INTER-NOISE 2007
28-31 AUGUST 2007
ISTANBUL, TURKEY

A new noise impact assessment method for noise policy

Mark Brink[a,1], Georg Thomann[2], Philipp Huber[2], and Christoph Schierz[1]
[1]ETH Zurich, Center for Organizational and Occupational Sciences
CH-8092 Zurich
[2]Empa Materials Science and Technology, Laboratory of Acoustics
CH-8600 Dübendorf
SWITZERLAND

ABSTRACT

When it comes to noise impact assessment, communities, and more generally, residents around an airport naturally expect to be treated equally. That does not mean equally in terms of the noise burden, but rather equitably in terms of the method of effect attribution. Most noise policy concepts are based on the calculation of average levels (such as the Leq or Lden) and the counting of the number of residents within a noise contour. However, even if the noise exposure in different communities is the same in terms of average level, the „net" effect of noise on people can depend on a variety of other factors of which the different sensitivities to noise at different times of day and hence their interaction with the flight schedule play a major role. In order to rate noise in an effect-equivalent way at each immission grid point, we developed a method that calculates the effects of aircraft noise based on the hourly proportion of people awake and asleep and based on hour-by-hour sensitivities to noise in respect to sleep disturbance (awakening reactions) as well as annoyance. This approach allows for a quite fair comparison of aircraft noise effects in communities, even when the timely distribution of aircraft noise events differs considerably.

1 INTRODUCTION

Aircraft noise and it's effects on humans is an undesirable by-product of today's mobility needs. Our knowledge about the effects of noise on psychological and physiological parameters is growing constantly. Nevertheless, it seems that this knowledge is used only seldom or with considerable delay as a basis for political or operational decisions at airports. As a consequence of emerging political pressure to tackle the noise problems at Zurich Airport, the government of the canton of Zurich decided in the year 2006 to establish an aircraft noise effects monitoring method in order to keep a close watch on how the noise situation around the airport develops. Therefore, a monitoring instrument had to be developed which preferably should also be capable of predicting the results from various future scenarios (e.g. changes in approaching routes which are currently discussed), such it can be used as a planning tool. The emphasis of the governmental initiative explicitly lied on a quantification of unwanted *effects* of noise, not just noise-mapping. In the following, ETH Zurich and Empa Materials Science and Technology were assigned to develop a calculation method that assesses detrimental effects of aircraft noise on a per-hectare per-hour basis. This paper reports about the core features which we thought are important for deploying such a method as an instrument of noise policy. The very first ideas for the implementation were put forward by Robert Hofmann,

[a] Email address: brink@ethz.ch

former head of the Laboratory of Acoustics at Empa, to whom we are very grateful for his ideas and support.

2 NOISE METRICS AND EFFECT INDICATORS

Most noise policy concepts are based on *average* noise exposure levels over longer periods (e.g. a "day" as defined as the time period from 06:00 to 22:00 hrs). Averaging immissions from single noisy events has many advantages, but also some drawbacks. One weakness of the concept of averaging over longer periods is that it does not account for varying noise sensitivity during the day. Even if the noise exposure in different communities is the same in terms of average level, the „net" effect of noise on people can depend on a variety of other factors of which the different sensitivities to noise at different times of day and hence their interaction with the flight schedule play a major role.

2.1 Noise immissions affect people differently at different times of day

It is a commonplace experience that noise immissions affect us differently at different times of day. To illustrate this, a loud plane overflight half an hour prior to the wake up time of one's alarm clock has a far stronger potential to disturb than the same plane in the afternoon while lawn mowing in the garden. This fact has to some degree, but not fully expanded into noise legislation yet. The Environmental Noise Directive (END) of the EU [1] for example proposes the use of the L_{den} noise metric to assess annoyance. The L_{den} uses three different time periods (day, evening and night) to reflect the different sensitivities to noise during a 24-hour day. Thus, the END implicitly states, that different times of day have to be treated differently. Whereas the END calls for a particular level adjustment (0 dB during the day period, 5 dB during the evening period, and 10 dB during the night period) for each of the time periods, these adjustments as well as the timing of the three different periods are rather normative agreements and not obviously based on empirical results. The question remains open, whether three time segments adequately capture all the variation of sensitivity during the day.

