. Noise mitigation strategies (e.g., [48]) may benefit from such insights. Finally, the *ZFI* may be well communicated to the population. The meaning of the 'number of affected persons' is easier to comprehend than acoustic measures. The government of the canton of Zurich has created a good internet platform to publish and communicate the *ZFI* data [49].

5.2.2. Criticism of the *ZFI* concept

Despite the advantages of the *ZFI*, criticism has also been raised, which, however, potentially applies to any noise effect index. Various aspects have been discussed recently, and the authors refer to the respective publications for details [5, 11, 18]. Here some of these aspects are discussed in relation to the data and insights obtained with the *ZFI*.

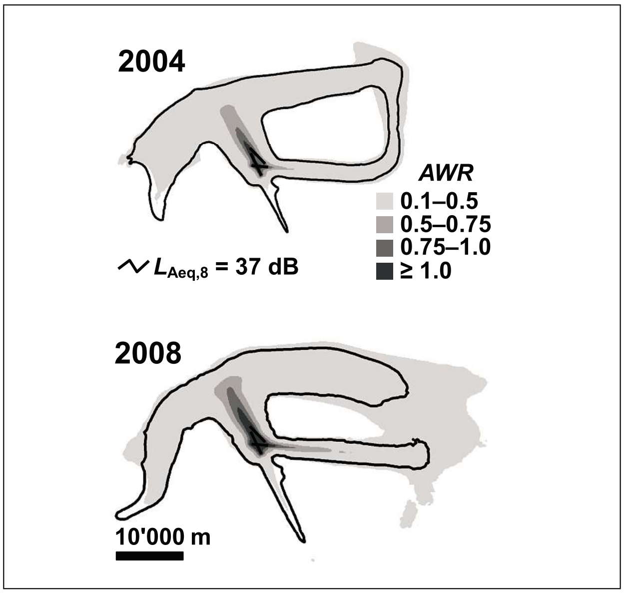

Figure 10. Comparison of the calculation perimeter for the highly sleep disturbed ($L_{\mathrm{Aeq,8}} = 37\,\mathrm{dB}$) with the additional awakening reactions (*AWR*) for Zurich airport in the years 2004 (top) and 2008 (bottom).

Firstly, the question of the 'optimal' exposure–response relationship remains unsolved. The generalized EU standard curve by Miedema and Oudshoorn [21] (f_{d3} for the *HA*) is based on a wide range of studies, which however date back to 1965–1992, while a trend of increasing annoyance towards noise exposure has been observed in the last decades (e.g., [31, 34]). This relationship is therefore considered to be outdated; it leads to at least conservative estimations of the *%HA*. While a regional curve, as used, e.g., for the 'Frankfurt Aircraft Noise Index' [17], may represent the local situation more adequately, data of a recent noise study on Zurich airport ('Lärmstudie 2000' [44]) was not available at the time the *ZFI* was developed, neither other recent studies, such as those described in [10, 34]. Whether local or generalized, every relationship will be outdated one day if sensitivities to aircraft noise change with time. Therefore, exposure–response functions of a noise effect index should be checked periodically and, where applicable, updated or replaced by more recent functions from time to time.

Secondly, replacing the L_{dn} of the original exposure–response function by Miedema and Oudshoorn [21] by the $L_{\mathrm{Aeq,16}}$ or $L^{*}_{\mathrm{Aeq,16}}$ instead of either converting the latter into the L_{dn} or modifying the parameters of the equation is delicate. Nevertheless, as the L_{dn}, $L_{\mathrm{Aeq,16}}$ and $L^{*}_{\mathrm{Aeq,16}}$ are closely related to each other in the case of Zurich airport, and as Schreckenberg *et al.* [11] recently reported that total aircraft noise annoyance around Frankfurt airport was more closely related to daytime than nighttime sound exposure, this step does not seem to be critical.

