Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study

Mathias Basner, Alexander Samel, and Ullrich Isermann

Citation: The Journal of the Acoustical Society of America **119**, 2772 (2006); doi: 10.1121/1.2184247
View online: https://doi.org/10.1121/1.2184247
View Table of Contents: http://asa.scitation.org/toc/jas/119/5
Published by the Acoustical Society of America

Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study[a)]

Mathias Basner[b)] and Alexander Samel
German Aerospace Center (DLR), Institute of Aerospace Medicine, 51170 Cologne, Germany

Ullrich Isermann
German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, Bunsenstr. 10, 37073 Goettingen, Germany

(Received 3 November 2005; accepted 11 February 2006)

The Institute of Aerospace Medicine at the German Aerospace Center (DLR) investigated the influence of nocturnal aircraft noise on sleep in polysomnographic laboratory and field studies between 1999 and 2004. The results of the field studies were used by the Regional Council of Leipzig (Germany) for the establishment of a noise protection plan in the official approval process for the expansion of Leipzig/Halle airport. Methods and results of the DLR field study are described in detail. Special attention is given to the dose-response relationship between the maximum sound pressure level of an aircraft noise event and the probability to wake up, which was used to establish noise protection zones directly related to the effects of noise on sleep. These protection zones differ qualitatively and quantitatively from zones that are solely based on acoustical criteria. The noise protection plan for Leipzig/Halle airport is presented and substantiated: (1) on average, there should be less than one additional awakening induced by aircraft noise, (2) awakenings recalled in the morning should be avoided as much as possible, and (3) aircraft noise should interfere as little as possible with the process of falling asleep again. Issues concerned with the representativeness of the study sample are discussed. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2184247]

PACS number(s): 43.50.Qp, 43.50.Sr, 43.50.Rq, 43.50.Lj [BSF] Pages: 2772–2784

I. INTRODUCTION

Between 1999 and 2004, the DLR–Institute of Aerospace Medicine (IAM) in Cologne, Germany, performed extensive laboratory and field studies on the effects of aircraft noise on sleep, mood, and performance in the DLR/HGF project "Quiet Air Traffic."[2–4] The Regional Council of Leipzig (RCL) asked the IAM to propose a concept for the protection of airport residents against the adverse effects of nocturnal aircraft noise on sleep based on the findings of these studies.

Leipzig/Halle airport is planned to be extended to an international freight hub with air traffic predominantly occurring during the night. In order to be able to handle the prognosticated traffic volumes, the southern runway will be turned and extended to a length of 3600 m. Together with the northern runway, this independent parallel runway system will allow for simultaneous takeoffs and landings on both runways. The traffic volume is predicted with 81 000 aircraft movements during the six busiest months in the year 2015.[1] Of these, 45 600 will take place during the day between 6:00 and 22:00 and 35 400 will occur during the night between 22:00 and 6:00. Thus, a large part of the aircraft movements will take place during the night. This situation distinguishes Leipzig/Halle airport from most other airports worldwide.

After an extensive course of consideration the RCL decided to develop a plan for the protection of airport residents against the adverse effects of nocturnal aircraft noise primarily based on the results of the DLR field study,[2] and therefore on the newest available scientific data. On 4 November 2004 the noise protection plan was presented for approval.[1] A few days later, DHL decided to move its international cargo hub from Brussels to Leipzig.

In this publication, methodological aspects of the DLR field study will be reported. The most important findings on the effects of nocturnal aircraft noise on sleep in general and on the probability of noise-induced awakenings in particular will be presented. Based on these results, it will be shown that noise protection plans based on number above threshold (NAT) and/or L_{eq} criteria are not suitable for an adequate description of the effects of nocturnal aircraft noise on sleep. Finally, a noise protection plan based on the findings of the DLR field study will be presented and substantiated.

II. METHODS

The DLR–Institute of Aerospace Medicine investigated the influence of nocturnal aircraft noise on human sleep, mood, and performance in a laboratory and a field study. The concepts of the noise protection plan for Leipzig/Halle airport are mainly based on the results of the field study. Therefore, study design and methods used in the field study will be briefly described. For a detailed description the reader is

[a)]Portions of this work were published in M. Basner, U. Isermann, and A. Samel, "Die Ergebnisse der DLR-Studie und ihre Umsetzung in einer lärmmedizinischen Beurteilung für ein Nachtschutzkonzept (The application of the DLR-study for a medical evaluation of a protective concept on adverse effects of nocturnal aircraft noise)," Z. Lärmbekämpfung **52**, 109–123 (2005).

[b)]Electronic mail: mathias.basner@dlr.de

asked to refer to the executive summary of the study.[2] The field study was conducted between September 2001 and November 2002 with 64 residents of Cologne-Bonn airport, which is one of the German airports with the highest nighttime traffic densities and mainly used for freight traffic during the night. Subjects were investigated for nine consecutive nights, starting on Mondays.

Participants, selected in a multi-level process, were between 19 and 61 years old (average: 38 years). Fifty-six percent of the participants were female. Subjects had to be free of intrinsic sleep disorders and had to have normal hearing thresholds according to age. A detailed description of the selection process can be found in the report DLR-FB 2004/7E.[2] Consequences of the selection process for the representativeness of the sample are discussed in detail in Sec. V F. The study protocol was approved by the ethics committee of the Medical Board of the district North Rhine. Subjects were instructed according to the Helsinki declaration, participated voluntarily, and were free to discontinue their participation at any time without explanation.

The electroencephalogram (brain current diagram, EEG), the electrooculogram (eye movements, EOG), the electromyogram (muscle tension, EMG), the electrocardiogram (ECG), respiratory movements, finger pulse amplitude, position in bed, and actigraphy were sampled continuously during the night. With the EEG, EOG, and EMG signals (also called polysomnography), sleep can be classified into different sleep stages.[5]

Wake is differentiated from sleep. Sleep itself is classified in REM sleep, with its typical rapid eye movements, and nonREM sleep. NonREM sleep can be further divided in the four sleep stages S1, S2, S3, and S4. Because of high arousal thresholds,[6] stages S3 and S4 are also called "deep sleep." Deep sleep as well as REM sleep are known to be very important for the restorative power of sleep.[7] Wake and stage S1, on the other hand, do not seem to contribute to recuperation, or only very little.[8]

Historically, each night is usually divided into 30-s epochs. A trained scorer then assigns one of the sleep stages or "awake" to each of the epochs. Since reliable procedures for an automatic sleep stage analysis do not yet exist, sampling and analysis of polysomnographic data are sumptuous, and therefore have only been applied in studies with relatively small sample sizes (see Sec. V F). However, only polysomnography allows the assessment of structural aspects of sleep. Studies using actigraphy try to draw conclusions on sleep quality and quantity based on movements of the wrist of one arm, and are therefore obviously inferior to polysomnography according to the informational value. With 64 subjects and 576 subject nights, the DLR study is the largest polysomnographic field study on the effects of nocturnal aircraft noise so far.

In the field study, sound pressure levels (SPL) and the actual sounds were recorded inside the bedroom (at the sleeper's ear) and outside (2 m in front of the window) with class-1 sound level meters. All events (e.g., aircraft noise, road traffic noise, snoring, etc.) were identified by a human scorer. The beginning and the end of each event were marked. The simultaneous recording of acoustical and electrophysiological signals allowed for an event-correlated analysis with a maximum resolution of 125 ms.

Aircraft noise is intermittent noise. An event-correlated analysis establishes a direct temporal association between the occurrence of an aircraft noise event (ANE) and the reaction of the investigated subject to the ANE. This is only possible because of the synchronous sampling of electrophysiological and acoustical signals. Variables like the nocturnal secretion rate of stress hormones, the annoyance of study subjects asked for in the morning by questionnaires, or the amounts of the different sleep stages are represented in a single datum, which summarizes the effects of all nocturnal ANEs. These integrative measures are unsuitable for an event-correlated analysis, because the connection to single noise events cannot be made.

The reactions of sleeping humans to aircraft noise are nonspecific, since they may also be observed during natural sleep otherwise undisturbed by external stimuli. Hence, reactions observed during an ANE cannot be differentiated from spontaneous reactions according to electrophysiological criteria. Therefore, it is necessary to use an event-correlated analysis to distinguish spontaneous reactions from reactions observed during an ANE. Furthermore, spontaneous reactions occur irregularly. Therefore, if there is a reaction during an ANE, it is important to ask how often this reaction would have taken place spontaneously anyway, i.e., without the influence of aircraft noise. In epidemiology the term *attributable risk* is often used in this context. The probability of a reaction induced by aircraft noise is calculated as

$$P_{\text{induced}} = P_{\text{ANE}} - P_{\text{spontaneous}}. \quad (1)$$

As the physiological reactions may not immediately start after the beginning of an ANE, a certain time interval is screened for reactions of the sleeper. This time interval is called a "noise window." With a size of three epochs (90 s) after the beginning of an ANE, the length of the noise window was chosen to maximize the probability of reactions induced by aircraft noise [P_{induced} in Eq. (1)].

