Attachment 2

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Regulating and predicting wind turbine sound in the U.S.

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ABSTRACT

There are very few states in the U.S. with a state-wide noise rule. In the 1980's President Reagan, disbanded the US EPA's Office of Noise Control as noise was determined to be a local land use issue that didn't warrant federal oversight. Thus, the development of noise control regulations often falls to a local land use planner. An acoustical professional is not typically involved in the development or review of such codes. As such, clarifying terminology is often lacking and seemingly simple plain language may be interpreted to be extraordinarily precise. This paper highlights key factors for local noise ordinances to consider to avoid potential future confusion.

In addition, requirements for the prediction of sound levels from wind turbines often differ between the various states and local governments. Underprediction of sound levels can lead to potential compliance issues for a wind project, while overprediction can result in projects restricting operations unnecessarily. This paper reviews various sound propagation modeling parameters and compares predicted values to the results of post-construction monitoring in the U.S.

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1 INTRODUCTION

US EPA's website states "EPA does not have any regulatory authority governing noise in local communities. You should consult with your local governmental (e.g., city and county) authorities to see if there are local or state laws that might apply to your situation[1]." While several Federal agencies have exclusive jurisdictions over noise requirements for activities they regulate (e.g., aviation noise is regulated by the Federal Aviation Administration, highway noise by the Federal Highway Administration, and interstate pipelines by the Federal Energy Regulatory Commission), other community sources of noise are regulated at the State or more often local level. California, a state associated with long history of environmental regulations, does not have a statewide noise rule, rather it requires local governments to address noise in their General Plan and ordinances, and in 1977 through its now disbanded Office of Noise Control, provided local governments with a 58-page annotated "Model Community Noise Ordinance[2]." This model ordinance established "Maximum Permissible Sound Levels by Receiving Land Use" which was a level not to be exceeded 30 minutes out of each hour (L_{50}) and that was supplemented with L_{25} (+5 dB), $L_{8.3}$ (+10 dB), $L_{1.7}$ (+15 dB) and L_0 metrics (+ 20 dB).

It is highly unusual for noise regulations, even in California, to be as detailed as this model ordinance. Rather it is common for noise codes to be simplified to few sentences or a paragraph. Local noise requirements may be drafted by land use planners, attorney's or others who may lack robust acoustical training and find it completely reasonable and unambiguous to copy portions of other codes and simply state the "Maximum permissible sound level is XX dBA" or "The sound level shall not exceed XX dBA". Reasonable interpretation of such codes would evaluate them using the most typical or common metric, such as the L_{50} established in the California model ordinance or an L_{eq} given it is the basis for the metric used by numerous Federal agencies that have established noise criteria. Using extraordinary metrics, such as the L_{max}, require the code to include extraordinary detail and precise terminology that clearly identify it as the metric. Such examples are very limited.

When permitting a new project or activity, one evaluates its potential compliance against applicable code requirements, including noise. Acoustical models are developed based on the proposed equipment layout, equipment sound emissions, surrounding environment (e.g., topography, other obstructions, etc.) and a variety of acoustical propagation factors. As the predictions use vendor sound emission information, the metric associated with the vendor sound specifications is the basis of the predicted result. Vendor emission data may be provided as sound power level or sound pressure level at a specified distance. The measurement methods to develop this emission data is time averaged or L_{eq} (e.g., ANSI S12.34, AMCA, AHRI, IEC 61400-11). Thus, the prediction is also based on the L_{eq}. As the L_{eq} and L_{50} are often in very close agreement, the model results may almost always be considered representative of both the L_{eq} and L_{50} metrics. This is not the case of the L_{max}, given the L_{max} represents such a short timescale (less than a second). Thus, generally accepted means and methods for evaluating compliance with a sound limit during permitting, prior to the construction and operation of a project, do not facilitate the evaluation of an L_{max} metric. This is another reason that simplified code language should be evaluated using common metrics (e.g, L_{eq} and L_{50}) as opposed to the L_{max} – doing so allows for an evaluation during the permitting phase that is based on emissions data obtained using the applicable standards (e.g., ANSI, ASME, NEMA, ISO, IEC, etc.).

2 GUIDELINES FOR LOCAL NOISE ORDINANCES

Many local jurisdictions are updating their existing municipal codes to address wind power projects. A critical component to these ordinances is the regulation of noise. It is a confusing task that is often left to local boards or committees. If the existing code establishes a noise limit, that may be a starting point. The process typically consists of committee members looking at what other jurisdictions have done, then selecting components from the various regulations that seem reasonable to them. This mixture of requirements may be end up being ambiguous, unworkable, or impractical and may also not achieve the goals of the committee.

In 2016, the State of Massachusetts issued a report on wind turbine acoustics to provide quantitative information to improve their wind turbine siting and approval processes.[3] The authors of the MassCEC report laid out four core principals in developing a regulatory framework:

- **Relevance** – The regulation should have some relevance to impacts on humans or wildlife and not be set arbitrarily.
- **Repeatability** – The metrics and procedures should result in a relatively low standard deviation among samples taken under similar conditions.
- **Predictability** – The element that is being regulated should be able to be predicted (i.e. modeled) with a high level of confidence and reliability.
- **Ease of Implementation** – The element that is being regulated should be able to be tested for compliance and enforcement purposes without a substantial burden on the public, regulating authorities, or the project operator.

The key factors to be considered when developing a standard include the metric (e.g., L_{eq}, L_{50}, L_{90}), the timescale (e.g., minutes, hours, days), location of evaluation (typically dwellings) as well as the method of evaluation (e.g., predictive modeling). While discussed separately below, these factors should be considered collectively.

Weighting. While the A-weighting is the most widely used weighting in sound standards, including wind turbines, the purpose of this paper is not to review the literature regarding the use of the A-weighting for wind turbines. The A-weighting has been extensively evaluated including research sponsored by the Japanese Ministry of the Environment which found "…that A-weighted sound pressure level should be uniformly applied to the assessment of general environmental noises including wind turbine noise." [4]

Metric. The choice of a metric (e.g. L_{eq}, L_{max}, L_{50}…) in a standard is just as important as the sound level. Different metrics may result in different outcomes for the same sound level. The MassCEC study evaluated the use of various metrics in regulating wind turbine noise.[3] Some metrics have been found to be relevant, repeatable, predictable and reasonable to implement. For example, the L_{eq}:

- The L_{eq} metric is relevant. Peer-reviewed studies on long-term exposure to wind turbine noise all use some type of L_{eq} metric. For example, the Health Canada studies on wind turbine noise use this metric.
- The L_{eq} is repeatable. Wind turbine sound levels measured under similar conditions yield similar results.

- The L_{eq} is predictable. Modeling using an L_{eq} metric has a high degree of reliability, as both sound emissions are provided as an L_{eq} and the ISO 9613-2 model is designed around predicting the L_{eq}.
- Measurements of the L_{eq} are relatively easy to implement. Most modern sound level meters can measure the L_{eq}.

Other statistical metrics such as the L_{50} and L_{90}, which can minimize the influence of ambient sound level fluctuations, are related to the L_{eq}, are also considered in multiple jurisdictions (including the United Kingdom, Australia, New Zealand), and can similarly satisfy the identified criteria.

The MassCEC study found that instantaneous or short-term metrics like the L_{max} were not reliable. They found that the "least predictable and stable" metrics were the L_{10} and L_{max} metrics and their use was not advised. Challenges with the L_{max} include:

- One cannot subtract background from L_{max} levels. It is extremely difficult to determine what portion of an L_{max} measurement is from the wind turbines and what is due to other background sounds.
- The L_{max} is highly variable as a metric that results in poor repeatability among similarly conducted measurements.
- The IEC 61400-11 turbine noise emissions specification do not report L_{max} so no turbine emissions information is available for modeling.
- The ISO 9613-2 outdoor sound propagation methodology is intended to be used for calculating equivalent continuous sound levels, not L_{max}.
- L_{max} is by definition a statistical anomaly, one that may occur 0.0000001% of a year (i.e. 1 second in a year if the period is 1-second).

Time. If measurements are required, the duration of the measurement interval and compliance period are needed. A common duration is one-hour and has been used in the assessment of highway noise. According to the MassCEC study, the longer the averaging time, up to one hour, the more predictable the outcome.[3]

A key challenge in the measurement of noise at receiving properties is contamination from non-project sources (e.g., noise from traffic, insects, aircraft overflights, rustling vegetation, etc.). Shorter duration measurement intervals (e.g., 10, 15 or 20 minute) can be screened for contamination and may be used to inform the assessment of a longer (e.g. one-hour) standard. For example, ANSI/ASA S12.9-2013/Part 3 provides a detailed methodology for removing "contaminated" (non-source) data and calculating a more accurate "source only" sound level.[5]

Given it is often difficult to completely rule out contamination from non-project sources, it may also be helpful to identify that measurements should not exceed the identified decibel threshold XX% of the time. Several jurisdictions, primarily in Europe, have avoided the inherent challenges of measuring sound at the receiver, where contamination issues (e.g. signal to noise concerns) are more pronounced by relying on measurements closer to the source and a propagation model. Germany, Denmark and the Netherlands utilize a modeling-based approach to assessing operational compliance.

Location. There are several options to consider when determining the location the sound requirement is to be evaluated at, including where the code currently evaluates sound levels from other sources. Options considered are primarily at the dwelling or some distance from the dwelling, or at the property line. The status and zoning of the property (e.g., participating or non-participating, agricultural or residential zoning) may also be considered. The selected location should correlate with the threshold level, that is, higher sound levels would be typically allowed at the property line, particularly on large agricultural parcels. Many ordinances identify that the standard be assessed at the residence of a non-participating property owner. If compliance measurements are required, the actual measurement location is about 25 feet from the façade of the home, to avoid reflections from the walls and other vertical surfaces.[5]

3 PREDICTION OF SOUND LEVELS FROM WIND TURBINES

As noted in the MassCEC study[3], compliance with the standard should be predictable. That is, the project proponent and the regulator should be able to reasonably ascertain whether the proposed project can meet the standard.

Bullmore, et al note that for wind energy projects, there is a balance between conservative predications and lost energy potential.[6] They write, "unlike other forms of development, conservative planning of wind farms cannot be offset by increased mitigation without incurring such lost energy generating potential." Larsson et al writes that, "If we now do not want the sound level to exceed a certain limit than we have to measure the sound during all possible sound propagation conditions that can occur at the site. Holding in mind that some of these conditions are very rare and may be occur once a year, once a thirty-year or even a once a hundred year or so [sic]. Even a very sophisticated sound propagation model cannot take all such situations into consideration. It is therefore necessary to accept that such rare conditions are not to be considered[7]." Thus, while the goal of a prediction model is to assess the sound level consistent with the regulatory noise limit, there can still be a probability of exceedance, so long as it is small. Statistically, one cannot predict the absolute maximum, because in a gaussian normal distribution, the tails are infinite.

A review of modeling by the Presiding Examiners in a recent wind energy permitting case discusses the balance of using conservative but realistic assumptions. Quoting the record "We are persuaded, however, that the PNIA [Preconstruction Noise Impact Assessment] provides an appropriate, conservative evaluation of the actual expected sound levels, including a likely worst-case scenario for the existing real-world conditions, over appropriate time intervals." They found that overly conservative modeling inputs "present an unrealistic worst-case scenario that is unlikely to happen. We do not think that is what is required by … the regulations."[8]

The MassCEC study found that the most predictable metrics are the A-weighted L_{90} and L_{eq}, with a one-hour averaging time. The L_{max} is the least predictable, as it relies on an instantaneous averaging time. The ISO 9613-2 sound propagation modeling methodology is the most commonly used in the U.S. for prediction of wind turbine sound levels.[9] In this methodology, there are several parameters that influence the predicted results and include:

- Ground factor – This factor ranges from 0 to 1, representing the proportion of porous ground.
- Terrain screening – Terrain blocking the line of sight reduces the sound level at receivers.
- Vegetation – Vegetation blocking the line of sight reduces the sound level at receivers.
- Receiver height – At ground factors other than zero, higher receiver heights tend to increase overall A-weighted sound levels. When a ground factor of 0 is used, receiver height does not alter the result.
- Temperature and Humidity – Atmospheric absorption is influenced by temperature and humidity and becomes more important at very large distances, distances beyond the typical critical prediction points. Typical values of 10 degrees C and 70% relative humidity result in the smallest reduction in sound levels caused by air absorption at the key frequencies which most influence the A-weighted sound level.

Ground factor. The ground factor has a substantial impact on modeled sound levels. Porous ground (G=1) leads to lower overall sound levels while hard ground (G=0) leads to higher overall sound levels. Most ground around wind projects are usually classified as porous, i.e., "ground covered by grass, trees or other vegetation, and all other ground surfaces suitable for the growth of vegetation, such as farming land." [10] However, many studies have shown that the use of a ground factor of 1.0 underestimates actual sound levels. Kaliski and Duncan[11] found that the use of G=1.0 over farmland underestimated by, on average, 5 dB, while the MassCEC study found underestimation by as much as 7 dB.[3]

A Noise Working Group on wind turbine noise in the United Kingdom suggested two options for modeling wind turbines using ISO 9613-2. The first is to use G=0 with the turbine vendors stated sound power level. The second is to use G=0.5 with a 4-meter receptor height and sound power level that includes an uncertainty adjustment. They recommended that G=1 not be used. [12] The United Kingdom's Institute of Acoustics (IoA) formalized these recommendations in their best practice guidelines.[13]

Additional reviews of multiple measurements have found that G=1 should be avoided and that the two suggested methods yield reasonable predictions.[14] As shown in the Validation section of this paper, G=0 with no added uncertainty yielded conservative results for both flat and mountainous (including constant-slope and concave) terrain on grassy and densely forested porous ground (both frozen and unfrozen). In our experience, G=0.5, + 2 dB uncertainty and 4-meter receiver height yields very similar results to G=0 (generally within 0.1 to 0.3 dB -- note that while computations can be predicted to 1/10 or 1/100th of a decibel, such precision is not supported by the data, instrumentation or field methods).

Other ground factors and methodologies can also be used. For example, for shorter averaging time, a higher uncertainty could be used. When overall average trends using a series of short-term (e.g., 10-minute) L_{90} or L_{50}, or long-term (e.g., annual) averaging periods, a softer ground or lower uncertainty can be considered. A ground factor of 1 has not been supported by the literature, except when ISO 9613-2 is used with a meteorological adjustment factor from CONCAWE. [11][14][15]

Alternatively, ISO 9613-2 offers the use of a non-spectral ground actuation method, which has been supported for uneven terrain when the A-weighted sound level is of interest. The MassCEC study [3] found that the measured five-minute L_{eq}s were overpredicted by about 1 to 3 dB when using non-spectral ground with receiver height of 1.0 meters and no uncertainty adjustment, with a greatest overprediction in mountainous terrain.

Terrain Screening. In mountainous or rolling terrain, terrain can shield some wind turbines from some receivers. Some authors suggest limiting terrain attenuation to 2 dB.[12][13] However, whether a project meets a regulation is usually governed by receivers that are close to the wind project, where the greatest contribution to the overall sound level is from the closest turbines. These turbines dominate the predicted sound level and are rarely blocked by terrain. If it is of concern, the potential influence of terrain screening can be evaluated by comparing the results with the source at tip height and hub height as well as predictions with and without terrain. Typically, terrain screening does not strongly influence the predicted results and limiting screening attenuation does not alter the findings.

Vegetation. Under ISO 9613-2, vegetation that is dense enough to block the line of sight between source and receiver can attenuate sound, mostly in higher frequencies. We have not found literature that clearly supports the inclusion of attenuation due to vegetation in the modeling of wind turbine noise. Because wind turbines are usually at a higher elevation than receivers, there is little actual biomass between the source and receiver. Literature supporting the use of vegetation screening is lacking.

Receiver Height. With porous or mixed ground, the receiver height can affect the modeled sound level. Taller receivers are modeled to have greater overall A-weighted sound levels. When comparing measurements to predictions, it should be noted that it is not necessary for the modeled receiver height to be the microphone height, rather it can be the height associated with the modeling parameters one is interested in evaluating. For example, it would not be inconsistent to model with a 4-meter receiver height to increase the conservatism of the model, with the expectation that compliance measurements will be done at a 1.5 meters height, a field measurement method that minimizes the potential contamination from wind induced noise. A microphone located four meters above the ground would typically be exposed to higher winds that would result in more wind induced noise than a measurement closer to the ground. For hard ground (G=0), the receiver height has no effect on modeled sound levels. In this case, any receiver height can be used. A receiver height of zero should not be used, as it could result in ambiguous ground attenuation calculations under ISO 9613-2.

Turbine Sound Power Uncertainty. Under IEC 61400-11, the uncertainty around the calculation of sound power is measured. The K-factor, or 95th percentile uncertainty usually ranges from 1 to 2 dB, with 2 dB being common. However, it is important to note that sound power uncertainty does not necessarily translate directly into the same level of uncertainty at the receiver. As noted in Probst, the combined modeling uncertainty for uncorrelated sources is lower than the individual uncertainties. [16] Take for example a simple five-turbine wind project where the uncertainty of each turbine is +/- 2 dB. The resulting uncertainty from the project at a receiver (the sum of all 5 turbines) will be lower than 2 dB. That is, it is unlikely that all turbines will be operating at the upper bounds (upper 95th percentile) of their rated sound level simultaneously. The combined uncertainty from each turbine yields a lower probability that each turbine will reach its highest deviation from the mean all at the same time.

When adding "manufacturer sound power uncertainty" as a constant to results (or to the sound power level), one is not technically addressing "sound power level uncertainty" rather the predictions are adjusted to conservatively account for various types of uncertainty by a factor that has been found to correlate well with field measurements of operating wind projects. This is in part because permitting assessments in the U.S. are typically based on evaluating conservative scenarios that presume the wind direction is downwind or equivalently under a moderate nighttime inversion and that all turbines are experiencing winds that correspond to their highest rated sound emission level.

Background sound level. The effect of background noise can be a significant complicating factor, particularly if measurements at substantial distances are required to demonstrate compliance. This becomes increasingly challenging with lower regulatory noise limits. Figure 1 shows the equivalent continuous average nighttime sound level at over 100 locations throughout the U.S., categorized by land use, and the mean for each land use. In agricultural and rural mountainous areas, where most wind projects in the U.S. are located, background sound levels average 41 dBA, with a range from 30 to 58 dBA (n=69). An on-going study on the attitudes of people living around U.S. wind projects found a similar range of daytime sound levels using the L50 metric. [17]

To subtract background sound levels from an overall measurement, the difference between background and turbine-plus-background should be at least 3 dB and when the difference is 10 dB, no adjustment is required which while optimum, may be challenging to achieve in practice.[5] For example, if a regulatory limit is 45 dBA, locations where the background sound level is already above 42 dBA documenting compliance with receptor-based measurements may be difficult. This presents the potential for false positives (exceedances not resulting from the project) and results in additional uncertainty.

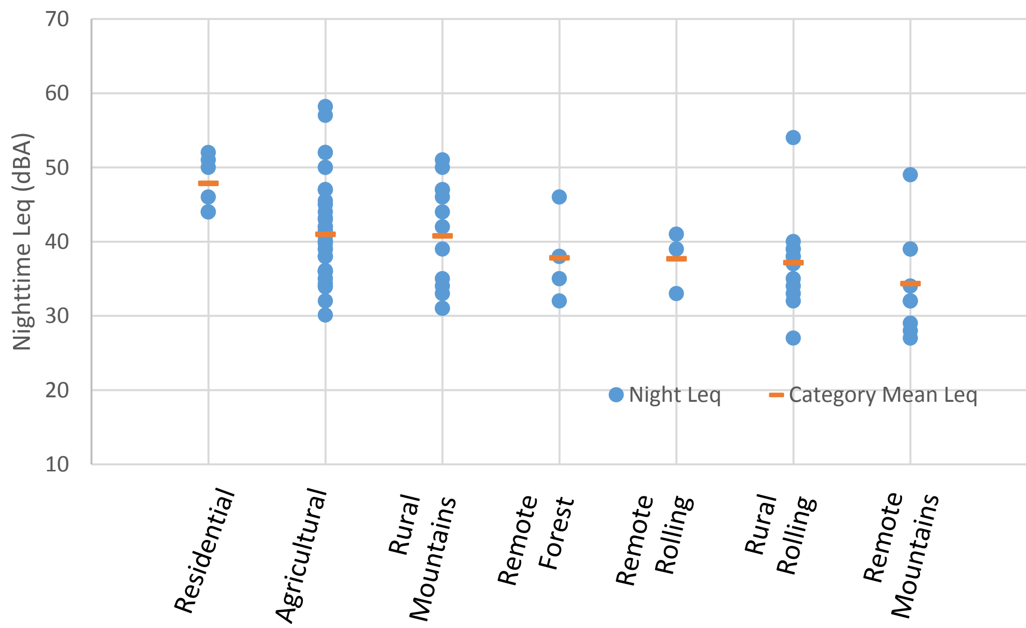

Fig. 1 –Background nighttime L_{eq} at 102 locations at potential wind turbine sites across the U.S. by land use category

Validation. Above it was stated that a ground factor of zero (G=0) or equivalent methods (G=0.5, receiver height at 4 meters, + 2 dB uncertainty) with ISO 9613-2 was found to result in conservative predictions. The following are measurements in the U.S. that support these conclusions:

Stetson Mountain I – Sound levels were measured over four seasons at a ridgeline wind farm and were found to be below modeled predictions even under worst-case operating conditions. The pre-construction modeling assumed maximum sound power levels, a +2 dB manufacturer's uncertainty and a +3 dB modeling uncertainty (for a total of +5 dB), receiver height at 1.5 meters, and G = 0.5. The highest measured 10-minute L_{eq} levels were 4 dB less than the highest modeled levels under worst-case wind turbine sound power and meteorological conditions.[18]

Kingdom Community Wind – Sound levels from these 21 turbines were measured for at least two weeks for eight seasons over two years of operation. Turbine shutdowns were used to allow for background noise to be subtracted. Figure 2 presents the results at a site 1,600 meters from the nearest turbine and predictions based on G = 0, the vendors specified maximum apparent sound power level, terrain screening, and no added uncertainty. The measurements are sorted from the lowest wind speed to highest.[2] Hub height wind speed for each measurement is depicted by the lower green line and the turbine reached its maximum sound power level at 9.8 m/s. During 529 hours of compliance measurements, one period exceeded the modeled sound level by 0.3 dB with the remaining 528 measurements 0.2 dB or more below the modeled level. The terrain between

[2] Periods of icing, rime snow, and rain were removed. Only periods with hub height winds greater than cut-in are included.

the source and receiver would qualify as concave by the Institute of Acoustics (IoA). [8] though the predictions do not implement the IoA adjustment.

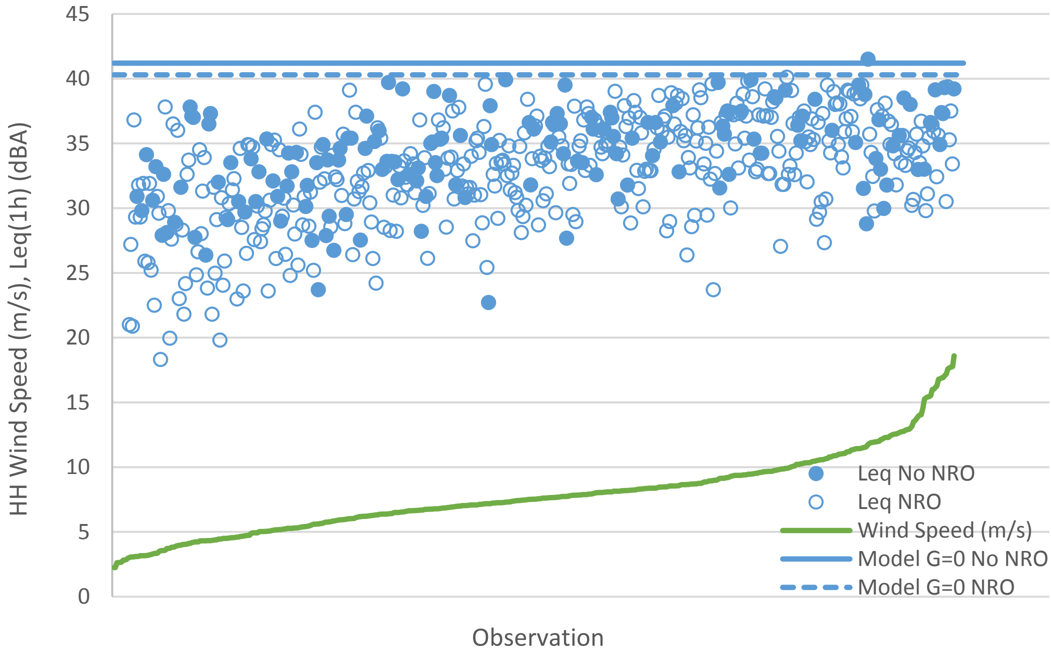

Fig. 2 – Comparison of modeled to monitored sound levels at Kingdom Community Wind

Spruce Mountain Wind – For five years, data for a two-week period was analyzed to determine times when the wind speeds result in the turbines maximum sound power level and also low enough at the monitoring location such that wind-induced noise is at a minimum. This high shear condition is indicative of "worst-case" meteorology. Figure 3 shows the 10-minute L_{eq} is generally 2 dB or more below the modeled sound levels. Periods exceeding the modeled levels were found to be influenced by rain or high wind induced noise. The terrain for this ridgeline project does not satisfy the IoA criteria for concavity.

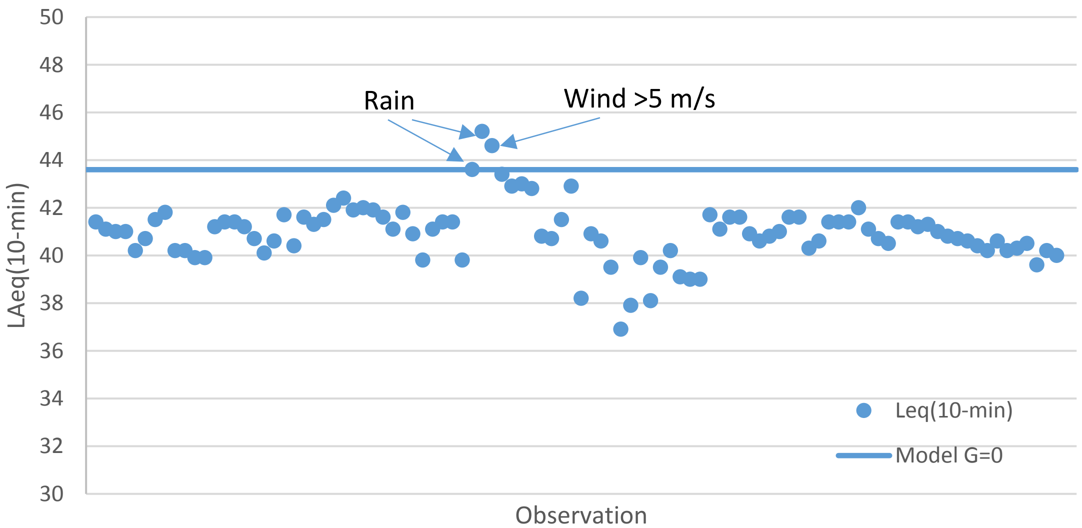

Fig. 3 – Comparison of modeled to monitored sound levels at Spruce Mountain Wind

Saddleback Wind – The same protocol mentioned above for Spruce Mountain was used to evaluate measurements at the Saddleback project. As shown in Figure 4, all 10-minute L_{eq}s were 1 dB or more below the modeled sound level at G=0. The terrain between the source and receiver would qualify as concave by the IoA[13] though the predictions do not implement the IoA adjustment.

