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FFI and FNI - two effect based aircraft noise indices at Frankfurt Airport

Dirk Schreckenberga,
ZEUS GmbH, Sennbrink 46, 58093 Hagen, Germany

Georg Thomannb,
Amt für Natur und Umwelt Graubünden ANU, Gürtelstrasse 89, 7000 Chur, Switzerland

Mathias Basnerc
German Aerospace Center, Institute of Aerospace Medicine, 51170 Köln, Germany

ABSTRACT

Within the planning process concerning the future expansion of Frankfurt Airport (construction of a new runway) in September 2007 the Regional Dialogue Forum Frankfurt Airport (RDF) proposed an Anti-Noise-Pact (ANP). ANP includes suggestions of upper limits and quantitative reduction goals for noise effects after the airport expansion and recommends the implementation of active noise control measures.

Moreover, two regional aircraft noise indices for the description and control of the noise development in the vicinity of Frankfurt Airport are proposed. These are the 'Frankfurt Aircraft Noise Index' (FFI), and 'Frankfurt Night Index' (FNI). FFI is the primary index. Based on the 24 hours of the day, it describes the number of subjects highly annoyed by aircraft noise in areas within L_{dn} -contour 55 dB. FNI solely serves to assess nocturnal air traffic by displaying the number of awakenings additionally induced by aircraft noise emitted between 10pm and 6am, including regions where at least 0.5 additionally aircraft noise induced awakenings are expected.

The proposed indices were subjected to a scientific evaluation by the authors of this contribution. In this contribution FFI and FNI and the involved requirements and objectives are described. It is concluded that effect based noise indices like FFI and FNI are in principle suitable to assess aircraft noise development around the airport as far as the underlying noise calculation method is able to reproduce the acoustical effects of changes in air traffic. However, several recommendations are given in order to improve the indices initially proposed by RDF.

1. INTRODUCTION

With an annual number of 486000 movements (10% at night-time), 53 Million passengers and 2 Million tons cargo (in 2008) Frankfurt Airport belongs to the most important international airports worldwide. For 2020 about 701000 movements (88 Mio passengers, more than 3 million tons cargo) are predicted. In order to manage this predicted amount of movements it is

^a Email address. schreckenberga@zeusgmbh.de, ^b Email address. mathias.basner@dlr.de

^c Email address. Georg.Thomann@anu.gr.ch

intended to construct a new 4th runway to increase the current capacity of 83 to 120 flight movements per hours. The opening of the new runway is expected in 2011.

In 1998 after the announcement of the planned airport expansion a mediation procedure was carried out for two years. The results of this mediation process presented in 2000 were the agreements in

- optimizing the existing flight operation system at the airport,
- an expansion of the airport as far as it is necessary to meet the capacity of 120 movements per hour,
- a night flight ban between 11pm and 5am ('mediation night') after the opening of the new runway,
- an Anti-Noise-Pact (ANP) including a program for aircraft noise control,
- formation of the Regional Dialogue Forum Frankfurt Airport (RDF), a round table in order to continue information on and discussion about the development of the airport. Members of the RDF are representatives of action groups, local authorities, trade unions, churches, regional industry and aviation industry.

Within the context of the ANP drafted in September 2007¹ the chairperson of the Regional Dialogue Forum Frankfurt Airport ('Regionales Dialogforum Flughafen Frankfurt', RDF) aims to establish a regional aircraft noise index for the description and control of the noise development in the vicinity of Frankfurt Airport. The following two indices are being proposed: 'Frankfurt Aircraft Noise Index' (FFI) and 'Frankfurt Night Index' (FNI).

FFI describes the number of residents highly annoyed by aircraft noise within the vicinity of Frankfurt Airport based on the 24 hours of the day. FNI is meant to supplement FFI and displays the number of awakenings additionally induced by aircraft noise emitted between 10pm and 6am. Specifications are proposed for the areas included in the calculation of FFI and FNI (see below).

According to the RDF the proposed indices should fulfil the following requirements:

- The indices should be a transparent description of the regional aircraft noise development.
- They should reproduce the effects of active noise control measures applied single and in combination and they should provide a comparative tool to assess advantages and disadvantages of active noise control measures.
- At least one of the proposed indices should be used for the definition of a regional noise limit, where action is needed if the limit is exceeded. As a goal the RDF proposed a 10% reduction of FFI in case of the airport extension for 2020.

The aim is to use the proposed indices to describe the noise situation at Frankfurt Airport on a regional, aggregate level. It is not the aim to use the indices as a measure of individual burden due to aircraft noise or for the definition of exposure limits marking individual health impairment.