Several potential indicators for noise-induced sleep disturbances have been identified and proposed in the past. Brief EEG and EMG activations are called **arousals**.[9] Because of their short duration they are not classified as stage "awake" according to the rules of Rechtschaffen and Kales.[5] **Awakenings** are longer arousals, defined as EEG and EMG activations that last for at least 15 s and therefore lead to a classification of the sleep stage as "awake." **Sleep stage changes** are defined as transitions from one sleep stage to a different sleep stage. In the context of noise effects research, commonly only those sleep stage changes leading to a lighter sleep are considered, e.g., changes from deep sleep stage S4 to the light sleep stage S2.

Polysomnographic studies conducted in the past predominantly used awakenings as the primary indicator of sleep disturbances induced by environmental noise.[10,11] Because of the following reasons awakenings are appropriate indicators for sleep disturbances induced by environmental noise:

(i) The awakening is the **strongest form of activation** of the sleeping organism. The consequences for the restorative functions of sleep are accordingly severe.

(ii) Awakenings are relatively **specific**, i.e., the frequency of spontaneous awakenings is relatively low compared to other indicators. In the 112 baseline nights of the experimental group in the laboratory study, on average about 24 spontaneous awakenings were observed.[4,2] Spontaneous sleep stage changes were seen more than twice as often (on average about 52 changes per night). Mathur and Douglas[12] investigated the spontaneous onset of EEG arousals according to ASDA criteria.[9] They found on average about 21 arousals per hour of sleep. If the mean sleep period time (SPT) of 411.5 min of the noise-free baseline nights of the laboratory study is taken as a basis, this value corresponds to about 144 spontaneous EEG arousals per night.

(iii) In contrast to arousal, awakenings are usually accompanied by prolonged and unimodal increases in heart frequency.[13] We observed in our own investigations that the amplitude and/or the frequency of heart frequency accelerations are relatively low if there is no simultaneous awakening. But especially the regular occurrence of these nocturnal **vegetative reactions** seems to be a possible cause for the development of high blood pressure and the associated diseases of the cardiovascular system (myocardial infarction, stroke).[14] The degree of vegetative reactions accompanied by sleep stage changes or short arousals alone is low compared to reactions associated with awakenings.

(iv) The majority of awakenings last for exactly one epoch (15 to 45 s) and, therefore, are too short to be remembered on the next day. On the other hand, single awakenings may last longer and, therefore, be associated with the occurrence of waking consciousness. As a consequence, these longer awakenings may be recalled on the next day. In this case, they will also dominate the subjective assessment of sleep quality and quantity on the next day. Sleep stage changes and arousals will not be remembered on the next day as they do not lead to the occurrence of waking consciousness.

Sleep stage S1 does not contribute or only little contributes to the recuperative value of sleep. On the contrary, increased fractions of sleep stage S1 were identified as typical effects of sleep fragmentation in the past.[8] Hence, in this analysis not only changes to stage awake were regarded as relevant sleep stage changes, but also changes to sleep stage S1. This preventive measure increased the fraction of reactions associated with ANEs without significantly lowering the specifity of the proposed indicator, which is also called the sleep fragmentation index (SFI). Other authors also prefer to use this indicator in noise effects research.[15] The SFI was shown to correlate highly with the arousal index following ASDA criteria.[16,14] Therefore, in this publication the term "awakenings" implicitly means transitions from sleep stages REM, S4, S3, or S2 to the sleep stages S1 or awake.

Awakening probability does not solely depend on the maximum SPL of the ANE. On the one hand, other acoustical characteristics of the noise event (spectral content, duration, etc.) play an important role. On the other hand, situative and individual factors moderate the reactions to aircraft noise.[2] Therefore, in order to assess the influence of the maximum SPL, the other moderating factors have to be controlled for, which is called adjustment. Since an awakening represents a dichotomous dependent variable (yes/no), logistic regression was used for the analyses. As every subject was exposed to multiple ANEs, the observed reactions within one subject were not independent. Hence, random effects logistic regression was used, which is able to handle clustered data.[17]

Environmental conditions are less controlled in field studies compared to laboratory studies. The emergence of an ANE from the background noise level was identified as an important factor for the incidence of noise-induced awakenings. Therefore, in the field the background noise level was estimated for the minute preceding each ANE. The $L_{\mathrm{AS,eq}}$ varied between 16.4 und 58.3 dB with a median of 27.1 dB.

Other noises originating from inside or outside the bedroom may occur during an ANE or between two ANEs. They were identified in the field study. An ANE contributed only to the final analysis if the following conditions were met: (1) In the minute before or during the ANE currently analyzed, only noises that were caused by the subject (except snoring) or by another ANE were allowed. Here, eliminating data with other ANEs in the minute before the start of the ANE currently analyzed could have led to a systematic underestimation of awakening probabilities in times of high air traffic. (2) Noises produced by the subject during the ANE currently analyzed were explicitly not discarded from the analysis, as they could have been caused by a reaction to the ANE. For each ANE, every of the other investigated nights was checked for ANEs in the same period according to the elapsed time after sleep onset. If there was no ANE, this period was used for the estimation of spontaneous awakening probability.

III. RESULTS

In total, 61 of 64 subjects contributed to the final analysis with 483 subject nights, in which 15 556 ANEs were recorded. The data of three subjects had to be discarded because of constant snoring (two subjects) or an intrinsic sleep disorder (one subject). The first night was not analyzed because of the so-called first-night effect.[18] In total, 10 658 ANEs met the inclusion criteria (see above) and contributed to the regression analyses.

Table I summarizes the results of a multivariable random effects logistic regression model (software Egret, Version 2.0.31, Cytel Corp.). The model contains the maximum A-weighted SPL ($L_{\mathrm{AS,max}}$) and the background noise level in the minute preceding the ANE ($L_{\mathrm{eq\_}}1\mathrm{min}$) as well as their interaction term $L_{\mathrm{AS,max}} \times L_{\mathrm{eq\_}}1\mathrm{min}$ as statistically significant variables. Additionally, the sleep stage prior to the occur-

TABLE I. Results of a random effects logistic regression based on 61 subjects, 483 subject nights, and 10 658 ANEs. $-2 \log L = 6659.8$ with 10 650 degrees of freedom.

	Coefficient	Standard error	p
Intercept	−7.0734	0.8816	<0.001
$L_{AS,max}$	0.0946	0.0185	<0.001
$L_{eq\_}1\text{min}$	0.1319	0.0327	<0.001
$L_{AS,max} \times L_{eq\_}1\text{min}$	−0.0027	0.0007	<0.001
Elapsed sleep time	0.0006	0.0002	<0.001
Prior stage S3 and stage S4	−0.3205	0.1161	0.0058
Prior REM	0.4195	0.0733	<0.001
Random subject effect	0.3395	0.0540	

rence of an ANE (indicator variables prior stage S3 and stage S4 and prior REM) as well as elapsed sleep time are incorporated as statistically significant moderators in the model.

Awakening probability increases with maximum SPL $L_{AS,max}$ of the ANE, with background noise level $L_{eq\_}1\text{min}$ as well as with elapsed sleep time (positive coefficients). Awakening probability is lower from deep sleep (stages S3 and S4) and higher from REM sleep compared to stage S2. Nevertheless, stage S2 constitutes the most vulnerable sleep stage according to noise-induced awakenings, as the probability of spontaneous awakenings was much higher from REM sleep than from stage S2 sleep [see Eq. (1)]. The statistically significant interaction of maximum SPL $L_{AS,max}$ and background noise level $L_{eq\_}1\text{min}$ corroborates the importance of the emergence of an ANE from the background noise level.

Figure 1 illustrates the relationship between the maximum SPL of an ANE and the percentage awakened based on results of the regression model presented in Table I (black line). The background noise level was assumed constant with 27.1 dB (median). For preventive reasons, the sleep stage prior to the ANE was assumed to be stage S2 in all cases, i.e., the most sensitive sleep stage. Likewise, elapsed sleep time was set to the middle of the more sensitive second half of the night (epoch 601, about 5 h after sleep onset in the field study).

The highest SPL measured in the field inside the bedroom was 73.2 dB. Spontaneous changes to awake or stage S1 occurred with a probability of 8.6% (dashed line). A threshold value of about 33 dB was found in the field study, i.e., awakening probability increased only for ANEs with maximum SPL above 33 dB compared to spontaneous awakening probability (see Fig. 1). This threshold was only 6 dB above the background noise level, which seems physiologically plausible: First noise-induced awakenings should be observed once the human auditory system is able to differentiate the ANE from the background noise. Nevertheless, it must be pointed out that the awakening probability just above the threshold is accordingly very low. Only 2 of 1000 people exposed to an ANE with a maximum SPL of 34 dB will show a noise-induced awakening. Due to the large number of subjects and ANEs, the precision of the point estimate is very high, i.e., the width of the 95% confidence interval is very low (3.1% at 39 dB and 10.5% at 73.2 dB).