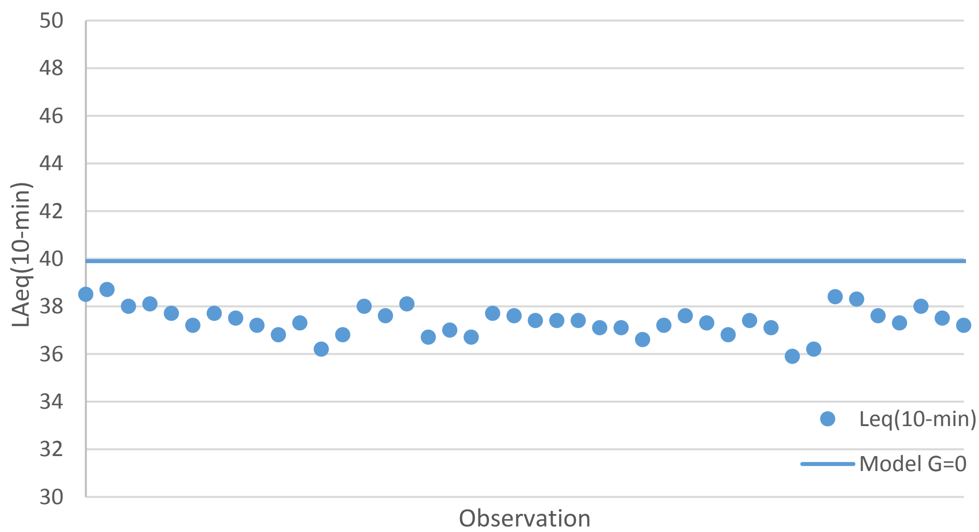

Fig. 4 – Comparison of modeled to monitored sound levels at Saddleback Wind

MassCEC study. The MassCEC study conducted measurements at both flat and mountainous sites. Under both terrain conditions, modeling under G=0 were found to be conservative, with none of the measurement points exceeding the modeled value (see Figure 5). One of the mountainous sites satisfied the IoA criteria for concavity, though predictions did not include this adjustment. Measurements are not corrected for background, but are for times when there was noticeable differences between turbine-on and turbine-shutdown periods.

4 CONCLUSIONS

Meaningful sound regulations should strive to use approaches that are relevant, repeatable, predictable, and reasonable to implement. The L_{eq}, or statistical levels such as the L_{50} or L_{90}, are more apt to be implemented in a manner that that is relevant, repeatable, predictable, and reasonable to implement. The L_{max} metric has not been found to satisfy these goals. The use of the L_{max} presumes detailed knowledge of acoustical terminology which is not demonstrated in typical sound level regulations that establish "maximum permissible sound levels" or state that the "sound level shall not exceed XX dBA".

During the approval phase of a project, predicted levels are compared to regulatory thresholds. Several common and recommended prediction methods used internationally were highlighted and compared favorably to measurements conducted in the U.S. Differences between typical prediction models are also generally not of sufficient magnitude to yield a different community response.

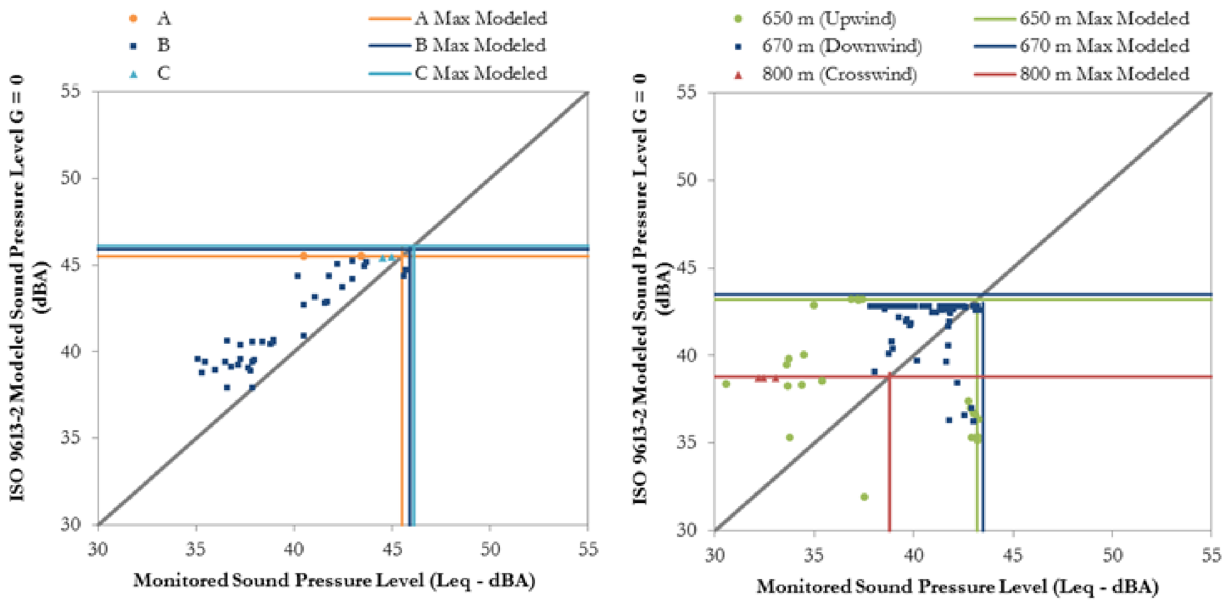

Fig. 5 – Comparison of modeled to monitored sound levels from Figures 18 and 24 of the MassCEC study[3] *– 5-minute Leq, G=0. On left, 330 meters downwind and flat terrain. On right, 660 meters upwind, downwind, and crosswind—all mountainous terrain.*

5 REFERENCES

1. https://publicaccess.zendesk.com/hc/en-us/articles/211393078-Does-the-EPA-regulate-noise-Where-can-I-find-resources-about-noise-pollution-

2. Office of Noise Control, California Department of Health, "Model Community Noise Control Ordinance", April 1977.

3. RSG, Epsilon Associates, Northeast Wind, "Massachusetts Study on Wind Turbine Acoustics," Massachusetts Clean Energy Center and Department of Environmental Protection (2016).

4. Sakamoto, S. et al., 2013. Loudness evaluation of general environmental noise containing low frequency components. *42nd International Congress and Exposition on Noise Control Engineering 2013, INTER-NOISE 2013: Noise Control for Quality of Life*, 7, pp.5368–5374.

5. American National Standards Institute, "Quantities and Procedures for Description and Measurement of Environmental Sound — Part 3: Short-term Measurements with an Observer Present," ANSI/ASA S12.9-2013/Part 3 (2013).

6. Andrew Bullmore, Justin Adcock, Mark Jiggins, Matthew Cand, "Wind farm predictions and comparison with measurements," *Third International Meeting on Wind Turbine Noise* (2009).

7. Conny Larsson, Olof Ohlund, "Wind turbine sound – metrics and guidelines," *Proceedings of InterNoise 2014*, Melbourne Australia (2014).

8. Case 14-F-0490 – Application of Cassadaga Wind LLC for a Certificate of Environmental Compatibility and Public Need Pursuant to Article 10 to Construct a Wind Energy Project, Recommended Decision, November 8, 2017.

9. Erik Kalapinski, Tricia Pellerin, "Wind turbine acoustic modeling with the ISO 9613-2 standard: Methodologies to address contraints," *Third International Meeting on Wind Turbine Noise* (2009).

10. International Organization for Standardization, "Acoustics – Attenuation of sound during propagation outdoors. Part 2: General method of calculation," ISO 9613-2 (1996).

11. Kenneth Kaliski, Eddie Duncan, "Propagation modeling parameters for wind power projects, *Sound & Vibration* December (2008).

12. Dick Bowdler, Andrew Bullmore, Bob Davis, Malcolm Hayes, Mark Jiggins, Geoff Leventhall, "Prediction and assessment of wind turbine noise: Agreement about relevant factors for noise assemment from wind energy projects," *Acoustics Bulletin,* March/April (2009).

13. Mathew Cand, Robert Davis, Chris Jordan, Malcolm Hayes, Richard Perkins, "A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise," Institute of Acoustics, United Kingdom (2013).

14. Evans, T. & Cooper, J., 2012. Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms. *Acoustics Australia*, 40(1), pp. 28–36.

15. C.J. Manning, "The Propagation of noise from petroleum and petrochemical complexes to neighbouring communities," CONCAWE Report 4/81, (1981).

16. Wolfgang Probst, "Uncertainties in the prediction of environmental noise and in noise mapping,", *Acoustique Techniques* **(40)** p34 (2005).

17. https://emp.lbl.gov/publications/exploring-prediction-wind-turbine

18. Wallace, Charles F. et al, *Wind turbine noise modeling and verification: two case studies – Mars Hill and Stetson Mountain I, Maine*, presented at NOISE-CON 2011, Portland, Oregon.

GUIDELINES

FOR

COMMUNITY NOISE

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This WHO document on the *Guidelines for Community Noise* is the outcome of the WHO- expert task force meeting held in London, United Kingdom, in April 1999. It bases on the document entitled "Community Noise" that was prepared for the World Health Organization and published in 1995 by the Stockholm University and Karolinska Institute.

World Health Organization, Geneva
Cluster of Sustainable Development and Healthy Environment (SDE)
Department of the Protection of the Human Environment (PHE)
Occupational and Environmental Health (OEH)

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Foreword

Noise has always been an important environmental problem for man. In ancient Rome, rules existed as to the noise emitted from the ironed wheels of wagons which battered the stones on the pavement, causing disruption of sleep and annoyance to the Romans. In Medieval Europe, horse carriages and horse back riding were not allowed during night time in certain cities to ensure a peaceful sleep for the inhabitants. However, the noise problems of the past are incomparable with those of modern society. An immense number of cars regularly cross our cities and the countryside. There are heavily laden lorries with diesel engines, badly silenced both for engine and exhaust noise, in cities and on highways day and night. Aircraft and trains add to the environmental noise scenario. In industry, machinery emits high noise levels and amusement centres and pleasure vehicles distract leisure time relaxation.

In comparison to other pollutants, the control of environmental noise has been hampered by insufficient knowledge of its effects on humans and of dose-response relationships as well as a lack of defined criteria. While it has been suggested that noise pollution is primarily a "luxury" problem for developed countries, one cannot ignore that the exposure is often higher in developing countries, due to bad planning and poor construction of buildings. The effects of the noise are just as widespread and the long term consequences for health are the same. In this perspective, practical action to limit and control the exposure to environmental noise are essential. Such action must be based upon proper scientific evaluation of available data on effects, and particularly dose-response relationships. The basis for this is the
process of risk assessment and risk management.

The extent of the noise problem is large. In the European Union countries about 40 % of the population are exposed to road traffic noise with an equivalent sound pressure level exceeding 55 dB(A) daytime and 20 % are exposed to levels exceeding 65 dB(A). Taking all exposure to transportation noise together about half of the European Union citizens are estimated to live in zones which do not ensure acoustical comfort to residents. More than 30 % are exposed at night to equivalent sound pressure levels exceeding 55 dB(A) which are disturbing to sleep. The noise pollution problem is also severe in cities of developing countries and caused mainly by traffic. Data collected alongside densely travelled roads were found to have equivalent sound pressure levels for 24 hours of 75 to 80 dB(A).

The scope of WHO's effort to derive guidelines for community noise is to consolidate actual scientific knowledge on the health impacts of community noise and to provide guidance to environmental health authorities and professional trying to protect people from the harmful effects of noise in non-industrial environments. Guidance on the health effects of noise exposure of the population has already been given in an early publication of the series of Environmental Health Criteria. The health risk to humans from exposure to environmental noise was evaluated and guidelines values derived. The issue of noise control and health protection was briefly addressed.
At a WHO/EURO Task Force Meeting in Düsseldorf, Germany, in 1992, the health criteria and guideline values were revised and it was agreed upon updated guidelines in consensus. The essentials of the deliberations of the Task Force were published by Stockholm University and Karolinska Institute in 1995. In a recent Expert Task Force Meeting convened in April 1999 in London, United Kingdom, the Guidelines for Community Noise were extended to provide global coverage and applicability, and the issues of noise assessment and control were addressed in more detail. This document is the outcome of the consensus deliberations of the WHO Expert Task Force.

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Preface

Community noise (also called environmental noise, residential noise or domestic noise) is defined as noise emitted from all sources except noise at the industrial workplace. Main sources of community noise include road, rail and air traffic, industries, construction and public work, and the neighbourhood. The main indoor sources of noise are ventilation systems, office machines, home appliances and neighbours. Typical neighbourhood noise comes from premises and installations related to the catering trade (restaurant, cafeterias, discotheques, etc.); from live or recorded music; sport events including motor sports; playgrounds; car parks; and domestic animals such as barking dogs. Many countries have regulated community noise from road and rail traffic, construction machines and industrial plants by applying emission standards, and by regulating the acoustical properties of buildings. In contrast, few countries have regulations on community noise from the neighbourhood, probably due to the lack of methods to define and measure it, and to the difficulty of controlling it. In large cities throughout the world, the general population is increasingly exposed to community due to the sources mentioned above and the health effects of these exposures are considered to be a more and more important public health problem. Specific effects to be considered when setting community noise guidelines include: interference with communication; noise-induced hearing loss; sleep disturbance effects; cardiovascular and psycho-physiological effects; performance reduction effects; annoyance responses; and effects on social behaviour.

Since 1980, the World Health Organization (WHO) has addressed the problem of community noise. Health-based guidelines on community noise can serve as the basis for deriving noise standards within a framework of noise management. Key issues of noise management include abatement options; models for forecasting and for assessing source control action; setting noise emission standards for existing and planned sources; noise exposure assessment; and testing the compliance of noise exposure with noise immission standards. In 1992, the WHO Regional Office for Europe convened a task force meeting which set up guidelines for community noise. A preliminary publication of the Karolinska Institute, Stockholm, on behalf of WHO, appeared in 1995. This publication served as the basis for the globally applicable *Guidelines for Community Noise* presented in this document. An expert task force meeting was convened by WHO in March 1999 in London, United Kingdom, to finalize the guidelines.

The *Guidelines for Community Noise* have been prepared as a practical response to the need for action on community noise at the local level, as well as the need for improved legislation, management and guidance at the national and regional levels. WHO will be pleased to see that these guidelines are used widely. Continuing efforts will be made to improve its content and structure. It would be appreciated if the users of the *Guidelines* provide feedback from its use and their own experiences. Please send your comments and suggestions on the WHO *Guidelines for Community Noise – Guideline document* to the Department of the Protection of the Human Environment, Occupational and Environmental Health, World Health Organization, Geneva, Switzerland (Fax: +41 22-791 4123, e-mail: schwelad@who.int).

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Executive Summary

1. Introduction

Community noise (also called environmental noise, residential noise or domestic noise) is defined as noise emitted from all sources except noise at the industrial workplace. Main sources of community noise include road, rail and air traffic; industries; construction and public work; and the neighbourhood. The main indoor noise sources are ventilation systems, office machines, home appliances and neighbours.

In the European Union about 40% of the population is exposed to road traffic noise with an equivalent sound pressure level exceeding 55 dB(A) daytime, and 20% are exposed to levels exceeding 65 dB(A). When all transportation noise is considered, more than half of all European Union citizens is estimated to live in zones that do not ensure acoustical comfort to residents. At night, more than 30% are exposed to equivalent sound pressure levels exceeding 55 dB(A), which are disturbing to sleep. Noise pollution is also severe in cities of developing countries. It is caused mainly by traffic and alongside densely-travelled roads equivalent sound pressure levels for 24 hours can reach 75–80 dB(A).

In contrast to many other environmental problems, noise pollution continues to grow and it is accompanied by an increasing number of complaints from people exposed to the noise. The growth in noise pollution is unsustainable because it involves direct, as well as cumulative, adverse health effects. It also adversely affects future generations, and has socio-cultural, esthetic and economic effects.

2. Noise sources and measurement

Physically, there is no distinction between sound and noise. Sound is a sensory perception and the complex pattern of sound waves is labeled noise, music, speech etc. Noise is thus defined as unwanted sound.

Most environmental noises can be approximately described by several simple measures. All measures consider the frequency content of the sounds, the overall sound pressure levels and the variation of these levels with time. Sound pressure is a basic measure of the vibrations of air that make up sound. Because the range of sound pressures that human listeners can detect is very wide, these levels are measured on a logarithmic scale with units of decibels. Consequently, sound pressure levels cannot be added or averaged arithmetically. Also, the sound levels of most noises vary with time, and when sound pressure levels are calculated, the instantaneous pressure fluctuations must be integrated over some time interval.

Most environmental sounds are made up of a complex mix of many different frequencies. Frequency refers to the number of vibrations per second of the air in which the sound is propagating and it is measured in Hertz (Hz). The audible frequency range is normally considered to be 20–20 000 Hz for younger listeners with unimpaired hearing. However, our hearing systems are not equally sensitive to all sound frequencies, and to compensate for this various types of filters or frequency weighting have been used to determine the relative strengths of frequency components making up a particular environmental noise. The A-weighting is most commonly used and weights lower frequencies as less important than mid- and higher-frequencies. It is intended to approximate the frequency response of our hearing system.

The effect of a combination of noise events is related to the combined sound energy of those events (the equal energy principle). The sum of the total energy over some time period gives a level equivalent to the average sound energy over that period. Thus, LAeq,T is the energy average equivalent level of the A-weighted sound over a period T. LAeq,T should be used to measure continuing sounds, such as road traffic noise or types of more-or-less continuous industrial noises. However, when there are distinct events to the noise, as with aircraft or railway noise, measures of individual events such as the maximum noise level (LAmax), or the weighted sound exposure level (SEL), should also be obtained in addition to LAeq,T. Time-varying environmental sound levels have also been described in terms of percentile levels.

Currently, the recommended practice is to assume that the equal energy principle is approximately valid for most types of noise and that a simple LAeq,T measure will indicate the expected effects of the noise reasonably well. When the noise consists of a small number of discrete events, the A-weighted maximum level (LAmax) is a better indicator of the disturbance to sleep and other activities. In most cases, however, the A-weighted sound exposure level (SEL) provides a more consistent measure of single-noise events because it is based on integration over the complete noise event. In combining day and night LAeq,T values, night-time weightings are often added. Night-time weightings are intended to reflect the expected increased sensitivity to annoyance at night, but they do not protect people from sleep disturbance.

Where there are no clear reasons for using other measures, it is recommended that LAeq,T be used to evaluate more-or-less continuous environmental noises. Where the noise is principally composed of a small number of discrete events, the additional use of LAmax or SEL is recommended. There are definite limitations to these simple measures, but there are also many practical advantages, including economy and the benefits of a standardized approach.

3. Adverse health effects of noise

The health significance of noise pollution is given in chapter 3 of the *Guidelines* under separate headings according to the specific effects: noise-induced hearing impairment; interference with speech communication; disturbance of rest and sleep; psychophysiological, mental-health and performance effects; effects on residential behaviour and annoyance; and interference with intended activities. This chapter also considers vulnerable groups and the combined effects of mixed noise sources.

Hearing impairment is typically defined as an increase in the threshold of hearing. Hearing deficits may be accompanied by tinnitus (ringing in the ears). Noise-induced hearing impairment occurs predominantly in the higher frequency range of 3 000–6 000 Hz, with the largest effect at 4 000 Hz. But with increasing LAeq,8h and increasing exposure time, noise-induced hearing impairment occurs even at frequencies as low as 2 000 Hz. However, hearing impairment is not expected to occur at LAeq,8h levels of 75 dB(A) or below, even for prolonged occupational noise exposure.

Worldwide, noise-induced hearing impairment is the most prevalent irreversible occupational hazard and it is estimated that 120 million people worldwide have disabling hearing difficulties. In developing countries, not only occupational noise but also environmental noise is an increasing risk factor for hearing impairment. Hearing damage can also be caused by certain diseases, some industrial chemicals, ototoxic drugs, blows to the head, accidents and hereditary origins. Hearing deterioration is also associated with the ageing process itself (presbyacusis).

The extent of hearing impairment in populations exposed to occupational noise depends on the value of LAeq,8h, the number of noise-exposed years, and on individual susceptibility. Men and women are equally at risk for noise-induced hearing impairment. It is expected that environmental and leisure-time noise with a LAeq,24h of 70 dB(A) or below will not cause hearing impairment in the large majority of people, even after a lifetime exposure. For adults exposed to impulse noise at the workplace, the noise limit is set at peak sound pressure levels of 140 dB, and the same limit is assumed to be appropriate for environmental and leisure-time noise. In the case of children, however, taking into account their habits while playing with noisy toys, the peak sound pressure should never exceed 120 dB. For shooting noise with LAeq,24h levels greater than 80 dB(A), there may be an increased risk for noise-induced hearing impairment.

The main social consequence of hearing impairment is the inability to understand speech in daily living conditions, and this is considered to be a severe social handicap. Even small values of hearing impairment (10 dB averaged over 2 000 and 4 000 Hz and over both ears) may adversely affect speech comprehension.

Speech intelligibility is adversely affected by noise. Most of the acoustical energy of speech is in the frequency range of 100–6 000 Hz, with the most important cue-bearing energy being between 300–3 000 Hz. Speech interference is basically a masking process, in which simultaneous interfering noise renders speech incapable of being understood. Environmental noise may also mask other acoustical signals that are important for daily life, such as door bells, telephone signals, alarm clocks, fire alarms and other warning signals, and music.

Speech intelligibility in everyday living conditions is influenced by speech level; speech pronunciation; talker-to-listener distance; sound level and other characteristics of the interfering noise; hearing acuity; and by the level of attention. Indoors, speech communication is also affected by the reverberation characteristics of the room. Reverberation times over 1 s produce loss in speech discrimination and make speech perception more difficult and straining. For full sentence intelligibility in listeners with normal hearing, the signal-to-noise ratio (i.e. the difference between the speech level and the sound level of the interfering noise) should be at least 15 dB(A). Since the sound pressure level of normal speech is about 50 dB(A), noise with sound levels of 35 dB(A) or more interferes with the intelligibility of speech in smaller rooms. For vulnerable groups even lower background levels are needed, and a reverberation time below 0.6 s is desirable for adequate speech intelligibility, even in a quiet environment.

The inability to understand speech results in a large number of personal handicaps and behavioural changes. Particularly vulnerable are the hearing impaired, the elderly, children in the process of language and reading acquisition, and individuals who are not familiar with the spoken language.

Sleep disturbance is a major effect of environmental noise. It may cause primary effects during sleep, and secondary effects that can be assessed the day after night-time noise exposure. Uninterrupted sleep is a prerequisite for good physiological and mental functioning, and the primary effects of sleep disturbance are: difficulty in falling asleep; awakenings and alterations of sleep stages or depth; increased blood pressure, heart rate and finger pulse amplitude; vasoconstriction; changes in respiration; cardiac arrhythmia; and increased body movements. The difference between the sound levels of a noise event and background sound levels, rather than the absolute noise level, may determine the reaction probability. The probability of being awakened increases with the number of noise events per night. The secondary, or after-effects, the following morning or day(s) are: reduced perceived sleep quality; increased fatigue; depressed mood or well-being; and decreased performance.

For a good night's sleep, the equivalent sound level should not exceed 30 dB(A) for continuous background noise, and individual noise events exceeding 45 dB(A) should be avoided. In setting limits for single night-time noise exposures, the intermittent character of the noise has to be taken into account. This can be achieved, for example, by measuring the number of noise events, as well as the difference between the maximum sound level and the background sound level. Special attention should also be given to: noise sources in an environment with low background sound levels; combinations of noise and vibrations; and to noise sources with low-frequency components.

Physiological Functions. In workers exposed to noise, and in people living near airports, industries and noisy streets, noise exposure may have a large temporary, as well as permanent, impact on physiological functions. After prolonged exposure, susceptible individuals in the general population may develop permanent effects, such as hypertension and ischaemic heart disease associated with exposure to high sound levels. The magnitude and duration of the effects are determined in part by individual characteristics, lifestyle behaviours and environmental conditions. Sounds also evoke reflex responses, particularly when they are unfamiliar and have a sudden onset.

Workers exposed to high levels of industrial noise for 5–30 years may show increased blood pressure and an increased risk for hypertension. Cardiovascular effects have also been demonstrated after long-term exposure to air- and road-traffic with LAeq,24h values of 65–70 dB(A). Although the associations are weak, the effect is somewhat stronger for ischaemic heart disease than for hypertension. Still, these small risk increments are important because a large number of people are exposed.

Mental Illness. Environmental noise is not believed to cause mental illness directly, but it is assumed that it can accelerate and intensify the development of latent mental disorders. Exposure to high levels of occupational noise has been associated with development of neurosis, but the findings on environmental noise and mental-health effects are inconclusive. Nevertheless, studies on the use of drugs such as tranquillizers and sleeping pills, on psychiatric symptoms and on mental hospital admission rates, suggest that community noise may have adverse effects on mental health.

Performance. It has been shown, mainly in workers and children, that noise can adversely affect performance of cognitive tasks. Although noise-induced arousal may produce better performance in simple tasks in the short term, cognitive performance substantially deteriorates for more complex tasks. Reading, attention, problem solving and memorization are among the cognitive effects most strongly affected by noise. Noise can also act as a distracting stimulus and impulsive noise events may produce disruptive effects as a result of startle responses.

Noise exposure may also produce after-effects that negatively affect performance. In schools around airports, children chronically exposed to aircraft noise under-perform in proof reading, in persistence on challenging puzzles, in tests of reading acquisition and in motivational capabilities. It is crucial to recognize that some of the adaptation strategies to aircraft noise, and the effort necessary to maintain task performance, come at a price. Children from noisier areas have heightened sympathetic arousal, as indicated by increased stress hormone levels, and elevated resting blood pressure. Noise may also produce impairments and increase in errors at work, and some accidents may be an indicator of performance deficits.

Social and Behavioural Effects of Noise; Annoyance. Noise can produce a number of social and behavioural effects as well as annoyance. These effects are often complex, subtle and indirect and many effects are assumed to result from the interaction of a number of non-auditory variables. The effect of community noise on annoyance can be evaluated by questionnaires or by assessing the disturbance of specific activities. However, it should be recognized that equal levels of different traffic and industrial noises cause different magnitudes of annoyance. This is because annoyance in populations varies not only with the characteristics of the noise, including the noise source, but also depends to a large degree on many non-acoustical factors of a social, psychological, or economic nature. The correlation between noise exposure and general annoyance is much higher at group level than at individual level. Noise above 80 dB(A) may also reduce helping behaviour and increase aggressive behaviour. There is particular concern that high-level continuous noise exposures may increase the susceptibility of schoolchildren to feelings of helplessness.