2.2 Choosing noise metrics and effect indicators

An issue that has always given rise to discussions in the public as well as among noise researchers is the predominant use of average levels (e.g. L_{eq}) in legislation instead of descriptors of individual noise events (e.g. L_{max}). We decided that, for any particular effect in question, the parameter which explains most of the variation of that effect should be used in the method. Therefore, one of the primary tasks to tackle was to take an existing scenario with the corresponding operational data like radar tracks and to calculate a variety of noise metrics for different time periods ($L_{eq}(t=1h)$, $L_{eq}(t=8h)$, L_{max}, L_r, L_{DEN}, L_{DN}, NNI, …). The metrics were calculated at Empa using the aircraft noise simulation program FLULA2 [2].

Annoyance is, although not the only, but undoubtedly one of the most important effect dimensions of noise pollution and was chosen to be used as the effect indicator for noise during the day. It was clear from the beginning, that in contrast to existing legislation, which is based on annoyance solely, a second effect indicator for night time sleep disturbance should be incorporated. We chose *awakening probability* (as determined by polysomnography) to be that indicator for a number of reasons: The indicator is sufficiently specific, occurring relatively rare in the absence of acoustic triggers and constitutes a severe disruption of the normal sleep process with potential health consequences. To assess sleep disturbance during the night, this paper will – in opposition to the END – not promote L_{night}, but favor single noise events metrics. The inclusion of awakening reactions in the method particularly requires the computation of L_{max} values of individual aircraft noise events and statistical distributions of the L_{max}-values.

3 DETERMINING THE SLEEP-WAKE RHYTHM OF THE POPULATION

Whereas the current noise legislation in many countries (e.g. in Germany and Switzerland) defines the start of the day period to be at 6:00 hrs, the EU's default value in the END is 7:00 hrs, but deviations from this are allowed for the member states to better reflect a particular country's customs [1]. It becomes obvious, that the de facto sleeping habits of a given population should be the only relevant information when "defining" night and day. Provided different classes of effects of aircraft noise can be attributed to day and night separately (e.g. awakening reactions may be an important indicator of detrimental effects of aircraft noise but do not occur during daytime when people are awake), empirical data of what constitutes "day" and "night" are needed. Data about sleeping habits of humans can be found in international time use databases, such as provided by the center for time use research[b] or must be gathered from the population of interest. In the following, we will explain how we got hold of the data that define „day" and "night" in our approach.

In two noise annoyance surveys that have been conducted in the years 2001 and 2003 [3], data about sleeping habits from 3096 inhabitants in the greater Zurich area have been collected. People were asked when they usually went to bed in the evenings and got up in the morning both for weekdays and weekends. Thus, for each of the 1440 minutes of a day it was known for each of the 3096 respondents whether they where "in bed" or „asleep" respectively or not. The first 21 minutes from the beginning of the bedtime on were still considered "wake" because this was the average sleep latency reported in the field study of the German aerospace center (DLR) about aircraft noise effects [4]. Thus, before the calculation of the proportion of persons "asleep" or "awake", 21 minutes were added to the respondents reported bed-time. Done so, the "sleeping proportion" of the sample was calculated for each hour of day T as follows:

$$\delta_T = \frac{\sum_{m_T=0}^{59} n_{m_T}}{N \cdot 60} \qquad (1)$$

where:

δ_T	Proportion of people asleep at hour T [where T=0 is the time period between 00:00 and 01:00 hrs]. δ_T is a value between 0 and 1
m_T	Minute 0 ... 59 within hour T
n_{mT}	Number of people in the sample that reported being asleep at that time
N	Sample size

One can either combine the responses pertaining to the weekdays and weekends in one value, weighting the weekend-bedtimes with a factor of 2/7 and the weekday-bedtimes with one of 5/7 and adding them together to reflect the pro rata proportion of a longer sleeping time and later falling asleep on weekends, or use the two datasets separately. Equation 2 shows how the weighted proportion is calculated

$$\delta_{T,weighted} = \frac{5}{7} \cdot \delta_{T,week} + \frac{2}{7} \cdot \delta_{T,weekend} \qquad (2)$$

where:

$\delta_{T,weighted}$	[Weighted] Proportion of people asleep at hour T
$\delta_{T,week}$	Proportion of people asleep at hour T on weekdays
$\delta_{T,weekend}$	Proportion of people asleep at hour T on weekends

[b] http://www.timeuse.org/mtus

Table 1 tabulates for each hour of the day the proportion of the respondents from the two surveys which are “asleep” (δ) or “awake” ($1-\delta$). The data have been weighted and rounded to 2 decimal places.

