Aircraft-noise induced awakenings as a more adequate indicator for better night noise protection concepts around airports

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ABSTRACT

Sleep disturbance is the main negative effect of nocturnal aircraft noise, known to increase the risks of adverse health effects and impair the quality of life. Protection zones for nocturnal aircraft noise are currently based mostly just on average sound levels. However, these physical measures usually correlate poorly with sleep quality. In order to develop a generalisable standard exposure-response model, within the EU-project ANIMA a re-analysis of the two worldwide available field studies using the gold standard polysomnography and simultaneous acoustical measures was carried out. Pooling of the data was performed to get a medium exposure-response curve based on the AIC. For a standard model, additional parameters should be considered, premised they do not significantly deplete the AIC. An exposure-response curve for the standard model will be presented. Results provide valuable information on new night noise protection concepts, based on physiological measures. The application of the model in ANIMA's Virtual Community tool, software to compute additional aircraft noise induced awakenings around airports, will also be presented.

INTRODUCTION

Sleep is an active and extremely complex event in which a variety of physiological processes take place like protein biosynthesis, excretion of specific hormones, or the consolidation of memory contents. Undisturbed sleep of sufficient duration is essential for maintaining the necessary daytime alertness, performance ability and health. Therefore, it is very important for the general quality of life [1] and thus the night should be especially protected against sleep disturbing influences.

Within the last decades, the growing need for mobility and transport of goods has led to increasing levels of noise during the night, which can result, amongst other outcomes, in disturbed sleep. Although there is not one single, generally accepted definition of "healthy sleep" it is undisputed that disturbed nocturnal sleep leads to an increased risk of metabolic syndrome, associated coronary heart disease, hypertension and diabetes, as well as depression and increased mortality [2].

The strongest immediate effect to nocturnal noise are awakening reactions and as a consequence thereof a greater sleep fragmentation. Effects such as the total number of sleep stage changes at night are generally less pronounced [3].

Up to now, the acoustical metric to report transport noise is the energy equivalent sound pressure level L_{eq} or its derivatives L_{dn} or L_{den} [4] which integrates a 10 dB-penalty for only night noise or a penalty for both the evening noise (7 – 11 pm, 5 dB (A)) and the night noise (10 pm – 6 am, 10 dB (A) for the L_{den} or for the L_{dn}. The problem with these energy equivalent levels is that several noise events of moderate maximum levels can generate the same equivalent level as a single noise event with a very high maximum level. This implies that these metrics are not adequately describing noise effects on sleep and therefore are not eligible for developing a nocturnal protection concept against aircraft noise. The human organism during sleep reacts to every single noise event (overflight) which must be therefore individually characterised by corresponding acoustical quantities (e.g., maximum level, SEL, [5]). The probabilities for additional awakenings due to single aircraft noise events must be summed up over the whole night in order to determine the additional noise-induced awakenings (a probability of 100% means one additional aircraft noise induced awakening). For a night noise protection concept, the number of additional aircraft-noise-induced awakenings must then be limited.

Due to the fact that using questionnaires are relatively cheap and easy to implement, there are numerous published studies claiming to have calculated the “mean” exposure-response curve of different levels of sleep disturbance with only considering the energy equivalent noise level $L_{eqNight}$ [6]. These studies neglect the problem that those mean levels, if not unrealistically low, are not suitable for communication or protection purposes because the same L_{eq} can be caused by many different noise situations, each causing different effects on sleep. However, the World Health Organization (WHO) recommends in its 2018 “Environmental Noise Guidelines for the European Region” an L_{night} of 40 dB(A) for aircraft noise due the number of highly sleep disturbed people (HSD) assessed only by questionnaire [7].

The gold standard in clinical research for objectively studying sleep is the multi-parametric polysomnography technique [8]. Sleep data can be combined with continuously recorded sound pressure levels and the sound itself to allow an exact event-related analysis at any time. Thereby, it is possible to develop an optimal statistical model, providing an exposure-response function that delivers the probability to awake for every single noise event depending on its maximum sound pressure level. These additional noise-induced awakenings per night can be calculated for every household around an airport, are easy to understand by laypersons but up to now are only used in the Zurich Aircraft Noise Index (ZFI) and the Frankfurt Night Noise Index (FNI) in order to communicate nocturnal aircraft noise development and at airport Leipzig / Halle to develop a night noise protection concept [9,10].