Stronger reactions have been observed when noise is accompanied by vibrations and contains low-frequency components, or when the noise contains impulses, such as with shooting noise. Temporary, stronger reactions occur when the noise exposure increases over time, compared to a constant noise exposure. In most cases, LAeq,24h and L_{dn} are acceptable approximations of noise exposure related to annoyance. However, there is growing concern that all the component parameters should be individually assessed in noise exposure investigations, at least in the complex cases. There is no consensus on a model for total annoyance due to a combination of environmental noise sources.

Combined Effects on Health of Noise from Mixed Sources. Many acoustical environments consist of sounds from more than one source, i.e. there are mixed sources, and some combinations of effects are common. For example, noise may interfere with speech in the day and create sleep disturbance at night.

These conditions certainly apply to residential areas heavily polluted with noise. Therefore, it is important that the total adverse health load of noise be considered over 24 hours, and that the precautionary principle for sustainable development be applied.

Vulnerable Subgroups. Vulnerable subgroups of the general population should be considered when recommending noise protection or noise regulations. The types of noise effects, specific environments and specific lifestyles are all factors that should be addressed for these subgroups. Examples of vulnerable subgroups are: people with particular diseases or medical problems (e.g. high blood pressure); people in hospitals or rehabilitating at home; people dealing with complex cognitive tasks; the blind; people with hearing impairment; fetuses, babies and young children; and the elderly in general. People with impaired hearing are the most adversely affected with respect to speech intelligibility. Even slight hearing impairments in the high-frequency sound range may cause problems with speech perception in a noisy environment. A majority of the population belongs to the subgroup that is vulnerable to speech interference.

4. Guideline values

In chapter 4, guideline values are given for specific health effects of noise and for specific environments.

Specific health effects.

Interference with Speech Perception. A majority of the population is susceptible to speech interference by noise and belongs to a vulnerable subgroup. Most sensitive are the elderly and persons with impaired hearing. Even slight hearing impairments in the high-frequency range may cause problems with speech perception in a noisy environment. From about 40 years of age, the ability of people to interpret difficult, spoken messages with low linguistic redundancy is impaired compared to people 20–30 years old. It has also been shown that high noise levels and long reverberation times have more adverse effects in children, who have not completed language acquisition, than in young adults.

When listening to complicated messages (at school, foreign languages, telephone conversation) the signal-to-noise ratio should be at least 15 dB with a voice level of 50 dB(A). This sound level corresponds on average to a casual voice level in both women and men at 1 m distance. Consequently, for clear speech perception the background noise level should not exceed 35 dB(A). In classrooms or conference rooms, where speech perception is of paramount importance, or for sensitive groups, background noise levels should be as low as possible. Reverberation times below 1 s are also necessary for good speech intelligibility in smaller rooms. For sensitive groups, such as the elderly, a reverberation time below 0.6 s is desirable for adequate speech intelligibility even in a quiet environment.

Hearing Impairment. Noise that gives rise to hearing impairment is by no means restricted to occupational situations. High noise levels can also occur in open air concerts, discotheques, motor sports, shooting ranges, in dwellings from loudspeakers, or from leisure activities. Other important sources of loud noise are headphones, as well as toys and fireworks which can emit impulse noise. The ISO standard 1999 gives a method for estimating noise-induced hearing impairment in populations exposed to all types of noise (continuous, intermittent, impulse) during working hours. However, the evidence strongly suggests that this method should also be used to calculate hearing impairment due to noise exposure from environmental and leisure time activities. The ISO standard 1999 implies that long-term exposure to LAeq,24h noise levels of up to 70 dB(A) will not result in hearing impairment. To avoid hearing loss from impulse noise exposure, peak sound pressures should never exceed 140 dB for adults, and 120 dB for children.

Sleep Disturbance. Measurable effects of noise on sleep begin at LAeq levels of about 30 dB. However, the more intense the background noise, the more disturbing is its effect on sleep. Sensitive groups mainly include the elderly, shift workers, people with physical or mental disorders and other individuals who have difficulty sleeping.

Sleep disturbance from intermittent noise events increases with the maximum noise level. Even if the total equivalent noise level is fairly low, a small number of noise events with a high maximum sound pressure level will affect sleep. Therefore, to avoid sleep disturbance, guidelines for community noise should be expressed in terms of the equivalent sound level of the noise, as well as in terms of maximum noise levels and the number of noise events. It should be noted that low-frequency noise, for example, from ventilation systems, can disturb rest and sleep even at low sound pressure levels.

When noise is continuous, the equivalent sound pressure level should not exceed 30 dB(A) indoors, if negative effects on sleep are to be avoided. For noise with a large proportion of low-frequency sound a still lower guideline value is recommended. When the background noise is low, noise exceeding 45 dB LAmax should be limited, if possible, and for sensitive persons an even lower limit is preferred. Noise mitigation targeted to the first part of the night is believed to be an effective means for helping people fall asleep. It should be noted that the adverse effect of noise partly depends on the nature of the source. A special situation is for newborns in incubators, for which the noise can cause sleep disturbance and other health effects.

Reading Acquisition. Chronic exposure to noise during early childhood appears to impair reading acquisition and reduces motivational capabilities. Evidence indicates that the longer the exposure, the greater the damage. Of recent concern are the concomitant psychophysiological changes (blood pressure and stress hormone levels). There is insufficient information on these effects to set specific guideline values. It is clear, however, that daycare centres and schools should not be located near major noise sources, such as highways, airports, and industrial sites.

Annoyance. The capacity of a noise to induce annoyance depends upon its physical characteristics, including the sound pressure level, spectral characteristics and variations of these properties with time. During daytime, few people are highly annoyed at LAeq levels below 55 dB(A), and few are moderately annoyed at LAeq levels below 50 dB(A). Sound levels during the evening and night should be 5–10 dB lower than during the day. Noise with low-frequency components require lower guideline values. For intermittent noise, it is emphasized that it is necessary to take into account both the maximum sound pressure level and the number of noise events. Guidelines or noise abatement measures should also take into account residential outdoor activities.

Social Behaviour. The effects of environmental noise may be evaluated by assessing its interference with social behavior and other activities. For many community noises, interference with rest/recreation/watching television seem to be the most important effects. There is fairly consistent evidence that noise above 80 dB(A) causes reduced helping behavior, and that loud noise also increases aggressive behavior in individuals predisposed to aggressiveness. In schoolchildren, there is also concern that high levels of chronic noise contribute to feelings of helplessness. Guidelines on this issue, together with cardiovascular and mental effects, must await further research.

Specific environments.

A noise measure based only on energy summation and expressed as the conventional equivalent measure, LAeq, is not enough to characterize most noise environments. It is equally important to measure the maximum values of noise fluctuations, preferably combined with a measure of the number of noise events. If the noise includes a large proportion of low-frequency components, still lower values than the guideline values below will be needed. When prominent low-frequency components are present, noise measures based on A-weighting are inappropriate. The difference between dB(C) and dB(A) will give crude information about the presence of low-frequency components in noise, but if the difference is more than 10 dB, it is recommended that a frequency analysis of the noise be performed. It should be noted that a large proportion of low-frequency components in noise may increase considerably the adverse effects on health.

In Dwellings. The effects of noise in dwellings, typically, are sleep disturbance, annoyance and speech interference. For bedrooms the critical effect is sleep disturbance. Indoor guideline values for bedrooms are 30 dB LAeq for continuous noise and 45 dB LAmax for single sound events. Lower noise levels may be disturbing depending on the nature of the noise source. At night-time, outside sound levels about 1 metre from facades of living spaces should not exceed 45 dB LAeq, so that people may sleep with bedroom windows open. This value was obtained by assuming that the noise reduction from outside to inside with the window open is 15 dB. To enable casual conversation indoors during daytime, the sound level of interfering noise should not exceed 35 dB LAeq. The maximum sound pressure level should be measured with the sound pressure meter set at “Fast”.

To protect the majority of people from being seriously annoyed during the daytime, the outdoor sound level from steady, continuous noise should not exceed 55 dB LAeq on balconies, terraces and in outdoor living areas. To protect the majority of people from being moderately annoyed during the daytime, the outdoor sound level should not exceed 50 dB LAeq. Where it is practical and feasible, the lower outdoor sound level should be considered the maximum desirable sound level for new development.

In Schools and Preschools. For schools, the critical effects of noise are speech interference, disturbance of information extraction (e.g. comprehension and reading acquisition), message communication and annoyance. To be able to hear and understand spoken messages in class rooms, the background sound level should not exceed 35 dB LAeq during teaching sessions. For hearing impaired children, a still lower sound level may be needed. The reverberation time in the classroom should be about 0.6 s, and preferably lower for hearing impaired children. For assembly halls and cafeterias in school buildings, the reverberation time should be less than 1 s. For outdoor playgrounds the sound level of the noise from external sources should not exceed 55 dB LAeq, the same value given for outdoor residential areas in daytime.

For preschools, the same critical effects and guideline values apply as for schools. In bedrooms in preschools during sleeping hours, the guideline values for bedrooms in dwellings should be used.

In Hospitals. For most spaces in hospitals, the critical effects are sleep disturbance, annoyance, and communication interference, including warning signals. The LAmax of sound events during the night should not exceed 40 dB(A) indoors. For ward rooms in hospitals, the guideline values indoors are 30dB LAeq, together with 40 dB LAmax during night. During the day and evening the guideline value indoors is 30 dB LAeq. The maximum level should be measured with the sound pressure instrument set at “Fast”.

Since patients have less ability to cope with stress, the LAeq level should not exceed 35 dB in most rooms in which patients are being treated or observed. Attention should be given to the sound levels in intensive care units and operating theaters. Sound inside incubators may result in health problems for neonates, including sleep disturbance, and may also lead to hearing impairment. Guideline values for sound levels in incubators must await future research.

Ceremonies, Festivals and Entertainment Events. In many countries, there are regular ceremonies, festivals and entertainment events to celebrate life periods. Such events typically produce loud sounds, including music and impulsive sounds. There is widespread concern about the effect of loud music and impulsive sounds on young people who frequently attend concerts, discotheques, video arcades, cinemas, amusement parks and spectator events. At these events, the sound level typically exceeds 100 dB LAeq. Such noise exposure could lead to significant hearing impairment after frequent attendances.

Noise exposure for employees of these venues should be controlled by established occupational standards; and at the very least, the same standards should apply to the patrons of these premises. Patrons should not be exposed to sound levels greater than 100 dB LAeq during a four-hour period more than four times per year. To avoid acute hearing impairment the LAmax should always be below 110 dB.

Headphones. To avoid hearing impairment from music played back in headphones, in both adults and children, the equivalent sound level over 24 hours should not exceed 70 dB(A). This implies that for a daily one hour exposure the LAeq level should not exceed 85 dB(A). To avoid acute hearing impairment LAmax should always be below 110 dB(A). The exposures are expressed in free-field equivalent sound level.

Toys, Fireworks and Firearms. To avoid acute mechanical damage to the inner ear from impulsive sounds from toys, fireworks and firearms, adults should never be exposed to more than 140 dB(lin) peak sound pressure level. To account for the vulnerability in children when playing, the peak sound pressure produced by toys should not exceed 120 dB(lin), measured close to the ears (100 mm). To avoid acute hearing impairment LAmax should always be below 110 dB(A).

Parkland and Conservation Areas. Existing large quiet outdoor areas should be preserved and the signal-to-noise ratio kept low.

Table 1 presents the WHO guideline values arranged according to specific environments and critical health effects. The guideline values consider all identified adverse health effects for the specific environment. An adverse effect of noise refers to any temporary or long-term impairment of physical, psychological or social functioning that is associated with noise exposure. Specific noise limits have been set for each health effect, using the lowest noise level that produces an adverse health effect (i.e. the critical health effect). Although the guideline values refer to sound levels impacting the most exposed receiver at the listed environments, they are applicable to the general population. The time base for LAeq for "daytime" and "night-time" is 12–16 hours and 8 hours, respectively. No time base is given for evenings, but typically the guideline value should be 5–10 dB lower than in the daytime. Other time bases are recommended for schools, preschools and playgrounds, depending on activity.

It is not enough to characterize the noise environment in terms of noise measures or indices based only on energy summation (e.g., LAeq), because different critical health effects require different descriptions. It is equally important to display the maximum values of the noise fluctuations, preferably combined with a measure of the number of noise events. A separate characterization of night-time noise exposures is also necessary. For indoor environments, reverberation time is also an important factor for things such as speech intelligibility. If the noise includes a large proportion of low-frequency components, still lower guideline values should be applied. Supplementary to the guideline values given in Table 1, precautions should be taken for vulnerable groups and for noise of certain character (e.g. low-frequency components, low background noise).

Table 1: Guideline values for community noise in specific environments.

Specific environment	Critical health effect(s)	L_{Aeq} [dB(A)]	Time base [hours]	L_{Amax} fast [dB]
Outdoor living area	Serious annoyance, daytime and evening Moderate annoyance, daytime and evening	55 50	16 16	- -
Dwelling, indoors Inside bedrooms	Speech intelligibility & moderate annoyance, daytime & evening Sleep disturbance, night-time	35 30	16 8	 45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
School class rooms & pre-schools, indoors	Speech intelligibility, disturbance of information extraction, message communication	35	during class	-
Pre-school bedrooms, indoor	Sleep disturbance	30	sleeping-time	45
School, playground outdoor	Annoyance (external source)	55	during play	-
Hospital, ward rooms, indoors	Sleep disturbance, night-time Sleep disturbance, daytime and evenings	30 30	8 16	40 -
Hospitals, treatment rooms, indoors	Interference with rest and recovery	#1		
Industrial, commercial shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110
Ceremonies, festivals and entertainment events	Hearing impairment (patrons:<5 times/year)	100	4	110
Public addresses, indoors and outdoors	Hearing impairment	85	1	110
Music and other sounds through headphones/ earphones	Hearing impairment (free-field value)	85 #4	1	110
Impulse sounds from toys, fireworks and firearms	Hearing impairment (adults) Hearing impairment (children)	- -	- -	140 #2 120 #2
Outdoors in parkland and conservations areas	Disruption of tranquillity	#3		

#1: As low as possible.

#2: Peak sound pressure (not LAF, max) measured 100 mm from the ear.
#3: Existing quiet outdoor areas should be preserved and the ratio of intruding noise to natural background sound should be kept low.
#4: Under headphones, adapted to free-field values.

5. Noise Management

Chapter 5 is devoted to noise management with discussions on: strategies and priorities in managing indoor noise levels; noise policies and legislation; the impact of environmental noise; and on the enforcement of regulatory standards.

The fundamental goals of noise management are to develop criteria for deriving safe noise exposure levels and to promote noise assessment and control as part of environmental health programmes. These basic goals should guide both international and national policies for noise management. The United Nation's Agenda 21 supports a number of environmental management principles on which government policies, including noise management policies, can be based: the principle of precaution; the "polluter pays" principle; and noise prevention. In all cases, noise should be reduced to the lowest level achievable in the particular situation. When there is a reasonable possibility that the public health will be endangered, even though scientific proof may be lacking, action should be taken to protect the public health, without awaiting the full scientific proof. The full costs associated with noise pollution (including monitoring, management, lowering levels and supervision) should be met by those responsible for the source of noise. Action should be taken where possible to reduce noise at the source.

A legal framework is needed to provide a context for noise management. National noise standards can usually be based on a consideration of international guidelines, such as these *Guidelines for Community Noise*, as well as national criteria documents, which consider dose-response relationships for the effects of noise on human health. National standards take into account the technological, social, economic and political factors within the country. A staged program of noise abatement should also be implemented to achieve the optimum health protection levels over the long term.

Other components of a noise management plan include: noise level monitoring; noise exposure mapping; exposure modeling; noise control approaches (such as mitigation and precautionary measures); and evaluation of control options. Many of the problems associated with high noise levels can be prevented at low cost, if governments develop and implement an integrated strategy for the indoor environment, in concert with all social and economic partners. Governments should establish a "National Plan for a Sustainable Noise Indoor Environment" that applies both to new construction as well as to existing buildings.

The actual priorities in rational noise management will differ for each country. Priority setting in noise management refers to prioritizing the health risks to be avoided and concentrating on the most important sources of noise. Different countries have adopted a range of approaches to noise control, using different policies and regulations. A number of these are outlined in chapter 5 and Appendix 2, as examples. It is evident that noise emission standards have proven insufficient and that the trends in noise pollution are unsustainable.

The concept of environmental an environmental noise impact analysis is central to the philosophy of managing environmental noise. Such an analysis should be required before implementing any project that would significantly increase the level of environmental noise in a community (typically, greater than a 5 dB increase). The analysis should include: a baseline description of the existing noise environment; the expected level of noise from the new source; an assessment of the adverse health effects; an estimation of the population at risk; the calculation of exposure-response relationships; an assessment of risks and their acceptability; and a cost-benefit analysis.

Noise management should:

1. Start monitoring human exposures to noise.
2. Have health control require mitigation of noise immissions, and not just of noise source emissions. The following should be taken into consideration:
   - specific environments such as schools, playgrounds, homes, hospitals.
   - environments with multiple noise sources, or which may amplify the effects of noise.
   - sensitive time periods such as evenings, nights and holidays.
   - groups at high risk, such as children and the hearing impaired.
3. Consider the noise consequences when planning transport systems and land use.
4. Introduce surveillance systems for noise-related adverse health effects.
5. Assess the effectiveness of noise policies in reducing adverse health effects and exposure, and in improving supportive "soundscapes".
6. Adopt these *Guidelines for Community Noise* as intermediary targets for improving human health.
7. Adopt precautionary actions for a sustainable development of the acoustical environments.

Conclusions and recommendations

In chapter 6 are discussed: the implementation of the guidelines; further WHO work on noise; and research needs are recommended.

Implementation. For implementation of the guidelines it is recommended that:

- Governments should protection the population from community noise and consider it an integral part of their policy of environmental protection.
- Governments should consider implementing action plans with short-term, medium-term and long-term objectives for reducing noise levels.
- Governments should adopt the *Health Guidelines for Community Noise* values as targets to be achieved in the long-term.
- Governments should include noise as an important public health issue in environmental impact assessments.
- Legislation should be put in place to allow for the reduction of sound levels.
- Existing legislation should be enforced.
- Municipalities should develop low noise implementation plans.
- Cost-effectiveness and cost-benefit analyses should be considered potential instruments for meaningful management decisions.
- Governments should support more policy-relevant research.

Future Work. The Expert Task Force worked out several suggestions for future work for the WHO in the field of community noise. WHO should:

- Provide leadership and technical direction in defining future noise research priorities.
- Organize workshops on how to apply the guidelines.

- Provide leadership and coordinate international efforts to develop techniques for designing supportive sound environments (e.g. "soundscapes").
- Provide leadership for programs to assess the effectiveness of health-related noise policies and regulations.
- Provide leadership and technical direction for the development of sound methodologies for environmental and health impact plans.
- Encourage further investigation into using noise exposure as an indicator of environmental deterioration (e.g. black spots in cities).
- Provide leadership and technical support, and advise developing countries to facilitate development of noise policies and noise management.

Research and Development. A major step forward in raising the awareness of both the public and of decision makers is the recommendation to concentrate more research and development on variables which have monetary consequences. This means that research should consider not only dose-response relationships between sound levels, but also politically relevant variables, such as noise-induced social handicap; reduced productivity; decreased performance in learning; workplace and school absenteeism; increased drug use; and accidents.

In Appendices 1–6 are given: bibliographic references; examples of regional noise situations (African Region, American Region, Eastern Mediterranean Region, South East Asian Region, Western Pacific Region); a glossary; a list of acronyms; and a list of participants.

Introduction

Community noise (also called environmental noise, residential noise or domestic noise) is defined as noise emitted from all sources, except noise at the industrial workplace. Main sources of community noise include road, rail and air traffic, industries, construction and public work, and the neighbourhood. Typical neighbourhood noise comes from premises and installations related to the catering trade (restaurant, cafeterias, discotheques, etc.); from live or recorded music; from sporting events including motor sports; from playgrounds and car parks; and from domestic animals such as barking dogs. The main indoor sources are ventilation systems, office machines, home appliances and neighbours. Although many countries have regulations on community noise from road, rail and air traffic, and from construction and industrial plants, few have regulations on neighbourhood noise. This is probably due to the lack of methods to define and measure it, and to the difficulty of controlling it. In developed countries, too, monitoring of compliance with, and enforcement of, noise regulations are weak for lower levels of urban noise that correspond to occupationally controlled levels (>85 dB LAeq,8h; Frank 1998). Recommended guideline values based on the health effects of noise, other than occupationally-induced effects, are often not taken into account.

The extent of the community noise problem is large. In the European Union about 40% of the population is exposed to road traffic noise with an equivalent sound pressure level exceeding 55 dBA daytime; and 20% is exposed to levels exceeding 65 dBA (Lambert & Vallet 19 1994). When all transportation noise is considered, about half of all European Union citizens live in zones that do not ensure acoustical comfort to residents. At night, it is estimated that more than 30% is exposed to equivalent sound pressure levels exceeding 55 dBA, which are disturbing to sleep. The noise pollution problem is also severe in the cities of developing countries and is caused mainly by traffic. Data collected alongside densely traveled roads were found to have equivalent sound pressure levels for 24 hours of 75–80 dBA (e.g. National Environment Board Thailand 19 1990; Mage & Walsh 19 1998).

(a) In contrast to many other environmental problems, noise pollution continues to grow, accompanied by an increasing number of complaints from affected individuals. Most people are typically exposed to several noise sources, with road traffic noise being a dominant source (OECD-ECMT 19 1995). Population growth, urbanization and to a large extent technological development are the main driving forces, and future enlargements of highway systems, international airports and railway systems will only increase the noise problem. Viewed globally, the growth in urban environmental noise pollution is unsustainable, because it involves not simply the direct and cumulative adverse effects on health. It also adversely affects future generations by degrading residential, social and learning environments, with corresponding economical losses (Berglund 1998). Thus, noise is not simply a local problem, but a global issue that affects everyone (Lang 1999; Sandberg 1999) and calls for precautionary action in any environmental planning situation.

The objective of the World Health Organization (WHO) is the attainment by all peoples of the highest possible level of health. As the first principle of the WHO Constitution the definition of ‘health’ is given as: “A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity". This broad definition of health embraces the concept of well-being and, thereby, renders noise impacts such as population annoyance, interference with communication, and impaired task performance as 'health' issues. In 1992, a WHO Task Force also identified the following specific health effects for the general population that may result from community noise: interference with communication; annoyance responses; effects on sleep, and on the cardiovascular and psychophysiological systems; effects on performance, productivity, and social behavior; and noise-induced hearing impairment (WHO 1993; Berglund & Lindvall 1995; *cf*. WHO 1980). Hearing damage is expected to result from both occupational and environmental noise, especially in developing countries, where compliance with noise regulation is known to be weak (Smith 1998).

Noise is likely to continue as a major issue well into the next century, both in developed and in developing countries. Therefore, strategic action is urgently required, including continued noise control at the source and in local areas. Most importantly, joint efforts among countries are necessary at a system level, in regard to the access and use of land, airspace and seawaters, and in regard to the various modes of transportation. Certainly, mankind would benefit from societal reorganization towards healthy transport. To understand noise we must understand the different types of noise and how we measure it, where noise comes from and the effects of noise on human beings. Furthermore, noise mitigation, including noise management, has to be actively introduced and in each case the policy implications have to be evaluated for efficiency.

This document is organized as follows. In Chapter 2 noise sources and measurement are discussed, including the basic aspects of source characteristics, sound propagation and transmission. In Chapter 3 the adverse health effects of noise are characterized. These include noise-induced hearing impairment, interference with speech communication, sleep disturbance, cardiovascular and physiological effects, mental health effects, performance effects, and annoyance reactions. This chapter is rounded out by a consideration of combined noise sources and their effects, and a discussion of vulnerable groups. In Chapter 4 the Guideline values are presented. Chapter 5 is devoted to noise management. Included are discussions of: strategies and priorities in the management of indoor noise levels; noise policies and legislation; environmental noise impact; and enforcement of regulatory standards. In Chapter 6 implementation of the WHO Guidelines is discussed, as well as future WHO work on noise and its research needs. In Appendices 1–6 are given: bibliographic references; examples of regional noise situations (African Region, American Region, Eastern Mediterranean Region, South East Asian Region, Western Pacific Region); a glossary; a list of acronyms; and a list of participants.

2. Noise sources and their measurement

2.1.Basic Aspects of Acoustical Measurements

Most environmental noises can be approximately described by one of several simple measures. They are all derived from overall sound pressure levels, the variation of these levels with time and the frequency of the sounds. Ford (1987) gives a more extensive review of various environmental noise measures. Technical definitions are found in the glossary in Appendix 3.

2.1.1. Sound pressure level

The sound pressure level is a measure of the air vibrations that make up sound. All measured sound pressures are referenced to a standard pressure that corresponds roughly to the threshold of hearing at 1 000 Hz. Thus, the sound pressure level indicates how much greater the measured sound is than this threshold of hearing. Because the human ear can detect a wide range of sound pressure levels (10–102 Pascal (Pa)), they are measured on a logarithmic scale with units of decibels (dB). A more technical definition of sound pressure level is found in the glossary.

The sound pressure levels of most noises vary with time. Consequently, in calculating some measures of noise, the instantaneous pressure fluctuations must be integrated over some time interval. To approximate the integration time of our hearing system, sound pressure meters have a standard *Fast* response time, which corresponds to a time constant of 0.125 s. Thus, all measurements of sound pressure levels and their variation over time should be made using the *Fast* response time, to provide sound pressure measurements more representative of human hearing. Sound pressure meters may also include a *Slow* response time with a time constant of 1 s, but its sole purpose is that one can more easily estimate the average value of rapidly fluctuating levels. Many modern meters can integrate sound pressures over specified periods and provide average values. It is not recommended that the *Slow* response time be used when integrating sound pressure meters are available.

Because sound pressure levels are measured on a logarithmic scale they cannot be added or averaged arithmetically. For example, adding two sounds of equal pressure levels results in a total pressure level that is only 3 dB greater than each individual sound pressure level. Consequently, when two sounds are combined the resulting sound pressure level will be significantly greater than the individual sound levels only if the two sounds have similar pressure levels. Details for combining sound pressure levels are given in Appendix 2.

2.1.2. Frequency and frequency weighting

The unit of frequency is the Hertz (Hz), and it refers to the number of vibrations per second of the air in which the sound is propagating. For tonal sounds, frequency is associated with the perception of pitch. For example, orchestras often tune to the frequency of 440 Hz. Most environmental sounds, however, are made up of a complex mix of many different frequencies. They may or may not have discrete frequency components superimposed on noise with a broad frequency spectrum (i.e. sound with a broad range of frequencies). The audible frequency range is normally considered to range from 20–20 000 Hz. Below 20 Hz we hear individual sound pulses rather than recognizable tones. Hearing sensitivity to higher frequencies decreases with age and exposure to noise. Thus, 20 000 Hz represents an upper limit of audibility for younger listeners with unimpaired hearing.