Table 1: Fractions of the population either “asleep” (δ) or “awake” ($1-\delta$) within each hour

T=	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
δ-1	.13	.04	.02	.01	.01	.08	.38	.67	.87	.95	.98	.99	.00	.00	.00	.00	.00	.00	.00	.00	.00	.98	.81	.40
δ	.87	.96	.98	.99	.99	.92	.62	.33	.13	.05	.02	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.19	.60

The proportions of people asleep during each hour T add up to 7.69 hours of "sleeping" per average day and, accordingly, 16.31 hours of being "awake". The effective sleeping time in terms of a polysomnographic staging is certainly a bit less, because on one hand, intermittent wake periods are – in our current definition – counted as “sleep” and on the other hand, people tend to slightly overestimate their total sleep time in general [5]. Indeed, the purpose of Table 1 and Figure 1 respectively is rather practical: it informs us on how to weight the two different effect dimensions annoyance and awakening reactions within each hour. E.g. between 22:00 and 23:00 hrs in the evening the proportion of sleeping persons is about 19%, so awakening reactions due to aircraft noise events at that time are weighted with a factor of 0.19, whereas the annoyance dimension is weighted with 0.81. On the other hand, at 3 o’clock at night, aircraft noise events almost only act on awakening probability, but not on annoyance. This proportionality makes sure, that “double counting” is not possible, which is especially important when combining the two effect dimensions (annoyance and awakening reactions) in one effect metric.

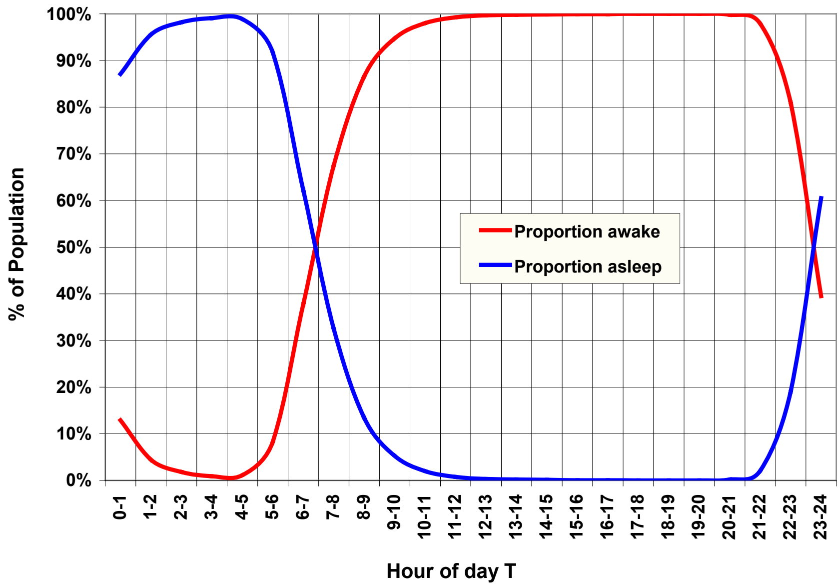

Figure 1: Fractions of the population asleep and awake during an average day. Data are from 3547 respondents from two noise annoyance surveys in 2001 and 2003 respectively.

4 DETERMINING DIURNALLY VARYING ANNOYANCE

One of the criteria that the new assessment method should fulfil according to the government, was accounting for diurnally varying annoyance. In short, this means that aircraft noise at times, when people are e.g. at work or don’t bother that much about noise, should be treated differently than noise at times, when people are more prone to be annoyed. Due to the fact that activities vary across the day, it is plausible to assume that people's responses to noise immissions differ depending on the times of day. Generally, shoulder hours (early morning, evening) are more prone to cause annoyances, regardless of the type of source [6; 7]. Dose-effect curves that are published in the noise effects literature (e.g. [8]) do not make a distinction in terms of what time of day they apply, because they are based on the retrospective and aggregated rating of being annoyed over a longer period of time.