As already mentioned, awakenings are not specific for aircraft noise, as they also occur spontaneously. The probability of noise-induced awakenings is calculated by sub-

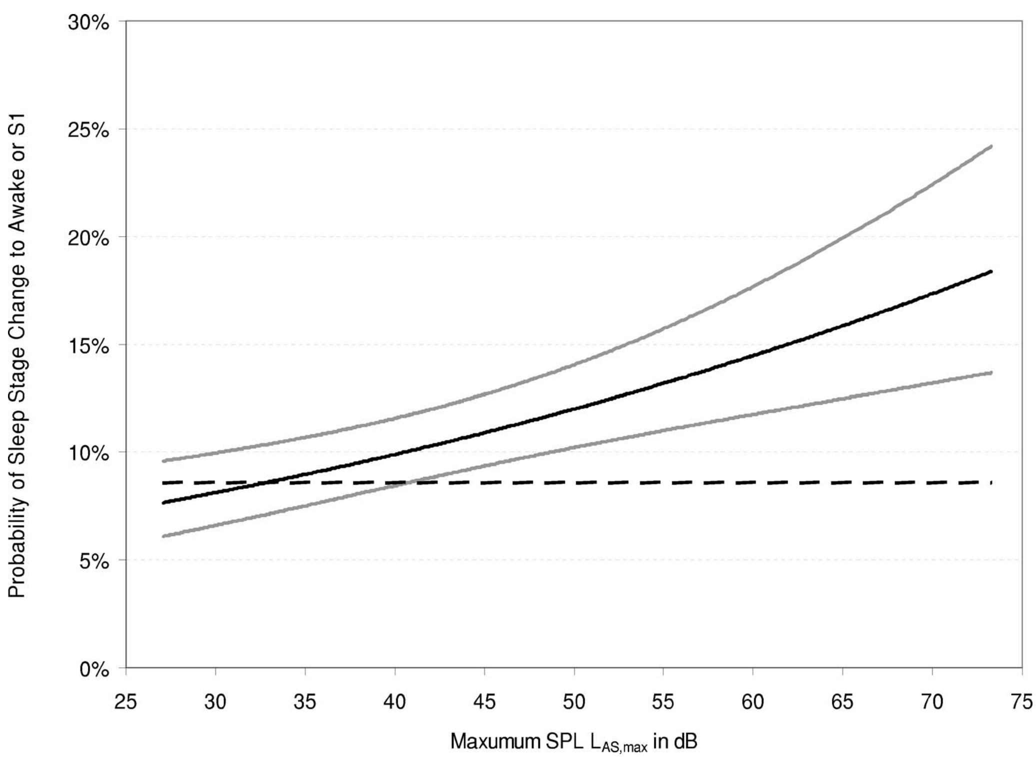

FIG. 1. Probability of sleep stage change to stage S1 or awake depending on maximum SPL $L_{AS,max}$ based on the regression results from Table I. Assumptions: Background noise level $L_{eq\_}1\text{min} = 27.1$ dB constant (median), prior sleep stage = stage 2, elapsed sleep time = 601 epochs (middle of second half of the night). Point estimates (black line), 95% confidence limits (gray lines), and spontaneous reaction probabilities (dashed line) are shown.

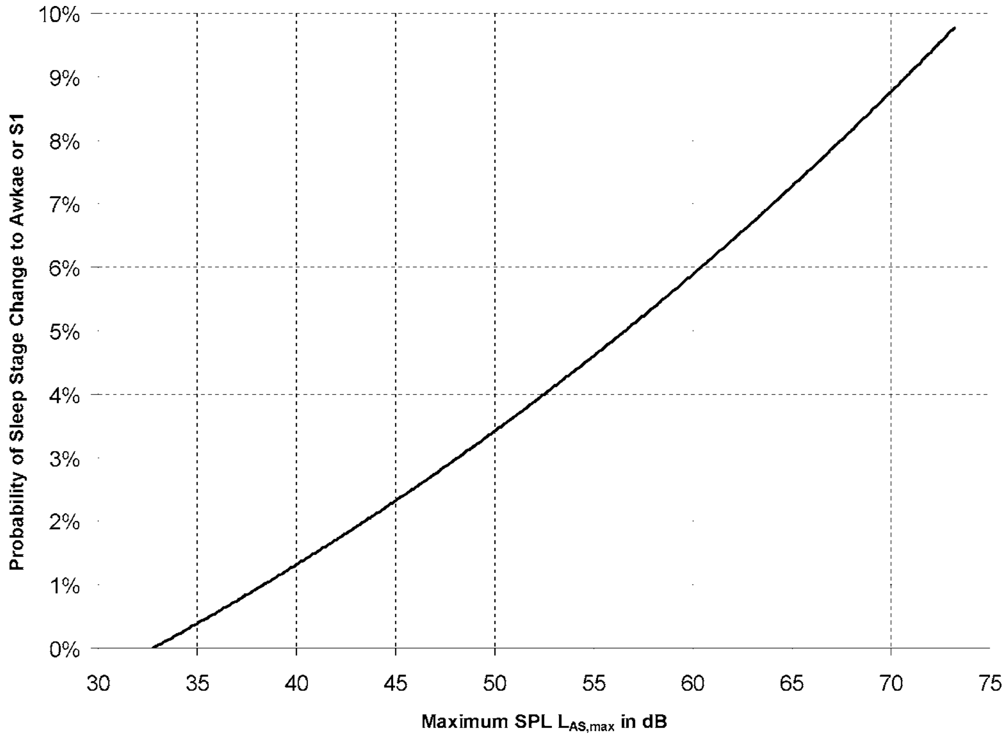

FIG. 2. Probability of aircraft-noise-induced awakenings depending on maximum SPL of ANEs. First reactions occur above maximum SPLs of 32.7 dB. This threshold exceeds the assumed background noise level of 27.1 dB only by 5.6 dB.

tracting spontaneous awakening probability (dashed line in Fig. 1) from awakening probability observed under the influence of aircraft noise (black line in Fig. 1) as indicated in Eq. (1). Aircraft-noise-induced awakening probability depending on the maximum SPL of an ANE is shown in Fig. 2.

The regression line can be approximated with a second-degree polynomial between 32.7 and 73.2 dB. Awakening probability in % is calculated as

$$P_{\mathrm{AWR}} = 1.894 \times 10^{-3} L_{\mathrm{AS,max}}^2 + 4.008 \times 10^{-2} L_{\mathrm{AS,max}} - 3.3243. \tag{2}$$

The awakening probabilities calculated by the polynomial deviate less than 0.1% from the original regression line within the specified interval.

Both the number and the duration of aircraft-noise-induced awakenings play an important role for the evaluation of the effects of aircraft noise on sleep, because the probability of a recalled awakening in the morning increases with the awakening duration. Thus, the results of the DLR laboratory study showed that awakening duration increased with the maximum SPL of an ANE (see Fig. 3).

Awakenings induced by ANEs with maximum SPLs of 65 dB or lower were relatively short. After 1.5 min, descriptively no difference in the percentage of subjects having fallen asleep again compared to spontaneous awakenings was observed. In contrast to that, awakenings induced by ANEs with maximum SPLs of 70 dB or higher were markedly longer than spontaneous awakenings.

IV. DISCUSSION OF NOISE PROTECTION STRATEGIES

In Germany, the most recent proposal for the protection against aircraft noise effects on sleep is based on a combination of *number above threshold* (NAT) and equivalent continuous sound level (L_{eq}) criteria ("Beschluss zur Novelle des Fluglärmgesetzes" from 25 May 2005). Pros and cons of NAT and L_{eq} criteria will be briefly discussed here based on the findings of the DLR field study. Both criteria are calculated from acoustical parameters (maximum SPL, time integrated SPL, or noise duration).

A. Number above threshold (NAT) criteria

NAT criteria are based on the assumption that below a defined threshold value no or only negligible effects of aircraft noise on sleep can be found. It was shown in Sec. III that first noise-induced awakenings can be expected if the maximum SPL exceeds 33 dB. Current proposals recommend limit values for NAT criteria between 52 and 55 dB, i.e., markedly above the threshold found in the DLR field study. Awakenings induced by ANEs with maximum SPLs between 33 dB and the proposed limit value are therefore not taken into account by the corresponding NAT criterion. Theoretically, an arbitrary number of ANEs with maximum SPLs below the NAT limit value are permitted without violating the NAT criterion, but simultaneously inducing relevant sleep disturbances.