The methodology demands a very high time and cost expense, thereby only an examination of subjects in the two- to lower three-digit number range can be realised. Due to the intricate and time-consuming application of the electrodes and the subsequent manual assessment of sleep, polysomnography is difficult to be used outside the sleep laboratory and limited to a number of subjects. On the other hand, the use of polysomnography in the field, e.g. the subjects’ homes, allows for a high ecological validity. Up to now there are only two field studies available worldwide using this approach.

The purpose of the present paper is to calculate and generate a standard exposure-response curve based on these field studies which can be generalised over different airports and be used for a night noise protection concept based on human sleep physiology. In the EU-project ANIMA (Aviation Noise Impact Management through Novel Approaches, 2017-2021) the derived standard exposure-response curve will be used as a basis for the Virtual Community Tool visualising the effect of aircraft noise on sleep.

The development of a standard exposure-response model is based on reanalyses of the only two worldwide available field studies providing polysomnographic sleep data, the STRAIN and the NORAH studies. Both studies were operated by the German Aerospace Center (DLR) and used nearly the same methodology which will be introduced in the following. For the present paper, the data of the STRAIN-study (Study on human response on aircraft noise, [10]) had been newly analysed with additional acoustic metrics which significantly improved the published model and were compared to the sleep data of the NORAH study (Noise-related Annoyance, Cognition, and Health) which were also improved by calculating additional acoustical metrics [11]. A pooled model was then developed.

METHODOLOGY

Database

STRAIN study

The STRAIN study took place between 1999 and 2003 and examined the impact of nocturnal aircraft noise on sleep by means of polysomnography in laboratory (128 subjects', 13 consecutive nights each) and field studies at Cologne-Bonn Airport (64 residents', 9 consecutive nights each). For this re-analysis only data from the field study were used. Cologne-Bonn Airport has no flight restrictions and the highest nocturnal air traffic in Germany. Peak hours are usually from 11 pm to 1 am and 3 am to 5 am.

NORAH study

The NORAH study was carried out between 2011 and 2015 around Frankfurt airport before and after the beginning of the operation of the 4th runway in October 2011 and the associated night flight ban between 11 pm and 5 am. For this analysis the sleep study data of 2012 were used where 83 subjects were investigated for 3 nights each.

In order to get a standard exposure-response and a medium exposure-response curve, datasets of the two studies were pooled.

Selection criteria for participants

Healthy normal-hearing persons aged 18 years and older were examined. Subjects with intrinsic sleeping disorders were excluded, with that being scanned in the first study night. Other exclusion criteria were cardiac arrhythmias, regular medication with sedating effects, excessive consumption of alcohol / drugs / nicotine, and regular shift-work. During the study, subjects were asked not to drink coffee or other caffeinated beverages after 3 pm and not to nap during the day.

In order to be able to clearly attribute possible awakening reactions of the residents to aircraft noise events, residential areas were selected in such a way that aircraft noise prevailed as the dominant noise and just few other (traffic) noises occurred in the bedroom. During the study, window position was allowed to be changed every night based on the resident's preference.

Sleep measurement and metrics

Historically, sleep quality, duration and awakening reactions have been scientifically measured using push-buttons, questionnaires, actigraphy and polysomnography. Polysomnography is regarded to have the highest predictive value among these methods with regard to the prediction of awakening reactions [8].

The amplitude and frequency of the wave patterns derived from polysomnography allow a classification into five sleep stages and the stage awake. Parameters of sleep architecture such as sleep onset time, total sleep time, and sleep stage shares can be derived.

However, these total night sleep parameters revealed only minor aircraft noise affected variability in the STRAIN and NORAH study and were not able to detect the effects of noise events. They are therefore regarded as a less appropriate basis for the development of a night protection concept. In contrast, awakening reactions show immediate effect of the acoustical characteristics of an overflight and, moreover, serve as a metric for sleep continuity.