4.1 Expressing diurnal variation of annoyance in decibels

When asking respondents for particular times during the day, when they felt highly annoyed, the influence of time of day on annoyance can be modeled with a binary logistic regression analysis. The dataset needed for such an analysis consists of one case for each respondent-time-of-day combination, making 24 cases per respondent, representing the annoyance ratings for 24 hours of a day. For each case, the value can either be 0 (not annoyed) or 1 (highly annoyed). With such a dataset, using N times 24 ratings of noise annoyance and 24 1-hour corresponding L_{eq} values, a binary logistic regression analysis on high annoyance (P_{HA}), consisting of time of day and corresponding 1-h- L_{eq} ($L_{eq,T}$) values as predictors can be performed. The task of that analysis can roughly be described as fitting a dose-response relationship between $L_{eq,T}$ and the probability $P_{HA,T}$ for an answer with code 1. The corresponding logistic function takes the form:

$$P_{HA,i,T} = \frac{1}{1 + \exp\left(-\left[\beta_0 + \beta_1 \cdot Leq_{i_T} + \beta_{2_T}\right]\right)} \tag{3}$$

where:

$P_{HA,i,T}$	Probability of high annoyance at location i and hour of day T
β_0	Constant
β_1	Parameter estimate for the 1-h- L_{eq} (which is a covariate in the model)
$\beta_{2,T}$	Parameter estimate for the hour of day T (which is a factor in the model)
$Leq_{i,T}$	1-h- L_{eq} at location i at hour of day T

Since annoyance varies with time of day, a particular L_{eq} -value might produce more or less probability of high annoyance, depending on the current hour of day that L_{eq} "acts upon". This variation can – like in a bonus/malus system – be expressed in decibels and can be calculated from the coefficients in the model. In this form, it can be interpreted as a level adjustment and was termed $K_{HA,T}$. $K_{HA,T}$ can be calculated from the coefficients of the binary logistic regression results according to the following equation:

$$K_{HA,T} = \frac{\beta_{2_T} - \frac{\sum_i \beta_{2_i}}{i}}{\beta_1} \tag{4}$$

where:

$K_{HA,T}$	Level adjustment for high annoyance at hour of day T [in dB]
i	Denominator for the number of factor levels of β_2 (hours of day) used

For a method that considers diurnally varying annoyance, $K_{HA,T}$ is of particular interest, because it directly expresses by how many decibels a given L_{eq} value must be lowered or increased in a particular hour of day to produce the same amount of annoyance as on average. Thus, $K_{HA,T}$, represents the particular noise sensitivity in a particular hour.

Figure 2 depicts the diurnal variation of annoyance ($K_{HA,T}$) based on questionnaire data from 1828 respondents of the 2001 survey. Both predictors (hour of day and 1-h- L_{eq}) in this logistic model proved highly significant ($p <0.001$). Due to relatively scarce night flying between 23:00 and 05:00 hrs at Zurich – and therefore a potentially unstable prediction – the hour of day was only coded as 18-level factor, beginning at 05:00 hrs and ending at 23:00 hrs. At airports with night traffic, more stable estimates for the night hours may be obtainable. The trend of the curve in the morning and the evening renders obvious that during core night hours, people are a good 10 dB more sensitive than during the day; the level adjustment for the night hours was therefore arbitrarily set at 10 dB, which is incidentally equivalent to the adjustment for the night period within the L_{DEN} in the END [1].