NAT criteria also limit the number of ANEs above the threshold value, but without a definition of how much this threshold value may be exceeded by single ANEs. For example, a NAT criterion of 4×52 dB states that a maximum

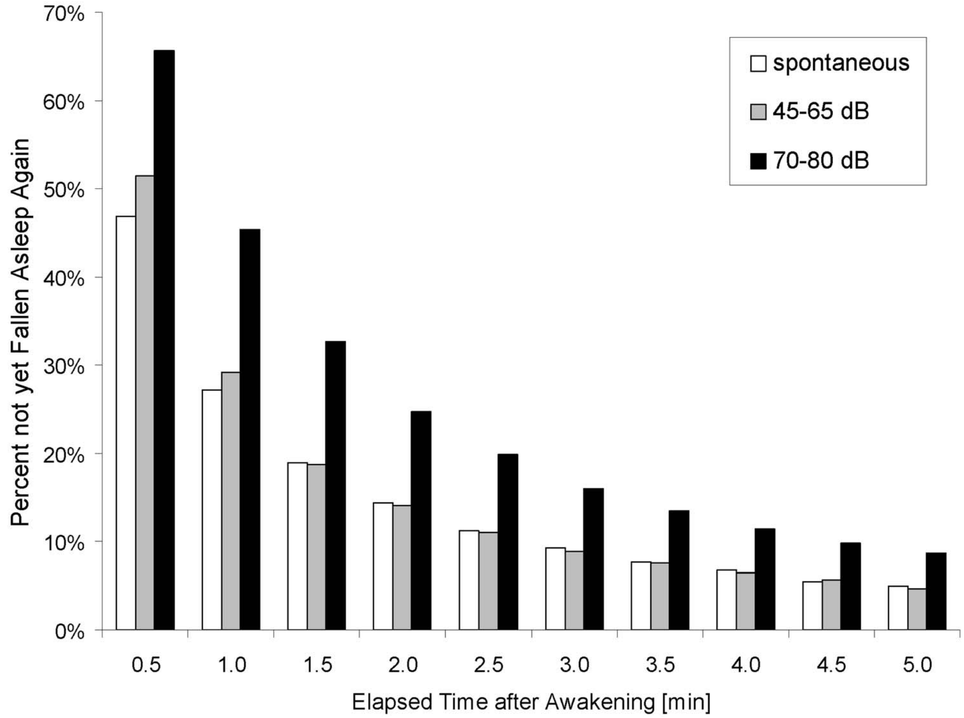

FIG. 3. Duration of noise-induced awakenings compared to spontaneous awakenings. Parameter is maximum SPL.

SPL of 52 dB may be exceeded no more than four times. Therefore, the criterion is neither violated by four ANEs with maximum SPLs of 53 dB nor by four ANEs with maximum SPLs of 73 dB. Calculations based on the dose-response relationship established in the DLR field study expect that 16 of 100 airport residents will be woken up by four events with 53 dB, whereas 39 of 100 residents, i.e., more than twice as many, will be woken up by four events with 73 dB (see Fig. 2).

B. L_{Aeq} criteria

Reducing the number of ANEs by 50% without changing the aircraft types means that the energy equivalent continuous sound level L_{Aeq} will decrease by 3 dB. Criteria solely depending on L_{Aeq} therefore implicitly assume that the effects of aircraft noise on sleep are simultaneously diminished by 50%, e.g., that the number of awakenings induced by aircraft noise is halved. Figure 4 demonstrates that this is not true. Following the epidemiologic concept of *numbers needed to harm*, it shows, depending on the maximum SPL of single ANEs, how many ANEs are needed to induce one additional awakening on average, where independent events were assumed.

If the maximum SPL of single ANEs is reduced by 3 dB from 72 to 69 dB, the permitted number of ANEs inducing one additional awakening may not be doubled but only in-

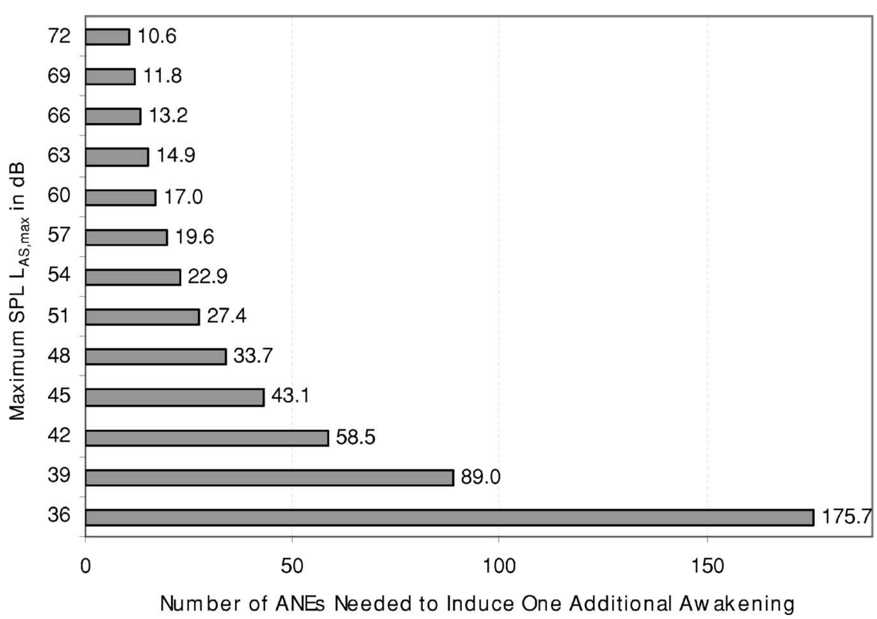

FIG. 4. Number of ANEs needed to induce one additional awakening on average and depending on the maximum SPL. Results are based on the dose-response relationship found in the field study (see Table I).

creased by 11% from 10.6 to 11.8 movements. The allowable change in the number of ANEs following reductions in maximum SPL of 3 dB increases continuously from 11% (decrease from 72 to 69 dB) to 97% (decrease from 39 to 36 dB), i.e., the number of ANEs may be nearly doubled only very close to the threshold value of 33 dB.

C. Combinations of NAT and L_{Aeq} criteria

Potentially, there are two main advantages of combining NAT and L_{Aeq} criteria:

(i) The L_{Aeq} is mainly influenced by events with high SPLs. If ANEs are much louder than the limit value of the NAT criterion, the L_{Aeq} criterion will be violated quickly.

(ii) The number of ANEs with maximum SPLs between the physiological threshold (33 dB) and the limit value of the NAT criterion cannot be increased at will without violating the L_{Aeq} criterion. Especially in the case of high traffic volumes, the L_{Aeq} criterion will dominate the combined criterion, although there is a strong dependence on the actual limit values for both criteria.

Nevertheless, the problems associated with each of the criteria are not completely solved by the combination of both criteria. There are several constellations concerning the number and the maximum SPL of ANEs with maximum SPLs between the physiological threshold and the limit value of the NAT criterion that violate neither the L_{Aeq} criterion nor the NAT criterion, but lead to a relevant number of noise-induced awakenings nevertheless. A publication of the Health Council of the Netherlands states that, given a certain L_{night}, the least favorable situation regarding a direct biological effect occurs if maximum SPLs of single ANEs are about 5 dB higher than the physiological effect threshold.[19] Of course, this noise pattern constitutes an unrealistic *worst case scenario*.

D. A physiological noise effects criterion

As mentioned above, combinations of the acoustical NAT and L_{Aeq} criteria dominate current proposals of concepts for the protection of sleep against adverse effects of aircraft noise. Practically, noise protection zones around airports are represented by noise contours, i.e., curves on which a certain noise descriptor has a constant value. Such contours are usually estimated by calculations rather than by measurements. They are derived from the maximum SPL as well as the duration and number of ANEs, which again are based upon the airport's traffic description. This description, which can be a forecast, specifies the number and types of aircraft operating at the airport during a well defined time period. Until now, noise contours around German airports were solely based on acoustical criteria, i.e., areas where a certain L_{Aeq} is exceeded (e.g., 50 dB outside) or a certain maximum SPL is exceeded too often (e.g., 6×75 dB outside). By establishing these purely acoustical contours, it was implicitly assumed that aircraft-noise-induced sleep disturbances are acceptable outside the contours without additional sound insulation measures.

The dose-response relationship established in the DLR field study (see Fig. 2) can be combined with the estimation of immission values in order to explicitly specify the effects of aircraft noise on sleep around airports. The average number of aircraft-noise-induced awakenings at a certain location in the airport environment is calculated from the distribution of A-weighted maximum SPLs $n(L_{\mathrm{AS,max}})$ at this location:

$$N_{\mathrm{AWR}} = \int_{-\infty}^{\infty} f_{\mathrm{AWR}}(L_{\mathrm{AS,max}})n(L_{\mathrm{AS,max}})\,dL. \tag{3a}$$

The function f_{AWR} follows from Eq. (2) as

$$f_{\mathrm{AWR}}(L_{\mathrm{AS,max}}) = \max(1.894\times 10^{-5}L_{\mathrm{AS,max}}^2 + 4.008 \times 10^{-4}L_{\mathrm{AS,max}} - 3.3243\times 10^{-2};0). \tag{4}$$

The max-function assures that there are no negative contributions of maximum SPLs below the threshold of 33 dB. The assumption that the function f_{AWR} is still valid above the range of 73 dB is arbitrary. In practice, there are no problems associated with this assumption, as maximum SPLs of this magnitude inside the bedroom only occur in highly exposed areas close to the airport.