The indices suggested by RDF were subjected to a scientific evaluation done by the authors of this contribution.

The evaluation task was to assess whether the indices fulfil the requirements described and, by doing this, to answer the following central questions:

- (a) Is a regional index principally suitable to assess aircraft noise development due to changes in number, location, and type of overflights?
- (b) Are the indices proposed by RDF adequate?
- (c) Which modifications would be required to fulfil the above mentioned purposes?

2. THE SUGGESTED AIRCRAFT NOISE EFFECT INDICES

An essential decision of RDF with regard to the indices is the idea of describing the regional aircraft noise situation in terms of noise impact instead of noise exposure.

The RDF considers noise annoyance and sleep disturbances (in the proposed night index operationalised by aircraft noise-induced awakenings) as the most important effects, for which exposure-response functions based on substantial scientific data are available.

A. The Frankfurt Aircraft Noise Index (FFI)

The primary aircraft noise effect index suggested by RDF is the Frankfurt Aircraft Noise Index ('Frankfurter Fluglärmindex' FFI). Based on the 24 hours of the day, it describes the number of subjects highly annoyed by aircraft noise (HA) in areas within L_{dn} -contour = 55 dBA:

$$FFI = \sum N_{pop,i} \cdot \frac{\%HA(L_{dn,i})}{100} \quad (1)$$

where:

i	numerator for the noise level in 1dB-steps
$L_{dn,i}$	Day-Night level L_{dn} with $i \geq 55$ dB(A).
$\%HA(L_{dn,i})$	Percentage of highly annoyed people for each $L_{dn,i}$, according to the simplified exposure-response relationship based on data of the RDF study ²
$N_{pop,i}$	Number of people living within respective L_{dn} -noise level i with $i \geq 55$ dB

The exposure-response relationship proposed for FFI relies on data of the RDF field study on noise annoyance carried out in communities in the vicinity of Frankfurt Airport in 2005².

The noise annoyance underlying this exposure-response relationship was ascertained with the standardised numerical 11-point scale (not at all (0) to extremely (10) disturbed or annoyed) as recommended by ICBEN³. A person was defined as highly annoyed (HA), if he or she chose the category 8 or higher on the annoyance scale to rate his or her annoyance. Based on visual inspection of the expose-response curve shown in Figure 1 (blue dots) RDF suggested a simplified linear exposure-response relationship.

While usually the assessment of aircraft noise implies the calculation of contours of average noise levels like L_{Aeq} ,

L_{den} or L_{dn} often combined with the calculation of the number of people *exposed* to the noise load within a particular noise contour, in FFI the number of people *affected* by noise is estimated. As 'number of (highly annoyed) persons' is more comprehensible than 'decibels', FFI fulfils at least the first requirement of a transparent and understandable description of the regional noise impact situation.

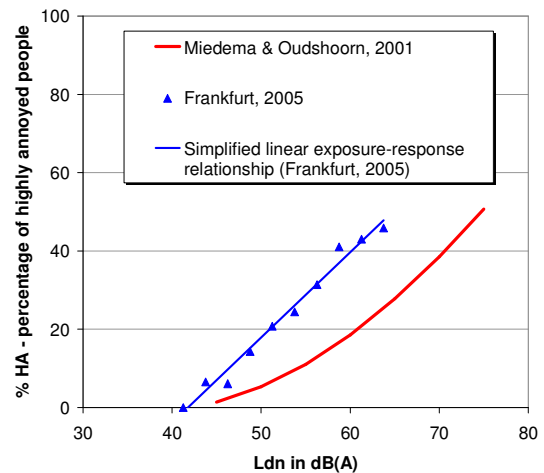


Figure 1: Percentage of highly annoyed people (%HA) by L_{dn} in the RDF study² (blue dots and line) in comparison to the generalised exposure-response curve from Miedema & Oudshoorn (2001)⁴ (red curve)

B. The Frankfurt Night Index

FNI is meant to supplement FFI. FNI solely serves to assess nocturnal aircraft noise effects by quantifying the number of awakenings additionally induced by aircraft noise emitted between 10pm and 6am, including regions (receiver points) where at least 0.5 additionally aircraft noise induced awakenings are expected.