Thirdly, the definition of perimeters, while necessary, is arbitrary and depends on the aim and scope of an index [5]. One may define acoustical or effect-oriented perimeters, although the latter are probably preferable [5, 11]. For daytime, the (acoustically defined) perimeter is equivalent to an effect-oriented one, as the $L^*_{\mathrm{Aeq},16}$ of 47 dB directly corresponds to *%HA* of 2.7% (section 2.2). For the night, however, this is not the case, as Figure 10 illustrates. While an $L_{\mathrm{Aeq},8}$ of 37 dB closely corresponds to *AWR* of ∼0.1 for 2004, large areas with $AWR > 0.1$ are excluded in 2008, because the relationship between the L_{Amax} and $L_{\mathrm{Aeq},8}$ is not unique. This problem is partly mitigated as the areas accounted for are in any case much larger than existing effect-oriented perimeters, such as for the 'Frankfurt Night Index' ($AWR = 0.5$ [11, 17] or $= 0.75$ [50]) or the noise protection zone for Leipzig/Halle airport ($AWR = 1.0$ [23]) (Figure 10). Defining perimeters may affect the ranking of scenarios [11] and even bias results [18]. However, while the *HA*, *HSD* and *ZFI* of the 'official' *ZFI* scenarios (Figure 6b) are 13–17%, 68–95% and 28–39%, respectively, larger without than with perimeters, the values are highly correlated ($r = 0.935$–0.998, $P < 0.003$–0.0001), and the ranking of the scenarios with respect to the values of the *ZFI* (while not *HA* and *HSD*) remain the same. This indicates that setting the perimeter demarcation lines close to the response threshold of exposure–response relationships (0% *HA* and *HSD*), as is the case for the *ZFI*, overcomes at least parts of the potential problems.

Fourthly, dividing the 24 h of a day into apt time periods to determine the *HA* and *HSD* is demanding. Accuracy may be increased with a refined calculation [5, 11].

Fifthly, linearly converting the *AWR* into *HSD* by a factor F_{SD} is rather daring, as such a conversion lacks scientific basis, and as it is questionable to compare verbal responses about the quality of nighttime sleep (assessed during daytime) with electrophysiological reactions during the night. However, the *HSD* values obtained with the official calculation (f_{n3}) closely correspond to those of self-reported sleep disturbance (f_{n1}) (Figure 2), indicating that the conversion yields reasonable results, at least for f_{n3}. Also, the underlying *AWR* can be easily re-calculated ($AWR = \%HSD/F_{\mathrm{SD}}$), allowing for comparison with other indices such as the Frankfurt Night Index [17]. Nevertheless, the conversion needs verification. This includes the underlying parameters of F_{SD} (section 2.4.2) and determining whether a linear conversion is appropriate, or whether sleep disturbance depends on the *AWR* by a higher power.

Sixthly, summing up the two effect dimensions *HA* and *HSD* to a single number (*ZFI*), the former representing verbal responses of the day and the latter – despite translation of *AWR* into *HSD* – electrophysiological responses of the night, assumes comparability between them, as well as equivalence ($1\,HA = 1\,HSD$). However, this assumption lacks any scientific basis. Also, summing up the *HA* and *HSD* bears the problem that the *HA* and *HSD* (or *AWR*) can be mutually compensated, despite their different effect dimensions (less annoyance cannot compensate for more sleep disturbance and *vice versa*). This step is therefore questionable, if not improper. This problem was overcome by the more recently developed Frankfurt Aircraft Noise Index [17], by introducing a second, separate Frankfurt Night Index, with both indices needing to comply to certain limits.

Seventhly, the question was raised whether or not to account for passive noise reduction measures [11]. To date, the official *ZFI* values (Figure 6b) do not include such measures (cf. section 2.2). However, complementary calculations for the year 2009, accounting for buildings with low-energy standard and sound insulated ventilation, showed that these measures may be well considered [51]. Their implementation in the official *ZFI* calculation thus remains a political decision. With the revised legislation [52] coming into effect in March 2012 and replacing [13], they are to be considered for the monitoring value in future. The rest of the calculation rule remains unchanged.