Awakenings are a good compromise in terms of sensitivity and specificity so that all relevant sleep disorders are encompassed. Since sleep stage 1 is a very shallow sleep stage and regarded as less important for recuperation processes, the term “awakening” in the present paper comprises both a sleep stage change to wake and stage 1.

The number of additional awakenings correlates well with changes in sleep structure, which are classified as sleep disorders. About 45% of the variance in the change of the deep sleep rate is elucidated by the number of additional wake-up reactions [3]. There has been the consensus among sleep researchers that noise-induced wakefulness is a relevant sleep disorder [12]. More recently researchers also suggested that awakening reactions are a suitable indicator of noise-induced sleep disorders [13, 14].

Spontaneous awakenings

It is part of normal, physiological sleep process during the night sleep to wake up without external disturbances. In the STRAIN study on average 24 awakenings per night were observed of total 112 undisturbed nights. It can be argued that only those awakening reactions can be considered noise-induced exceeding the natural number of spontaneous awakenings [15]. In the STRAIN study the probability of additional awakening due to aircraft noise was calculated from the difference between the aircraft-noise-related (awakenings observed at the time of an aircraft noise event) and the spontaneous probability of awakenings [10]. As the calculation of the spontaneous awakenings contains scientifically problems the following procedure was established to estimate the probability of awakening:

- All awakenings at maximum levels below the median of the background levels before the noise events (1-min L_{eq} before) considered in the statistical model are defined as spontaneous reactions
- First awakening reactions are not already expected when the background level is exceeded. Therefore 3 dB are added to this median of the background level.

Acoustics

To ensure noise event-related evaluations of the EEG data, class-one sound level meters were placed near the sleepers' ear in the NORAH and STRAIN study. The A-weighted and slow-corrected sound pressure levels L_{AS} were measured. The acoustical data had then been analysed by skilled personnel who listened, marked and commented every noise event that had reached the sleepers` ear. Table 1 summarises the acoustical parameters used for the event-related statistical analysis, visualised in Figure 1.

Table 1: Acoustical parameters used for the event-related statistical analysis.

Parameter	**Explanation**
L_{ASmax}	A-weighted maximum sound pressure level, time weighting slow [dB(A)]
L_{Aeq3_Event}	A-weighted equivalent continuous sound level of the aircraft noise event, based on an exchange rate of 3 [dB(A)]
$SEL_{\_Event}$	Sound exposure level of the aircraft noise event
Background	Sound pressure level in the absence of any alleged noise nuisance sources
Emergence	Maximum Sound pressure level minus the background level
Event_duration	Time duration for an aircraft noise event above the background noise [s]
Time_to_peak	Time duration from an aircraft noise event start right above the background noise up to the maximum sound pressure level.
T10 dB downtime	Time within a single noise event where the level is below 10dB of the maximum level.
Steepest rise time	Steepest increase of sound pressure level from start of the noise event to the maximum level.
Mean rise time	Mean increase of sound pressure level from start of the noise event to the maximum level.
L_{Aeq3_1min}	A-weighted equivalent continuous sound level 1 min before the aircraft noise event, based on an exchange rate of 3 dB(A). Can be labelled as the background noise of the specific aircraft noise event.
$N_{Aircraft\_before}$	Number of previous aircraft noise events before the analysed aircraft noise event.