Our hearing systems are not equally sensitive to all sound frequencies (ISO 1987a). Thus, not all frequencies are perceived as being equally loud at the same sound pressure level, and when calculating overall environmental noise ratings it is necessary to consider sounds at some frequencies as more important than those at other frequencies. Detailed frequency analyses are commonly performed with standard sets of octave or 1/3 octave bandwidth filters. Alternatively, Fast Fourier Transform techniques or other types of filters can be used to determine the relative strengths of the various frequency components making up a particular environmental noise.

Frequency weighting networks provide a simpler approach for weighting the importance of different frequency components in one single number rating. The A-weighting is most commonly used and is intended to approximate the frequency response of our hearing system. It weights lower frequencies as less important than mid- and higher-frequency sounds. C-weighting is also quite common and is a nearly flat frequency response with the extreme high and low frequencies attenuated. When no frequency analysis is possible, the difference between A-weighted and C-weighted levels gives an indication of the amount of low frequency content in the measured noise. When the sound has an obvious tonal content, a correction to account for the additional annoyance may be used (ISO 1987b).

2.1.3. Equivalent continuous sound pressure level

According to the equal energy principle, the effect of a combination of noise events is related to the combined sound energy of those events. Thus, measures such as the equivalent continuous sound pressure level (LAeq,T) sum up the total energy over some time period (T) and give a level equivalent to the average sound energy over that period. Such average levels are usually based on integration of A-weighted levels. Thus LAeq,T is the average energy equivalent level of the A-weighted sound over a period T.

2.1.4. Individual noise events

It is often desired to measure the maximum level (LAmax) of individual noise events. For cases such as the noise from a single passing vehicle, LAmax values should be measured using the *Fast* response time because it will give a good correlation with the integration of loudness by our hearing system. However, for very short-duration impulsive sounds it is often desirable to measure the instantaneous peak amplitude to assess potential hearing-damage risk. If actual instantaneous pressure cannot be determined, then a time-integrated ‘peak’ level with a time constant of no more than 0.05 ms should be used (ISO 1987b). Such peak readings are often made using the C- (or linear) frequency weightings.

Alternatively, discrete sound events can be evaluated in terms of their A-weighted sound exposure level (SEL, for defintion see appendix 5). The total amount of sound energy in a particular event is assessed by the SEL. One can add up the SEL values of individual events to calculate a LAeq,T over some time period, T, of interest. In some cases the SEL may provide more consistent evaluations of individual noise events because they are derived from the complete history of the event and not just one maximum value. However, A-weighted SEL measurements have been shown to be inadequate for assessing the (perceived) loudness of complex impulsive sounds, such as those from large and small weapons (Berglund et al. 1986). In contrast, C-weighted SEL values have been found useful for rating impulsive sounds such as gun shots (Vos 1996; Buchta 1996; ISO 1987b).

2.1.5. Choice of noise measure

LAeq,T should be used to measure continuing sounds such as road traffic noise, many types of industrial noises and noise from ventilation systems in buildings. When there are distinct events to the noise such as with aircraft or railway noise, measures of the individual events should be obtained (using, for example, LAmax or SEL), in addition to LAeq,T measurements.

In the past, time-varying environmental sound levels have also been described in terms of percentile levels. These are derived from a statistical distribution of measured sound levels over some period. For example, L10 is the A-weighted level exceeded 10% of the time. L10 values have been widely used to measure road-traffic noise, but they are usually found to be highly correlated measures of the individual events, as are LAmax and SEL. L90 or L95 can be used as a measure of the general background sound pressure level that excludes the potentially confounding influence of particular local noise events.

2.1.6. Sound and noise

Physically, there is no distinction between sound and noise: sound is a sensory perception evoked by physiological processes in the auditory brain. The complex pattern of sound waves is perceptually classified as “Gestalts” and are labeled as noise, music, speech, etc. Consequently, it is not possible to define noise exclusively on the basis of the physical parameters of sound. Instead, it is common practice to define noise simply as unwanted sound. However, in some situations noise may adversely affect health in the form of acoustical energy.

2.2. Sources of Noise

This section describes various sources of noise that can affect a community. Namely, noise from industry, transportation, and from residential and leisure areas. It should be noted that equal values of LAeq,T for different sources do not always imply the same expected effect.

2.2.1. Industrial noise

Mechanized industry creates serious noise problems. It is responsible for intense noise indoors as well as outdoors. This noise is due to machinery of all kinds and often increases with the power of the machines. Sound generation mechanisms of machinery are reasonably well understood. The noise may contain predominantly low or high frequencies, tonal components, be impulsive or have unpleasant and disruptive temporal sound patterns. Rotating and reciprocating machines generate sound that includes tonal components; and air-moving equipment tends also to generate noise with a wide frequency range. The high sound pressure levels are caused by components or gas flows that move at high speed (for example, fans, steam pressure relief valves), or by operations involving mechanical impacts (for example, stamping, riveting, road breaking). Machinery should preferably be silenced at the source.

Noise from fixed installations, such as factories or construction sites, heat pumps and ventilation systems on roofs, typically affect nearby communities. Reductions may be achieved by encouraging quieter equipment or by zoning of land into industrial and residential areas. Requirements for passive (sound insulating enclosures) and active noise control, or restriction of operation time, may also be effective.

2.2.2. Transportation noise

Transportation noise is the main source of environmental noise pollution, including road traffic, rail traffic and air traffic. As a general rule, larger and heavier vehicles emit more noise than smaller and lighter vehicles. Exceptions would include: helicopters and 2- and 3-wheeled road vehicles.

The noise of road vehicles is mainly generated from the engine and from frictional contact between the vehicle and the ground and air. In general, road-contact noise exceeds engine noise at speeds higher than 60 km/h. The physical principle responsible for generating noise from tire-road contact is less well understood. The sound pressure level from traffic can be predicted from the traffic flow rate, the speed of the vehicles, the proportion of heavy vehicles, and the nature of the road surface. Special problems can arise in areas where the traffic movements involve a change in engine speed and power, such as at traffic lights, hills, and intersecting roads; or where topography, meteorological conditions and low background levels are unfavourable (for example, mountain areas).

Railway noise depends primarily on the speed of the train, but variations are present depending upon the type of engine, wagons, and rails and their foundations, as well as the roughness of wheels and rails. Small radius curves in the track, such as may occur for urban trains, can lead to very high levels of high-frequency sound referred to as wheel squeal. Noise can be generated in stations because of running engines, whistles and loudspeakers, and in marshaling yards because of shunting operations. The introduction of high-speed trains has created special noise problems with sudden, but not impulsive, rises in noise. At speeds greater than 250 km/h, the proportion of high-frequency sound energy increases and the sound can be perceived as similar to that of overflying jet aircraft. Special problems can arise in areas close to tunnels, in valleys or in areas where the ground conditions help generate vibrations. The long-distance propagation of noise from high-speed trains will constitute a problem in the future if otherwise environment-friendly railway systems are expanded.

Aircraft operations generate substantial noise in the vicinity of both commercial and military airports. Aircraft takeoffs are known to produce intense noise, including vibration and rattle. The landings produce substantial noise in long low-altitude flight corridors. The noise is produced by the landing gear and automatic power regulation, and also when reverse thrust is applied, all for safety reasons. In general, larger and heavier aircraft produce more noise than lighter aircraft. The main mechanism of noise generation in the early turbojet-powered aircraft was the turbulence created by the jet exhaust mixing with the surrounding air. This noise source has been significantly reduced in modern high by-pass ratio turbo-fan engines that surround the high-velocity jet exhaust with lower velocity airflow generated by the fan. The fan itself can be a significant noise source, particularly during landing and taxiing operations. Multi-bladed turbo-prop engines can produce relatively high levels of tonal noise. The sound pressure level from aircraft is, typically, predicted from the number of aircraft, the types of airplanes, their flight paths, the proportions of takeoffs and landings and the atmospheric conditions. Severe noise problems may arise at airports hosting many helicopters or smaller aircraft used for private business, flying training and leisure purposes. Special noise problems may also arise inside airplanes because of vibration. The noise emission from future superjets is unknown.

A sonic boom consists of a shock wave in the air, generated by an aircraft when it flies at a speed slightly greater than the local speed of sound. An aircraft in supersonic flight trails a sonic boom that can be heard up to 50 km on either side of its ground track, depending upon the flight altitude and the size of the aircraft (Warren 1972). A sonic boom can be heard as a loud double-boom sound. At high intensity it can damage property.

Noise from military airfields may present particular problems compared to civil airports (von Gierke & Harris 1987). For example, when used for night-time flying, for training interrupted landings and takeoffs (so-called touch-and-go), or for low-altitude flying. In certain instances, including wars, specific military activities introduce other intense noise pollution from heavy vehicles (tanks), helicopters, and small and large fire-arms.

2.2.3. Construction noise and building services noise

Building construction and excavation work can cause considerable noise emissions. A variety of sounds come from cranes, cement mixers, welding, hammering, boring and other work processes. Construction equipment is often poorly silenced and maintained, and building operations are sometimes carried out without considering the environmental noise consequences. Street services such as garbage disposal and street cleaning can also cause considerable disturbance if carried out at sensitive times of day. Ventilation and air conditioning plants and ducts, heat pumps, plumbing systems, and lifts (elevators), for example, can compromise the internal acoustical environment and upset nearby residents.

2.2.4. Domestic noise and noise from leisure activities

In residential areas, noise may stem from mechanical devices (e.g. heat pumps, ventilation systems and traffic), as well as voices, music and other kinds of sounds generated by neighbours (e.g. lawn movers, vacuum cleaners and other household equipment, music reproduction and noisy parties). Aberrant social behavior is a well-recognized noise problem in multifamily dwellings, as well as at sites for entertainment (e.g. sports and music events). Due to predominantly low-frequency components, noise from ventilation systems in residential buildings may also cause considerable concern even at low and moderate sound pressure levels.

The use of powered machines in leisure activities is increasing. For example, motor racing, off-road vehicles, motorboats, water skiing, snowmobiles etc., and these contribute significantly to loud noises in previously quiet areas. Shooting activities not only have considerable potential for disturbing nearby residents, but can also damage the hearing of those taking part. Even tennis playing, church bell ringing and other religious activities can lead to noise complaints.

Some types of indoor concerts and discotheques can produce extremely high sound pressure levels. Associated noise problems outdoors result from customers arriving and leaving. Outdoor concerts, fireworks and various types of festivals can also produce intense noise. The general problem of access to festivals and leisure activity sites often adds to road traffic noise problems. Severe hearing impairment may also arise from intense sound produced as music in headphones or from children's toys.

2.3. The Complexity of Noise and Its Practical Implications

2.3.1. The problem

One must consider many different characteristics to describe environmental noises completely. We can consider the sound pressure level of the noise and how this level varies over a variety of periods, ranging from minutes or seconds to seasonal variations over several months. Where sound pressure levels vary quite substantially and rapidly, such as in the case of low-level jet aircraft, one might also want to consider the rate of change of sound pressure levels (Berry 1995; Kerry et al. 1997). At the same time, the frequency content of each noise will also determine its effect on people, as will the number of events when there are relatively small numbers of discrete noisy events. Combinations of these characteristics determine how each type of environmental noise affects people. These effects may be annoyance, sleep disturbance, speech interference, increased stress, hearing impairment or other health-related effects.

Thus, in total there is a very complex multidimensional relationship between the various characteristics of the environmental noise and the effects it has on people. Unfortunately, we do not completely understand all of the complex links between noise characteristics and the resulting effects on people. Thus, current practice is to reduce the assessment of environmental noise to a small number of quite simple quantities that are known to be reasonably well related to the effects of noise on people (LAeq,T for continuing sounds and LAmax or SEL where there are a small number of distinct noise events). These simple measures have the distinct advantage that they are relatively easy and inexpensive to obtain and hence are more likely to be widely adopted. On the other hand, they may ignore some details of the noise characteristics that relate to particular types of effects on people.

2.3.2. Time variation

There is evidence that the pattern of noise variation with time relates to annoyance (Berglund et al. 1976). It has been suggested that the equal-energy principle is a simple concept for obtaining a measure representative of the annoyance of a number of noise events. For example, the LAeq,T of the noise from a busy road may be a good indicator of the annoyance this noise may cause for nearby residents. However, such a measure may not be very useful for predicting the disturbance to sleep of a small number of very noisy aircraft fly-overs. The disturbance caused by small numbers of such discrete events is usually better related to maximum sound pressure levels and the number of events.

While using LAeq,T measures is the generally accepted approach, it is still important to appreciate the limitations and errors that may occur. For example, some years ago measures that assessed the variation of sound pressure levels with time were popular. Subsequently, these have been shown not to improve predictions of annoyance with road traffic noise (Bradley 1978). However, it is possible that time variations may contribute to explaining the very different amounts of annoyance caused by equal LAeq,T levels of road-traffic noise, train noise and aircraft noise (*cf*. Miedema & Vos 1998).

More regular variations of sound pressure levels with time have been found to increase the annoying aspects of the noise. For example, noises that vary periodically to create a throbbing or pulsing sensation can be more disturbing than continuous noise (Bradley 1994b). Research suggests that variations at about 4 per second are most disturbing (Zwicker 1989). Noises with very rapid onsets could also be more disturbing than indicated by their LAeq,T (Berry 1995; Kerry et al. 1997).

LAeq,T values can be calculated for various time periods and it is very important to specify this period. It is quite common to calculate LAeq,T values separately for day- and night-time periods. In combining day and night LAeq,T values it is usually assumed that people will be more sensitive to noise during the night-time period. A weighting is thus normally added to night-time LAeq,T values when calculating a combined measure for a 24 hour period. For example, day-night sound pressure measures commonly include a 10 dB night-time weighting. Other night-time weightings have been proposed, but it has been suggested that it is not possible to determine precisely an optimum value for night-time weightings from annoyance survey responses, because of the large variability in responses within groups of people (Fields 1986; see also Berglund & Lindvall 1995). Night-time weightings are intended to indicate the expected increased sensitivity to annoyance at night and do not protect people from sleep disturbance.

2.3.3. Frequency content and loudness

Noise can also be characterized by its frequency content. This can be assessed by various types of frequency analysis to determine the relative contributions of the frequency components to the total noise. The combined effects of the different frequencies on people, perceived as noise, can be approximated by simple frequency weightings. The A-weighting is now widely used to obtain an approximate, single-number rating of the combined effects of the various frequencies. The A-weighting response is a simplification of an equal-loudness contour. There is a family of these equal-loudness contours (ISO 1987a) that describe the frequency response of the hearing system for a wide range of frequencies and sound pressure levels. These equal-loudness contours can be used to determine the perceived loudness of a single frequency sound. More complicated procedures have been derived to estimate the perceived loudness of complex sounds (ISO 1975). These methods involve determining the level of the sound in critical bands and the mutual masking of these bands.

Many studies have compared the accuracy of predictions based on A-weighted levels with those based on other frequency weightings, as well as more complex measures such as loudness levels and perceived noise levels (see also Berglund & Lindvall 1995). The comparisons depend on the particular effect that is being predicted, but generally the correlation between the more complex measures and subjective scales are a little stronger. A-weighted measures have been particularly criticized as not being accurate indicators of the disturbing effects of noises with strong low-frequency components (Kjellberg et al. 1984; Persson & Björkman 1988; Broner & Leventhall 1993; Goldstein 1994). However, these differences in prediction accuracy are usually smaller than the variability of responses among groups of people (Fields 1986; see also Berglund & Lindvall 1995). Thus, in practical situations the limitations of A-weighted measures may not be so important.

In addition to equal-loudness contours, equal-noisiness contours have also been developed for calculating perceived noise levels (PNL) (Kryter 1959; Kryter 1994; see also section 2.7.2). Critics have pointed out that in addition to equal-loudness and equal-noisiness contours, we could have many other families of equal-sensation contours corresponding to other attributes of the noises (Molino 1974). There seems to be no limit to the possible complexity and number of such measures.

2.3.4. Influence of ambient noise level

A number of studies have suggested that the annoyance effect of a particular noise would depend on how much that noise exceeded the level of ambient noise. This has been shown to be true for noises that are relatively constant in level (Bradley 1993), but has not been consistently found for time-varying noises such as aircraft noise (Gjestland et al. 1990; Fields 1998). Because at some time during an aircraft fly-over the noise almost always exceeds the ambient level, responses to this type of noise are less likely to be influenced by the level of the ambient noise.

2.3.5. Types of noise

A number of studies have concluded that equal levels of different noise types lead to different annoyance (Hall et al. 1981; Griffiths 1983; Miedema 1993; Bradley 1994a; Miedema & Vos 1998). For example, equal LAeq,T levels of aircraft noise and road traffic noise will not lead to the same mean annoyance in groups of people exposed to these noises. This may indicate that the LAeq,T measure is not a completely satisfactory description of these noises and perhaps does not completely reflect the characteristics of these noises that lead to annoyance. Alternatively, the differences may be attributed to various other factors that are not part of the noise characteristics (e.g. Flindell & Stallen 1999). For example, it has been said that aircraft noise is more disturbing, because of the associated fear of aircraft crashing on people’s homes (cf. Berglund & Lindvall 1995).

2.3.6. Individual differences

Finally, there is the problem of individual response differences. Different people will respond quite differently to the same noise stimulus (Job 1988). These individual differences can be quite large and it is often most useful to consider the average response of groups of people exposed to the same sound pressure levels. In annoyance studies the percentage of highly annoyed individuals is usually considered, because it correlates better with measured sound pressure levels. Individual differences also exist for susceptibility to hearing impairment (e.g. Katz 1994).

2.3.7. Recommendations

In many cases we do not have specific, accurate measures of how annoying sound will be and must rely on the simpler quantities. As a result, current practice is to assume that the equal energy principle is approximately valid for most types of noise, and that a simple LAeq,T type measure will indicate reasonably well the expected effects of the noise. Where the noise consists of a small number of discrete events, the A-weighted maximum level (LAmax) will be a better indicator of the disturbance to sleep and other activities. However, in most cases the A-weighted sound exposure level (SEL) will provide a more consistent measure of such single-noise events, because it is based on an integration over the complete noise event.

2.4. Measurement Issues

2.4.1. Measurement objectives

The details of noise measurements must be planned to meet some relevant objective or purpose. Some typical objectives would include:

a. Investigating complaints.
b. Assessing the number of persons exposed.
c. Compliance with regulations.
d. Land use planning and environmental impact assessments.
e. Evaluation of remedial measures.
f. Calibration and validation of predictions.
g. Research surveys.
h. Trend monitoring.

The sampling procedure, measurement location, type of measurements and the choice of equipment should be in accord with the objective of the measurements.

2.4.2. Instrumentation

The most critical component of a sound pressure meter is the microphone, because it is difficult to produce microphones with the same precision as the other, electronic components of a pressure meter. In contrast, it is usually not difficult to produce the electronic components of a microphone with the desired sensitivity and frequency-response characteristics. Lower quality microphones will usually be less sensitive and so cannot measure very low sound pressure levels. They may also not be able to accurately measure very high sound pressure levels found closer to loud noise sources. Lower quality microphones will also have less well-defined frequency-response characteristics. Such lower quality microphones may be acceptable for survey type measurements of overall A-weighted levels, but would not be preferred for more precise measurements, including detailed frequency analysis of the sounds.

Sound pressure meters will usually include both A- and C-weighting frequency-response curves. The uses of these frequency weightings were discussed above. They may also include a linear weighting. Linear weightings are not defined in standards and may in practice be limited by the response of the particular microphone being used. Instead of, or in addition to, frequency-response weightings, more complex sound pressure meters can also include sets of standard bandpass filters, to permit frequency analysis of sounds. For acoustical measurements, octave and one-third octave bandwidth filters are widely used with centre frequencies defined in standards (ISO 1975b).

The instantaneous sound pressures are integrated with some time constant to provide sound pressure levels. As mentioned above most meters will include both *Fast*- and *Slow*-response times. *Fast*-response corresponds to a time constant of 0.125 s and is intended to approximate the time constant of the human hearing system. *Slow*-response corresponds to a time constant of 1 s and is an old concept intended to make it easier to obtain an approximate average value of fluctuating levels from simple meter readings.

Standards (IEC 1979) classify sound pressure meters as type 1 or type 2. Type 2 meters are adequate for broad band A-weighted level measurements, where extreme precision is not required and where very low sound pressure levels are not to be measured. Type 1 meters are usually much more expensive and should be used where more precise results are needed, or in cases where frequency analysis is required.

Many modern sound pressure meters can integrate sound pressure levels over some specified time period, or may include very sophisticated digital processing capabilities. Integrating meters make it possible to directly obtain accurate measures of LAeq,T values over a user-specified time interval, T. By including small computers in some sound pressure meters, quite complex calculations can be performed on the measured levels and many such results can be stored for later read out. For example, some meters can determine the statistical distribution of sound pressure levels over some period, in addition to the simple LAeq,T value. Recently, hand-held meters that perform loudness calculations in real time have become available. Continuing rapid developments in instrumentation capabilities are to be expected.

2.4.3. Measurement locations

Where local regulations do not specify otherwise, measurements of environmental noise are usually best made close to the point of reception of the noise. For example, if there is concern about residents exposed to road traffic noise it is better to measure close to the location of the residents, rather than close to the road. If environmental noises are measured close to the source, one must then estimate the effect of sound propagation to the point of reception. Sound propagation can be quite complicated and estimates of sound pressure levels at some distance from the source will inevitably introduce further errors into the measured sound pressure levels. These errors can be avoided by measuring at locations close to the point of reception.

Measurement locations should normally be selected so that there is a clear view of the sound source and so that the propagation of the sound to the microphone is not shielded or blocked by structures that would reduce the incident sound pressure levels. For example, measurements of aircraft noise should be made on the side of the building directly exposed to the noise. The position of the measuring microphone relative to building façades or other sound-reflective surfaces is also important and will significantly influence measured sound pressure levels (ISO 1978). If the measuring microphone is located more than several meters from reflecting surfaces, it will provide an unbiased indication of the incident sound pressure level. At the other extreme, when a measuring microphone is mounted on a sound-reflecting surface, such as a building façade, sound pressure levels will be increased by 6 dB, because the direct and reflected sound will coincide. Some standards recommend a position 2 m from the façade and an associated 3 dB correction (ISO 1978; ASTM 1992). The effect of façade reflections must be accounted for to represent the true level of the incident sound. Thus, while locating the measuring microphone close to the point of reception is desirable, it leads to some other issues that must be considered to accurately interpret measurement results. Where exposures are measured indoors, it is necessary to measure at several positions to characterize the average sound pressure level in a room. In other situations, it may be necessary to measure at the position of the exposed person.

2.4.4. Sampling

Many environmental noises vary over time, such as for different times of day or from season to season. For example, road traffic noise may be considerably louder during some hours of the day but much quieter at night. Aircraft noise may vary with the season due to different numbers of aircraft operations. Although permanent noise monitoring systems are becoming common around large airports, it is usually not possible to measure sound pressure levels continuously over a long enough period of time to completely define the environmental noise exposure. In practice, measurements usually only sample some part of the total exposure. Such sampling will introduce uncertainties in the estimates of the total noise exposure.

Traffic noise studies have identified various sampling schemes that can introduce errors of 2-3 dB in estimates of daytime LAeq,T values and even larger errors in night-time sound pressure levels (Vaskor et al. 1979). These errors relate to the statistical distributions of sound pressure levels over time (Bradley et al. 1979). Thus, the sampling errors associated with road traffic noise may be quite different from those associated with other noise, because of the quite different variations of sound pressure levels over time. It is also difficult to give general estimates of sampling errors due to seasonal variations. When making environmental noise measurements it is important that the measurement sample is representative of all of the variations in the noise in question, including variations of the source and variations in sound propagation, such as due to varying atmospheric conditions.

2.4.5. Calibration and quality assurance

Sound pressure meters can be calibrated using small calibrated sound sources. These devices are placed on the measurement microphone and produce a known sound pressure level with a specified accuracy. Such calibrations should be made at least daily, and more often if there is some possibility that handling of the sound pressure meter may have modified its sensitivity. It is also important to have a complete quality assurance plan. This should require annual calibration of all noise measuring equipment to traceable standards and should clearly specify correct measurement and operating procedures (ISO 1994).

2.5. Source Characteristics and Sound Propagation

To make a correct assessment of noise it is important to have some appreciation of the characteristics of environmental noise sources and of how sound propagates from them. One should consider the directionality of noise sources, the variability with time and the frequency content. If these are in some way unusual, the noise may be more disturbing than expected. The most common types of environmental noise sources are directional and include: road-traffic noise, aircraft noise, train noise, industrial noise and outdoor entertainment facilities (*cf*. section 2.2). All of these types of environmental noise are produced by multiple sources, which in many cases are moving. Thus, the characteristics of individual sources, as well as the characteristics of the combined sources, must be considered.

For example, we can consider the radiation of sound from individual vehicles, as well as from a line of vehicles on a particular road. Sound from an ideal point source (i.e. non-directional source) will spread out spherically and sound pressure levels would decrease 6 dB for each doubling of distance from the source. However, for a line of such sources, or for an integration over the complete pass-by of an individual moving source, the combined effect leads to sound that spreads cylindrically and to sound pressure levels that decrease at 3 dB per doubling of distance. Thus, there are distinct differences between the propagation of sound from an ideal point source and from moving sources. In practice one cannot adequately assess the noise from a fixed source with measurements at a single location; it is essential to measure in a number of directions from the source. If the single source is moving, it is necessary to measure over a complete pass-by, to account for sound variation with direction and time.

In most real situations this simple behaviour is considerably modified by reflections from the ground and from other nearby surfaces. One expects that when sound propagates over loose ground, such as grass, that some sound energy will be absorbed and sound pressure levels will actually decrease more rapidly with distance from the source. Although this is approximately true, the propagation of sound between sources and receivers close to the ground is much more complicated than this. The combination of direct and ground-reflected sound can combine in a complex manner which can lead to strong cancellations at some frequencies and not at others (Embleton & Piercy 1976). Even at quite short source-to-receiver distances, these complex interference effects can significantly modify the propagating sound. At larger distances (approximately 100 m or more), the propagation of sound will also be significantly affected by various atmospheric conditions. Temperature and wind gradients as well as atmospheric turbulence can have large effects on more distant sound pressure levels (Daigle et al. 1986). Temperature and wind gradients can cause propagating sound to curve either upwards or downwards, creating either areas of increased or decreased sound pressure levels at points quite distant from the source. Atmospheric turbulence can randomize sound so that the interference effects resulting from combinations of sound paths are reduced. Higher frequency sound is absorbed by air depending on the exact temperature and relative humidity of the air (Crocker &

Price 1975; Ford 1987). Because there are many complex effects, it is not usually possible to accurately predict sound pressure levels at large distances from a source.

Using barriers or screens to block the direct path from the source to the receiver can reduce the propagation of sound. The attenuating effects of the screen are limited by sound energy that diffracts or bends around the screen. Screens are more effective at higher frequencies and when placed either close to the sound source or the receiver; they are less effective when placed far from the receiver. Although higher screens are better, in practice it is difficult to achieve more than about a 10 dB reduction. There should be no gaps in the screen and it must have an adequate mass per unit area. A long building can be an effective screen, but gaps between buildings will reduce the sound attenuation.