Finally, while the *ZFI* effectively reveals conflicts between the development of the air traffic and the growing population as well as the reasons, measures to reduce the *ZFI* are difficult to take. Not only does the cantonal law not clearly define the kind of measures. Also, because the *ZFI* concept is based on (subordinate) cantonal law, the canton of Zurich is not entitled to enforce regulations to the superordinate Swiss federation which supervises the airport. Particularly in areas where superordinate sound exposure limits by federal law [20] are not exceeded, measures are almost impossible to take, because other – again superordinate – interests such as land use planning are often of higher priority. The latter point, however, is a Swiss peculiarity that does not necessarily apply to other countries.

In summary, the *ZFI* calculation rule could be scientifically improved in particular by replacing the EU standard curve by Miedema and Oudshoorn for the estimation of the *HA* [21] by a more recent function, by not summing up the two effect dimensions annoyance and disturbance and instead establishing two separate guide values, and by directly using the *AWR* instead of converting them into *%HSD*. Such modifications, however, by necessity need to be involved in a political process as they also mean a change in policy.

5.3. Refinement of the *ZFI* calculation

In this study, also a refined approach to determine the *HA* and *HSD* according to Brink *et al.* [5, 53] was implemented. This approach divides the day into 24 time slices of 1 h duration, accounts for the hourly proportions of people asleep and awake, charges the L_{Aeq} and L_{Amax} of each hour with specific penalties as level adjustments for the diurnal variations in annoyance and awakening probability, respectively, and uses hourly F_{SD} values to convert the *AWR* to *%HSD*. For the years 2000 and 2004, this approach yielded substantially larger *ZFI* values than the official calculation rule, namely 78'164 (+31%) and 54'837 (+44%), respectively, with the *HA* values being smaller (−8% and −14%) and the *HSD* much larger (+141% and +208%). While the refined approach is thus realizable, it still has certain shortcomings. Calculation is quite time consuming, the required parameters are afflicted with increased uncertainty, and further effects such as the mobility of the population [51] still remain unaccounted for. In future, however, such approaches may become of interest.

6. Conclusions

The *ZFI*, a recently developed noise effect index, is a monitoring tool for the number of persons affected by aircraft noise around Zurich airport, serving noise abatement policy in the canton of Zurich since 2007. The *ZFI* concept aims at limiting the effects of aircraft noise on the population, instead of primarily restricting the air traffic.

Studying various exposure–response functions and parameter settings showed that it is not critical which function to choose, as the main goal of the *ZFI* concept is to compare scenarios, particularly to the guide value, rather than yielding absolute numbers of affected persons. The absolute values, however, are afflicted with large uncertainty, as various effects, such as over-reactions to step changes in aircraft noise exposure, remain unaccounted for. Consequently, it would be reasonable to determine relative monitoring values in percentage of the guide value, instead of absolute (but uncertain) numbers. Crucial, in contrast, is that one strictly sticks to a certain calculation rule once a guide value has been established. Results obtained with the official calculation rule for 12 years show that changes in the population and air traffic parameters strongly affect the *ZFI*. While scientific debate is still ongoing on several aspects such as critical parameter settings, the update of exposure–response functions, the summation of the effect dimensions annoyance and disturbance, or the conversion of awakening reactions into sleep disturbance, the *ZFI* was found to be a powerful tool in assessing the integral effects of aircraft noise on the population, helping to identify the parameters by which the *ZFI* and thus the number of affected persons may be most effectively reduced.