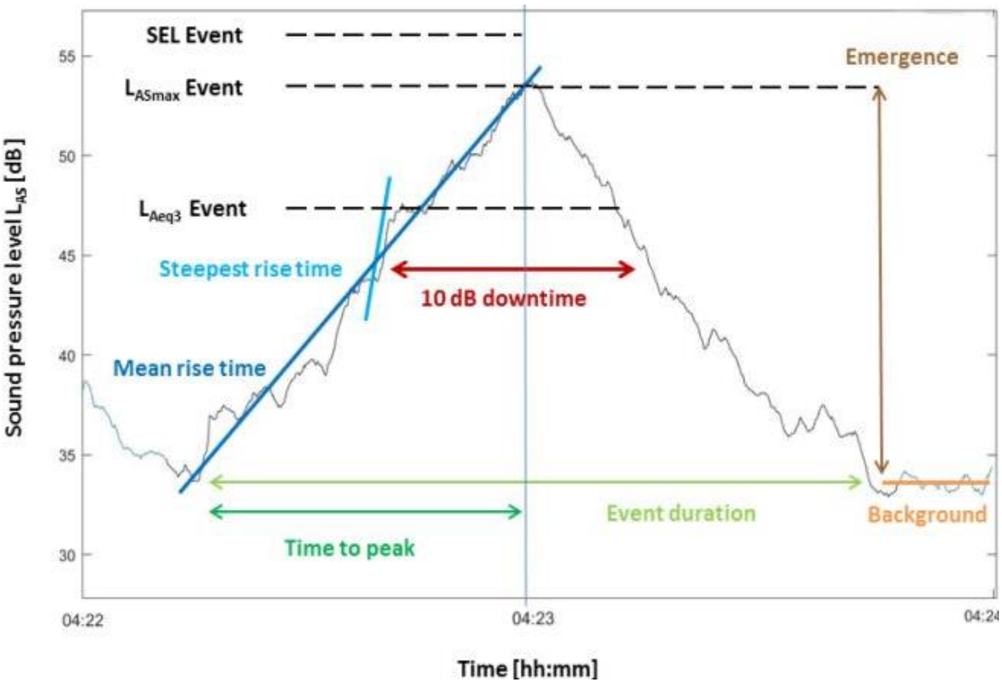


Figure 1: Schematic description of how the acoustical parameters for the statistical analysis were determined.

Statistical analysis

Event-related evaluation

The polysomnography data are evaluated in 30 s epochs by default. The window which is screened for an awakening reaction covers three epochs, i.e. the time interval of 90 s after the beginning of an aircraft noise event. Awakening reactions occurring during this time window are considered to be noise-associated. For these so-called event-related analyses, only aircraft noise events are considered which occur during sleep periods, which are not preceded or followed by another noise event within 60 s prior to or after the individual aircraft noise event.

Multiple regression analysis

To derive an exposure-response curve, it is necessary to calculate the probability of an awakening. This is realised by means of a regression model, with the dependent variable being dichotomous (awakening reaction, yes / no). Thereby a model using random intercept is being used [16]. The selection of predictive factors that enter into the regression model is carried out by stepwise selection [17], with the decision based on the AIC (Akaike Information Criterion). The AIC is a measure of the goodness of fit of a regression model [18]. A variety of acoustical, personal and situational variables may have potential impact on the probability of awakening. For the calculation of the exposure-response relationship, in addition to the acoustical parameters (see Table 1) the influence of the following variables was examined: i) sleep stage before awakening, ii) time spent in sleep stage before awakening, iii) sleep period time before awakening (in 30 s epochs), iv) age, and v) gender.

Model selection

Reanalysis of the 12 acoustical and 6 sleep parameters was conducted in a variety of different statistical models. They were tested by means of a stepwise selection procedure, for both studies individually. This procedure was then repeated until there was no improvement with respect to the AIC (Akaike information criterion).

RESULTS

Standard exposure response model

For both, the NORAH and the STRAIN study, it was shown that the re-analysis with additional parameters led to statistically better results than the original published models. (Revised models not in the text).

In sleep research, it is undisputed that the sleep structure changes with age, with shifting to shallower sleep overall. Therefore, elderly people are generally easier to awake from noise events. Due to a lower number of elderly tested subjects, age was not incorporated into the models so far. The standard exposure-response model which was based on a pooled dataset of the STRAIN and NORAH study however, does not only consider the model which resulted from the selection process but also age as an influencing personal variable. Table 2 shows this standard model. The exposure-response curved derived from the standard model is depicted in Figure 2. The parameters and its values considered in the exposure-response curve are listed in Table 3.