In some cases, it may be desirable to estimate environmental sound pressure levels using mathematical models implemented as computer programmes (House 1987). Such computer programmes must first model the characteristics of the source and then estimate the propagation of the sound from the source to some receiver point. Although such prediction schemes have several advantages, there will be some uncertainty as to the accuracy of the predicted sound pressure levels. Such models are particularly useful for road traffic noise and aircraft noise, because it is possible to create data bases of information describing particular sources. For more varied types of noise, such as industrial noise, it would be necessary to first characterize the noise sources. The models then sum up the effects of multiple sources and calculate how the sound will propagate to receiver points. Techniques for estimating sound propagation are improving and the accuracy of these models is also expected to improve. These models can be particularly useful for estimating the combined effect of a large number of sources over an extended period of time. For example, aircraft noise prediction models are typically used to predict average yearly noise exposures, based on the combination of aircraft events over a complete year. Such models can be applied to predict sound pressure level contours around airports for these average yearly conditions. This is of course much less expensive than measuring at many locations over a complete one year-period. However, such models can be quite complex, and require skilled users and accurate data bases. Because environmental noise prediction models are still developing, it is advisable to confirm predictions with measurements.

2.6. Sound transmission Into and Within Buildings

Sources of environmental noise are usually located outdoors; for example, road traffic, aircraft or trains. However, people exposed to these noises are often indoors, inside their home or some other building. It is, therefore, important to understand how environmental noises are transmitted into buildings. Most of the same fundamentals discussed earlier apply to airborne sound propagation between homes in multifamily dwellings, via common walls and floors. However, within buildings we can also consider impact sound sources, such as footsteps, as well as airborne sounds.

The amount of incident sound that is transmitted through a building façade is measured in terms of the sound reduction index. The sound reduction index, or transmission loss, is defined as 10 times the logarithm of the ratio of incident-to-transmitted sound power, and it describes in decibels how much the incident sound is reduced on passing through a particular panel. This index of constructions usually increases with the frequency of the incident sound and with the mass of the construction (Kremer 1950). Thus, heavier or more massive constructions tend to have higher sound reductions. When it is not possible to achieve the desired transmission loss by increasing the mass of a panel, increased sound reduction can be achieved by a double panel construction. The two layers should be isolated with respect to vibrations and there should be sound absorbing material in the cavity. Such double panel constructions can provide much greater sound reduction than a single panel. Because sound reduction is also greater at higher frequencies most problems occur at lower frequencies, where most environmental noise sources produce relatively high sound pressure levels.

The sound reduction of buildings can be measured in standard laboratory tests, where the test panel is constructed in an opening between two reverberant test chambers (ISO 1995; ASTM 1997). In these tests sound fields are quite diffuse in both test chambers and the sound reduction index is calculated as the difference between the average sound pressure levels in the two rooms, plus a correction involving the area of the test panel and the total sound absorption in the receiving room. The sound reduction of a complete building façade can also be measured in the field using either natural environmental noises or test signals from loudspeakers (ISO 1978; ASTM 1992). In either case the noise, as transmitted through the façade, must be greater in level than other sounds in the receiving room. For this outdoor-to-indoor sound propagation case, the measured sound reduction index will also depend on the angle of incidence of the outdoor sound, as well as the position of the outdoor measuring microphone relative to the building façade. Corrections of up to 6 dB must be made to the sound pressure level measured outdoors, to account for the effect of reflections from the façade (see also section 2.4.3).

The sound reduction of most real building façades is determined by a combination of several different elements. For example, a wall might include windows, doors or some other type of element. If the sound reduction index values of each element are known, the values for the combined construction can be calculated from the area-weighted sums of the sound energy transmitted through each separate element. Although parts of the building façade, such as massive wall constructions, can be very effective barriers to sound, the sound reduction index of the complete façade is often greatly reduced by less effective elements such as windows, doors or ventilation openings. Completely open windows as such would have a sound reduction index of 0 dB. If window openings makes up 10% of the area of a wall, the sound reduction index of the combined wall and open window could not exceed 10 dB. Thus it is not enough to specify effective sound reducing façade constructions, without also solving the problem of adequate ventilation that does not compromise the sound transmission reduction by the building façade.

Sound reduction index values are measured at different frequencies and from these, single number ratings are determined. Most common are the ISO weighted sound reduction index (ISO 1996) and the equivalent ASTM sound transmission class (ASTM 1994a). However, in their original form these single number ratings are only appropriate for typical indoor noises that usually do not have strong low frequency components. Thus, they are usually not appropriate single number ratings of the ability of a building façade to block typical environmental noises. More recent additions to the ISO procedure have included source spectrum corrections intended to correct approximately for other types of sources (ISO 1996). Alternatively, the ASTM-Outdoor-Indoor Transmission Class rating calculates the A-weighted level reduction to a standard environmental noise source spectrum (ASTM 1994b). Within buildings the impact sound insulation index can be measured with a standard impact source and determined according to ISO and ASTM standards (ISO 1998; ASTM 1994c 1996)

2.7. More Specialized Noise Measures

2.7.1. Loudness and perceived noise levels

There are procedures to accurately rate the loudness of complex sounds (Zwicker 1960; Stevens 1972; ISO 1975a). These usually start from a 1/3 octave spectrum of the noise. The combination of the loudness contributions of each 1/3 octave band with estimates of mutual masking effects, leads to a single overall loudness rating in sones. A similar system for rating the noisiness of sounds has also been developed (Kryter 1994). Again a 1/3 octave spectrum of the noise is required and the 1/3 octave noise levels are compared with a set of equal-noisiness contours. The individual 1/3 octave band noisiness estimates are combined to give an overall perceived noise level (PNL) that is intended to accurately estimate subjective evaluations of the same sound. The PNL metric was initially developed to rate jet aircraft noise.

PNL values will vary with time, for example when an aircraft flies by a measuring point. The effective perceived noise level measure (EPNL) is derived from PNL values and is intended to provide a complete rating of an aircraft fly-over. EPNL values add both a duration correction and a tone correction to PNL values. The duration correction ensures that longer duration events are rated as more disturbing. Similarly, noise spectra that seem to have prominent tonal components are rated as more disturbing by the tone-correction procedure. There is some evidence that these tone corrections are not always successful in improving predictions of adverse responses to noise events (Scharf & Hellman 1980). EPNL values are used in the certification testing of new aircraft. These more precise measures ensure that the noise from new aircraft is rated as accurately as possible.

2.7.2. Aviation noise measures

There are many measures for evaluating the long-term average sound pressure levels from aircraft near airports (Ford 1987; House 1987). They include different frequency weightings, different summations of levels and numbers of events, as well as different time-of-day weightings. Most measures are based on either A-weighted or PNL-weighted sound pressure levels. Because of the many other large uncertainties in predicting community response to aircraft noise, there seems little justification for using the more complex PNL-weighted sound pressure levels and there is a trend to change to A-weighted measures.

Most aviation noise measures are based on an equal energy approach and hence they sum up the total energy of a number of aircraft fly-overs. However, some older measures were based on different combinations of the level of each event and the number of events. These types of measures are gradually being replaced by measures based on the equal energy hypothesis such as LAeq,T values. There is also a range of time-of-day weightings incorporated into current aircraft noise measures. Night-time weightings of 6–12 dB are currently in use. Some countries also include an intermediate evening weighting.

The day-night sound pressure level L_{dn} (von Gierke 1975; Ford 1987) is an LAeq,T based measure with a 10 dB night-time weighting. It is based on A-weighted sound pressure levels and the equal energy principle. The noise exposure forecast (NEF) (Bishop & Horonjeff 1967) is based on the EPNL values of individual aircraft events and includes a 12 dB night-time weighting. It sums multiple events on an equal energy basis. However, the Australian variation of the NEF measure has a 6 dB evening weighting and a 6 dB night-time weighting (Bullen & Hede 1983). The German airport noise equivalent level (LEQ(FLG)) is based on A-weighted levels, but does not follow the equal energy principle.

The weighted equivalent continuous perceived noise level (WECPNL) measure (Ford 1987) proposed by ICAO is based on the equal energy principle and maximum PNL values of aircraft fly-overs. However, in Japan an approximation to this measure is used and is based on maximum A-weighted levels. The noise and number index (NNI), formerly used in the United Kingdom, was derived from maximum PNL values but was not based on the equal energy principle. An approximation to the original version of the NNI has been used in Switzerland and is based on maximum A-weighted levels of aircraft fly-overs, but its use will soon be discontinued. Changes in these measures are slow because their use is often specified in national legislation. However, several countries have changed to measures that are based on the equal energy principle and A-weighted sound pressure levels.

2.7.3. Impulsive noise measures

Impulsive sounds, such as gun shots, hammer blows, explosions of fireworks or other blasts, are sounds that significantly exceed the background sound pressure level for a very short duration. Typically each impulse lasts less than one second. Measurements with the meter set to 'Fast' response (section 2.1.1) do not accurately represent impulsive sounds. Therefore the meter response time must be shorter to measure such impulse type sounds. C-weighted levels have been found useful for ratings of gun shots (ISO 1987). Currently no mathematical description exists which unequivocally defines impulsive sounds, nor is there a universally accepted procedure for rating the additional annoyance of impulsive sounds (HCN 1997). Future versions of ISO Standard 1996 (present standard in ISO 1987b) are planned to improve this situation.

2.7.4. Measures of speech intelligibility

The intelligibility of speech depends primarily on the speech-to-noise ratio. If the level of the speech sounds are 15 dB or more above the level of the ambient noise, the speech intelligibility at 1 m distance will be close to 100% (Houtgast 1981; Bradley 1986b). This can be most simply rated in terms of the speech-to-noise ratio of the A-weighted speech and noise levels. Alternatively, the speech intelligibility index (formerly the articulation index) can be used if octave or 1/3 octave band spectra of the speech and noise are available (ANSI 1997).

When indoors, speech intelligibility also depends on the acoustical properties of the space. The acoustical properties of spaces have for many years been rated in terms of reverberation times. The reverberation time is approximately the time it takes for a sound in a room to decrease to inaudibility after the source has been stopped. Optimum reverberation times for speech have been specified as a function of the size of the room. In large rooms, such as lecture halls and theaters, a reverberation time for speech of about 1 s is recommended. In smaller rooms such as classrooms, the recommended value for speech is about 0.6 s (Bradley 1986b,c). More modern measures of room acoustics have been found to be better correlates of speech intelligibility, and some combine an assessment of both the speech/noise ratio and room acoustics (Bradley 1986a,c). The most widely known is the speech transmission index (STI) (Houtgast & Steeneken 1983), or the abbreviated version of this measure referred to as RASTI (Houtgast & Steeneken 1985; IEC 1988). In smaller rooms, such as school classrooms, the conventional approach of requiring adequately low ambient noise levels, as well as some optimum reverberation time, is probably adequate to ensure good speech intelligibility (Bradley 1986b). In larger rooms and other more specialized situations, use of the more modern measures may be helpful.

2.7.5. Indoor noise ratings

The simplest procedure for rating levels of indoor noise is to measure them in terms of integrated A-weighted sound pressure levels, as measured by LAeq,T. As discussed earlier, this approach has been criticized as not being the most accurate rating of the negative effects of various types of noises, and is thought to be particularly inadequate when there are strong low-frequency components. Several more complex rating schemes are available based on octave band measurements of indoor noises. In Europe the noise rating system (Burns 1968), and in North America the noise criterion (Beranek 1971), both include sets of equal-disturbance type contours. Measured octave band sound pressure levels are compared with these contours and an overall noise rating is determined. More recently, two new schemes have been proposed: the balanced noise criterion procedure (Beranek 1989) and the room criterion system (Blazier 1998). These schemes are based on a wider range of octave bands extending from 16–8 000 Hz. They provide both a numerical and a letter rating of the noise. The numerical part indicates the level of the central frequencies important for speech communication and the letter indicates whether the quality of the sound is predominantly low-, medium- or high-frequency in nature. Extensive comparisons of these room noise rating procedures have yet to be performed. Because the newer measures include a wider range of frequencies, they can better assess a wider range of noise problems.

2.8. Summary

Where there are no clear reasons for using other measures, it is recommended that LAeq,T be used to evaluate more-or-less continuous environmental noises. LAeq,T should also be used to assess ongoing noises that may be composed of individual events with randomly varying sound pressure levels. Where the noise is principally composed of a small number of discrete events the additional use of LAmax or SEL is recommended. As pointed out in this chapter, there are definite limitations to these simple measures, but there are also many practical advantages, including economy and the benefits of a standardized approach.

The sound pressure level measurements should include all variations over time to provide results that best represent the noise in question. This would include variations in both the source and in propagation of the noise from the source to the receiver. Measurements should normally be made close to typical points of reception. The accuracy of the measurements and the details of the measurement procedure must be adapted to the type of noise and to other details of the noise exposure. Assessment of speech intelligibility, aviation noise or impulse noise may require the use of more specialized methods. Where the exposed people are indoors and noise measurements are made outdoors, the sound attenuating properties of the building façade must also be measured or estimated.

3. Adverse Health Effects Of Noise

3.1. Introduction

The perception of sounds in day-to-day life is of major importance for human well-being. Communication through speech, sounds from playing children, music, natural sounds in parklands, parks and gardens are all examples of sounds essential for satisfaction in every day life. Conversely, this document is related to the adverse effects of sound (noise). According to the International Programme on Chemical Safety (WHO 1994), an adverse effect of noise is defined as a change in the morphology and physiology of an organism that results in impairment of functional capacity, or an impairment of capacity to compensate for additional stress, or increases the susceptibility of an organism to the harmful effects of other environmental influences. This definition includes any temporary or long-term lowering of the physical, psychological or social functioning of humans or human organs. The health significance of noise pollution is given in this chapter under separate headings, according to the specific effects: noise-induced hearing impairment; interference with speech communication; disturbance of rest and sleep; psychophysiological, mental-health and performance effects; effects on residential behaviour and annoyance; as well as interference with intended activities. This chapter also considers vulnerable groups and the combined effects of sounds from different sources. Conclusions based on the details given in this chapter are given in Chapter 4 as they relate to guideline values.

3.2. Noise-Induced Hearing Impairment

Hearing impairment is typically defined as an increase in the threshold of hearing. It is assessed by threshold audiometry. Hearing handicap is the disadvantage imposed by hearing impairment sufficient to affect one’s personal efficiency in the activities of daily living. It is usually expressed in terms of understanding conventional speech in common levels of background noise (ISO 1990). Worldwide, noise-induced hearing impairment is the most prevalent irreversible occupational hazard. In the developing countries, not only occupational noise, but also environmental noise is an increasing risk factor for hearing impairment. In 1995, at the World Health Assembly, it was estimated that there are 120 million persons with disabling hearing difficulties worldwide (Smith 1998). It has been shown that men and women are equally at risk of noise-induced hearing impairment (ISO 1990; Berglund & Lindvall 1995).

Apart from noise-induced hearing impairment, hearing damage in populations is also caused by certain diseases; some industrial chemicals; ototoxic drugs; blows to the head; accidents; and hereditary origins. Deterioration of hearing capability is also associated with the aging process *per se* (presbyacusis). Present knowledge of the physiological effects of noise on the auditory system is based primarily on laboratory studies on animals. After noise exposure, the first morphological changes are usually found in the inner and outer hair cells of the cochlea, where the stereocilia become fused and bent. After more prolonged exposure, the outer and inner hair cells related to transmission of high-frequency sounds are missing. See Berglund & Lindvall (1995) for further discussion.

The ISO Standard 1999 (ISO 1990) gives a method for calculating noise-induced hearing impairment in populations exposed to all types of noise (continuous, intermittent, impulse) during working hours. Noise exposure is characterized by LAeq over 8 hours (LAeq,8h). In the Standard, the relationships between LAeq,8h and noise-induced hearing impairment are given for frequencies of 500–6 000 Hz, and for exposure times of up to 40 years. These relations show that noise-induced hearing impairment occurs predominantly in the high-frequency range of 3 000–6 000 Hz, the effect being largest at 4 000 Hz. With increasing LAeq,8h and increasing exposure time, noise-induced hearing impairment also occurs at 2 000 Hz. But at LAeq,8h levels of 75 dBA and lower, even prolonged occupational noise exposure will not result in noise-induced hearing impairment (ISO 1990). This value is equal to that specified in 1980 by the World Health Organization (WHO 1980a).

The ISO Standard 1999 (ISO 1990) specifies hearing impairment in statistical terms (median values, and percentile fractions between 0.05 and 0.95). The extent of noise-induced hearing impairment in populations exposed to occupational noise depends on the value of LAeq,8h and the number of years of noise exposure. However, for high LAeq,8h values, individual susceptibility seems to have a considerable effect on the rate of progression of hearing impairment. For daily exposures of 8–16 h, noise-induced hearing impairment can be reasonably well estimated from LAeq,8h extrapolated to the longer exposure times (Axelsson et al. 1986). In this adaptation of LAeq,8h for daily exposures other than 8 hours, the equal energy principle is assumed to be applicable. For example, the hearing impairment due to a 16 h daily exposure is equivalent to that at LAeq,8h plus 3 dB (LAeq,16h = LAeq,8h + 10*$\log_{10}$ (16/8) = LAeq,8h + 3 dB. For a 24 h exposure, LAeq,24h = LAeq,8h + 10*$\log_{10}$ (24/8) = LAeq,8h + 5 dB).

Since the calculation method specified in the ISO Standard 1999 (ISO 1990) is the only universally adopted method for estimating occupational noise-induced hearing impairment, attempts have been made to assess whether the method is also applicable to hearing impairment due to environmental noise, including leisure-time noise. There is ample evidence that shooting noise, with LAeq,24h values of up to 80 dB, induces the same hearing impairment as an equivalent occupational noise exposure (Smoorenburg 1998). Moreover, noise-induced hearing impairment studies from motorbikes are also in agreement with results from ISO Standard 1999 (ISO 1990). Hearing impairment in young adults and children 12 years and older has been assessed by LAeq on a 24 h time basis, for a variety of environmental and leisure-time exposure patterns (e.g. Passchier-Vermeer 1993; HCN 1994). These include pop music in discotheques and concerts (Babisch & Ising 1989; ISO 1990); pop music through headphones (Ising et al. 1994; Struwe et al. 1996; Passchier-Vermeer et al. 1998); music played by brass bands and symphony orchestras (van Hees 1992). The results are in agreement with values predicted by the ISO Standard 1999 method on the basis of adjusted time.

In the publications cited above, exposure to noise with known characteristics, such as duration and level, was related to hearing impairment. In addition to these publications, there is also an extensive literature showing hearing impairment in populations exposed to specific types of non-occupational noise, although these exposures are not well characterized. These noises originate from shooting, motorcycling, snowmobile driving, playing in arcades, listening to music at concerts and through headphones, using noisy toys, and fireworks (e.g. Brookhouser et al. 1992; see also Berglund & Lindvall 1995). Although the characteristics of these exposures are to a certain extent unknown, the details in the publications suggest that LAeq,24h values of these exposures exceed 70 dB.

In contrast, epidemiological studies failed to show hearing damage in populations exposed to an LAeq,24h of less than 70 dB (Lindemann et al. 1987). The data imply that even a lifetime exposure to environmental and leisure-time noise with an LAeq,24h <70 dBA would not cause hearing impairment in the large majority of people (over 95%). Overall, the results of many studies strongly suggest that the method from ISO Standard 1999 can also be used to estimate hearing impairment due to environmental and leisure-time noise, in addition to estimating the effects of occupational noise exposure.

Although the evidence suggests that the calculation method from ISO Standard 1999 (ISO 1990) should also be accepted for environmental and leisure time noise exposures, large-scale epidemiological studies of the general population do not exist to support this proposition. Taking into account the limitations of the studies, care should be taken with respect to the following aspects:

a. Data from animal experiments indicate that children may be more vulnerable in acquiring noise-induced hearing impairment than adults.

b. At very high instantaneous sound pressure levels, mechanical damage to the ear may occur (Hanner & Axelsson 1988). Occupational limits are set at peak sound pressure levels of 140 dB (EU 1986a). For adults exposed to environmental and leisure-time noise, this same limit is assumed to be valid. In the case of children, however, taking into account their habits while playing with noisy toys, peak sound pressure levels should never exceed 120 dB.

c. For shooting noise with LAeq,24h over 80 dB, studies on temporary threshold shift suggest the possibility of an increased risk for noise-induced hearing impairment (Smoorenburg 1998).

d. Risk for noise-induced hearing impairment may increase when the noise exposure is combined with exposure to vibrations, the use of ototoxic drugs, or some chemicals (Fechter 1999). In these circumstances, long-term exposure to LAeq,24h of 70 dBA may induce small hearing impairments.

e. It is uncertain whether the relationships between hearing impairment and noise exposure given in ISO Standard 1999 (ISO 1990) are applicable for environmental sounds of short rise time. For example, in the case of military low-altitude flying areas (75–300 m above ground) LAmax values of 110–130 dB occur within seconds after the onset of the sound.

Usually noise-induced hearing impairment is accompanied by an abnormal loudness perception which is known as loudness recruitment (*cf*. Berglund & Lindvall 1995). With a considerable loss of auditory sensitivity, some sounds may be perceived as distorted (paracusis). Another sensory effect that results from noise exposure is tinnitus (ringing in the ears). Commonly, tinnitus is referred to as sounds that are emitted by the inner ear itself (physiological tinnitus).

Tinnitus is a common and often disturbing accompaniment of occupational hearing impairment (Vernon and Moller 1995) and has become a risk for teenagers attending pop concerts and discotheques (Hetu & Fortin 1995; Passchier-Vermeer et al. 1998; Axelsson & Prasher 1999). Noise-induced tinnitus may be temporary, lasting up to 24 hours after exposure, or may have a more permanent character, such as after prolonged occupational noise exposure. Sometimes tinnitus is due to the sound produced by the blood flow through structures in the ear.

The main social consequence of hearing impairment is an inability to understand speech in daily living conditions, which is considered a severe social handicap. Even small values of hearing impairment (10 dB averaged over 2 000 and 4 000 Hz, and over both ears) may have an effect on the understanding of speech. When the hearing impairment exceeds 30 dB (again averaged over 2 000 and 4 000 Hz and both ears) a social hearing handicap is noticeable (*cf*. Katz 1994; Berglund & Lindvall 1995).

In the past, hearing protection has mainly emphasized occupational noise exposures at high values of LAeq,8h, or situations with high impulsive sounds. The near-universal adoption of an LAeq,8h value of 85 dB (or lower) as the limit for unprotected occupational noise exposure, together with requirements for personal hearing protection, has made cases of severe unprotected exposures more rare. This is particularly true for developed countries. However, monitoring of compliance and enforcement action for sound pressure levels just over the limits may be weak, especially in non-industrial environments in developed countries (Franks 1998), as well as in occupational and urban environments in developing countries (Smith 1998). Nevertheless, regulations for occupational noise exposure exist almost worldwide and exposures to occupational noise are to a certain extent under control.

On the other hand, environmental noise exposures due to a number of noisy activities, especially those during leisure-time activities of children and young adults, have scarcely been regulated. Given both the increasing number of noisy activities and the increasing exposure duration, such as loud music in cars and the use of Walkmen and Discmen, regulatory activities in this field are to be encouraged. Dose-response data are lacking for the general population. However, judging from the limited data for study groups (teenagers, young adults and women), and the assumption that time of exposure can be equated with sound energy, the risk for hearing impairment would be negligible for LAeq,24h values of 70 dBA over a lifetime. To avoid hearing impairment, impulse noise exposures should never exceed 140 dB peak sound pressure in adults, and 120 dB peak sound pressure in children.

3.3. Interference with Speech Communication

Noise interference with speech comprehension results in a large number of personal disabilities, handicaps and behavioural changes. Problems with concentration, fatigue, uncertainty and lack of self-confidence, irritation, misunderstandings, decreased working capacity, problems in human relations, and a number of stress reactions have all been identified (Lazarus 1998). Particularly vulnerable to these types of effects are the hearing impaired, the elderly, children in the process of language and reading acquisition, and individuals who are not familiar with the spoken language (e.g., Lazarus 1998). Thus, vulnerable persons constitute a substantial proportion of a country’s population.

Most of the acoustical energy of speech is in the frequency range 100–6 000 Hz, with the most important cue-bearing energy being between 300–3 000 Hz. Speech interference is basically a masking process in which simultaneous, interfering noise renders speech incapable of being understood. The higher the level of the masking noise, and the more energy it contains at the most important speech frequencies, the greater will be the percentage of speech sounds that become indiscernible to the listener. Environmental noise may also mask many other acoustical signals important for daily life, such as door bells, telephone signals, alarm clocks, fire alarms and other warning signals, and music (e.g., Edworthy & Adams 1996). The masking effect of interfering noise in speech discrimination is more pronounced for hearing-impaired persons than for persons with normal hearing, particularly if the interfering noise is composed of speech or babble.

As the sound pressure level of an interfering noise increases, people automatically raise their voice to overcome the masking effect upon speech (increase of vocal effort). This imposes an additional strain on the speaker. For example, in quiet surroundings, the speech level at 1 m distance averages 45–50 dBA, but is 30 dBA higher when shouting. However, even if the interfering noise is moderately loud, most of the sentences during ordinary conversation can still be understood fairly well. Nevertheless, the interpretation required for compensating the masking effect of the interfering sounds, and for comprehending what was said, imposes an additional strain on the listener. One contributing factor could be that speech spoken loudly is more difficult to understand than speech spoken softly, when compared at a constant speech-to-noise ratio (*cf*. Berglund & Lindvall 1995).

Speech levels vary between individuals because of factors such as gender and vocal effort. Moreover, outdoor speech levels decrease by about 6 dB for a doubling in the distance between talker and listener. Speech intelligibility in everyday living conditions is influenced by speech level, speech pronunciation, talker-to-listener distance, sound pressure levels, and to some extent other characteristics of interfering noise, as well as room characteristics (e.g. reverberation). Individual capabilities of the listener, such as hearing acuity and the level of attention of the listener, are also important for the intelligibility of speech. Speech communication is affected also by the reverberation characteristics of the room. For example, reverberation times greater than 1 s produce loss in speech discrimination. Longer reverberation times, especially when combined with high background interfering noise, make speech perception more difficult. Even in a quiet environment, a reverberation time below 0.6 s is desirable for adequate speech intelligibility by vulnerable groups. For example, for older hearing-handicapped persons, the optimal reverberation time for speech intelligibility is 0.3–0.5 s (Plomp 1986).

For complete sentence intelligibility in listeners with normal hearing, the signal-to-noise ratio (i.e. the difference between the speech level and the sound pressure level of the interfering noise) should be 15–18 dBA (Lazarus 1990). This implies that in smaller rooms, noise levels above 35 dBA interferes with the intelligibility of speech (Bradley 1985). Earlier recommendations suggested that sound pressure levels as high as 45 dBA would be acceptable (US EPA 1974). With raised voice (increased vocal effort) sentences may be 100% intelligible for noise levels of up to 55 dBA; and sentences spoken with straining vocal effort can be 100% intelligible with noise levels of about 65 dBA. For speech to be intelligible when listening to complicated messages (at school, listening to foreign languages, telephone conversation), it is recommended that the signal-to-noise ratio should be at least 15 dBA. Thus, with a speech level of 50 dBA, (at 1 m distance this level corresponds to a casual speech level of both women and men), the sound pressure level of interfering noise should not exceed 35 dBA. For vulnerable groups even lower background levels are needed. If it is not possible to meet the strictest criteria for vulnerable persons in sensitive situations (e.g. in classrooms), one should strive for as low background levels as possible.