Acknowledgement

The authors are very grateful to the Office of Transport of the canton of Zurich (Amt für Verkehr, AFV) for the funding of this work (assignments No. 441’255, 448’143, 448’144, 448’451, 450’617, 451’116, 452’380 and 455’224) and for the permission to publish the data. The authors would also like to thank Martin Bissegger and Andreas Rappo of Flughafen Zürich AG for providing them with the data on persons above exposure limits of NAO, and Kurt Eggenschwiler for the stimulating discussions regarding this study. The Swiss National Science Foundation is acknowledged for partly financing the IPAZIA computational cluster (project 206021_128754) used for the calculations.

References

[1] MPD: European Commission, Directorate-General for Energy and Transport, Directorate F - Air Transport. Study of aircraft noise exposure at and around community airports: evaluation of the effect of measures to reduce noise. Final report. Tender No. TREN/F3/15-2006. MPD Group Limited, London, UK. `http://ec.europa.eu/transport/air/studies/environment_en.htm`, 2007.

[2] BAFU: Noise pollution in Switzerland. Results of the SonBase national noise monitoring programme. State of the Environment No. 0907. Federal Office for the Environment (BAFU / FOEN), Berne, Switzerland. `http://www.bafu.admin.ch/publikationen/`, 2009.

[3] R. Freestone, D. Baker: Challenges in land use planning around Australian airports. Journal of Air Transport Management **16** (2010) 264–271.

[4] M. May, S. B. Hill: Questioning airport expansion – a case study of Canberra International Airport. Journal of Transport Geography **14** (2006) 437–450.

[5] M. Brink, D. Schreckenberg, G. Thomann, M. Basner: Aircraft noise indexes for effect oriented noise assessment. Acta Acustica united with Acustica **96** (2010) 1012–1025.

[6] L. Jarup, W. Babisch, D. Houthuijs, G. Pershagen, K. Katsouyanni, E. Cadum, M.-L. Dudley, P. Savigny, I. Seiffert, W. Swart, O. Breugelmans, G. Bluhm, J. Selander, A. Haralabidis, K. Dimakopoulou, P. Sourtzi, M. Velonakis, F. Vigna-Taglianti: Hypertension and exposure to noise near airports: the HYENA study. Environmental Health Perspectives **116** (2008) 329–333.

[7] A. Huss, A. Spoerri, M. Egger, M. Röösli: Aircraft noise, air pollution, and mortality from myocardial infarction. Epidemiology **21** (2010) 829–836.

[8] H. M. E. Miedema, H. Vos: Exposure-response relationships for transportation noise. Journal of the Acoustical Society of America **104** (1998) 3432–3445.

[9] B. Berglund, S. Stansfeld, R. Kim: Overview of the World Health Organization workshop on aircraft noise and health. Proceedings of the 9th Congress of the International Commission on the Biological Effects of Noise (ICBEN), Noise as a Public Health Problem, Foxwoods, CT, 2008, 757–764.

[10] D. Schreckenberg, M. Meis, C. Kahl, C. Peschel, T. Eikmann: Aircraft noise and quality of life around Frankfurt airport. International Journal of Environmental Research and Public Health **7** (2010) 3382–3405.

[11] D. Schreckenberg, M. Basner, G. Thomann: Wirkungsbezogene Fluglärmindizes (Effect based aircraft noise indices). Lärmbekämpfung **4** (2009) 47–62.

[12] Gesetz über den Flughafen Zürich (Flughafengesetz) vom 12. Juli 1999 (Act on Zurich Airport (Airport Act) from 12 July 1999). LS 748.1. `http://www.zhlex.zh.ch/Erlass.html?Open&Ordnr=748.1`, 1999.

[13] Verordnung über den Zürcher Fluglärm-Index vom 4. November 2009 (Ordinance on the Zurich Aircraft Noise Index from 4 November 2009). LS 748.15. To be replaced in March 2012 by [52], 2009.