Table 2: Standard exposure-response model predicting the probability of an awakening as a function of the maximum sound pressure level indoors of one overflight and further acoustical and non-acoustical predictors

Predictor	**Regression coefficient**	**Standard Error**	**p-value**	**Odds Ratio**
Intercept	-6.0043598	0.2779726	<.001	0.002
L_{pAS_Max} indoors	0.0804070	0.0048181	<.001	1.084
Event duration	-0.0058474	0.0011256	<.001	0.994
L_{pAS}_steepest_level_rise_time indoors	0.0399624	0.0091569	<.001	1.041
Background_before_noise_event indoors	0.0764112	0.0059805	<.001	1.079
Time_since_Sleepstart	0.0016601	0.0002336	<.001	1.002
Sleepstage3_before	-0.2145659	0.1041066	<.05	0.807
Sleepstage4_before	-0.4533692	0.1388330	<.01	0.635
SleepstageREM_before	0.3482393	0.0557374	<.001	1.417
Age	-0.0022583	0.0047294		0.998
SPL L_{pAS_Max} indoors * Background_before_noise_event indoors	-0.0018619	0.0001051	<.001	0.998

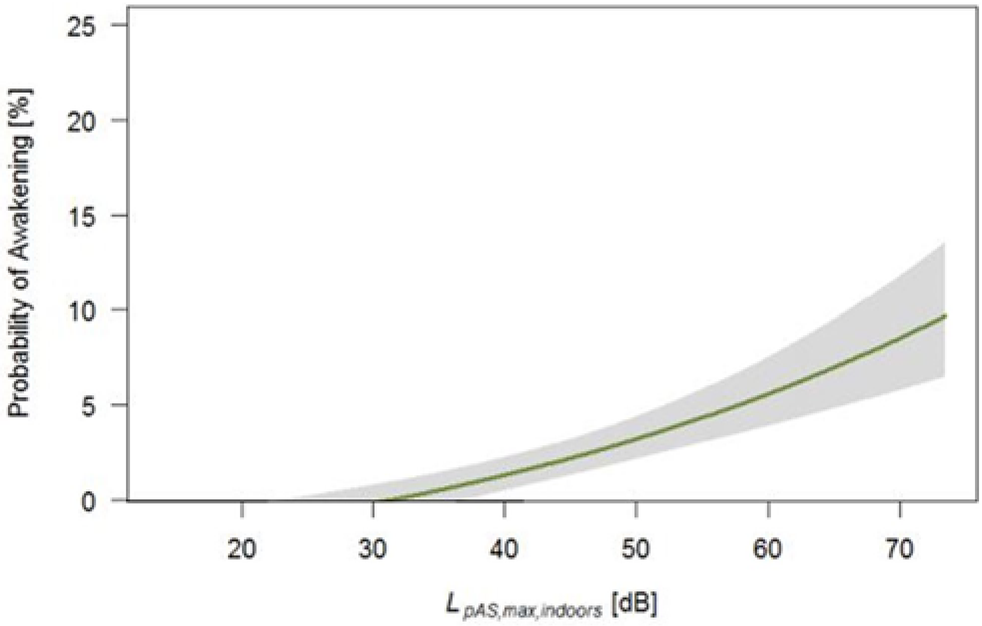


Figure 2: Probability of an awakening as a function of the maximum sound pressure level indoors of one overflight and further acoustical and non-acoustical predictors (cf.

Table 3).

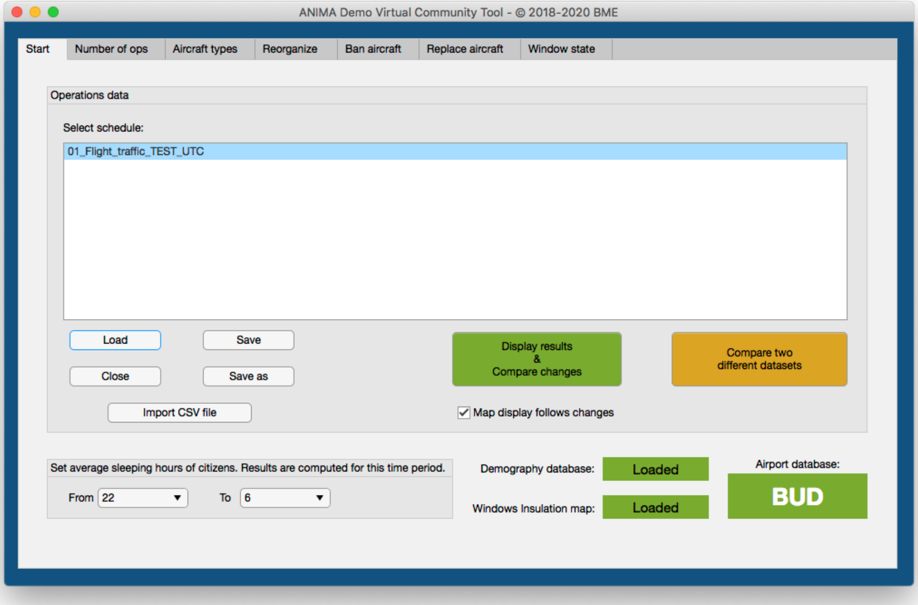
Table 3: Parameters used for the exposure response curve. Median parameters were calculated from all undisturbed aircraft noise measurements of the STRAIN/NORAH study.