The index FNI for a particular receiver point is given by

$$FNI = \sum_i N_{pop,i} \cdot N_{AWR,i} \text{ for } N_{AWR,i} \geq 0.5 \quad (3)$$

$$\text{with } N_{AWR,i} = \sum_{j=1}^n P_{AWR} (L_{AS,max,ij} + D) \quad (4)$$

$$\text{and } P_{AWR} (L_{AS,max,ij} + D) = 1,894 \cdot 10^{-5} \cdot (L_{AS,max,ij} + D)^2 + 4,008 \cdot 10^{-4} \cdot (L_{AS,max,ij} + D) - 3,3243 \cdot 10^{-2} \quad (5)$$

where

D attenuation for the transition from outdoor to indoor sound level; $D = -15$ dBA for tilt windows.

$L_{AS,max,ij}$ A-weighted maximum sound pressure level (delay time = slow) produced by aircraft type j at immission point i

n number of nocturnal overflights j at immission point i

N_{AWR} number of aircraft-noise induced awakenings

P_{AWR} probability of additional awakening reaction due to overflight j with maximum sound pressure level $L_{AS,max,ij}$ at immission point i

The exposure-response relationship for the probability of an aircraft-noise induced awakening bases on results of the field study of the German Aerospace Center (DLR) on the effects of nocturnal aircraft noise⁵. Similar to FFI the FNI combines exposure measures, an exposure-response relationship and population density measures within a single number and therewith expresses a (nocturnal) noise impact and not aircraft noise exposure only.

3. DISCUSSION OF THE INDICES

A. Discussion of FFI

It is reasonable to consider noise annoyance as an overall noise impact descriptor because in noise effect research annoyance is a central psychological variable considered to be a major if not most important noise effect. There are numerous studies reporting exposure-response relationships for noise annoyance⁶. Several authors^(e.g.4) carried out extensive meta analyses on data of different field studies to establish generalised exposure-response curves for the percentage of highly annoyed people related to average (weighted) noise levels like the Day Night Average Sound Level L_{dn} or Day Evening Night Average Sound Level L_{den} .

RDF decided to incorporate a regional exposure-response curve in FFI. In contrast to this the quite similar index ZFI introduced 2006 at Zurich Airport⁷, which sums up the number of highly annoyed and the number of highly sleep disturbed people in a single figure, includes the aircraft noise-related generalised exposure-response curve for %HA from Miedema and Oudshoorn⁴. The main advantages of this generalised curve are that it bases on a sophisticated meta analysis of a large set of different field studies carried out at different airports (for aircraft noise: 19 field studies with altogether 27081 respondents) including control for study and site effects, respectively. As the meta analyses of Miedema and colleagues are often cited and referred to in the Environmental noise directive (END)⁸ they form a de-facto standard for the assessment of noise annoyance for noise policy issues.

On the other hand the generalised exposure-response curve does not reflect the regional annoyance situation as can be seen from Figure 1 in comparison to the exposure-response relationship found in the RDF study. The underlying data of the so-called Miedema curves date from 1965 to 1992. Some authors suggest that recently published studies on aircraft noise annoyance (among them the RDF study) indicate a trend of increasing annoyance at a given noise level over the last decades⁹⁻¹⁰ and consider the respective Miedema exposure-response curve as outdated. Another point is that different assessments of noise annoyance are included in the generalised curves and in addition, different methods of ascertaining the noise exposure (e.g. different exposure calculation models) might cause strong differences in resulting exposure-response relationships. A better fit between the number of highly annoyed people calculated with a regional noise effect index like FFI and the real regional noise annoyance situation can be achieved by adopting a regional instead of a generalised exposure-response relationship with the same exposure calculation method underlying the exposure-effect function and used for the index. Therefore, the authors support the decision of RDF to rely on a regional exposure-effect relationship.

Another premise of FFI is the choice of the Day Night Average Sound Level L_{dn} as an indicator of the average noise exposure for the 24 hours of a day including a penalty weight of 10 dB for the night-time. The aim of RDF was to use an indicator for noise exposure, which indicates the noise impacts at day and night-time, is able to reflect compensations of alterations of flight movements in the night versus movements at daytime, is internationally common and therewith allows international comparisons. However, with regard to noise annoyance the findings in literature concerning the adequateness of a 10dB weighting of nocturnal noise load are not consistent¹¹⁻¹².

Looking into the data of the RDF study it turns out that the aircraft noise annoyance shows about 0.1 and 0.2 higher correlation coefficients with $L_{Aeq,1h}$ -noise levels at daytime than with most of the hourly noise levels at night-time (s. Figure 2). Accordingly, $L_{Aeq,16h}$ for daytime (6am to 10pm) correlates higher with aircraft noise annoyance than L_{dn} ($r = .44$ vs. $r = .41$, respectively; $p < .001$ for the correlation difference). To conclude, the night-time, a time period for which a weighting of 10 dB is included in L_{dn} , is a period residents living in the vicinity of Frankfurt Airport seem to have less in mind when referring to aircraft noise annoyance.