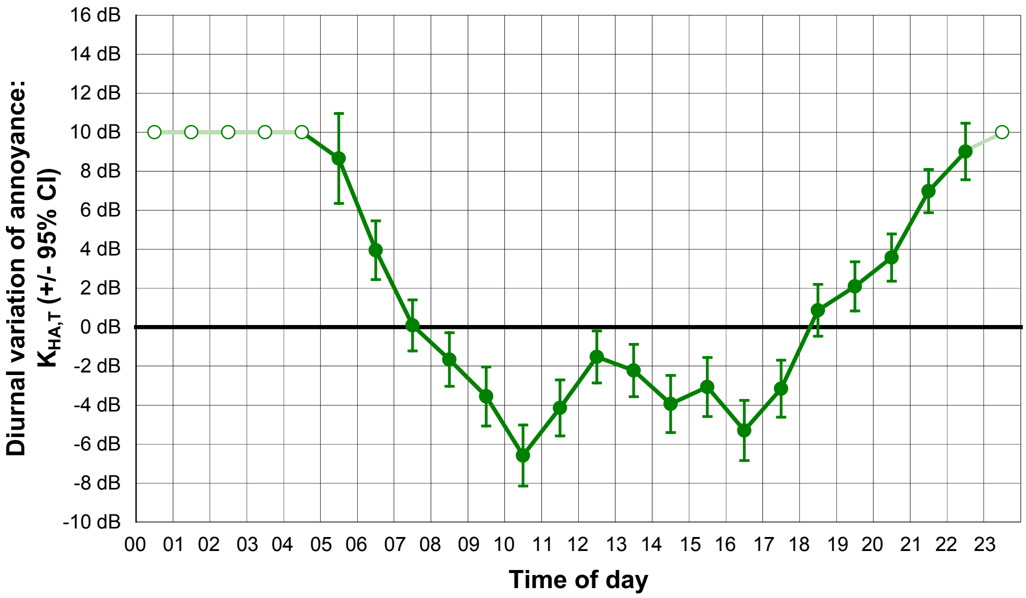

Figure 2: Diurnal variation of annoyance, expressed in Decibels ($K_{HA,T}$), including 95% confidence intervals.

As becomes obvious from Figure 2, the level adjustment values do not even out to 0 dB across the 24-hour period, but the adjustments are balanced around 0 dB for the time period between 05:00 and 23:00 hrs. Notably, all calculations based on Equation 4 (with i being the number of factor levels) will, over i factor levels, yield a sum (or mean, for that matter) of 0 dB. This is a prerequisite for applying the same dose-effect function for either any particular time of day or using the function in its original sense where the "average" level adjustment should be 0 dB. Depending on the noise metric of the dose-effect function that will be used to determine annoyance for each hour of the day, the level adjustments should be calculated for the time period the intended dose-effect function is based on. Usually this will be a 16- or 24-h- L_{eq} function, which consequently demands to model 16 or 24 factor levels respectively.

4.2 Calculating %HA for each hour of the day

Once $K_{HA,T}$ has been determined for all hours of day of interest, any suitable dose-effect function can be taken from the literature and be used to forecast the percentage of highly annoyed people per hour of day. The dose-effect function must be applied on the (arithmetic) sum of the noise exposure and the level adjustment:

$$\%HA_{i,T} = f(Leq_{i,T} + K_{HA,T}) \quad (5)$$

where:

$\%HA_{i,T}$ Percentage of highly annoyed people at location i at hour of day T

$Leq_{i,T}$ Noise exposure at location i at hour of day T

For the integral assessment of the noise immissions resulting in annoyance at location i, the following more sophisticated formula can be used:

$$\%HA_i = \frac{\sum_{T=0}^{23} \%HA_{i,T} \cdot (1-\delta_T)}{\sum_{T=0}^{23} (1-\delta_T)} \qquad (6)$$

where:

$\%HA_i$	Percentage of highly annoyed people at location i, according to the dose-effect function from Equation 5
δ_T	Proportion of population asleep during hour T

Equation 6 accounts for both the variation of noise annoyance across a day as well as the *interaction* of varying annoyance with the corresponding 1-h-L_{eq}. The result (the percentage of HA) at one location will therefore *not* necessarily be the same as at another location sharing the same 24h- or 16h-L_{eq}. High exposure at one location at times, where people are rather sensitive will yield a higher percentage of HA than e.g. at a location with relatively quiet shoulder hours and noise mainly in the mid-afternoon. Particularly at airports where due to meteorological, topographical and/or political reasons, landing and takeoff routes often change during a day, this method allows for a more effect-oriented assessment of aircraft noise impact on annoyance and also allows for more fair comparisons between different neighborhoods around an airport.

In addition, Equation 6 weights the value of $\%HA_{i,T}$ according to the proportion of the population awake ($1-\delta_T$) as tabulated in Table 1. This is important with regard to the modeling of awakening reactions and when the two effect dimensions are combined into one single effect metric. Before further developing the method, we will in the next paragraph look at awakening probability and how it increases during a night's sleep.