These equations can easily be implemented in any calculation procedure capable of providing distributions of maximum SPLs (e.g., the German AzB procedure, which was used for the calculations in this publication). In practice level distributions are realized by SPL classes of a certain width rather than by a distribution function $n(L_{\mathrm{As,max}})$. In that case, Eq. (3a) migrates to the following equation:

$$N_{\mathrm{AWR}} = \sum_i f_{\mathrm{AWR}}(L_{\mathrm{AS,max},i})n(L_{\mathrm{AS,max},i}). \tag{3b}$$

The summation has to be performed over all level classes denoted by the index i. It is likely that there will be an influence of the class width. In order to minimize this effect, the calculations performed for this investigation were carried out with a class width of 0.2 dB. Additionally, normally distributed maximum SPLs with a standard deviation of 3 dB were assumed instead of the discrete maximum SPL values provided by the AzB algorithm for the particular aircraft categories. This is currently also a common approach for the calculation of NAT contours. There is some potential to improve the implementation of the $\mathrm{N_{AWR}}$-calculation scheme into existing aircraft noise calculation tools. Such optimizations are currently the subject of further investigations.

With the method described above, the number of aircraft-noise-induced awakenings can be predicted for each location around the airport. Hence, the need for protective measures against the adverse effects of aircraft noise can be quantified explicitly and precisely. This is illustrated in Fig. 5 for Frankfurt airport. Two areas based on L_{Aeq} criteria are compared with three areas outside of which less than one, two, or three additional noise-induced awakenings are expected.

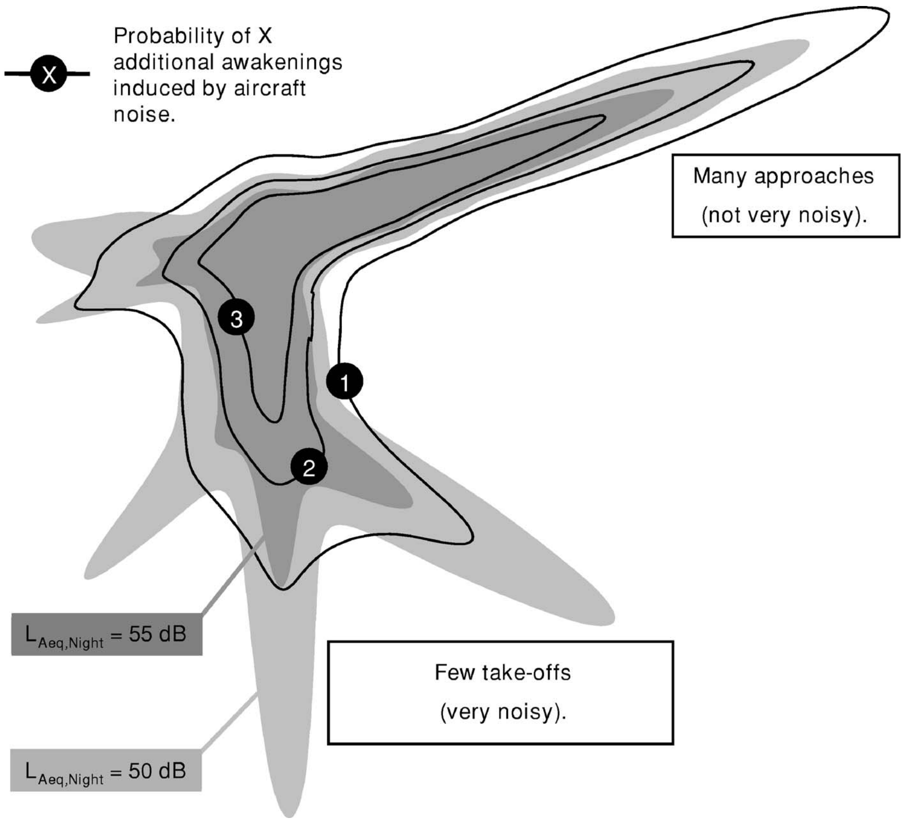

FIG. 5. Prognosis of noise effects for Frankfurt airport: on average one, two, or three additional awakenings induced by aircraft noise (black lines), L_{Aeq}=55 dB (dark gray), and L_{Aeq} =50 dB (light gray). Calculations are based on 25 000 nocturnal aircraft movements in the busiest six months of the year.

Apparently, there are qualitative differences: On the one hand, the contours for additional awakenings extend into areas with many but relatively quiet fly-overs (approaching aircrafts). On the other hand, in areas with few but relatively loud fly-overs (departures) they are not as pronounced as the L_{Aeq} contours. This illustrates the fact that L_{Aeq} criteria are not suitable for an adequate description of the effects of nocturnal aircraft noise on sleep.

The introduction of a physiological measure for sleep disturbances (i.e., the probability of awakenings) reflects a more medical- and health-related position than acoustical dimensions can do. The combination of a physiological reaction and an acoustical event, represented in a dose-response curve, and the calculation of acoustical immissions at a given location in the vicinity of airports provides a powerful tool for the protection of the affected population. Therefore, an easily applicable concept for the protection against adverse effects of nocturnal aircraft noise on sleep has been developed.

V. CONCEPT FOR THE PROTECTION AGAINST ADVERSE EFFECTS OF NOCTURNAL AIRCRAFT NOISE

The DLR concept for the protection against adverse effects of nocturnal aircraft noise on sleep will be presented and substantiated. Potential restrictions of the concept will also be discussed.

A. Objectives of the concept

The adequate protection of people affected by nocturnal aircraft noise has to be the main objective of a protective concept in order to prevent negative health consequences. Changes in sleep structure that may lead to a nonrestorative sleep are the primary effects of nocturnal aircraft noise. Sleepiness and impaired mental capacities are two of the possible immediate consequences. Furthermore, annoyance may be induced by consciously perceived noise events during the night. It is also being discussed whether repeatedly (over years) occurring noise-induced sleep disturbances may lead to other health impairments, such as an increased risk for high blood pressure or myocardial infarction.[20–22] If established, these noise impacts on health would be of major societal importance. However, in practice it is very difficult to substantiate a causal link between noise and long-term health effects, as many different and well-proven risk factors lead to the same diseases and induction periods are usually very long. Until now, there is no study corroborating this causal link for nocturnal aircraft noise.[19]

In order to overcome this dilemma, the DLR concept is based on two assumptions:

(1) Because of biological plausibility, it is hypothesized that a causal link between noise-induced sleep disturbances and long-term health effects exists. Vice versa, long-term health effects can be prevented with a high probability if noise-induced sleep disturbances are minimized.
(2) It is assumed that humans—like any organism—represent an adaptive system, which is able to compensate for certain strains without negative effects for the organism. Hence, it is not necessary to eliminate strains completely. It is simultaneously assumed that there are very sensitive subjects, who fail to compen-

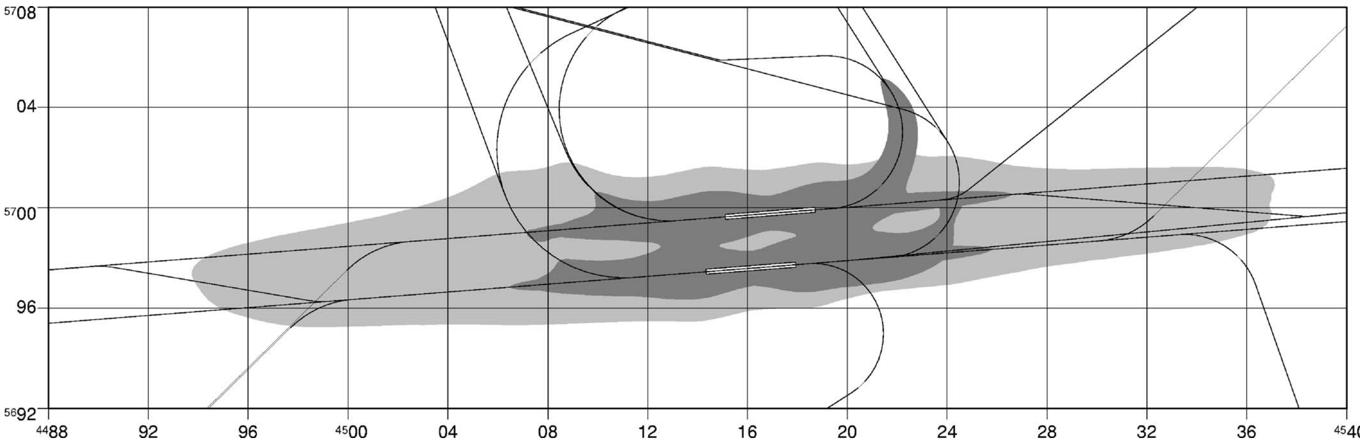

FIG. 6. Noise protection zone for Leipzig/Halle airport (traffic prognosis for 2015) consisting of the combination of two areas: (1) area outside of which less than one additional awakening induced by aircraft noise is expected on average (light gray) and (2) area outside of which maximum SPLs of 80 dB or higher (measured outside) occur less than once (dark gray, envelope of two contours calculated separately for 100% flight movements in each direction).

sate for small strains, as well as there are very robust subjects, who endure strong strains without negative consequences.