Therefore, taking into account that the RDF proposed a separate aircraft noise index for noise effects at night-time, the authors recommend to calculate the exposure-response relationship for %HA on the base of the $L_{Aeq,16h}$ instead of the L_{dn} . The higher degrees of annoyance between 6am and 8am as found in the RDF study should be accounted for in the FFI with sound pressure level surcharges. The magnitude of the sound pressure level surcharges still needs to be estimated. With regard to the higher aircraft noise sensitivity in the evening, which is also a result of the RDF study, it is suggested to incorporate this in the FNI (see below). The recommendation of an aircraft noise effect index for daytime with regard to noise annoyance

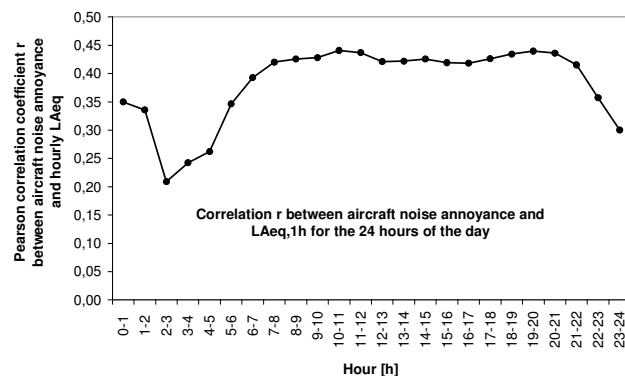


Figure 2: Pearson coefficients of the correlation between aircraft noise annoyance and hourly $L_{Aeq,1h}$ levels. Data from Schreckenber and Meis² (n= 2272)

is suitable for the situation at Frankfurt Airport with a relative proportion of 10% of the flight movements at night-time and can not be necessarily generalised to situation at other airports with other proportions of nocturnal air traffic.

A critical issue of FFI is the definition of the 55 dBA L_{dn} -noise contour as a stop criterion for the calculation of FFI. The size of the perimeter (a set of areas or receiver points, which are included in the calculation of the noise effect index by a defined criterion) determines to a large extent the noise effect index values and therewith the evaluation of noise control measures, if the index is used as a monitoring tool. The authors calculated the FFI exemplarily for 18 scenarios with different flight operations and found changes in the rank for 14 of the 18 scenarios when expanding the perimeter for FFI calculation (L_{dn} -contours) from 65 to 60 dB and changes in the rank for all scenarios when expanding the perimeter from 60 to 55 dB.

The larger the size of the perimeter the more do alterations of FFI reflect effects of population size on the index in particular when areas with higher population density are combined with low aircraft noise exposure. Thus, in case of a too large perimeter size including all (highly) annoyed people FFI would be less useful as a monitoring tool of aircraft noise control measures. In addition, the inaccuracy of noise exposure calculation increases with increasing distance to the airport¹³. Therefore, the area in which FFI is calculated should be somehow limited.

Using L_{dn} contour to define the perimeter for calculating FFI means that the target variable 'number of highly annoyed people' is restricted by an exposure limit. With this it is aimed to focus on 'relevant' burdened people. Instead of setting an exposure limit it seems to be more logical to set an effect threshold to define the 'relevance' of burden and to limit the calculation of noise effects. In fact, this idea is included in the FNI, which incorporates regions where at least 0.5 additionally aircraft noise induced awakenings are expected. Accordingly, an effect minimum expressed in %HA above which resident points are included in the calculation of FFI should be defined, keeping in mind that this is already a restriction because not highly but moderately annoyed people are not included in the definition of the noise effect index. This threshold cannot be defined by scientific evidence due to the continuous increase in annoyance with increasing noise level but is a matter of socio-political agreement.

However, at noise levels above $L_{dn} = 55$ dB the percentage of people highly annoyed due to aircraft noise exceeds 30% HA. This is above the common criterion of 25 to 28% HA marking the maximum limit of tolerable noise annoyance in the population¹⁴. Although as mentioned above the perimeter for FFI should be somehow limited as the FFI is intended to be used as a monitoring tool it is not suitable to set a perimeter for the index in a range of annoyance in communities, which is seen as intolerable. In fact, regarding the distribution of highly annoyed people over noise levels, it turns out that 49% of highly annoyed people exposed to $L_{dn} \geq 50$ dBA are not included in the FFI (below 50 dBA no data of population density was available for the authors in time). A reasonable compromise would be to set a demarcation criterion for calculating FFI between the response threshold (0% HA) and the critical threshold to protect the population against intolerable annoyance (25% HA).