5 PROBABILITY OF AWAKENING FROM SLEEP

The most commonly published dose-response relationships for sleep disturbance pertain to the relationship between the maximum sound pressure level (L_{max}) of an aircraft noise event and the probability of awakening. These kinds of dose-response relationships are derived from scoring the relative frequencies of awakening while being exposed to aircraft noise events with particular maximum sound pressure levels inside the dwelling or at the ear of the sleeper respectively ($L_{max,in}$). The probability of an awakening reaction ($P_{AWR,}$) due to an aircraft noise event with a given L_{max} outside the dwelling ($L_{max,out}$) is most often expressed as a polynomial fit which takes, in the case of a second-order polynomial, the form:

$$P_{AWR} = (C2 \cdot (L_{max,out} - D)^2 - C1 \cdot (L_{max,out} - D) + C0) \qquad (7)$$

where:

P_{AWR}	Awakening probability
C2,C1,C0	Coefficients for the 2^{nd}, 1^{st} and zero-order (constant) term
$L_{max,out}$	Maximum sound pressure level outside the dwelling
D	Sound attenuation through walls and windows [in dB]

To simplify matters, reactions to noise events in the night are typically regarded as being independent from each other and independent from the time of the night (the noise event occurs). Potential pitfalls with applying any one dose-effect function to any immission situation in conjunction with forecasting awakening reactions have been discussed in [9; 10]. Similar to annoyance, proneness to be awaken by an aircraft during the night is not just depending on its noise level (e.g. its SEL or L_{max}), but – besides other important factors – also on the time the noise event occurs. On one hand this is simply the case because one can only be awaken when asleep, on the other because sleep itself is a dynamic and complex process and hence produces different vulnerabilities to be awaken in each moment someone is asleep [4]. Basically, the longer one has slept, the easier one can be awaken. In the literature, in particular early morning noise events are considered to relatively easily disturb sleep. The impact of noise events that leads to awakening reactions and further to annoyance seems to be stronger in the early morning than during the night. This has one obvious reason: Chances that awakening reactions can be remembered are higher at the end of the night than at its beginning. During the first half of the night, the proportion of slow wave sleep (SWS) is considerably higher than during the second half of the night and awakeability is generally reduced during SWS. For all these reasons, a simple dose-response function (such as in Equation 7) is not suitable to forecast awakening probability at any one point in time in the night: for awakening reactions, we need an approach which considers for each $L_{max,in}$ of a noise event and its corresponding awakening probability, how long the average person has already slept.

Extensive research on awakening reactions due to aircraft noise has been carried out by the German Aerospace Center (DLR) which published a set of binary regression coefficients that can be used to predict the probability of awakening as depending on the $L_{max,in}$, *background level, sleep stage* and *time asleep* [11]. Usable predictors for a prognostic model are $L_{max,in}$ and time asleep, most other predictors succumb individual variation and can at the moment not be used in a meaningful way. Although also average background levels (in sleeping rooms) systematically vary depending on the time of day, we did not yet integrate that predictor in the method but established a simplified binary logistic model that keeps background level (27.1 dB at the ear was assumed in this case as this was the median value in [11]) and sleep stage (S2 in this case) constant[c]. It can be formalized as:

$$P_{AWR,add} = \left(1+e^{-(\beta_0 + \beta_{L_{max,in}} \cdot L_{max,in} + \beta_{L_{eq,back}} \cdot L_{eq,back} + \beta_{L_{max,in} \cdot L_{eq,back}} \cdot L_{max,in} \cdot L_{eq,back} + \beta_{ts} \cdot ts)}\right)^{-1} - P_{AWR,spont} \qquad (8)$$

where:

$P_{AWR,add}$	Probability of an awakening reaction that is solely attributable to aircraft noise events („additional probability")
$L_{max,in}$	Maximum sound pressure level at the ear of the sleeper
$L_{eq,back}$	Background noise level (27.1 dB in this case)
ts	Time passed since sleep onset
β_0	Constant
$\beta_{Lmax,in}$	Parameter estimate for $L_{max,in}$
$\beta_{Leq,back}$	Parameter estimate for background level
$\beta_{Lmax,in \cdot Leq,back}$	Parameter estimate for the interaction $L_{max,in} \cdot L_{eq,back}$
β_{ts}	Parameter estimate for ts
$P_{AWR,spont}$	Probability of spontaneous (not aircraft induced) awakenings

Omitting sleep stage, the β_0-coefficient (Constant) in Equation 8 had to be assessed using an optimization algorithm (Generalized Reduced Gradient Method implemented in Microsoft Excel Solver [12]) so that the curve from Equation 8 got as close to the published polynomial in [11] as possible.