3.4. Sleep Disturbance

Uninterrupted sleep is known to be a prerequisite for good physiological and mental functioning of healthy persons (Hobson 1989); sleep disturbance, on the other hand, is considered to be a major environmental noise effect. It is estimated that 80-90% of the reported cases of sleep disturbance in noisy environments are for reasons other than noise originating outdoors. For example, sanitary needs; indoor noises from other occupants; worries; illness; and climate (e.g. Reyner & Horne 1995). Our understanding of the impact of noise exposure on sleep stems mainly from experimental research in controlled environments. Field studies conducted with people in their normal living situations are scarce. Most of the more recent field research on sleep disturbance has been conducted for aircraft noise (Fidell et al. 1994 1995a,b 1998; Horne et al. 1994 1995; Maschke et al. 1995 1996; Ollerhead et al. 1992; Passchier-Vermeer 1999). Other field studies have examined the effects of road traffic and railway noise (Griefahn et al. 1996 1998).

The primary sleep disturbance effects are: difficulty in falling asleep (increased sleep latency time); awakenings; and alterations of sleep stages or depth, especially a reduction in the proportion of REM-sleep (REM = rapid eye movement) (Hobson 1989). Other primary physiological effects can also be induced by noise during sleep, including increased blood pressure; increased heart rate; increased finger pulse amplitude; vasoconstriction; changes in respiration; cardiac arrhythmia; and an increase in body movements (cf. Berglund & Lindvall 1995). For each of these physiological effects, both the noise threshold and the noise-response relationships may be different. Different noises may also have different information content and this also could affect physiological threshold and noise-response relationships (Edworthy 1998).

Exposure to night-time noise also induces secondary effects, or so-called after effects. These are effects that can be measured the day following the night-time exposure, while the individual is awake. The secondary effects include reduced perceived sleep quality; increased fatigue; depressed mood or well-being; and decreased performance (Öhrström 1993a; Passchier-Vermeer 1993; Carter 1996; Pearsons et al. 1995; Pearsons 1998).

Long-term effects on psychosocial well-being have also been related to noise exposure during the night (Öhrström 1991). Noise annoyance during the night-time increased the total noise annoyance expressed by people in the following 24 h. Various studies have also shown that people living in areas exposed to night-time noise have an increased use of sedatives or sleeping pills. Other frequently reported behavioural effects of night-time noise include closed bedroom windows and use of personal hearing protection. Sensitive groups include the elderly, shift workers, persons especially vulnerable to physical or mental disorders and other individuals with sleeping difficulties.

Questionnaire data indicate the importance of night-time noise on the perception of sleep quality. A recent Japanese investigation was conducted for 3 600 women (20–80 years old) living in eight roadside zones with different road traffic noise. The results showed that four measures of perceived sleep quality (difficulty in falling asleep; waking up during sleep; waking up too early; feelings of sleeplessness one or more days a week) correlated significantly with the average traffic volumes during night-time. An in-depth investigation of 19 insomnia cases and their matched controls (age,work) measured outdoor and indoor sound pressure levels during sleep (Kageyama et al. 1997). The study showed that road traffic noise in excess of 30 dB LAeq for nighttime induced sleep disturbance, consistent with the results of Öhrström (1993b).

Meta-analyses of field and laboratory studies have suggested that there is a relationship between the SEL for a single night-time noise event and the percentage of people awakened, or who showed sleep stage changes (e.g. Ollerhead et al. 1992; Passchier-Vermeer 1993; Finegold et al. 1994; Pearsons et al. 1995). All of these studies assumed that the number of awakenings per night for each SEL value is proportional to the number of night-time noise events. However, the results have been criticized for methodological reasons. For example, there were small groups of sleepers; too few original studies; and indoor exposure was estimated from outdoor sound pressure levels (NRC-CNRC 1994; Beersma & Altena 1995; Vallet 1998). The most important result of the meta-analyses is that there is a clear difference in the dose-response curves for laboratory and field studies, and that noise has a lower effect under real-life conditions (Pearsons et al. 1995; Pearsons 1998).

However, this result has been questioned, because the studies were not controlled for such things as the sound insulation of the buildings, and the number of bedrooms with closed windows. Also, only two indicators of sleep disturbance were considered (awakening and sleep stage changes). The meta-analyses thus neglected other important sleep disturbance effects (Öhrström 1993b; Carter et al. 1994a; Carter et al. 1994b; Carter 1996; Kuwano et al. 1998). For example, for road traffic noise, perceived sleep quality is related both to the time needed to fall asleep and the total sleep time (Öhrström & Björkman 1988). Individuals who are more sensitive to noise (as assessed by different questionnaires) report worse sleep quality both in field studies and in laboratory studies.

A further criticism of the meta-analyses is that laboratory experiments have shown that habituation to night-time noise events occurs, and that noise-induced awakening decreases with increasing number of sound exposures per night. This is in contrast to the assumption used in the meta-analyses, that the percentage of awakenings is linearly proportional to the number of night-time noise events. Studies have also shown that the frequency of noise-induced awakenings decreases for at least the first eight consecutive nights. So far, habituation has been shown for awakenings, but not for heart rate and after effects such as perceived sleep quality, mood and performance (Öhrström and Björkman 1988).

Other studies suggest that it is the difference in sound pressure levels between a noise event and background, rather than the absolute sound pressure level of the noise event, that determines the reaction probability. The time interval between two noise events also has an important influence of the probability of obtaining a response (Griefahn 1977; *cf*. Berglund & Lindvall 1995). Another possible factor is the person's age, with older persons having an increased probability of awakening. However, one field study showed that noise-induced awakenings are independent of age (Reyner & Horne 1995).

For a good sleep, it is believed that indoor sound pressure levels should not exceed approximately 45 dB LAmax more than 10–15 times per night (Vallet & Vernet 1991), and most studies show an increase in the percentage of awakenings at SEL values of 55–60 dBA (Passchier-Vermeer 1993; Finegold et al. 1994; Pearsons et al. 1995). For intermittent events that approximate aircraft noise, with an effective duration of 10–30 s, SEL values of 55–60 dBA correspond to a LAmax value of 45 dB. Ten to 15 of these events during an eight-hour night-time implies an LAeq,8h of 20–25 dB. This is 5–10 dB below the LAeq,8h of 30 dB for continuous night-time noise exposure, and shows that the intermittent character of noise has to be taken into account when setting night-time limits for noise exposure. For example, this can be achieved by considering the number of noise events and the difference between the maximum sound pressure level and the background level of these events.

Special attention should also be given to the following considerations:

a. Noise sources in an environment with a low background noise level. For example, night-traffic in suburban residential areas.

b. Environments where a combination of noise and vibrations are produced. For example, railway noise, heavy duty vehicles.

c. Sources with low-frequency components. Disturbances may occur even though the sound pressure level during exposure is below 30 dBA.

If negative effects on sleep are to be avoided the equivalent sound pressure level should not exceed 30 dBA indoors for continuous noise. If the noise is not continuous, sleep disturbance correlates best with LAmax and effects have been observed at 45 dB or less. This is particularly true if the background level is low. Noise events exceeding 45 dBA should therefore be limited if possible. For sensitive people an even lower limit would be preferred. It should be noted that it should be possible to sleep with a bedroom window slightly open (a reduction from outside to inside of 15 dB). To prevent sleep disturbances, one should thus consider the equivalent sound pressure level and the number and level of sound events. Mitigation targeted to the first part of the night is believed to be effective for the ability to fall asleep.

3.5. Cardiovascular and Physiological Effects

Epidemiological and laboratory studies involving workers exposed to occupational noise, and general populations (including children) living in noisy areas around airports, industries and noisy streets, indicate that noise may have both temporary and permanent impacts on physiological functions in humans. It has been postulated that noise acts as an environmental stressor (for a review see Passchier-Vermeer 1993; Berglund & Lindvall 1995). Acute noise exposures activate the autonomic and hormonal systems, leading to temporary changes such as increased blood pressure, increased heart rate and vasoconstriction. After prolonged exposure, susceptible individuals in the general population may develop permanent effects, such as hypertension and ischaemic heart disease associated with exposures to high sound pressure levels (for a review see Passchier-Vermeer 1993; Berglund & Lindvall 1995). The magnitude and duration of the effects are determined in part by individual characteristics, lifestyle behaviours and environmental conditions. Sounds also evoke reflex responses, particularly when they are unfamiliar and have a sudden onset.

Laboratory experiments and field quasi-experiments show that if noise exposure is temporary, the physiological system usually returns - after the exposure terminates - to a normal (pre-exposure) state within a time in the range of the exposure duration. If the exposure is of sufficient intensity and unpredictability, cardiovascular and hormonal responses may appear, including increases in heart rate and peripheral vascular resistance; changes in blood pressure, blood viscosity and blood lipids; and shifts in electrolyte balance (Mg/Ca) and hormonal levels (epinephrine, norepinephrine, cortisol). The first four effects are of interest because of noise-related coronary heart disease (Ising & Günther 1997). Laboratory and clinical data suggest that noise may significantly elevate gastrointestinal motility in humans.

By far the greatest number of occupational and community noise studies have focused on the possibility that noise may be a risk factor for cardiovascular disease. Many studies in occupational settings have indicated that workers exposed to high levels of industrial noise for 5–30 years have increased blood pressure and statistically significant increases in risk for hypertension, compared to workers in control areas (Passchier-Vermeer 1993). In contrast, only a few studies on environmental noise have shown that populations living in noisy areas around airports and on noisy streets have an increased risk for hypertension. The overall evidence suggests a weak association between long-term environmental noise exposure and hypertension (HCN 1994; Berglund & Lindvall 1995; IEH 1997), and no dose-response relationships could be established.

Recently, an updated summary of available studies for ischaemic heart disease has been presented (Babisch 1998a; Babisch 1998b; Babisch et al. 1999; see also Thompson 1996). The studies reviewed include case-control and cross-sectional designs, as well as three longitudinal studies. However, it has not yet been possible to conduct the most advanced quantitative integrated analysis of the available studies. Relative risks and their confidence intervals could be estimated only for the classes of high noise levels (mostly >65 dBA during daytime) and low levels (mostly <55 dBA during daytime), rather than a range of exposure levels. For methodological reasons identified in the meta-analysis, a cautious interpretation of the results is warranted (Lercher et al. 1998).

Prospective studies that controlled for confounding factors suggest an increase in ischaemic heart disease when the noise levels exceed 65–70 dB for LAeq (6–22). (For road traffic noise, the difference between LAeq (6-22h) and LAeq,24h usually is of the order of 1.5 dB). When orientation of the bedroom, window opening habits and years of exposure are taken into account, the risk of heart disease is slightly higher (Babisch et al. 1998; Babisch et al. 1999). However, disposition, behavioural and environmental factors were not sufficiently accounted for in the analyses carried out to date. In epidemiological studies the lowest level at which traffic noise had an effect on ischaemic heart disease was 70 dB for LAeq,24h (HCN 1994).

The overall conclusion is that cardiovascular effects are associated with long-term exposure to LAeq,24h values in the range of 65–70 dB or more, for both air- and road-traffic noise. However, the associations are weak and the effect is somewhat stronger for ischaemic heart disease than for hypertension. Nevertheless, such small risks are potentially important because a large number of persons are currently exposed to these noise levels, or are likely to be exposed in the future. Furthermore, only the average risk is considered and sensitive subgroups of the populations have not been sufficiently characterized. For example, a 10% increase in risk factors (a relative risk of 1.1) may imply an increase of up to 200 cases per 100 000 people at risk per year. Other observed psychophysiological effects, such as changes in stress hormones, magnesium levels, immunological indicators, and gastrointestinal disturbances are too inconsistent for conclusions to be drawn about the influence of noise pollution.

3.6. Mental Health Effects

Mental health is defined as the absence of identifiable psychiatric disorders according to current norms (Freeman 1984). Environmental noise is not believed to be a direct cause of mental illness, but it is assumed that it accelerates and intensifies the development of latent mental disorder. Studies on the adverse effects of environmental noise on mental health cover a variety of symptoms, including anxiety; emotional stress; nervous complaints; nausea; headaches; instability; argumentativeness; sexual impotency; changes in mood; increase in social conflicts, as well as general psychiatric disorders such as neurosis, psychosis and hysteria. Large-scale population studies have suggested associations between noise exposure and a variety of mental health indicators, such as single rating of well-being; standard psychological symptom profiles; the intake of psychotropic drugs; and consumption of tranquilizers and sleeping pills. Early studies showed a weak association between exposure to aircraft noise and psychiatric hospital admissions in the general population surrounding an airport (see also Berglund & Lindvall 1995). However, the studies have been criticized because of problems in selecting variables and in response bias (Halpern 1995).

Exposure to high levels of occupational noise has been associated with development of neurosis and irritability; and exposure to high levels of environmental noise with deteriorated mental health (Stansfeld 1992). However, the findings on environmental noise and mental health effects are inconclusive (HCN 1994; Berglund & Lindvall 1995; IEH 1997). The only longitudinal study in this field (Stansfeld et al. 1996) showed an association between the initial level of road traffic noise and minor psychiatric disorders, although the association for increased anxiety was weak and non-linear. It turned out that psychiatric disorders are associated with noise sensitivity, rather than with noise exposure, and the association was found to disappear after adjustment for baseline trait anxiety. These and other results show the importance of taking vulnerable groups into account, because they may not be able to cope sufficiently with unwanted environmental noise (e.g. Stansfeld 1992). This is particularly true of children, the elderly and people with preexisting illnesses, especially depression (IEH 1997). Despite the weaknesses of the various studies, the possibility that community noise has adverse effects on mental health is suggested by studies on the use of medical drugs, such as tranquilizers and sleeping pills, on psychiatric symptoms and on mental hospital admission rates.

3.7. The Effects of Noise on Performance

It has been documented in both laboratory subjects and in workers exposed to occupational noise, that noise adversely affects cognitive task performance. In children, too, environmental noise impairs a number of cognitive and motivational parameters (Cohen et al. 1980; Evans & Lepore 1993; Evans 1998; Hygge et al. 1998; Haines et al. 1998). However, there are no published studies on whether environmental noise at home also impairs cognitive performance in adults. Accidents may also be an indicator of performance deficits. The few field studies on the effects of noise on performance and safety showed that noise may produce some task impairment and increase the number of errors in work, but the effects depend on the type of noise and the task being performed (Smith 1990).

Laboratory and workplace studies showed that noise can act as a distracting stimulus. Also, impulsive noise events (e.g. sonic booms) may produce disruptive effects as a result of startle responses. In the short term, noise-induced arousal may produce better performance of simple tasks, but cognitive performance deteriorates substantially for more complex tasks (i.e. tasks that require sustained attention to details or to multiple cues; or tasks that demand a large capacity of working memory, such as complex analytical processes). Some of the effects are related to loss in auditory comprehension and language acquisition, but others are not (Evans & Maxwell 1997). Among the cognitive effects, reading, attention, problem solving and memory are most strongly affected by noise. The observed effects on motivation, as measured by persistence with a difficult cognitive task, may either be independent or secondary to the aforementioned cognitive impairments.

Two types of memory deficits have been identified under experimental noise exposure: incidental memory and memory for materials that the observer was not explicitly instructed to focus on during a learning phase. For example, when presenting semantic information to subjects in the presence of noise, recall of the information content was unaffected, but the subjects were significantly less able to recall, for example, in which corner of the slide a word had been located. There is also some evidence that the lack of "helping behavior" that was noted under experimental noise exposure may be related to inattention to incidental cues (Berglund & Lindvall 1995). Subjects appear to process information faster in working memory during noisy performance conditions, but at a cost of available memory capacity. For example, in a running memory task, in which subjects were required to recall in sequence letters that they had just heard, subjects recalled recent items better under noisy conditions, but made more errors farther back into the list.

Experimental noise exposure consistently produces negative after-effects on performance (Glass & Singer 1972). Following exposure to aircraft noise, schoolchildren in the vicinity of Los Angeles airport were found to be deficient in proofreading, and in persistence with challenging puzzles (Cohen et al. 1980). The uncontrollability of noise, rather than the intensity of the noise, appears to be the most critical variable. The only prospective study on noise-exposed schoolchildren, designed around the move of the Munich airport (Hygge et al. 1996; Evans et al. 1998), confirmed the results of laboratory and workplace studies in adults, as well the results of the Los Angeles airport study with children (Cohen et al. 1980). An important finding was that some of the adaptation strategies for dealing with aircraft noise, such as tuning out or ignoring the noise, and the effort necessary to maintain task performance, come at a price. There is heightened sympathetic arousal, as indicated by increased levels of stress hormone, and elevation of resting blood pressure (Evans et al. 1995; Evans et al. 1998). Notably, in the airport studies reported above, the adverse effects were larger in children with lower school achievement.

For aircraft noise, it has been shown that chronic exposure during early childhood appears to impair reading acquisition and reduces motivational capabilities. Of recent concern are concomitant psychophysiological changes (blood pressure and stress hormone levels). Evidence indicates that the longer the exposure, the greater the damage. It seems clear that daycare centers and schools should not be located near major sources of noise, such as highways, airports and industrial sites.

3.8. Effects of Noise on Residential Behaviour and Annoyance

Noise annoyance is a global phenomenon. A definition of annoyance is “a feeling of displeasure associated with any agent or condition, known or believed by an individual or group to adversely affect them” (Lindvall & Radford 1973; Koelega 1987). However, apart from “annoyance”, people may feel a variety of negative emotions when exposed to community noise, and may report anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion (Job 1993; Fields et al. 1997 1998). Thus, although the term annoyance does not cover all the negative reactions, it is used for convenience in this document.

Noise can produce a number of social and behavioural effects in residents, besides annoyance (for review see Berglund & Lindvall 1995). The social and behavioural effects are often complex, subtle and indirect. Many of the effects are assumed to be the result of interactions with a number of non-auditory variables. Social and behavioural effects include changes in overt everyday behaviour patterns (e.g. closing windows, not using balconies, turning TV and radio to louder levels, writing petitions, complaining to authorities); adverse changes in social behaviour (e.g. aggression, unfriendliness, disengagement, non-participation); adverse changes in social indicators (e.g. residential mobility, hospital admissions, drug consumption, accident rates); and changes in mood (e.g. less happy, more depressed).

Although changes in social behaviour, such as a reduction in helpfulness and increased aggressiveness, are associated with noise exposure, noise exposure alone is not believed to be sufficient to produce aggression. However, in combination with provocation or pre-existing anger or hostility, it may trigger aggression. It has also been suspected that people are less willing to help, both during exposure and for a period after exposure. Fairly consistent evidence shows that noise above 80 dBA is associated with reduced helping behaviour and increased aggressive behaviour. Particularly, there is concern that high-level continuous noise exposures may contribute to the susceptibility of schoolchildren to feelings of helplessness (Evans & Lepore 1993)

The effects of community noise can be evaluated by assessing the extent of annoyance (low, moderate, high) among exposed individuals; or by assessing the disturbance of specific activities, such as reading, watching television and communication. The relationship between annoyance and activity disturbances is not necessarily direct and there are examples of situations where the extent of annoyance is low, despite a high level of activity disturbance. For aircraft noise, the most important effects are interference with rest, recreation and watching television. This is in contrast to road traffic noise, where sleep disturbance is the predominant effect (Berglund & Lindvall 1995).

A number of studies have shown that equal levels of traffic and industrial noises result in different magnitudes of annoyance (Hall et al. 1981; Griffiths 1983; Miedema 1993; Bradley 1994a; Miedema & Vos 1998). This has led to criticism (e.g. Kryter 1994; Bradley 1994a) of averaged dose-response curves determined by meta-analysis, which assumed that all traffic noises are the same (Fidell et al. 1991; Fields 1994a; Finegold et al. 1994). Schultz (1978) and Miedema & Vos (1998) have synthesized curves of annoyance associated with three types of traffic noise (road, air, railway). In these curves, the percentage of people highly or moderately annoyed was related to the day and night continuous equivalent sound level, L_{dn}. For each of the three types of traffic noise, the percentage of highly annoyed persons in a population started to increase at an L_{dn} value of 42 dBA, and the percentage of moderately annoyed persons at an L_{dn} value of 37 dBA (Miedema & Vos 1998). Aircraft noise produced a stronger annoyance response than road traffic, for the same L_{dn} exposure, consistent with earlier analyses (Kryter 1994; Bradley 1994a). However, caution should be exercised when interpreting synthesized data from different studies, since five major parameters should be randomly distributed for the analyses to be valid: personal, demographic, and lifestyle factors, as well as the duration of noise exposure and the population experience with noise (Kryter 1994).

Annoyance in populations exposed to environmental noise varies not only with the acoustical characteristics of the noise (source, exposure), but also with many non-acoustical factors of social, psychological, or economic nature (Fields 1993). These factors include fear associated with the noise source, conviction that the noise could be reduced by third parties, individual noise sensitivity, the degree to which an individual feels able to control the noise (coping strategies), and whether the noise originates from an important economic activity. Demographic variables such as age, sex and socioeconomic status, are less strongly associated with annoyance. The correlation between noise exposure and general annoyance is much higher at the group level than at the individual level, as might be expected. Data from 42 surveys showed that at the group level about 70% of the variance in annoyance is explained by noise exposure characteristics, whereas at the individual level it is typically about 20% (Job 1988).

When the type and amount of noise exposure is kept constant in the meta-analyses, differences between communities, regions and countries still exist (Fields 1990; Bradley 1996). This is well demonstrated by a comparison of the dose-response curve determined for road-traffic noise

(Miedema & Vos 1998) and that obtained in a survey along the North-South transportation route through the Austrian Alps (Lercher 1998b). The differences may be explained in terms of the influence of topography and meteorological factors on acoustical measures, as well as the low background noise level on the mountain slopes.

Stronger reactions have been observed when noise is accompanied by vibrations and contains low frequency components (Paulsen & Kastka 1995; Öhrström 1997; for review see Berglund et al. 1996), or when the noise contains impulses, such as shooting noise (Buchta 1996; Vos 1996; Smoorenburg 1998). Stronger, but temporary, reactions also occur when noise exposure is increased over time, in comparison to situations with constant noise exposure (e.g. HCN 1997; Klæboe et al. 1998). Conversely, for road traffic noise, the introduction of noise protection barriers in residential areas resulted in smaller reductions in annoyance than expected for a stationary situation (Kastka et al. 1995).

To obtain an indicator for annoyance, other methods of combining parameters of noise exposure have been extensively tested, in addition to metrics such as LAeq,24h and L_{dn}. When used for a set of community noises, these indicators correlate well both among themselves and with LAeq,24h or L_{dn} values (e.g. HCN 1997). Although LAeq,24h and L_{dn} are in most cases acceptable approximations, there is a growing concern that all the component parameters of the noise should be individually assessed in noise exposure investigations, at least in the complex cases (Berglund & Lindvall 1995).

3.9. The Effects of Combined Noise Sources

Many acoustical environments consist of sounds from more than one source. For these environments, health effects are associated with the total noise exposure, rather than with the noise from a single source (WHO 1980b). When considering hearing impairment, for example, the total noise exposure can be expressed in terms of LAeq,24h for the combined sources. For other adverse health effects, however, such a simple model most likely will not apply. It is possible that some disturbances (e.g. speech interference, sleep disturbance) may more easily be attributed to specific noises. In cases where one noise source clearly dominates, the magnitude of an effect may be assessed by taking into account the dominant source only (HCN 1997). Furthermore, at a policy level, there may be little need to identify the adverse effect of each specific noise, unless the responsibility for these effects is to be shared among several polluters (*cf*. The Polluter Pays Principle in Chapter 5, UNCED 1992).

There is no consensus on a model for assessing the total annoyance due to a combination of environmental noise sources. This is partly due to a lack of research into the temporal patterns of combined noises. The current approach for assessing the effects of “mixed noise sources” is limited to data on “total annoyance” transformed to mathematical principles or rules of thumb (Ronnebaum et al. 1996; Vos 1992; Miedema 1996; Berglund & Nilsson 1997). Models to assess the total annoyance of combinations of environmental noises may not be applicable to those health effects for which the mechanisms of noise interaction are unknown, and for which different cumulative or synergistic effects cannot be ruled out. When noise is combined with different types of environmental agents, such as vibrations, ototoxic chemicals, or chemical odours, again there is insufficient knowledge to accurately assess the combined effects on health

(Berglund & Lindvall 1995; HCN 1994; Miedema 1996; Zeichart 1998; Passchier-Vermeer & Zeichart 1998). Therefore, caution should be exercised when trying to predict the adverse health effects of combined factors in residential populations.

The evidence on low-frequency noise is sufficiently strong to warrant immediate concern. Various industrial sources emit continuous low-frequency noise (compressors, pumps, diesel engines, fans, public works); and large aircraft, heavy-duty vehicles and railway traffic produce intermittent low-frequency noise. Low-frequency noise may also produce vibrations and rattles as secondary effects. Health effects due to low-frequency components in noise are estimated to be more severe than for community noises in general (Berglund et al. 1996). Since A-weighting underestimates the sound pressure level of noise with low-frequency components, a better assessment of health effects would be to use C-weighting.

In residential populations heavy noise pollution will most certainly be associated with a combination of health effects. For example, cardiovascular disease, annoyance, speech interference at work and at home, and sleep disturbance. Therefore, it is important that the total adverse health load over 24 hours be considered and that the precautionary principle for sustainable development is applied in the management of health effects (see Chapter 5).

3.10. Vulnerable Groups

Protective standards are essentially derived from observations on the health effects of noise on "normal" or "average" populations. The participants of these investigations are selected from the general population and are usually adults. Sometimes, samples of participants are selected because of their easy availability. However, vulnerable groups of people are typically underrepresented. This group includes people with decreased personal abilities (old, ill, or depressed people); people with particular diseases or medical problems; people dealing with complex cognitive tasks, such as reading acquisition; people who are blind or who have hearing impairment; fetuses, babies and young children; and the elderly in general (Jansen 1987; AAP 1997). These people may be less able to cope with the impacts of noise exposure and be at greater risk for harmful effects.

Persons with impaired hearing are the most adversely affected with respect to speech intelligibility. Even slight hearing impairments in the high-frequency range may cause problems with speech perception in a noisy environment. From about 40 years of age, people typically demonstrate an impaired ability to understand difficult, spoken messages with low linguistic redundancy. Therefore, based on interference with speech perception, a majority of the population belongs to the vulnerable group.

Children have also been identified as vulnerable to noise exposure (see Agenda 21: UNCED 1992). The evidence on noise pollution and children's health is strong enough to warrant monitoring programmes at schools and preschools to protect children from the effects of noise. Follow up programmes to study the main health effects of noise on children, including effects on speech perception and reading acquisition, are also warranted in heavily noise polluted areas (Cohen et al. 1986; Evans et al. 1998).