[14] AFV: Der Zürcher Fluglärm-Index (ZFI) im Jahr 2007. Beschluss des Regierungsrates des Kantons Zürich vom 3. Dezember 2008 (The Zurich Aircraft Noise Index (ZFI) in the year 2007. Resolution of the government of the canton of Zurich from 3 December 2008) (RRB Nr. 1893 / 2008) Volkswirtschaftsdirektion des Kantons Zürich, Amt für Verkehr (AFV), Zurich, Switzerland. Webpage: see [49], 2008.

[15] A. J. Hede: Impact descriptors versus exposure indices in environmental assessment. Acoustics Australia **21** (1993) 41–44.

[16] T. Gjestland, S. Tremoen, J. B. Kielland: SPI - An indicator for assessing total noise impact. Proceedings of the 2002 Forum Acusticum, 3rd European Congress on Acoustics, including the XXXIII Spanish Congress on Acoustics (TecniAcústica 2002), the European and Japanese Symposium on Acoustics and the 3rd Iberian Congress on Acoustics (ExpoAcústica 2002), Sevilla, Spain, 2002, paper NOI–02–005.

[17] J.-D. Wörner: Anti-Lärm-Pakt, Zusammenfassung (Anti-noise pact, summary). Regionales Dialogforum Flughafen Frankfurt (RDF), Frankfurt, Germany. `http://www.forum-flughafen-region.de/fileadmin/files/Archiv/Archiv_RDF_Doku_allg._Teil/Anti-Laerm-Pakt_vom_14.09.2007.pdf`, 2007.

[18] B. Fuld, R. Rahn: Lärmbewertung mittels Lärmindex (Noise evaluation by an index). Lärmbekämpfung **5** (2010) 64–73.

[19] Empa: Zürcher Fluglärmindex ZFI, Berechnungsvorschrift (Zurich Aircraft Noise Index ZFI, calculation rule). Version 2. Report No. 441'255 - 4. Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory of Acoustics/Noise Control, Dübendorf, Switzerland. Webpage: see [49], 2006.

[20] 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. `http://www.admin.ch/ch/d/sr/8/814.41.de.pdf`, 1986.

[21] H. M. E. Miedema, C. G. M. Oudshoorn: Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environmental Health Perspectives **109** (2001) 409–416.

[22] M. Basner, H. Buess, D. Elmenhorst, A. Gerlich, N. Luks, H. Maaß, L. Mawet, E.-W. Müller, U. Müller, G. Plath, J. Quehl, A. Samel, M. Schulze, M. Vejvoda, J. Wenzel: Nachtfluglärmwirkungen, Band 1, Zusammenfassung. Forschungsbericht 2004-07/D (Effects of nocturnal aircraft noise, volume 1, executive summary. Research report 2004-07/D). Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Luft- und Raumfahrtmedizin, Köln, Germany, 2004.

[23] M. Basner, A. Samel, U. Isermann: Aircraft noise effects on sleep: application of the results of a large polysomnographic field study. Journal of the Acoustical Society of America **119** (2006) 2772–2784.

[24] M. Basner, U. Müller, A. Samel: Nachtfluglärmwirkungen, Band 2, Methodik, Akustik. Forschungsbericht 2004-08/D (Effects of nocturnal aircraft noise, volume 2, methodology, acoustics. Research report 2004-08/D). Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Luft- und Raumfahrtmedizin, Köln, Germany, 2006.

[25] C. Oliva: Streuung / Konzentration, Änderung von Abflugverfahren und Neuverteilung von Flugbewegungen. Bericht und Empfehlungen, im Auftrag der Flughafendirektion Zürich (Dispersion / concentration, changes in departure procedures and reallocation of movements, report and recommendations, on behalf of the airport management Zurich). Oliva & Co., Zurich, Switzerland, 1996.

[26] C. Oliva, C. Hüttenmoser: Festsetzung von Lärmgrenzwerten – Methodische Anforderungen (Definition of noise limiting values – methodological requirements). Zeitschrift für Lärmbekämpfung **49** (2002) 13–22.