[c] The dose-effect relationship using these parameters is conservative, that means it rather overestimates than underestimates awakening probability.

From Equation 8 is inferable the level adjustment $K_{AWR,ts}$ that expresses the amount in decibels a $L_{max,in}$-value decreases after a sleep duration of ts to evoke the same awakening probability as if ts were 0. It is:

$$K_{AWR,ts} = \frac{\beta_{ts} \cdot ts}{\beta_{L_{max,in}} + \beta_{L_{max,in} \cdot L_{eq,back}} \cdot L_{eq,back}} [dB] \tag{9}$$

where:

$K_{AWR,ts}$	Level adjustment after a sleep duration of ts

Using the regression coefficients in [11], each full hour asleep reduces the $L_{max,in}$ needed to evoke awakening by 3.36 dB. The polynomial published in [11] reflects the awakening probability after 300.5 minutes of sleep, thus, at that point in time the level adjustment ought to be 0 dB. The adjusted values for the 0^{th} to the 9^{th} hour of sleep are thus -15.15, -11.79, -8.43, -5.07, -1.70, +1.66, +5.01, +8.37, +11.73, +15.09 dB. These values are sleep-time based. To obtain a set of 24 level adjustments similar to the one's plotted in Figure 2 with annoyance, further calculation steps are needed: First, for all subjects in the sample, each minute (out of 1440 minutes in a day) they were asleep (according to self-report data) the level adjustment value according to their current time asleep was assigned. Secondly for each minute of the day, the values were averaged, omitting empty („awake") cells. As a third step, all available adjustment values within each hour of the day were again averaged, resulting in 24 adjustment values, as shown in Table 2.

Table 2: Level adjustments for awakening probability $K_{AWR,T}$

T=	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
$K_{AWR,T}$ [dB]	-12.0	-9.5	-6.0	-3.0	+0.5	+3.5	+6.5	+9.0	+9.5	+7.5	+4.0	+2.0	+1.5	+4.0	+6.5	+7.5	+9.5	+4.0	0.0	-1.5	-13.5	-15.0	-15.0	-14.0

The values in Table 2 reflect, similar to annoyance in Figure 2, the amount a particular L_{max}-value has to be decreased or increased for the dose-effect function expressed in the polynomial in [11] to „correctly" forecast awakening probability.

For any particular hour T and location i, the number of awakening reactions due to aircraft noise can – based on the distribution of L_{max}-values for the relevant aircraft types – now be estimated as:

$$N_{AWR_{i,T}} = \sum_j n_{T,j} \cdot f(L_{max,out,T,j} - D + K_{AWR,T}) \tag{10}$$

where:

$N_{AWR,i,T}$	Average number of aircraft noise induced awakening reactions of a single person at location i within hour T
$f(L_{max,out,Tj}-D+K_{AWR,T})$	Dose-effect function for awakening probability with all necessary level adjustments
$L_{max,out,T,j}$	Maximum sound pressure level produced by aircraft type j within hour T (outside the dwelling)
$n_{T,j}$	Number of flight operations of aircraft type i within hour T

It has to be noted that the number of awakening reactions per hour T as calculated with Equation 10 is based on the assumption of a full hour of sleep without intermittent wake periods. This will on average not be the case in reality and Equation 10 therefore overestimates the true number of awakening reactions. However, aircraft noise events experienced while awake possibly impede falling asleep again and therefore still contribute to the overall disturbing effect (not to mention the impact such incidents have on annoyance). It therefore seems justifiable to calculate the night noise impact this way.

Finally, the total average number of awakening reactions, per night per person at a particular location i amounts to:

$$N_{AWR_i} = \sum_{T=0}^{23} N_{AWR_{i,T}} \cdot \delta_T \qquad (11)$$

where:

$N_{AWR,i}$ Average number of aircraft noise induced awakening reactions of a single person at location i

The calculation of number of awakening reactions according to the method described is solely based on empirical findings about the relationship between maximum sound pressure levels of single noise events and the different sensitivities to be awaken by noise events. The question of *severity* of a particular number of aircraft noise induced awakenings in terms of possible health impacts is part of an ongoing discussion in the scientific community and can not be treated sufficiently within the scope of this paper. However, to the general public, awakening reactions are an easily explainable and plausible indicator for detrimental night noise effects. To obtain an indicator similar to %HA, e.g. a sigmoid function relating $N_{AWR,i}$ to a percentage „highly sleep disturbed" persons (%HSD) may be arbitrarily defined and used alongside %HA to rate aircraft noise impact at a particular immission location.