From a medical point of view, sound insulation should only be used if all other measures fail. Methods for the reduction of noise emissions are an active research field (e.g., silent engines, noise reduced takeoff and landing procedures, etc.). They should be consequently and quickly applied in practice.

B. Description of the concept

The DLR concept is based on three objectives, which reflect three highly correlated dimensions of sleep:

(1) On average, there should be less than one additional awakening induced by aircraft noise. Here, awakenings are defined as an electrophysiological phenomenon classified according to the rules of Rechtschaffen *et al.*[5]
(2) Awakenings recalled in the morning should be prevented as much as possible.
(3) There should be no relevant impairment of the process of falling asleep again.

Figure 6 illustrates the proposed noise protection zone for Leipzig/Halle airport for the night (22:00 until 06:00), based on a traffic prognosis for 2015. Two contours are combined: Outside of the light gray area on average less than one additional awakening induced by aircraft noise is expected. This contour is based on the expected, average distribution of flight movements on the two operation directions. Outside of the dark gray area, maximum SPLs of 80 dB or higher (measured outside) occur less than once. This contour is the envelope of two contours estimated for a 100% distribution of flight movements in both operating directions. This leads to an overestimation of effects, which was intended as awakenings recalled in the morning are regarded as especially severe sleep disturbances. The three columns of the DLR concept will be discussed in detail in Secs. V C to V E.

C. Less than one additional awakening induced by aircraft noise on average (first criterion)

Self-evidently, humans either wake up or they do not, i.e., on the individual level and within one night noninteger values for the number of additional awakenings do not make sense. However, they do if one refers to more than one night or to more than one subject (i.e., to averages). The criterion "on average less than one awakening per night" would be violated if a subject is woken up by aircraft noise 365 times in one year. However, it would just not be violated if the subject is woken up by aircraft noise 364 times in one year. When interpreting these numbers it has to be kept in mind that about 24 spontaneous awakenings can be expected per night on average and therefore about 8760 spontaneous awakenings can be expected per year.[2]

If and how often a subject is actually woken up by aircraft noise depends on the amount of air traffic in the special night, other situative and individual factors, as well as on chance. Therefore, in single nights it is possible that a subject is woken up more than once, e.g., two times. If the criterion should not be violated it has to be guaranteed that the subject is not woken up by aircraft noise in one other night, thus compensating for the two awakenings. The same is true for an even higher number of noise-induced awakenings: If a subject is woken up four times by aircraft noise in one night, this has to be compensated for by three nights with no additional awakenings, otherwise the criterion would be violated in the long run.

A Monte Carlo Markov chain (MCMC) simulation was used to calculate how the numbers of noise-induced awakenings per night are distributed over the 365 nights of one year: Maximum SPLs were randomly drawn from the maximum SPL distribution found in the DLR field study. For each SPL, awakening probabilities were calculated according to the dose-response relationship shown in Fig. 2. With a random number generator and based on the derived awakening probability it was determined whether the simulated human subject woke up or did not wake up induced by aircraft noise. This procedure was repeated and awakening probabilities were summed until the criterion of one additional aircraft-

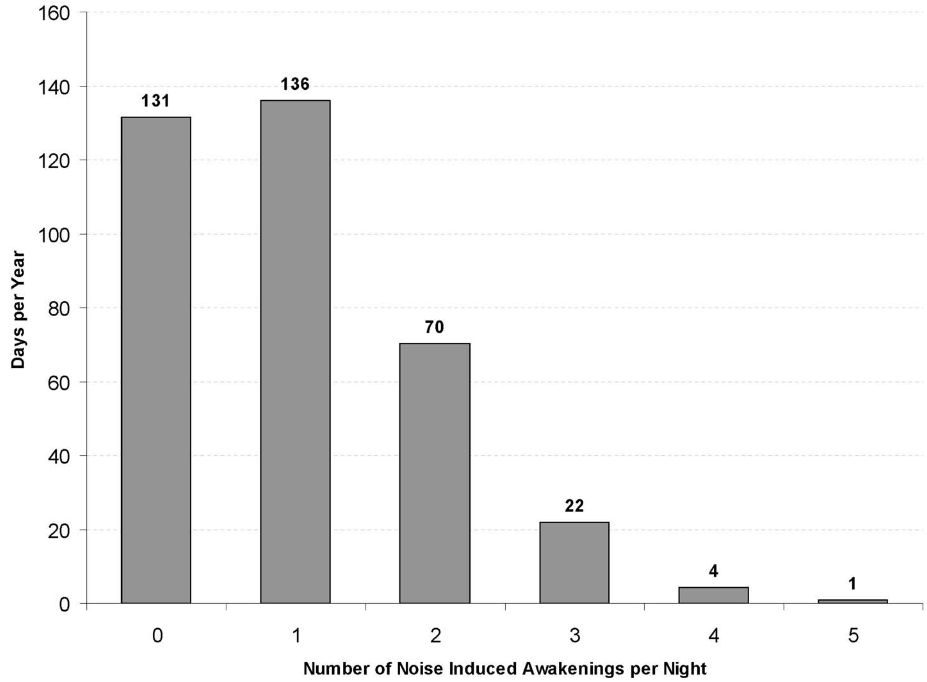

FIG. 7. Distribution of aircraft-noise-induced awakenings over the 365 days of one year if the criterion "on average less than one noise-induced awakening" is just not violated.

noise-induced awakening was just violated. This noise event was the last event counted, unless the sum of awakening probabilities up to the previous noise event, that just did not violate the criterion, was closer to the limit value in absolute terms. In that case, the previous noise event was the last event counted. With this method, 1 000 000 noise nights were simulated.

The expected distribution of aircraft noise-induced awakenings over the 365 days of one year is shown in Fig. 7.

In 131 nights there is no, in 136 nights there is one, in 70 nights there are two, and in 22 nights there are three additional awakenings. Four or five noise-induced awakenings per night occur extremely seldomly, and six or more awakenings practically do not occur.

These reactions are electrophysiological awakenings based on the definition by Rechtschaffen and Kales.[5] They are usually too short to be remembered on the next day (see above). From a preventive point of view, however, the number of electrophysiological awakenings induced by aircraft noise should be restricted as much as possible,[23] although the impact of electrophysiological awakenings on health, quality of life, and psychological outcomes remains a matter of scientific debate and therefore uncertain.[24] As electrophysiological awakenings go along with vegetative arousal reactions (e.g., increases in heart frequency and blood pressure), it is at least biologically plausible that repeatedly occurring noise-induced awakenings over years may impact health.[13] It is currently not known how many noise-induced awakenings are tolerable without leading to middle- or long-term impairments of well-being and health. With the high number of spontaneous awakenings and the high variability in several nights of the same person in mind, it is not deemed necessary from a medical point of view to completely avoid additional awakenings induced by aircraft noise. It is rather assumed that impacts of aircraft noise on health can be excluded in areas where less than one additional awakening is expected to be induced by aircraft noise on average.

D. Recalled awakening (second criterion)

The risk of recalled awakening increases with the duration of the awakening. Recalled awakenings are correlated with the subjective evaluation of sleep quality and sleep quantity: The higher the number of recalled awakenings, the worse is the evaluation of sleep quality (field study: $r_{\text{Spearman}}=-0.316$) and sleep quantity (field study: $r_{\text{Spearman}}=-0.269$). Additionally, ANEs occurring in the sleep period influence the assessment of annoyance only when they are perceived consciously by airport residents, and longer awakenings are a prerequisite for regaining consciousness.[19]

Recalled awakenings not only fragment sleep: They go along with psychological disadvantages as well and therefore constitute a major sleep disturbance. Psychosomatic disorders cannot be excluded if recalled awakenings are induced over longer time periods. Therefore, special attention has to be drawn to recalled awakenings in the process of evaluating the impacts of aircraft noise on sleep. From a medical point of view, recalled awakenings induced by aircraft noise should be prevented as much as possible.

The first criterion limits the number of noise-induced awakenings irrespective of the duration of the awakenings. Therefore, the number of recalled awakenings is limited as well. Most of the spontaneous awakenings are too short to be remembered on the next day. Analyses of the laboratory study showed that the duration of noise-induced awakenings increases with the maximum SPL of ANEs. Relevant differences compared to spontaneous awakenings were observed for maximum SPLs of more than 65 dB (see Fig. 3).

For this reason, maximum SPLs of more than 65 dB should be avoided in the bedroom. For a partly opened window with an assumed difference in SPLs of 15 dB between inside and outside, the 1×80 $dB_{outside}$ contour of Fig. 6 (dark gray) assures that outside this area maximum SPLs of 65 dB are exceeded less than once inside the bedroom on average. As recalled awakenings should be avoided as much as possible, this contour is based on a 100% flight movement in one direction estimation, i.e., a worst case.