[27] C. Oliva: Belastung der Bevölkerung durch Flug- und Strassenlärm, eine Lärmstudie am Beispiel der Flughäfen Genf und Zürich (Exposure of the population to aircraft and road traffic noise, a noise study using the example of Geneva and Zurich airports). Duncker & Humblot, Berlin, Germany, 1998.

[28] C. Oliva: Zürcher Fluglärmindex ZFI, Schalldosis-Lärmwirkungsbeziehungen auf der Basis der Lärmstudie 90, Entwurfsversion vom 09. Mai 2006 (Zurich Aircraft Noise Index ZFI, exposure-response relationships on the basis of the noise study 90, draft version of 09 Mai 2006). Oliva & Co., Zurich, Switzerland, 2006.

[29] R. Hofmann: ZFI, ein Zürcher Fluglärmindex? Machbarkeitsstudie im Auftrag des Amts für Verkehr des Kt. Zürich (ZFI, a Zurich Aircraft Noise Index? Feasibility study on behalf of the office of transport of the canton of Zurich). Wallisellen, Switzerland, 2006.

[30] European Commission Working Group on Health and Socio-Economic Aspects: Position paper on dose-effect relationships for night time noise. Environment Directorate-General of the European Commission, Bruxelles, Belgium. `http://ec.europa.eu/environment/noise/pdf/positionpaper.pdf`, 2004.

[31] R. Guski: Neuer Fluglärm gleich alter Fluglärm? (New aircraft noise equal to old aircraft noise?). Zeitschrift für Lärmbekämpfung **50** (2003) 14–25.

[32] BAFU: Noise abatement in Switzerland. Status and perspectives. Environmental Series No. 329, Noise. Federal Office for the Environment (BAFU / FOEN), Berne, Switzerland. `www.bafu.admin.ch/publikationen/`, 2002.

[33] J. M. Bland, D. G. Altman: Measuring agreement in method comparison studies. Statistical Methods in Medical Research **8** (1999) 135–160.

[34] W. Babisch, D. Houthuijs, G. Pershagen, E. Cadum, K. Katsouyanni, M. Velonakis, M.-L. Dudley, H.-D. Marohn, W. Swart, O. Breugelmans, G. Bluhm, J. Selander, F. Vigna-Taglianti, S. Pisani, A. Haralabidis, K. Dimakopoulou, I. Zachos, L. Järup, HYENA Consortium: Annoyance due to aircraft noise has increased over the years – results of the HYENA study. Environment International **35** (2009) 1169–1176.

[35] G. Thomann: Mess- und Berechnungsunsicherheit von Fluglärmbelastungen und ihre Konsequenzen (Uncertainties of measured and calculated aircraft noise and consequences in relation to noise limits). Ph.D. dissertation, Diss. ETH Nr. 17433. ETH Zurich, Zurich, Switzerland. `http://e-collection.ethbib.ethz.ch/view/eth:29931`, 2007.

[36] Empa: FLULA2, ein Verfahren zur Berechnung und Darstellung der Fluglärmbelastung. Technische Programm-Dokumentation (FLULA2, a method for the calculation and illustration of aircraft noise exposure. Technical program documentation). Version 4. Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory of Acoustics/Noise Control, Dübendorf, Switzerland. `http://www.empa.ch/plugin/template/empa/*/99854`, 2010.

[37] S. Pietrzko, R. F. Hofmann: Prediction of A-weighted aircraft noise based on measured directivity patterns. Applied Acoustics **23** (1988) 29–44.

[38] W. Krebs, R. Bütikofer, S. Plüss, G. Thomann: Sound source data for aircraft noise simulation. Acta Acustica united with Acustica **90** (2004) 91–100.

[39] ICAO: Annex 16 to the Convention on International Civil Aviation, environmental protection, volume I, aircraft noise. 4th ed. International Standards and Recommended Practices. International Civil Aviation Organization (ICAO), Montréal, Canada, 2005.