B. Discussion of the FNI

In noise effect research different indicators and measurements are being used to assess the effects of noise on sleep. Among these are the assessment of reported sleep disturbances in questionnaires, the measurement of noise-induced body movements (motility) during sleep (actigraphy), the measurement of noise-induced behavioural (signalised) awakenings, and

noise-induced awakenings as assessed by means of polysomnographic parameters (EEG, EOG, EMG).

Noise-induced awakenings, defined as a changeover from sleep stages to wake stage, have become important indicators of noise-related sleep disturbance in recent years and have been adopted as criteria in night-time noise protection concepts. Among sleep researchers there is agreement that the number of awakenings additionally induced by noise is a suitable indicator of noise induced sleep disturbances¹⁵⁻¹⁷. Noise-induced awakenings are regarded as a strong reaction to environmental stimuli during sleep and add up to serious disruption of normal sleep. Awakenings are a good compromise between sensitivity and specificity and allow for capturing all relevant sleep disturbances as awakenings occur relative rare in the absence of acoustical stimuli (on average 24 spontaneous awakenings per night⁵).

Noise exposure-response functions for awakenings refer commonly to the relationship between a single acoustic event and the probability of awakening reaction where the acoustic event is characterised by the maximum sound pressure level (SPL) L_{max} . Equivalent noise levels like the L_{night} are not suitable to be related to awakenings because of the implicit underlying assumption that equivalence in sound energy of acoustical events comes along with equivalence in noise impact. This is not the case for awakenings as halving the number of events does not lead to a 50% reduction of awakenings (s. Figure 3).

As no exposure-response relationship for aircraft noise-induced awakenings at Frankfurt Airport is currently available, RDF decided to use the exposure-response function of the DLR-field-study⁵, which bases on field data collected at Airport Cologne/Bonn, for FNI calculation. This function is consistent with current scientific knowledge and corroborated by other field studies on the effects of aircraft noise on sleep. However, it should be examined whether the exposure-response relationship applies to the situation at Frankfurt Airport.

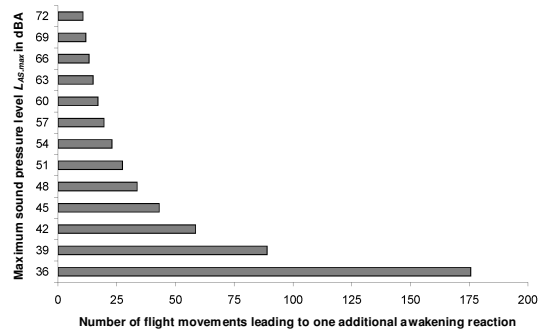


Figure 3: Number of aircraft noise events leading to on additional awakening reaction against the maximum SPL $L_{5,AS,max}$. Data from Basner et al.

Besides the maximum SPL of single flyovers the background noise, the actual sleep stage, and the elapsed time of sleep are taken into account in the DLR exposure-response function for the probability of aircraft noise-induced awakenings.

Not all awakenings during the night are necessarily severe in terms of possible health effects. The question of how many awakenings are tolerable in this regard is a matter of ongoing discussion in the scientific community. In the DLR protection concept for Airport Leipzig/Halle¹⁸ a protection zone is defined outside of which less than one (1.0) additional awakening reaction induced by aircraft noise is expected on average. This is regarded as a critical value above which severe disturbance of sleep is expected. A stop criterion of 0.5 additionally aircraft noise-induced awakenings as proposed for the FNI between the response threshold (below maximum SPL 33 dB at the ear of the sleeping person according to the DLR field study) and the critical threshold (1.0 awakening reaction on average) seems to be reasonable.

The FNI is to be calculated for night-time between 10pm and 6am. According to analyses of the sleep time of the participants of the RDF study² 88% of the people are in bed within this period. Before 10pm and after 8am less than 5% are in bed, between 6am and 7am and 7am

and 8am 62.5% and 21.4%, respectively; are still in bed. That is, outside the legally defined night-time between 10pm and 6am a considerable number of people are in bed. This is particular true for children and youngsters, which usually go to bed earlier and often sleep longer than adults. Therefore, from the experts' point of view, aircraft noise effects on sleep would be optimally replicated if, for each hour between 8pm and 11am, the number of additional aircraft noise induced awakenings is calculated and then weighted with the percentage of the population in bed, before the value is again weighted with the population density at the point of immission. Only in this way it is possible to take the sleep behaviour of the non-adult population into account. This extended time period for the calculation of FNI allows to accounting for the higher sensitivity to aircraft noise in the evening shoulder hours.