Parameter	**Set value**
Event duration (median)	71.1 s
t_{10}_dB_downtime indoors (median)	30.0 s
L_{PAs}_steepest_level_rise_time indoors (median)	2.4 dB(A)/s
Background_before_noise_event indoors (median)	28.6 dB(A)
Time_since_sleep_start (specification)	300 min
Age (median)	40
Spontaneous Awakening (median from pooled dataset STRAIN/NORAH)	5.4 %
Spontaneous Awakening (STRAIN)	8.4 %
Spontaneous Awakening (NORAH)	4.0 %

VIRTUAL COMMUNITY TOOL

The final Virtual Community tool using the standard exposure-response curve as a data basis will be a web-based application, but to better find the right specifications for it, a standalone mock-up software has been developed as well [19]. It is implemented in Matlab, which allows fast development and easy implementation of complex mathematical formulae. In Figure 3, the main window of the mock-up tool is displayed. At the current status of the software, flight schedules, an airport database (containing ground acoustics data for all possible aircraft, on all possible flight tracks combinations) and a corresponding demography database and a buildings insulation quality map can be loaded.

On the other tabs of the Main Window, the loaded flight schedule: e.g. by changing the overall or hourly percentage of traffic amount, by rescheduling a certain amount of flights from one hour to another, by replacing aircraft types with others (i.e. study the effect of fleet renewal), etc. can be changed. To visualise additional awakenings around the airport area, to compare the extension of critical zones defined by different metrics (e.g. LDEN vs Awakening) or to study the effect of changes performed in the Main Window, a Results Display Window is available to users (see Figure 4).



Select schedule: 01_Flight_traffic_TEST_UTC

☑ Map display follows changes

Set average sleeping hours of citizens. Results are computed for this time period.