[40] B. Schäffer, R. Bütikofer, S. Plüss, G. Thomann: Aircraft noise: accounting for changes in air traffic with time of day. Journal of the Acoustical Society of America **129** (2011) 185–199.

[41] BAFU: Belastungsgrenzwerte für den Lärm der Landesflughäfen. Schriftenreihe Umwelt Nr. 296, Lärm (Exposure limits for the noise of the national airports. Environmental Series No. 296, Noise). Federal Office for the Environment (BAFU / FOEN), Berne, Switzerland, 1998.

[42] AFV: Projekt Massnahmenkonzept ZFI, Synthesebericht (Project of concept of measures for the ZFI, synthesis report). Volkswirtschaftsdirektion des Kantons Zürich, Amt für Verkehr (AFV), Zurich, Switzerland. Webpage: see [49], 2009.

[43] M. R. Ismail, D. J. Oldham: The effect of the urban street canyon on the noise from low flying aircraft. Building Acoustics **9** (2002) 233–251.

[44] M. Brink, K. E. Wirth, C. Schierz, G. Thomann, G. Bauer: Annoyance responses to stable and changing aircraft noise exposure. Journal of the Acoustical Society of America **124** (2008) 2930–2941.

[45] A. L. Brown, I. van Kamp: Response to a change in transport noise exposure: a review of evidence of a change effect. Journal of the Acoustical Society of America **125** (2009) 3018–3029.

[46] A. Marks, B. Griefahn, M. Basner: Event-related awakenings caused by nocturnal transportation noise. Noise Control Engineering Journal **56** (2008) 52–62.

[47] V. E. Mestre: Describing the uncertainty associated with low aircraft noise level data derived from noise models: implications for noise effects studies. Proceedings of the Inter-Noise 2010, 39th International Congress and Exposition on Noise Control Engineering, Noise and Sustainability, Lisbon, Portugal, 2010, paper no. 204.

[48] R. Girvin: Aircraft noise-abatement and mitigation strategies. Journal of Air Transport Management **15** (2009) 14–22.

[49] AFV: Webpage: Zürcher Fluglärm-Index ZFI (Zurich Aircraft Noise Index ZFI). Volkswirtschaftsdirektion des Kantons Zürich, Amt für Verkehr (AFV), Zurich, Switzerland. `http://www.afv.zh.ch/internet/volkswirtschaftsdirektion/afv/de/luftfahrt_neu/flugbetrieb_und_umwelt/zuercher_fluglaermindexzfi.html`, 2012.

[50] FFR: Vorstellung der Eckpunkte zum Lärmindex und Ausblick. Pressebriefing 4.12.2009 (Presentation of the cornerstones for the noise index and outlook. Press briefing 12/04/2009). Forum Flughafen und Region (FFR), Kelsterbach, Germany. `http://www.fluglaerm-eppstein.de/Downloads/FFR_091204_Laermindex.pps`, 2009.

[51] B. Schäffer, M. Brink, G. Thomann, P. Huber, S. Plüss, R. Hofmann: Zurich Aircraft Noise Index ZFI – basics, application, and special aspects. Proceedings of Forum Acusticum 2011, Aalborg, Denmark, 2011, 695–700.

[52] Verordnung zum Zürcher Fluglärm-Index (ZFI-VO) vom 7. Dezember 2011 (Ordinance on the Zurich Aircraft Noise Index (ZFI-VO) from 7 December 2011). LS 748.15 `http://www.zhlex.zh.ch/Erlass.html?Open&Ordnr=748.15`, 2011.

[53] M. Brink, G. Thomann, P. Huber, C. Schierz: A new noise impact assessment method for noise policy. Proceedings of the Inter-Noise 2007, 36th International Congress and Exhibition on Noise Control Engineering, Global Approaches to Noise Control, Istanbul, Turkey, 2007, paper no. 91.