TABLE II. Relevant polysomnographic field studies on the effects of aircraft noise on sleep. In the study of Hume *et al.*[15] SPLs were measured outside the bedroom only.

Study	No. of subjects	No. of subject nights	Age range (years)
Basner *et al.*[2] (2004)	64	576	19–61
Hume *et al.*[15] (2003)	46	178	20–70
Flindell *et al.*[11] (2000)	18	90	30–40
Ehrenstein *et al.*[26] (1982)	3	30–45	8–10
Vallet *et al.*[25] (1980)	40	160	20–55

E. Falling asleep again (third criterion)

The problem of falling asleep again is practically not considered in the literature of noise effects on sleep, disregarding the fact that about 7% of the sleep period is spent awake.[13] ANEs can prevent the sleeper from falling asleep again in these situations, and therefore have a negative impact on sleep structure.[2]

The traffic prognosis for Leipzig/Halle airport in 2015 forecasts two very busy periods during the night caused by freight handling. Between 0:00 and 1:30 up to 60 approaches per hour and between 4:00 and 5:30 up to 50 starts per hour are expected. The short time period of 1 to 1.5 min between two noise events in these peak hours leads to an increased risk of preventing the affected population from falling asleep again. If a subject already regained consciousness, annoyance reactions may result from consciously perceived noise events. Indeed, many airport residents complain about ANEs in early morning hours. At this time of the night, sleep pressure and awakening thresholds are low: Falling asleep again is difficult anyhow and aggravated by aircraft noise events.

Extensive analyses based on the data of the DLR field study were performed to assess the impact of aircraft noise on falling asleep again. The analyses are complicated by the fact that people who are prevented from falling asleep again stay awake and may be repeatedly prevented from falling asleep again by additional ANEs. In statistical terms, probabilities are no longer independent, but they are conditional on what happened in the past.

The results of these analyses will be presented elsewhere. They are based on a Markov state transition model which differentiates between two states only: awake and sleep. In the model, transitions between these two states depend on maximum SPL $L_{AS,max}$ of the ANE, elapsed sleep time, the current state (awake/sleep), and the elapsed time spent in the same sleep stage and estimated with autoregressive logistic regression based on the data of the field study. The Markov model was used to predict the number of awakenings, the duration of wake periods, the number of awakenings recalled in the morning, and the percentage of highly annoyed subjects. The results indicated that maximum SPLs of ANEs in the second half of the night should receive a malus of 1.4 dB, i.e., they should be artificially elevated by 1.4 dB, in order to assure an undisturbed process of falling asleep again similarly in all regions around Leipzig/Halle airport.

F. Transferring study results to the population level

Polysomnography is the only method that allows us to draw conclusions on structural aspects of sleep. At the same time, data acquisition and analysis are cumbersome, time consuming, and therefore expensive. Hence, polysomnographic studies on the impact of aircraft noise on sleep are scarce and were usually based upon small samples. These studies differed considerably in study design and the methods applied, thus complicating comparisons or meta-analyses between them. As there is considerable intersubject variability in noise sensitivity, small studies may per chance investigate only very sensitive or only very insensitive subjects according to aircraft-noise-induced changes in sleep structure. Hence, transferring the results of small studies to the population level is not possible or limited.

The sample size of the DLR field study is compared to other relevant field studies using polysomnography in Table II.

Vallet[25] investigated the effects of aircraft noise on sleep in the field on 40 subjects aged 20 to 55 years (160 subject nights). Flindell *et al.*[11] examined 18 subjects aged 30 to 40 years on five consecutive nights (90 subject nights). The authors call their study a pilot study for a potential extension of the Ollerhead *et al.* study.[10] Ehrenstein[26] investigated three children aged 8 to 10 years in the vicinity of Munich airport. As there was no air traffic after 21:30, only ANEs between 20:00 and 21:30 could be analyzed. Ollerhead *et al.*[10] performed an actigraphic study in the vicinity of several British airports. Polysomnography was additionally performed on 46 of the 178 subjects. The results of the polysomnographic data were published by Hume *et al.*[15] in 2003. In this study, the SPL was measured only outside of the dwellings, restricting the validity of the results. None of the studies investigated nonhealthy subjects.

In the DLR field study, 64 subjects were studied for 576 subject nights, resulting in the largest polysomnographic study with identical methodological approach so far. Nevertheless, the study does not claim representativeness for the whole population. It is impossible to be representative for a whole population in a study with huge methodological expenses for a single subject like the DLR study. Additionally, some inclusion criteria had to be met in order to be eligible for study participation, leading to a higher internal validity of the results. This is a prerequisite for external validation, but also it restricts it to some extent.[2]

Therefore, the results of the field study were not trans-

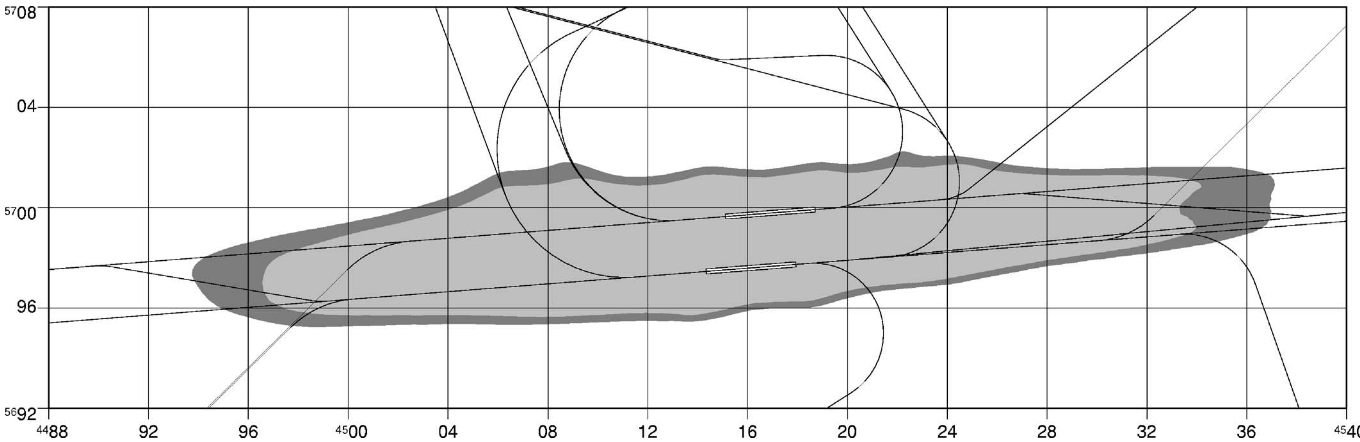

FIG. 8. Areas outside of which less than one awakening is additionally induced by aircraft noise. Comparison of preventive approach (sleep stage S2, middle of second half of the night, outer dark gray area) with approach based on actual data found in the field study (inner light gray area). By the preventive approach the noise protection zone is increased by 28% (=43 km^2).

ferred 1:1 to the population living in the vicinity of Leipzig/Halle airport. Instead, several preventive measures were taken in order to protect those parts of the population that were not represented in the DLR field study and that are more sensitive to aircraft noise at the same time. Some of these measures shall be briefly summarized:

(i) Subjects assessing themselves as sensitive to and annoyed by aircraft noise were included preferably into the study. Seventy-five percent of study subjects assessed themselves as moderately, strongly, or very strongly annoyed, compared to 15% of a representative German survey.[27]

(ii) Not only awakenings but also sleep stage changes to stage S1 were counted as relevant noise-induced sleep disturbances, increasing the probability of reactions to aircraft noise.

(iii) For the calculation of the dose-response curve based on the regression results it was assumed that the sleeper spent the whole night in the most sensitive sleep stage S2 and in the middle of the more sensitive second half of the night. In reality, an average night contains only about 50% of sleep stage S2. Hence, the dose-response curve is shifted to higher probabilities compared to calculations where the actual sleep stage distribution is used. Because of this measure alone the noise protection zone increases from 156 km^2 by 28% to 199 km^2 (see Fig. 8).

(iv) Subjects with illnesses leading to a lower noise sensitivity (e.g., hypakusis, hypersomnolence) were excluded from study participation.

(v) The calculations for the noise protection zone were based on the six busiest months of the year according to air traffic.

(vi) Sound insulation was increased by 3 dB for sensitive institutions (e.g., hospitals) and individuals with relevant diseases accompanied by a higher noise sensitivity.

(vii) The proposal of allowing only one additional awakening induced by aircraft noise makes sense in terms of preventive medicine. It has to be taken into account that on average 24 spontaneous awakenings can be observed in an otherwise undisturbed night anyway.

VI. CONCLUSIONS

The DLR-Institute of Aerospace Medicine investigated the influence of aircraft noise on sleep, mood, and performance in an extensive polysomnographic field study between 1999 and 2004 as part of the DLR/HGF-project "Quiet Air Traffic." The dose-response relationship developed in this study was used to establish a concept for the protection of subjects against the adverse effects of nocturnal aircraft noise on sleep. Advantages of this new concept compared to conventional NAT criteria, L_{eq} criteria, or combinations of NAT and L_{eq} criteria were discussed.