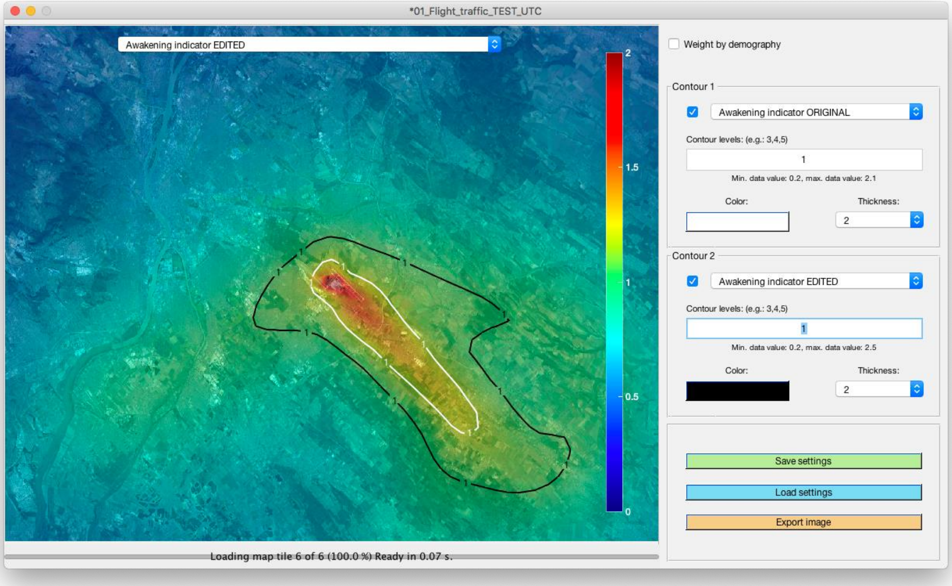
From 22 To 6

Demography database: Loaded

Windows Insulation map: Loaded

Airport database: BUD

Figure 3: Main Window of the mock-up ANIMA Virtual Community Tool



☐ Weight by demography

Contour 1
☑ Awakening indicator ORIGINAL
Contour levels: (e.g.: 3,4,5) 1
Min. data value: 0.2, max. data value: 2.1
Color: ☐
Thickness: 2

Contour 2
☑ Awakening indicator EDITED
Contour levels: (e.g.: 3,4,5) 1
Min. data value: 0.2, max. data value: 2.5
Color: ■
Thickness: 2

Loading map tile 6 of 6 (100.0 %) Ready in 0.07 s.

Figure 4: Results Display Window showing the increased zone boundaries of 1 additional awakening for an increase of air traffic for a hypothetic (exemplary) airport scenario.

DISCUSSION AND CONSIDERATIONS FOR A BETTER NIGHT NOISE PROTECTION CONCEPT

The standard model for calculating additional aircraft noise-induced awakenings presented here can be used for (1) communicating the effect of aircraft noise in the night in an “easy-to-understand” metric and (2) to develop protection concepts that can prevent physiological acute-effects of aircraft noise. So far this is not possible with currently established average acoustical sound level measures like the L_{eq}, because humans react to the single aircraft noise event and not to an average value which can get the same magnitude in completely different noise scenarios. Further on, ANIMA was looking for adequate metrics, and found that the awakening indictor is a viable metric as (1) it expresses something, which is more human-oriented than acoustical metrics, (2) it expresses something, which is important to airport communities and (3) can still be computed purely from acoustical and air traffic data.

The main idea of a protection concept should be to prevent the residents living around an airport from harmful adverse health effects. Although very little is known about the pathways how years of nocturnal aircraft noise lead to possible health consequences, it makes sense that if a protection concept can prevent primary physiological reactions (i.e. additional noise-related awakenings), it will also reduce the risk of harmful long-term consequences.

The protective assumptions are here considered by defining an awakening not only by transition to the stage *awake*, but also for the transition to the light sleep stage *S1* and not just for the whole aircraft noise event duration, but within 90 s after the start of the aircraft noise event, which is on average an around one third longer time interval. The corresponding curve were calculated for subjects being in the previous light sleep stage 2 before the noise event, which reflects a situation of the resident being already in a light sleep and thus has a higher awakening probability than from deep sleep stages. A similar effect was achieved by calculating the curve for 5 hours after sleep start, which usually corresponds to the last third of the night characterised by significantly more light sleep phases due to an decrease of sleep pressure.

The original analysis of the STRAIN data already served as a base for a night noise protection concept around the Airport Leipzig / Halle since 2006.

There the following limits were set for the protection concept [10]:

- Allow on average less than one additional aircraft noise induced awakening per night (one additional aircraft noise induced awakening = sum of 100% probability of awakening)
- Avoid awakenings that can be recalled in the morning (from laboratory studies it can be derived that this means that only one aircraft noise event with a maximum level of 65 dB(A) indoors per night is allowed)
- Avoid interference with the process of falling asleep again (1.4 dB(A) malus for the second half of the night)

OUTLOOK

Future epidemiological noise effects research must clarify the question of how many additional noise-induced awakening reactions lead to which increased health risk after a long-term exposure to aircraft noise. Subsequent, this must be accompanied by a social debate which determinates the risks that are tolerated by the society in order to facilitate nocturnal flight movements. From a scientific point of view, it would be desirable to have further data from field studies using polysomnography. However, there should not be a further delay in improving the urgently required adequate protection of airport residents during the night. The existing results are completely sufficient to improve the level of protection for residents and to shift the calculation concepts for night noise protection zones from purely physical quantitates to a measure that takes into account the human sleep physiology.

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