6 DISCUSSION

In this paper, we have outlined the basic steps needed to deploy an effect-oriented noise assessment method which, in contrast to conventional noise indicators, delivers a much more detailed picture of unwanted noise effects while keeping the computational effort on a reasonable level. One of the most important features of our assessment method is that it is free of arbitrary assumptions (e.g. about the sleep-wake rhythm of the population) and solely based on empirical findings. This makes it a credible instrument for noise policy, especially at airports where due to operational characteristics a simple assessment method based on day- or night-average levels does not reflect the variation in annoyance and/or sleep disturbance in a sufficiently accurate manner. Our approach will therefore also allow for a fairer comparison of aircraft noise effects in different communities around an airport.

There are further refinements to be made to the method. Our goal is to finally arrive at one combined descriptor which rates aircraft noise according to its true „net" effect and expresses this effect as „number of people highly affected (by noise)" at a particular location. This will require to compare and equiponderate different effect dimensions regarding their contribution to the overall „negative" effect, but also to look for other intervening modifiers, e.g. for each hour of the day the proportion of people being „at home" or – more generally – at the location for which the effects are calculated.

7 REFERENCES

[1] European Union. (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

[2] Thomann, G. (2001). FLULA2 - Ein Simulationsverfahren zur Berechnung und Darstell ung der Fluglärmbelastung [Technische Programmdokumentation. Bericht Nr. 840'143, September 2001.]. Dübendorf, Switzerland: Eidgenössische Materialprüfungs- und Forschungsanstalt (EMPA), Abteilung Akustik.

[3] Brink, M., Wirth, K., Rometsch, R., & Schierz, C. (2005). Lärmstudie 2000 Zusammenfassung, from http://e-collection.ethbib.ethz.ch/show?type=bericht&nr=444

[4] Basner, M. (2006). Markov state transition models for the prediction of changes in sleep structure induced by aircraft noise (Forschungsbericht 2006-07), from http://www.eid.dlr.de/me/Institut/Abteilungen/Flugphysiologie/Fluglaerm/Lit_Laermw_Reports/FB_2006-07_markov.pdf

[5] Meier, U. (2004). Das Schlafverhalten der deutschen Bevölkerung – eine repräsentative Studie. Somnologie, 8(3), 87-94.

[6] Schreckenberg, D., & Meis, M. (2006). Belästigung durch Fluglärm im Umfeld des Frankfurter Flughafens. Kurzfassung des Endberichts., from http://www.dialogforum-flughafen.de/fileadmin/PDF/Presse/Belaestigungsstudie_Kurzfassung.pdf

[7] Schreckenberg, D., & Guski, R. (2005). Lärmbelästigung durch Strassen- und Schienenverkehr zu unterschiedlichen Tageszeiten. Umweltmedizin in Forschung und Praxis, 10(2), 67-76.

[8] Miedema, H., & Vos, H. (1998). Exposure-response relationships for transportation noise. Journal of the Acoustical Society of America, 104(6), 3432-3445.

[9] Brink, M., Schierz, C., Basner, M., Samel, A., Spreng, M., Scheuch, K., et al. (2006). Bericht zum Workshop "Aufwachwahrscheinlichkeit": Bestimmung lärminduzierter Aufwachwahrscheinlichkeiten in der Nachtlärmwirkungsforschung und Anwendung entsprechender Wirkungsmodelle für Prognosezwecke, from http://e-collection.ethbib.ethz.ch/show?type=bericht&nr=485

[10] Brink, M., Wirth, K., & Schierz, C. (2006). Effects of early morning aircraft overflights on sleep and implications for policy making. Paper presented at the Euronoise 2006, Tampere, Finland.

[11] Basner, M., Samel, A., & Isermann, U. (2006). Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study. Journal of the Acoustical Society of America, 119(5), 2772-2784.

[12] Fylstra, D., Lasdon, L., Watson, J., & Waren, A. (1998). Design and Use of the Microsoft Excel Solver. Interfaces, 28, 29-55.