The issue of vulnerable subgroups in the general population should thus be considered when developing regulations or recommendations for the management of community noise. This consideration should take into account the types of effects (communication, recreation, annoyance, etc.), specific environments (*in utero*, incubator, home, school, workplace, public institutions, etc.) and specific lifestyles (listening to loud music through headphones, or at discotheques and festivals; motor cycling, etc.).

4. Guideline Values

4.1. Introduction

The human ear and lower auditory system continuously receive stimuli from the world around us. However, this does not mean that all the acoustical inputs are necessarily disturbing or have harmful effects. This is because the auditory nerve provides activating impulses to the brain that enable us to regulate the vigilance and wakefulness necessary for optimal performance. On the other hand, there are scientific reports that a completely silent world can have harmful effects, because of sensory deprivation. Thus, both too little sound and too much sound can be harmful. For this reason, people should have the right to decide for themselves the quality of the acoustical environment they live in.

Exposure to noise from various sources is most commonly expressed as the average sound pressure level over a specific time period, such as 24 hours. This means that identical average sound levels for a given time period could be derived from either a large number of sound events with relatively low, almost inaudible levels, or from a few events with high sound levels. This technical concept does not fully agree with common experience on how environmental noise is experienced, or with the neurophysiological characteristics of the human receptor system.

Human perception of the environment through vision, hearing, touch, smell and taste is characterized by a good discrimination of stimulus intensity differences, and by a decaying response to a continuous stimulus (adaptation or habituation). Single sound events cannot be discriminated if the interval between events drops below a threshold value; if this occurs, the sound is interpreted as continuous. These characteristics are linked to survival, since new and different stimuli with low probability and high information value indicate warnings. Thus, when assessing the effects of environmental noise on people it is relevant to consider the importance of the background noise level, the number of events, and the noise exposure level independently.

Community noise studies have traditionally considered noise annoyance from single specific sources such as aircraft, road traffic or railways. In recent years, efforts have been made to compare the results from road traffic, aircraft and railway surveys. Data from a number of sources show that aircraft noise is more annoying than road traffic noise, which, in turn, is more annoying than railway noise. However, there is not a clear understanding of the mechanisms that create these differences. Some populations may also be at greater risk for the harmful effects of noise. Young children (especially during language acquisition), the blind, and perhaps fetuses are examples of such populations. There are no definite conclusions on this topic, but the reader should be alerted that guidelines in this report are developed for the population at large; guidelines for potentially more vulnerable groups are addressed only to a limited extent.

In the following, guideline values are summarized with regard to specific environments and effects. For each environment and situation, the guideline values take into consideration the identified health effects and are set, based on the lowest levels of noise that affect health (critical health effect). Guideline values typically correspond to the lowest effect level for general populations, such as those for indoor speech intelligibility. By contrast, guideline values for annoyance have been set at 50 or 55 dBA, representing daytime levels below which a majority of the adult population will be protected from becoming moderately or seriously annoyed, respectively.

In these *Guidelines for Community Noise* only guideline values are presented. These are essentially values for the onset of health effects from noise exposure. It would have been preferred to establish guidelines for exposure-response relationships. Such relationships would indicate the effects to be expected if standards were set above the WHO guideline values and would facilitate the setting of standards for sound pressure levels (noise immission standards). However, exposure-response relationships could not be established as the scientific literature is very limited. The best-studied exposure-response relationship is that between L_{dn} and annoyance (WHO 1995a; Berglund & Lindvall 1995; Miedema & Vos 1998). Even the most recent relationships between integrated noise levels and the percentage of highly or moderately annoyed people are still being scrutinized. The results of a forthcoming meta-analysis are expected to be published in the near future (Miedema, personal communication).

4.2. Specific Effects

4.2.1. Interference with communication

Noise tends to interfere with auditory communication, in which speech is a most important signal. However, it is also vital to be able to hear alarming and informative signals such as door bells, telephone signals, alarm clocks, fire alarms etc., as well as sounds and signals involved in occupational tasks. The effects of noise on speech discrimination have been studied extensively and deal with this problem in lexical terms (mostly words but also sentences). For communication distances beyond a few metres, speech interference starts at sound pressure levels below 50 dB for octave bands centered on the main speech frequencies at 500, 1 000 and 2 000 Hz. It is usually possible to express the relationship between noise levels and speech intelligibility in a single diagram, based on the following assumptions and empirical observations, and for speaker-to-listener distance of about 1 m:

a. Speech in relaxed conversation is 100% intelligible in background noise levels of about 35 dBA, and can be understood fairly well in background levels of 45 dBA.

b. Speech with more vocal effort can be understood when the background sound pressure level is about 65 dBA.

A majority of the population belongs to groups sensitive to interference with speech perception. Most sensitive are the elderly and persons with impaired hearing. Even slight hearing impairments in the high-frequency range may cause problems with speech perception in a noisy environment. From about 40 years of age, people demonstrate impaired ability to interpret difficult, spoken messages with low linguistic redundancy, when compared to people aged 20–30 years. It has also been shown that children, before language acquisition has been completed, have more adverse effects than young adults to high noise levels and long reverberation times.

For speech outdoors and for moderate distances, the sound level drops by approximately 6 dB for a doubling of the distance between speaker and listener. This relationship is also applicable to indoor conditions, but only up to a distance of about 2 m. Speech communication is affected also by the reverberation characteristics of the room, and reverberation times beyond 1 s can produce a loss in speech discrimination. A longer reverberation time combined with background noise makes speech perception still more difficult.

Speech signal perception is of paramount importance, for example, in classrooms or conference rooms. To ensure any speech communication, the signal-to-noise relationship should exceed zero dB. But when listening to complicated messages (at school, listening to foreign languages, telephone conversation) the signal-to-noise ratio should be at least 15 dB. With a voice level of 50 dBA (at 1 m distance this corresponds on average to a casual voice level in both women and men), the background level should not exceed 35 dBA. This means that in classrooms, for example, one should strive for as low background levels as possible. This is particularly true when listeners with impaired hearing are involved, for example, in homes for the elderly. Reverberation times below 1 s are necessary for good speech intelligibility in smaller rooms; and even in a quiet environment a reverberation time below 0.6 s is desirable for adequate speech intelligibility for sensitive groups.

4.2.2. Noise-induced hearing impairment

The ISO Standard 1999 (ISO 1990) gives a method of calculating noise-induced hearing impairment in populations exposed to all types of occupational noise (continuous, intermittent, impulse). However, noise-induced hearing impairment is by no means restricted to occupational situations alone. High noise levels can also occur in open-air concerts, discotheques, motor sports, shooting ranges, and from loudspeakers or other leisure activities in dwellings. Other loud noise sources, such as music played back in headphones and impulse noise from toys and fireworks, are also important. Evidence strongly suggests that the calculation method from ISO Standard 1999 for occupational noise (ISO 1990) should also be used for environmental and leisure time noise exposures. This implies that long term exposure to LAeq,24h of up to 70 dBA will not result in hearing impairment. However, given the limitations of the various underlying studies, care should be taken with respect to the following:

a. Data from animal experiments indicate that children may be more vulnerable in acquiring noise-induced hearing impairment than adults.

b. At very high instantaneous sound pressure levels mechanical damage to the ear may occur (Hanner & Axelsson 1988). Occupational limits are set at peak sound pressure levels of 140 dBA (EU 1986a). For adults, this same limit is assumed to be in order for exposure to environmental and leisure time noise. In the case of children, however, considering their habits while playing with noisy toys, peak sound pressure levels should never exceed 120 dBA.

c. For shooting noise with LAeq,24h over 80 dB, studies on temporary threshold shift suggest there is the possibility of an increased risk for noise-induced hearing impairment (Smoorenburg 1998).

d. The risk for noise-induced hearing impairment increases when noise exposure is combined with vibrations, ototoxic drugs or chemicals (Fechter 1999). In these circumstances, long-term exposure to LAeq,24h of 70 dB may induce small hearing impairments.

e. It is uncertain whether the relationships in ISO Standard 1999 (ISO 1990) are applicable to environmental sounds having a short rise time. For example, in the case of military low-altitude flying areas (75–300 m above ground) LAmax values of 110–130 dB occur within seconds after onset of the sound.

In conclusion, dose-response data are lacking for the general population. However, judging from the limited data for study groups (teenagers, young adults and women), and on the assumption that time of exposure can be equated with sound energy, the risk for hearing impairment would be negligible for LAeq,24h values of 70 dB over a lifetime. To avoid hearing impairment, impulse noise exposures should never exceed a peak sound pressure of 140 dB peak in adults, and 120 dB in children.

4.2.3. Sleep disturbance effects

Electrophysiological and behavioral methods have demonstrated that both continuous and intermittent noise indoors lead to sleep disturbance. The more intense the background noise, the more disturbing is its effect on sleep. Measurable effects on sleep start at background noise levels of about 30 dB LAeq. Physiological effects include changes in the pattern of sleep stages, especially a reduction in the proportion of REM sleep. Subjective effects have also been identified, such as difficulty in falling asleep, perceived sleep quality, and adverse after-effects such as headache and tiredness. Sensitive groups mainly include elderly persons, shift workers and persons with physical or mental disorders.
Where noise is continuous, the equivalent sound pressure level should not exceed 30 dBA indoors, if negative effects on sleep are to be avoided. When the noise is composed of a large proportion of low-frequency sounds a still lower guideline value is recommended, because low-frequency noise (e.g. from ventilation systems) can disturb rest and sleep even at low sound pressure levels. It should be noted that the adverse effect of noise partly depends on the nature of the source. A special situation is for newborns in incubators, for which the noise can cause sleep disturbance and other health effects.

If the noise is not continuous, LAmax or SEL are used to indicate the probability of noise-induced awakenings. Effects have been observed at individual LAmax exposures of 45 dB or less. Consequently, it is important to limit the number of noise events with a LAmax exceeding 45 dB. Therefore, the guidelines should be based on a combination of values of 30 dB LAeq,8h and 45 dB LAmax. To protect sensitive persons, a still lower guideline value would be preferred when the background level is low. Sleep disturbance from intermittent noise events increases with the maximum noise level. Even if the total equivalent noise level is fairly low, a small number of noise events with a high maximum sound pressure level will affect sleep.

Therefore, to avoid sleep disturbance, guidelines for community noise should be expressed in terms of equivalent sound pressure levels, as well as LAmax/SEL and the number of noise events. Measures reducing disturbance during the first part of the night are believed to be the most effective for reducing problems in falling asleep.

4.2.4. Cardiovascular and psychophysiological effects

Epidemiologial studies show that cardiovascular effects occur after long-term exposure to noise (aircraft and road traffic) with LAeq,24h values of 65–70 dB. However, the associations are weak. The association is somewhat stronger for ischaemic heart disease than for hypertension. Such small risks are important, however, because a large number of persons are currently exposed to these noise levels, or are likely to be exposed in the future. Other possible effects, such as changes in stress hormone levels and blood magnesium levels, and changes in the immune system and gastro-intestinal tract, are too inconsistent to draw conclusions. Thus, more research is required to estimate the long-term cardiovascular and psychophysiological risks due to noise. In view of the equivocal findings, no guideline values can be given.

4.2.5. Mental health effects

Studies that have examined the effects of noise on mental health are inconclusive and no guideline values can be given. However, in noisy areas, it has been observed that there is an increased use of prescription drugs such as tranquilizers and sleeping pills, and an increased frequency of psychiatric symptoms and mental hospital admissions. This strongly suggests that adverse mental health effects are associated with community noise.

4.2.6. Effects on performance

The effects of noise on task performance have mainly been studied in the laboratory and to some extent in work situations. But there have been few, if any, detailed studies on the effects of noise on human productivity in community situations. It is evident that when a task involves auditory signals of any kind, noise at an intensity sufficient to mask or interfere with the perception of these signals will also interfere with the performance of the task. A novel event, such as the start of an unfamiliar noise, will also cause distraction and interfere with many kinds of tasks. For example, impulsive noises such as sonic booms can produce disruptive effects as the result of startle responses; and these types of responses are more resistant to habituation.

Mental activities involving high load in working memory, such as sustained attention to multiple cues or complex analysis, are all directly sensitive to noise and performance suffers as a result. Some accidents may also be indicators of noise-related effects on performance. In addition to the direct effects on performance, noise also has consistent after-effects on cognitive performance with tasks such as proof-reading, and on persistence with challenging puzzles. In contrast, the performance of tasks involving either motor or monotonous activities is not always degraded by noise.

Chronic exposure to aircraft noise during early childhood appears to damage reading acquisition.

Evidence indicates that the longer the exposure, the greater the damage. Although there is insufficient information on these effects to set specific guideline values, it is clear that day-care centres and schools should not be located near major noise sources, such as highways, airports and industrial sites.

4.2.7. Annoyance responses

The capacity of a noise to induce annoyance depends upon many of its physical characteristics, including its sound pressure level and spectral characteristics, as well as the variations of these properties over time. However, annoyance reactions are sensitive to many non-acoustical factors of social, psychological or economic nature, and there are also considerable differences in individual reactions to the same noise. Dose-response relations for different types of traffic noise (air, road and railway) clearly demonstrate that these noises can cause different annoyance effects at equal LAeq,24h values. And the same type of noise, such as that found in residential areas around airports, can also produce different annoyance responses in different countries.

The annoyance response to noise is affected by several factors, including the equivalent sound pressure level and the highest sound pressure level of the noise, the number of such events, and the time of day. Methods for combining these effects have been extensively studied. The results are not inconsistent with the simple, physically based equivalent energy theory, which is represented by the LAeq noise index.

Annoyance to community noise varies with the type of activity producing the noise. Speech communication, relaxation, listening to radio and TV are all examples of noise-producing activities. During the daytime, few people are seriously annoyed by activities with LAeq levels below 55 dB; or moderately annoyed with LAeq levels below 50 dB. Sound pressure levels during the evening and night should be 5–10 dB lower than during the day. Noise with low-frequency components require even lower levels. It is emphasized that for intermittent noise it is necessary to take into account the maximum sound pressure level as well as the number of noise events. Guidelines or noise abatement measures should also take into account residential outdoor activities.

4.2.8. Effects on social behaviour

The effects of environmental noise may be evaluated by assessing the extent to which it interferes with different activities. For many community noises, interference with rest, recreation and watching television seem to be the most important issues. However, there is evidence that noise has other effects on social behaviour: helping behaviour is reduced by noise in excess of 80 dBA; and loud noise increases aggressive behavior in individuals predisposed to aggressiveness. There is concern that schoolchildren exposed to high levels of chronic noise could be more susceptible to helplessness. Guidelines on these issues must await further research.

4.3. Specific Environments

Noise measures based solely on LAeq values do not adequately characterize most noise environments and do not adequately assess the health impacts of noise on human well-being. It is also important to measure the maximum noise level and the number of noise events when deriving guideline values. If the noise includes a large proportion of low-frequency components, values even lower than the guideline values will be needed, because low-frequency components in noise may increase the adverse effects considerably. When prominent low-frequency components are present, measures based on A-weighting are inappropriate. However, the difference between dBC (or dBlin) and dBA will give crude information about the presence of low-frequency components in noise. If the difference is more than 10 dB, it is recommended that a frequency analysis of the noise be performed.

4.3.1. Dwellings

In dwellings, the critical effects of noise are on sleep, annoyance and speech interference. To avoid sleep disturbance, indoor guideline values for bedrooms are 30 dB LAeq for continuous noise and 45 dB LAmax for single sound events. Lower levels may be annoying, depending on the nature of the noise source. The maximum sound pressure level should be measured with the instrument set at "*Fast*".

To protect the majority of people from being seriously annoyed during the daytime, the sound pressure level on balconies, terraces and outdoor living areas should not exceed 55 dB LAeq for a steady, continuous noise. To protect the majority of people from being moderately annoyed during the daytime, the outdoor sound pressure level should not exceed 50 dB LAeq. These values are based on annoyance studies, but most countries in Europe have adopted 40 dB LAeq as the maximum allowable level for new developments (Gottlob 1995). Indeed, the lower value should be considered the maximum allowable sound pressure level for all new developments whenever feasible.

At night, sound pressure levels at the outside façades of the living spaces should not exceed 45 dB LAeq and 60 dB LAmax, so that people may sleep with bedroom windows open. These values have been obtained by assuming that the noise reduction from outside to inside with the window partly open is 15 dB.

4.3.2. Schools and preschools

For schools, the critical effects of noise are on speech interference, disturbance of information extraction (e.g. comprehension and reading acquisition), message communication and annoyance. To be able to hear and understand spoken messages in classrooms, the background sound pressure level should not exceed 35 dB LAeq during teaching sessions. For hearing impaired children, an even lower sound pressure level may be needed. The reverberation time in the classroom should be about 0.6 s, and preferably lower for hearing-impaired children. For assembly halls and cafeterias in school buildings, the reverberation time should be less than 1 s. For outdoor playgrounds, the sound pressure level of the noise from external sources should not exceed 55 dB LAeq, the same value given for outdoor residential areas in daytime.

For preschools, the same critical effects and guideline values apply as for schools. In bedrooms in preschools during sleeping hours, the guideline values for bedrooms in dwellings should be used.

4.3.3. Hospitals

For most spaces in hospitals, the critical effects of noise are on sleep disturbance, annoyance and communication interference, including interference with warning signals. The LAmax of sound events during the night should not exceed 40 dB indoors. For wardrooms in hospitals, the guideline values indoors are 30 dB LAeq, together with 40 dB LAmax during the night. During the day and evening the guideline value indoors is 30 dB LAeq. The maximum level should be measured with the instrument set at "*Fast*".

Since patients have less ability to cope with stress, the equivalent sound pressure level should not exceed 35 dB LAeq in most rooms in which patients are being treated or observed. Particular attention should be given to the sound pressure levels in intensive care units and operating theatres. Sound inside incubators may result in health problems, including sleep disturbance, and may lead to hearing impairment in neonates. Guideline values for sound pressure levels in incubators must await future research.

4.3.4. Ceremonies, festivals and entertainment events

In many countries, there are regular ceremonies, festivals and other entertainment to celebrate life events. Such events typically produce loud sounds including music and impulsive sounds. There is widespread concern about the effect of loud music and impulse sounds on young people who frequently attend concerts, discotheques, video arcades, cinemas, amusement parks and spectator events, etc. The sound pressure level is typically in excess of 100 dB LAeq. Such a noise exposure could lead to significant hearing impairment after frequent attendance.

Noise exposure for employees of these venues should be controlled by established occupational standards. As a minimum, the same standards should apply to the patrons of these premises. Patrons should not be exposed to sound pressure levels greater than 100 dB LAeq during a 4-h period, for at most four times per year. To avoid acute hearing impairment the LAmax should always be below 110 dB.

4.3.5. Sounds through headphones

To avoid hearing impairment in both adults and children from music and other sounds played back in headphones, the LAeq,24h should not exceed 70 dB. This implies that for a daily one-hour exposure the LAeq should not exceed 85 dB. The exposures are expressed in free-field equivalent sound pressure levels. To avoid acute hearing impairment, the LAmax should always be below 110 dB.

4.3.6. Impulsive sounds from toys, fireworks and firearms

To avoid acute mechanical damage to the inner ear, adults should never be exposed to more than 140 dB peak sound pressure. To account for the vulnerability in children, the peak sound pressure level produced by toys should not surpass 120 dB, measured close to the ears (100 mm). To avoid acute hearing impairment, LAmax should always be below 110 dB.

4.3.7. Parkland and conservation areas

Existing large quiet outdoor areas should be preserved and the signal-to-noise ratio kept low.

4.4. WHO Guideline Values

The WHO guideline values in Table 4.1 are organized according to specific environments. When multiple adverse health effects are identified for a given environment, the guideline values are set at the level of the lowest adverse health effect (the critical health effect). An adverse health effect of noise refers to any temporary or long-term deterioration in physical, psychological or social functioning that is associated with noise exposure. The guideline values represent the sound pressure levels that affect the most exposed receiver in the listed environment.

The time base for LAeq for “daytime” and “night-time” is 16 h and 8 h, respectively. No separate time base is given for evenings alone, but typically, guideline value should be 5 –10 dB lower than for a 12 h daytime period. Other time bases are recommended for schools, preschools and playgrounds, depending on activity.

The available knowledge of the adverse effects of noise on health is sufficient to propose guideline values for community noise for the following:

a. Annoyance.
b. Speech intelligibility and communication interference.
c. Disturbance of information extraction.
d. Sleep disturbance.
e. Hearing impairment.

The different critical health effects are relevant to specific environments, and guideline values for community noise are proposed for each environment. These are:

a. Dwellings, including bedrooms and outdoor living areas.
b. Schools and preschools, including rooms for sleeping and outdoor playgrounds.
c. Hospitals, including ward and treatment rooms.
d. Industrial, commercial shopping and traffic areas, including public addresses, indoors and outdoors.
e. Ceremonies, festivals and entertainment events, indoors and outdoors.
f. Music and other sounds through headphones.
g. Impulse sounds from toys, fireworks and firearms.
h. Outdoors in parkland and conservation areas.

It is not enough to characterize the noise environment in terms of noise measures or indices based only on energy summation (e.g. LAeq), because different critical health effects require different descriptions. Therefore, it is important to display the maximum values of the noise fluctuations, preferably combined with a measure of the number of noise events. A separate characterization of noise exposures during night-time would be required. For indoor environments, reverberation time is also an important factor. If the noise includes a large proportion of low frequency components, still lower guideline values should be applied.

Supplementary to the guideline values given in Table 4.1, precautionary recommendations are given in Section 4.2 and 4.3 for vulnerable groups, and for noise of a certain character (e.g. low-frequency components, low background noise), respectively. In Section 3.10, information is given regarding which critical effects and specific environments are considered relevant for vulnerable groups, and what precautionary noise protection would be needed in comparison to the general population.

Table 4.1: Guideline values for community noise in specific environments.

Specific environment	**Critical health effect(s)**	**LAeq [dB]**	**Time base [hours]**	**LAmax, fast [dB]**
Outdoor living area	Serious annoyance, daytime and evening Moderate annoyance, daytime and evening	55 50	16 16	- -
Dwelling, indoors Inside bedrooms	Speech intelligibility and moderate annoyance, daytime and evening Sleep disturbance, night-time	35 30	16 8	 45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
School class rooms and pre-schools, indoors	Speech intelligibility, disturbance of information extraction, message communication	35	during class	-
Pre-school Bedrooms, indoors	Sleep disturbance	30	sleeping -time	45
School, playground outdoor	Annoyance (external source)	55	during play	-
Hospital, ward rooms, indoors	Sleep disturbance, night-time Sleep disturbance, daytime and evenings	30 30	8 16	40 -
Hospitals, treatment rooms, indoors	Interference with rest and recovery	#1		
Industrial, commercial, shopping and traffic areas, indoors and Outdoors	Hearing impairment	70	24	110
Ceremonies, festivals and entertainment events	Hearing impairment (patrons:<5 times/year)	100	4	110
Public addresses, indoors and outdoors	Hearing impairment	85	1	110
Music through headphones/ Earphones	Hearing impairment (free-field value)	85 #4	1	110
Impulse sounds from toys, fireworks and firearms	Hearing impairment (adults) Hearing impairment (children)	- -	- -	140 #2 120 #2
Outdoors in parkland and conservation areas	Disruption of tranquillity	#3		

#1: as low as possible;
#2: peak sound pressure (not LAmax, fast), measured 100 mm from the ear;
#3: existing quiet outdoor areas should be preserved and the ratio of intruding noise to natural background sound should be kept low;
#4: under headphones, adapted to free-field values

5. Noise Management

The goal of noise management is to maintain low noise exposures, such that human health and well-being are protected. The specific objectives of noise management are to develop criteria for the maximum safe noise exposure levels, and to promote noise assessment and control as part of environmental health programmes. This is not always achieved (Jansen 1998). The United Nations´ Agenda 21 (UNCED 1992), as well as the European Charter on Transport, Environment and Health (London Charter 1999), both support a number of environmental management principles on which government policies, including noise management policies, can be based. These include:

a. **The precautionary principle**. In all cases, noise should be reduced to the lowest level achievable in a particular situation. Where there is a reasonable possibility that public health will be damaged, action should be taken to protect public health without awaiting full scientific proof.

b. **The polluter pays principle**. The full costs associated with noise pollution (including monitoring, management, lowering levels and supervision) should be met by those responsible for the source of noise.

c. **The prevention principle**. Action should be taken where possible to reduce noise at the source. Land-use planning should be guided by an environmental health impact assessment that considers noise as well as other pollutants.

The government policy framework is the basis of noise management. Without an adequate policy framework and adequate legislation it is difficult to maintain an active or successful noise management programme. A policy framework refers to transport, energy, planning, development and environmental policies. The goals are more readily achieved if the interconnected government policies are compatible, and if issues which cross different areas of government policy are co-ordinated.

5.1. Stages in Noise Management

A legal framework is needed to provide a context for noise management (Finegold 1998; Hede 1998a). While there are many possible models, an example of one is given in Figure 5.1. This model depicts the six stages in the process for developing and implementing policies for community noise management. For each policy stage, there are groups of ‘policy players’ who ideally would participate in the process.

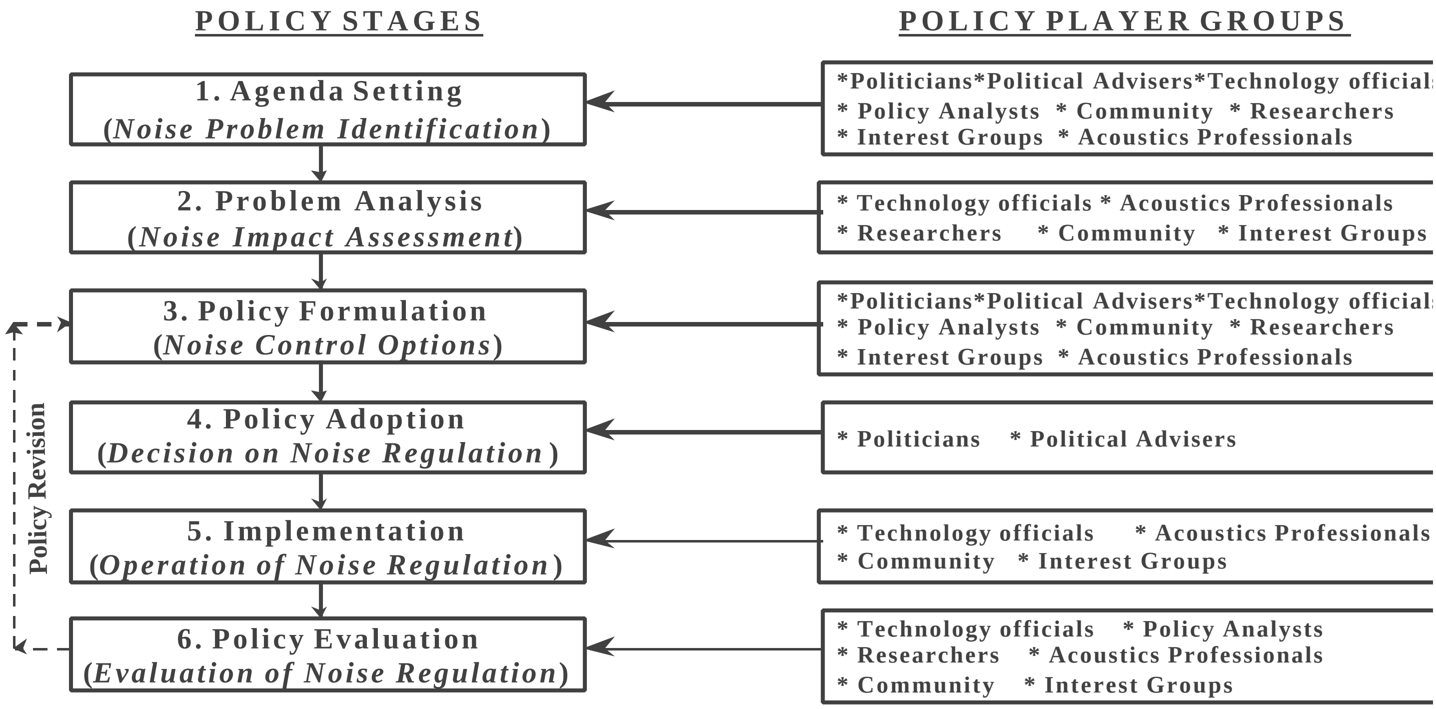

Figure 5.1. A model of the policy process for community noise management (Hede 1998a)

When goals and policies have been developed, the next stage is the development of the strategy or plan. Figure 5.2 summarizes the stages involved in the development of a noise management strategy. Specific abatement measures 19 are listed in Table 5.1.