In this context it is suggested to describe possible compensations of flight movements within the 'mediation night' from 11pm to 5am completely within the framework of the FNI. (In the zoning decision of the Hessian Minister for Economics, Transport and Regional Development the night flight ban was softened allowing for 17 flights on average in the mediation night). If the compensation of flights within the 'mediation night' should be effect-equivalent, the FNI may not change (especially not increase). It is not recommended as intended by RDF to describe such compensation within a 24-hour index like FFI because (more) sleep disturbances in terms of awakenings in the night cannot be compensated by (less) annoyance at daytime. In line with this, any reduction goal with regard to the indices should be fulfilled by each index separately.

The FNI includes a fixed attenuation for the transition from outdoor to indoor sound level of $D = -15$ dBA (average value of attenuation for tilt windows). The inclusion of a fixed attenuation means that passive insulation measures are disregarded in FNI. As people usually sleep in their bedrooms, passive sound insulation of bedrooms can relevantly reduce the degree of sleep disturbance. Only if passive sound insulation measures are considered, will it be possible and of interest for the airport to reduce the FNI by providing passive sound insulation measures exceeding those set forward in legal regulations. Therefore, the FNI should be calculated taking into account real differences in indoor and outdoor sound levels of bedrooms with and without passive sound insulation measures. This can be done by registering sound insulation properties of each insulated building in a database.

C. Drawbacks and opportunities of present-day noise exposure calculation models

Both FFI and FNI base on the German calculation model for aircraft noise AzB. Present-day calculation methods like AzB model active noise control measures rather crudely and globally. Basically, major improvements of noise calculation methods and noise data are needed in order to facilitate the aspired controlling of active noise control measures. This is also true, if exposure-oriented values (sound pressure levels) are used for the evaluation of active noise control measures instead of noise effect indices. Until new and more appropriate methods are available and tested for practicability, existing methods can be used. In the latter case it is essential that the degree of calculation imprecision is stated explicitly and taken into account for the evaluation of the reduction potential of active noise control measures¹³.

4. CONCLUSION

Two noise effect indices are proposed by the Regional Dialogue Forum Frankfurt Airport (RDF) to describe the development of the aircraft noise situation in communities in the vicinity of Frankfurt Airport. These are the FFI displaying the number of highly annoyed people based on the 24 hours of the day in areas within L_{dn} -contour 55 dB and the FNI quantifying the

number of awakenings additionally induced by aircraft noise emitted between 10pm and 6am, including regions where at least 0.5 additionally aircraft noise induced awakenings are expected.

The proposed indices were subjected to a scientific evaluation done by the authors of this contribution. In general, effect based noise indices like FFI and FNI are in principle suitable to assess aircraft noise development around the airport as far as the underlying noise calculation method is able to reproduce the acoustical effects of changes in air traffic. The strength of FFI and FNI is that both indices refer to effects of noise not on physical exposure measures only. 'Number of highly annoyed person' and 'number of awakenings' seem to be more easily comprehensible than abstract decibel values, energy equivalent noise levels or weighted average sound pressure levels. Therefore, FFI and FNI manage to transparently describe the impact of aircraft noise. Model calculations show that both indices can be used to assess and order the effects of active noise control measures based on the technical properties of AzB (German aircraft noise calculation model).

However, several recommendations are given in order to improve the indices of which some are mentioned in this contribution. With regard to noise effect indices many aspects still remain unclear, difficulties up to now are unsolved and have to be clarified in future research.

One aspect is the combination of different effect indicators (e.g. annoyance, awakenings) in one single figure as it is done for the Zurich Aircraft Noise Index (ZFI). This is currently not recommended.

Indices including other noise effects than noise annoyance and sleep disturbances may be possible in future. Disturbances of communication and restoration may be candidates as effect indicators for a noise effect index, although much less exposure-response functions are available (published) for these noise effects in comparison to annoyance. Other effects (e.g. cardiovascular and physiological effects) for which (limited) evidence of a noise impact is available cannot be suggested to be included in a noise effect index at present due to the lack of clear verified exposure-response relationships.

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