It is planned to extend Leipzig/Halle airport to a freight hub with an independent parallel runway system. Major parts of air traffic will take place during the night. The Regional Council of Leipzig decided to use the results of the DLR field study for a new noise protection concept at Leipzig/Halle airport. This concept culminates in the three propositions presented and discussed in Sec. V and reflects three correlated dimensions of sleep: There should be on average less than one additional awakening induced by aircraft noise, noise-induced awakenings recalled in the morning should be prevented as much as possible, and no relevant impairments of the process of falling asleep again should occur. These three provisions have been proposed in order to consider the special conditions under which Leipzig/Halle airport will operate: (1) construction of a second independent runway, (2) settlement of a night cargo hub for a big service integrator, (3) heavy air traffic during night including peak hours with up to 60 movements per hour, and (4) practically no nocturnal air traffic in the present. These circumstances necessitate a special concept for the protection of the affected population against the adverse effects of nocturnal aircraft noise on sleep.

With the decision for the implementation of the results of the DLR field study, fresh ground was broken, as noise protection zones solely depended on acoustical criteria so far. The noise protection zone for nocturnal air traffic proposed by DLR exceeds the one of the current law amendment under discussion, which should come in force in 2011, by 60 km^2, and will be correspondingly accompanied by additional financial burdens for the airport resulting from the installation of sound insulation.

Shortly after the publication of the official documents of the approval process for the extension of Leipzig/Halle airport in November 2004, the integrator DHL decided to move its European freight hub from Brussels to Leipzig/Halle. In the long run, this could lead to several thousands of new jobs in this region. Despite the very conservative approach taken in constructing the noise protection zones, some residents living in the vicinity of Leipzig/Halle airport were still not satisfied with the concept: They sued in order to prevent the start of construction at the airport. The Federal Administrative Court rebutted this legal action in May 2005 in the first instance, and the construction measures started without delay in August 2005.

ACKNOWLEDGMENTS

We would like to thank all subjects who agreed to participate in our studies as well as the investigators from the DLR flight physiology department for their extraordinary effort in sampling and analyzing the data.

[1]Regierungspräsidium Leipzig (Leipzig Regional Council), "Planfeststellungsbeschluss für das Vorhaben Ausbau des Verkehrsflughafens Leipzig/Halle Start-/Landebahn Süd mit Vorfeld" (official documents for the approval process of Leipzig/Halle airport, available on the internet http://www.rpl.sachsen.de/de/internet/service/planung/flughafen/startseite.htm last visited 11/03/2005), Leipzig, Germany, Az.: 14-0513.20-10/14 (2004).
[2]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, and J. Wenzel, "Effects of nocturnal aircraft noise (Volume 1): Executive summary," German Aerospace Center (DLR), Cologne, Germany, FB2004-07/E, ISSN 1434-8454 (2004).
[3]M. Basner and A. Samel, "Effects of nocturnal aircraft noise on sleep structure," Somnologie **9**, 84–95 (2005).
[4]A. Samel, M. Basner, H. Maaß, U. Müller, J. Quehl, and J. Wenzel, "Wirkungen des Nachtfluglärms auf den Schlaf: Ergebnisse aus dem Projekt 'Leiser Flugverkehr' (Effects of nocturnal aircraft noise on sleep: Results from the 'Quiet Air Traffic' project)," Umweltmed. Forsch. Prax. **10**, 89–104 (2005).
[5]A. Rechtschaffen, A. Kales, R. J. Berger, W. C. Dement, A. Jacobsen, L. C. Johnson, M. Jouvet, L. J. Monroe, I. Oswald, H. P. Roffwarg, B. Roth, and R. D. Walter, "A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects," Public Health Service, U.S. Government, Printing Office, Washington, DC (1968).
[6]H. L. Williams, J. T. Hammack, R. L. Daly, W. C. Dement, and A. Lubin, "Responses to auditory stimulation, sleep loss and the EEG stages of sleep," Electroencephalogr. Clin. Neurophysiol. **16**, 269–279 (1964).
[7]M. H. Bonnet, "Performance and sleepiness following moderate sleep disruption and slow wave sleep deprivation," Physiol. Behav. **37**, 915–918 (1986).
[8]N. J. Wesensten, T. J. Balkin, and G. Belenky, "Does sleep fragmentation impact recuperation? A review and reanalysis," J. Sleep Res. **8**, 237–245 (1999).
[9]M. Bonnet, D. W. Carley, M. A. Carskadon, P. Easton, C. Guilleminault, R. Harper, B. Hayes, M. Hirshkowitz, P. Y. Ktonas, S. Keenan, M. Pressman, T. Roehrs, J. Smith, J. K. Walsh, S. Weber, and P. R. Westbrook, "EEG arousals: Scoring rules and examples. A preliminary report from the Sleep Disorders Atlas Task Force of the American Sleep Disorders Association," Sleep **15**, 173–184 (1992).
[10]J. B. Ollerhead, C. J. Jones, R. E. Cadoux, A. Woodley, B. J. Atkinson, J. A. Horne, F. L. Pankhurst, L. A. Reyner, K. Hume, F. Van, A. Watson, I. D. Diamond, P. Egger, D. Holmes, and J. McKean, "Report of a field study of aircraft noise and sleep disturbance," Department of Transport, London, United Kingdom (1992).
[11]I. Flindell, A. Bullmore, K. Robertson, N. Wright, C. Turner, C. Birch, M. Jiggins, B. Berry, M. Davison, and M. Dix, "Aircraft noise and sleep 1999 UK Trial Methodology Study," ISRV Consultancy Services, Southampton, United Kingdom, Ref. 6131 R01 (2000).
[12]R. Mathur and N. J. Douglas, "Frequency of EEG arousals from nocturnal sleep in normal subjects," Sleep **18**, 330–333 (1995).
[13]E. Sforza, F. Chapotot, S. Lavoie, F. Roche, R. Pigeau, and A. Buguet, "Heart rate activation during spontaneous arousals from sleep: Effect of sleep deprivation," Clin. Neurophysiol. **115**, 2442–2451 (2004).
[14]M. J. Morrell, L. Finn, H. Kim, P. E. Peppard, M. S. Badr, and T. Young, "Sleep fragmentation, awake blood pressure, and sleep-disordered breathing in a population-based study," Am. J. Respir. Crit. Care Med. **162**, 2091–2096 (2000).
[15]K. Hume, F. Van, and A. Watson, "Effects of aircraft noise on sleep: EEG-based measurements," Manchester Metropolitan University, Manchester, United Kingdom (2003).
[16]J. Haba-Rubio, V. Ibanez, and E. Sforza, "An alternative measure of sleep fragmentation in clinical practice: The sleep fragmentation index," Sleep Med. **5**, 577–581 (2004).
[17]D. H. Hosmer and S. Lemeshow, *Applied Logistic Regression*, 2nd ed. (Wiley, New York, 2000).
[18]H. W. Agnew, Jr., W. B. Webb, and R. L. Williams, "The first night effect: An EEG study of sleep," Psychophysiology **2**, 263–266 (1966).
[19]Health Council of the Netherlands, 'The influence of night time noise on sleep and health," The Hague: Health Council of The Netherlands, Publication No. 2004/14E, ISBN 90-5549-550-6 (2004).
[20]W. Babisch, "Traffic noise and cardiovascular disease: Epidemiological review and synthesis," Noise Health **2**, 9–32 (2000).
[21]S. Morrell, R. Taylor, and D. Lyle, "A review of health effects of aircraft noise," Aust. N. Z. J. Public Health **21**, 221–236 (1997).
[22]W. Babisch, B. Beule, M. Schust, N. Kersten, and H. Ising, "Traffic noise and risk of myocardial infarction," Epidemiology **16**, 33–40 (2005).
[23]T. Akerstedt, M. Billiard, M. Bonnet, G. Ficca, L. Garma, M. Mariotti, P. Salzarulo, and H. Schulz, "Awakening from sleep," Sleep Med. Rev. **6**, 267–286 (2002).
[24]R. Cluydts, "Comparing the effects of sleep loss after experimental sleep deprivation and in clinical patients," Sleep Med. Rev. **7**, 293–295 (2003).
[25]M. Vallet, J. M. Gagneux, and F. Simonet, "Effects of aircraft noise on sleep: An in situ experiment,"ASHA Report No. 10, 391–396 Rockville, Maryland (1980).
[26]W. Ehrenstein, M. Schuster, and W. Müller-Limroth, "Felduntersuchungen über Wirkungen von Lärm auf den schlafenden Menschen (Field studies on the effects of noise on the sleeping human)," Abschlussbericht des Umweltbundesamtes 1–101, Dessau, Germany (1982).
[27]J. Ortscheid and H. Wende, "Lärmbelästigung in Deutschland—Ergebnisse einer repräsentativen Umfrage (Annoyance caused by noise in Germany)," Z. Lärmbekämpfung **49**, 41–45 (2002).