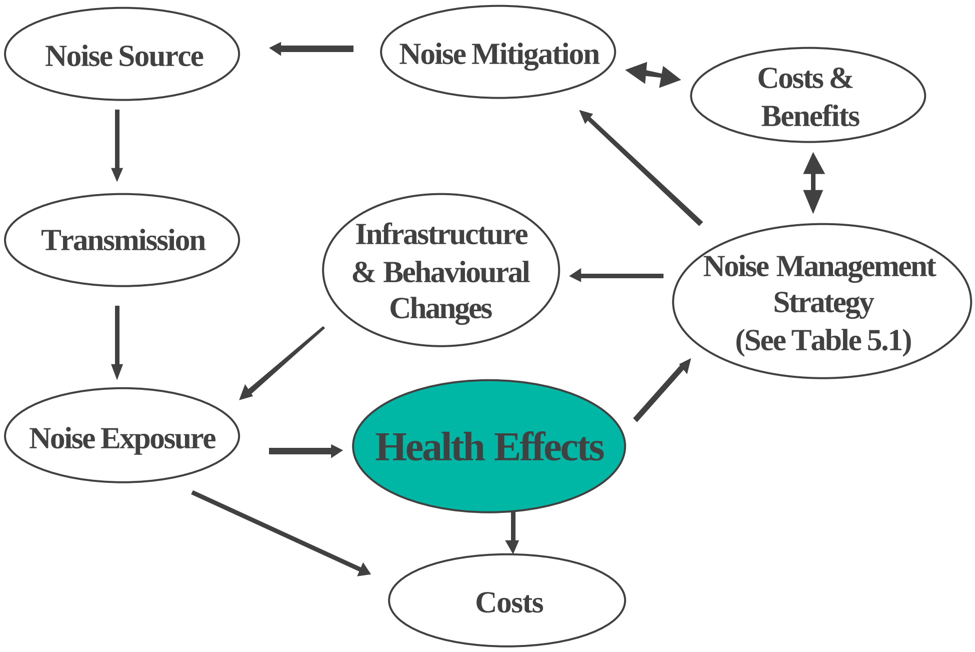

Figure 5.2. Stages involved in the development of a noise abatement strategy.

Table 5.1. Recommended Noise Management Measures (following EEA 1995)

Legal measures	Examples
Control of noise emissions	Emission standards for road and off-road vehicles; emission standards for construction equipment; emission standards for plants; national regulations, EU Directives
Control of noise transmission	Regulations on sound-obstructive measures
Noise mapping and zoning around roads, airports, industries	Initiation of monitoring and modeling programmes
Control of noise immissions	Limits for exposure levels such as national immission standards; noise monitoring and modeling; regulations for complex noise situations; regulations for recreational noise
Speed limits	Residential areas; hospitals
Enforcement of regulations	Low Noise Implementation Plan
Minimum requirements for acoustical properties of buildings	Construction codes for sound insulation of building parts
Engineering Measures	
Emission reduction by source modification	Tyre profiles; low-noise road surfaces; changes in engine properties
New engine technology	Road vehicles; aircraft; construction machines
Transmission reduction	Enclosures around machinery; noise screens
Orientation of buildings	Design and structuring of tranquille uses; using buildings for screening purposes
Traffic management	Speed limits; guidance of traffic flow by electronic means
Passive protection	Ear plugs; ear muffs; insulation of dwellings; façade design
Implementation of land-use planning	Minimum distance between industrial, busy roads and residential areas; location of tranquillity areas; by-pass roads for heavy traffic; separating out incompatible functons
Education and information	
Raising public awareness	Informing the public on the health impacts of noise, enforcement action taken, noise levels, complaints
Monitoring and modeling of soundscapes	Publication of results
Sufficient number of noise experts	University or highschool curricula
Initiation of research and development	Funding of information generation according to scientific research needs
Initiation of behaviour changes	Speed reduction when driving; use of horns; use of loudspeakers for advertisements

The process outlined in Figure 5.2 can start with the development of noise standards or guidelines. Ideally, it should also involve the identification and mapping of noise sources and exposed communities. Meteorological conditions and noise levels would also normally be monitored. These data can be used to validate the output of models that estimate noise levels. Noise standards and model outputs may be considered in devising noise control tactics aimed at achieving the noise standards. Before being enforced, current control tactics need to be revised, and if the standards are achieved they need continued enforcement. If the standards are not achieved after a reasonable period of time, the noise control tactics may need to be revised.

National noise standards can usually be based on a consideration of international guidelines, such as these Guidelines for Community Noise, as well as national criteria documents, which consider dose-response relations for the effects of noise on human health. National standards take into account the technological, social, economic, political and other factors specific for the country.

In many cases monitoring may show that noise levels are considerably higher than established guidelines. This may be particularly true in developing countries, and the question has to be raised as to whether national standards should reflect the optimum levels needed to protect human health, when this objective is unlikely to be achieved in the short- or medium-term with available resources. In some countries noise standards are set at levels that are realistically attainable under prevailing technological, social, economic and political conditions, even though they may not be fully consistent with the levels needed to protect human health. In such cases, a staged programme of noise abatement should be implemented to achieve the optimum health protection levels over the long term. Noise standards periodically change after reviews, as conditions in a country change over time, and with improved scientific understanding of the relationship between noise pollution and the health of the population. Noise level monitoring (Chapter 2) is used to assess whether noise levels at particular locations are in compliance with the standards selected.

5.2. Noise Exposure Mapping

A crucial component of a low-noise implementation plan is a reasonably quantitative knowledge of exposure (see Figure 5.2). Exposure should be mapped for all noise sources impacting a community; for example, road traffic, aircraft, railway, industry, construction, festivals and human activity in general. For some components of a noise exposure map or noise exposure inventory, accurate data may be available. In other cases, exposure can be calculated from the characteristics of the mechanical processes. While estimates of noise emissions are needed to develop exposure maps, measurements should be undertaken to confirm the veracity of the assumptions used in the estimates. Sample surveys may be used to provide an overall picture of the noise exposure. Such surveys would take account of all the relevant characteristics of the noise source. For example motor vehicle emissions may be estimated by calculations involving the types of vehicles, their number, their age and the characteristic properties of the road surface.

In developing countries, there is usually a lack of appropriate statistical information to produce noise exposure estimates. However, where action is needed to lower noise levels, the absence of comprehensive information should not prevent the development of provisional noise exposure estimates. Basic information about the exposed population, transport systems, industry and other relevant factors can be used to calculate provisional noise exposures. These can then be used to develop and implement interim noise management plans. The preliminary exposure estimates can be revised as more accurate information becomes available.

5.3. Noise Exposure Modeling

As indicated in Chapter 2 modeling is a powerful tool for the interpolation, prediction and optimization of control strategies. However, models need to be validated by monitoring data. A strength of models is that they enable examination and comparison of the consequences for noise exposure of the implementation of the various options for improving noise. However, the accuracy of the various models available depends on many factors, including the accuracy of the source emissions data and details of the topography (for which a geographical information system may be used). For transportation noise parameters such as the number, type and speed of vehicles, aircraft or trains, and the noise characteristics of each individual event must be known. An example of a model is the annoyance prediction model of the Government of the Netherlands (van den Berg 1996).

5.4. Noise Control Approaches

An integrated noise policy should include several control procedures: measures to limit the noise at the source, noise control within the sound transmission path, protection at the receiver's site, land-use planning, education and raising of public awareness. Ideally, countries should give priority to precautionary measures that prevent noise, but they must also implement measures to mitigate existing noise problems.

5.4.1. Mitigation measures

The most effective mitigation measure is to reduce noise emissions at the source. Therefore, regulations with noise level limits for the main noise sources should be introduced.

Road traffic noise. Limits on the noise emission of vehicles have been introduced in many countries (Sandberg 1995). Such limits, together with the relevant measuring methods, should also be introduced in other regions of the world. Besides these limits a special class of "low-noise trucks" has been introduced in Europe. These trucks follow state-of-the-art noise control and are widely used in Austria and Germany (Lang 1995). Their use is encouraged by economic incentives; for example, low-noise trucks are excepted from a night-time ban on certain routes, and their associated taxes are lower than for other trucks. In Europe, the maximum permissible noise levels range from 69 dBA for motor vehicles to 77 dBA for cars, and 83 dBA for heavy two-wheeled vehicles to 84 dBA for trucks. A number of European Directives give permissible sound levels for motor vehicles and motorcycles (EU 1970; EU 1978; EU 1996a; EU 1997). In addition to noise level limits for new vehicles (type test), noise emissions of vehicles already in use should be controlled regularly. Limits on the sound pressure levels for vehicles reduce the noise emission from the engines.

However, the main noise from traffic on highways is rolling noise. This may be reduced by quiet road surfaces (porous asphalt, "drain asphalt") or by selection of quiet tires. Road traffic noise may also be reduced by speed limits, provided the limits are enforced. For example, reducing the speed of trucks from 90 to 60 km/h on concrete roads would reduce the maximum sound pressure level by 5 dB, and the equivalent sound pressure level by 4 dB. Decreasing the speed of cars from 140 to 100 km/h would result in the same noise reduction (WHO 1995a). In the central parts of cities a speed limit of 30 km/h may be introduced. At 30 km/h cars produce maximum sound pressure levels that are 7 dB lower, and equivalent sound pressure levels that are 5 dB lower, than cars driving at 50 km/h.

Noise emission from road traffic may be further reduced by a night-time ban for all vehicles, or especially for heavy vehicles. Traffic management designed to ensure uniform traffic flow in towns also serves to reduce noise. "Low-noise behaviour" of drivers should be encouraged as well, by advocating defensive driving manners. In some countries, car drivers use their horns frequently, which results in noise with high peak levels. The unnecessary use of horns within cities should be forbidden, especially during night-time, and this rule should be enforced.

Railway noise and noise from trams. The main noise sources are the engine and the wheel-rail contact. Noise at the source can be reduced by well-maintained rails and wheels, and by the use of disc brakes. Sound pressure levels may vary by more than 10 dB, depending on the type of railway material. Replacement of steel wheels by rubber wheels could also reduce noise from railways and trams substantially. Other measures include innovations in engine and track technology (Moehler 1988; Öhrström & Skånberg 1996).

Aircraft noise. The noise emission of aircraft is limited by ICAO Annex 16, Chapter 2 and Chapter 3, which estimates maximum potential sound emissions under certification procedures (ICAO 1993). Aircraft following the norms of Chapter 3 represent the state-of-the-art of noise control of the 1970s. In many countries, non-certified aircraft (i.e. aircraft not fulfilling the ICAO requirements) are not permitted and Chapter 2 aircraft may not be registered again. After the year 2002 only Chapter 3 aircraft will be allowed to operate in many countries.

Similar legislation should be adopted in other countries. The use of low-noise aircraft may also be encouraged by setting noise-related charges (that is, landing charges that are related not only to aircraft weight and capacity, but also to noise emission). Examples of systems for noise-related financial charges are given in OECD 1991 (see also OECD-ECMT 1995). Night-time aircraft movements should be discouraged where they impact residential communities. Particular categories of aircraft (such as helicopters, rotorcraft and supersonic aircraft) pose additional problems that require appropriate controls. For subsonic airplanes two EU Directive give the permissible sound levels (EU 1980; EU 1989).

Machines and Equipment. Noise emission has to be considered a main property of all types of machines and equipment. Control measures include design, insulation, enclosure and maintenance.

Consumers should be encouraged to take noise emission into account when buying a product. Declaring the A-weighted sound power level of a product would assist the consumer in making this decision. The introduction of sound labeling is a major tool for reducing the noise emission of products on the market. For example, within the European Community, "permissible sound levels" and "sound power levels" have to be stated for several groups of machines; for example, lawn mowers, construction machines and household equipment (EU 1984a-f; EU 1986b,c). For other groups of machines sound level data have been compiled and are state-of-the-art with respect to noise control.

A second step would be the introduction of limits on the sound power levels for certain groups of machines, heating and ventilation systems (e.g. construction machines, household appliances). These limits may be set by law, in recommendations and by consumers, using state-of-the-art measurements. There have also been promising developments in the use of active noise control (involving noise cancellation techniques). These are to be encouraged.

Noise control within the sound transmission path. The installation of noise barriers can protect dwellings close to the traffic source. In several European countries noise barrier regulations have been established (WHO 1995b), but in practice they are often not adequately implemented. These regulations must define:

a. Measuring and calculation methods for deriving the equivalent sound pressure level of road or railway traffic, and schemes for determining the effectiveness of the barrier.

b. The sound pressure limits that are to be achieved by installing barriers.

c. The budgetary provisions.

d. The responsible authority.

Noise protection at the receiver's site. This approach is mainly used for existing situations. However, this approach must also be considered for new and, eventually, for old buildings in noisy areas. Residential buildings near main roads with heavy traffic, or near railway lines, may be provided with sound-proofed windows.

5.4.2. Precautionary measures

With careful planning, noise exposure can be avoided or reduced. A sufficient distance between residential areas and an airport will make noise exposure minimal, although the realization of such a situation is not always possible. Additional insulation of houses can help to reduce noise exposure from railroad and road traffic. For new buildings, standards or building codes should describe the positions of houses, as well as the ground plans of houses with respect to noise sources. The required sound insulation of the façades should also be described. Various countries have set standards for the maximum sound pressure levels in front of buildings and for the minimum sound insulation values required for façades.

Land use planning. Land use planning is one of the main tools for noise control and includes:

a. Calculation methods for predicting the noise impact caused by road traffic, railways, airports, industries and others.

b. Noise level limits for various zones and building types. The limits should be based on annoyance responses to noise.

c. Noise maps or noise inventories that show the existing noise situation. The construction of noise-sensitive buildings in noisy areas, or the construction of noisy buildings in quiet areas may thus be avoided.

Suggestions on how to use land use planning tools are given in several dedicated books (e.g. Miller & de Roo 1997). Different zones, such as quiet areas, hospitals, residential areas, commercial and industrial districts, can be characterized by the maximum equivalent sound pressure levels permissible in the zones. Examples of this approach can be found in OECD 1991 (also see OECD-ECMT 1995). More emphasis needs to be given to the design or retrofit of urban centres, with noise management as a priority (e.g. "soundscapes").

It is recommended that countries adopt the precautionary principle in their national noise policies. This principle should be applied to all noise situations where adverse noise effects are either expected or possible, even when the noise is below standard values.

Education and public awareness. Noise abatement policies can only be established if basic knowledge and background material is available, and the people and authorities are aware that noise is an environmental hazard that needs to be controlled. It is, therefore, necessary to include noise in school curricula and to establish scientific institutes to study acoustics and noise control. People working in such institutes should have the option of studying in other countries and exchanging information at international conferences. Dissemination of noise control information to the public is an issue for education and public awareness. Ideally, national and local advisory groups should be formed to promote the dissemination of information, to establish uniform methods of noise measurement and impact assessment, and to participate in the development and implementation of educational and public awareness programmes.

5.5. Evaluation of Control Options

Unless legal constraints in a country prescribe a particular option, the evaluation of control options must take into account technical, financial, social, health and environmental factors. The speed with which control options can be implemented, and their enforceability, must also be considered. Although considerable improvements in noise levels have been achieved in some developed countries, the financial costs have been high, and the resource demands of some of these approaches make them unsuitable for the poorer developing countries.

Technical factors. There needs to be confidence that the selected options are technically practical given the resources of the region. It must be possible to bring a selected option into operation, and maintain the expected level of performance in the long term, given the resources available. This may require regular staff training and other programmes, especially in developing countries.

Financial factors. The selected options must be financially viable in the long term. This may require a comparative cost-benefit assessment of different options. These assessments must include not only the capital costs of bringing an option into operation, but also the costs of maintaining the expected level of performance in the long term.

Social factors. The costs and benefits of each option should be assessed for social equity, and the potential impact of an option on people's way of life, community structures and cultural traditions must be considered. Impacts may include disruption or displacement of residents, changes of land-use, and impacts on community, culture and recreation. Some impacts can be managed; in other cases, the impacts of an option can be mitigated by substitution of resources or uses.

Health and environmental factors. The costs and benefits of each option should be assessed for health and environmental factors. This may involve use of dose-response relations, or risk assessment techniques.

Effect-oriented and source-oriented principles. Noise control requirements in European countries are typically determined from the effects of noise on health and the environment (effect oriented) (e.g. Gottlob 1995; ten Wolde 1998). Increased noise emissions may be permitted if there would be no adverse health impacts, or if noise standards would not be exceeded. Action may be taken to reduce noise levels when it is shown that adverse health impacts will occur, or when noise levels exceed limits. Other countries base their noise management policies on the requirement for best available technology, or for best available techniques that do not entail excessive cost (source-oriented) (e.g. for aircraft noise, ICAO 1993; for road traffic noise, Sandberg 1995). Most developed countries apply a combination of both source-oriented and effect-oriented principles (EU 1996b; Jansen 1998; ten Wolde 1998).

5.6. Management of Indoor Noise

In modern societies, human beings spend most of their time in indoor environments. Pollution and degradation of the indoor environment cause illness, increased mortality, loss of productivity, and have major economic and social implications. Indoor noise problems are related to inadequate urban planning, design, operation and maintenance of buildings, and to the materials and equipment in buildings. Problems with indoor noise affect all types of buildings, including homes, schools, offices, health care facilities and other public and commercial buildings. The health effects of indoor noise include an increase in the rates of diseases and disturbances described in chapter 2. World-wide, the medical and social cost associated with these illnesses, and the related reduction in human productivity, can result in substantial economic losses.

Protection against noise generated within a building, or originating from outside the building, is a very complex problem. Soundproofing of ceilings, walls, doors and windows against airborne noise is important. Soundproofing of ceilings has to be sufficient to absorb sounds due to treading. Finally, noise emissions from the technological devices in the house must be sufficiently low. Governments should provide measurement protocols and data for use in reducing noise exposures in buildings. Governments should also be encouraged to support research on the relationship between noise levels inside buildings and health effects.

5.6.1. Government policy on indoor noise

Many of the problems associated with high noise levels can be prevented at low cost if governments develop and implement an integrated strategy for the indoor environment, in concert with all social and economic partners. Governments should establish a "National Plan for a Sustainable Indoor Noise Environment", that would apply to new construction as well as to existing buildings. Governments should set up a specific structure at an appropriate governmental level to achieve acceptable sound exposure levels within buildings. An example of existing documents that provide guidance and regulations, including strategies and management for the design of buildings, is given by Jansen & Gottlob (1996).

Guidance/education. Because our understanding of indoor noise is still developing, government activity should be focused on raising the awareness of various audiences. This education can take the form of providing general information, as well as providing technical guidance and training on how to minimize indoor noise levels. General information presented in the form of documents, videos, and other media can bring indoor noise issues to the attention of the general public and building professionals, including architects

Research support. Research is needed to develop technology for indoor noise diagnosis, mitigation and control. Efforts are also required to provide economical and practical alternatives for mitigation and control. Better means of measuring the effectiveness of absorption devices are needed; and diagnostic tools that are inexpensive and easy to use also need to be developed to help facility personnel. There is a particular need, too, for improving soundproofing methods, their implementation and for predicting the health effects of soundproofing techniques.

To provide accurate information for use in setting priorities for public health problems, governments should support problem assessment and surveys of indoor noise conditions. Building surveys are also necessary to provide baseline information about building characteristics and noise levels. When combined with occupant health surveys, these studies will help to establish the correlations between noise levels and adverse health effects. Surveys should be conducted to identify building types or vintages in which problems occur more frequently. The results of these studies will support effective risk reduction programmes. Epidemiological studies are also needed to aid in differentiating between noise-related symptoms and those due to other causes. Moreover, epidemiological studies are needed to assist in quantifying the extent of risk for indoor noise levels.

Economic research is needed to measure the costs of indoor noise control strategies to individuals, businesses and society. This includes developing methods for quantifying productivity loss and increased health costs due to noise, and for measuring the costs of various control strategies, including increased soundproofing and source control.

Development of standards and protocols. Efforts should be made to protect public health by setting reasonable noise exposure limits (immission standards) from known dose-response relationships. In cases where dose-response relationships have yet to be determined, but where health effects are generally recognized, exposure limits should be set conservatively and take into account risk, economic impact and feasibility. Efforts should also be made to incorporate noise-related specifications into building codes. Areas to target with building codes include ventilation design, building envelope design, site preparation, materials selection and commissioning. Standards and other regulations governing the use of sound proofing materials should also be developed.

Individuals involved in the diagnosis and mitigation of indoor noise problems should be trained in the multidisciplinary nature of the noise field. By instituting a series of credentials that recognize and highlight areas of expertise, consumers would be provided with the information to make informed choices when procuring indoor noise services. Companies which provide such services should be officially accredited. Guidelines or standards for sound emissions of air-conditioners, power generators and other building devices, would also provide useful information for manufacturers, architects, design engineers, building managers and others who play a role in selecting products used indoors.

5.6.2. Design considerations

Site investigation. Potential sites should be evaluated to determine whether they are prone to indoor noise problems. This evaluation should be consistent with national and local land use planning guidelines. Sites should be investigated to determine past uses and whether any sources of sound remain as a result. The potential for outdoor noise being carried to the site from adjacent areas, such as busy streets, should also be evaluated.

Building design. Buildings should be designed to be soundproof, to improve control over indoor noise. Soundproofing requires that outside noise be prevented from entering the building, and this should be estimated as part of the architectural and engineering design process. When soundproofing for outdoor noise, the total indoor noise load and the desired quality of the indoor space should be considered. Adequate soundproofing against outdoor noise is important in residential as well as commercial properties, and should be re-evaluated when interior spaces are rebuilt or renovated.

Indoor Spaces. The architectural layout should aim to reduce noise and provide a good sound quality to the space. This would include designing indoor spaces to have sufficiently short reverberation times. Designers and contractors should be encouraged to use sound-absorbing materials that lead to lower indoor noise levels, and materials with the best sound-absorbing properties should be specified. However, use of these materials should not be the only solution (Harris 1991). Possible conflicts with other environmental demands should also be identified; for example, the special demands by allergic people.

5.6.3. Indoor noise level control

Building maintenance personnel should be trained to understand the indoor noise aspects of their work, and be aware of how their work can directly impact the health and comfort of occupants. Many maintenance activities directly affect indoor noise levels, and some may indicate potential problems. Preventive maintenance is essential for the building systems to operate correctly and to provide suitable comfort conditions and low indoor noise levels. Detailed maintenance logs should be kept for all equipment. A schedule should be developed for routine equipment checks and calibration of control system components. Selection of low-noise domestic products should encouraged as far as is possible.

5.6.4. Resolving indoor noise problems

Addressing occupant complaints and symptoms. When complaints are received from occupants of a building, the cognizant authority should be responsive. The initial investigation into the cause of the complaint may be conducted by the in-house management staff, and they should continue an investigation as far as possible. If necessary, they should be responsible for hiring an outside consultant

Building diagnostic procedures. After receiving complaints related to indoor noise levels, facility personnel or consultants should attempt to identify the cause of the problem through an iterative process of information collection and hypothesis testing. To begin, a walkthrough inspection of the building, including the affected areas and the mechanical systems serving these spaces is required. A walkthrough can provide information on the soundproofing system of the building, the sound pathways and sound sources. Visual indicators of sound sources and soundproofing malfunctions should be evaluated first. Symptom logs and schedules of building activities may provide enough additional information to resolve the problem.

If a walkthrough alone does not provide a solution, measurements of sound pressure levels at various locations should be taken, and indoor and ambient levels of noise pollution should be compared. As part of the investigation, the absorption characteristics of walls and ceilings should be evaluated. Sophisticated sampling methods may be necessary to provide proof of a problem to the building owner or other responsible party. The results may be used to confirm a hypothesis or ascertain the source of the indoor noise problem. Whenever a problem is discovered during the investigation, a remedy to the situation should be attempted and a determination made of whether the complaint has been resolved.

In some cases, it should be recognized that difficulties in interpreting the sampling results may exist. The costs of certain types of testing should also be taken into account. Simple, cost-effective screening methods should be developed to make sampling a more attractive option for both investigators and clients. Finally, it must be remembered that several factors cause symptoms similar to those induced by noise pollution. Examples include air pollutants, ergonomics, lighting, vibration and psychosocial factors. Consequently, any investigation of noise complaints should also evaluate non-noise factors.

5.7. Priority Setting in Noise Management

Priorities in noise management will differ between countries, according to policy objectives, needs and capabilities. Priority setting in noise management refers to prioritizing health risks and concentrating on the most important sources of noise. For effective noise management, the goals, policies and noise control schemes have to be defined. Goals for noise management include eliminating noise, or reducing noise to acceptable levels, and avoiding the adverse health effects of noise on human health. Policies for noise management encompass laws and regulations for setting noise standards and for ensuring compliance. The amount of information to be included in low-noise implementation plans and the use of cost-benefit comparisons also fall within the purview of noise management policies. Techniques for noise control include source control, barriers in noise pathways and receiver protection. Adequate calculation models for noise propagation, as well as programmes for noise monitoring, are part of an overall noise control scheme.

As emphasized above, a framework for a political, regulatory and administrative approach is required to guarantee the consistent and transparent promulgation of noise standards. This ensures a sound and practical framework for risk-reducing measures and for the selection of abatement strategies.

5.7.1. Noise policy and legislation

Noise is both a local and a global problem. Governments in every country have a responsibility to set up policies and legislation for controlling community noise. There is a direct relationship between the level of development in a country and the degree of noise pollution impacting its people. As a society develops, it increases its level of urbanization and industrialization, and the extent of its transportation system. Each of these developments brings an increase in noise load. Without appropriate intervention the noise impact on communities will escalate (see Figure 5.3). If governments implement only weak noise policies and regulations, they will not be able to prevent a continuous increase in noise pollution and associated adverse health effects. Failure to enforce strong regulations is ineffective in combating noise as well.

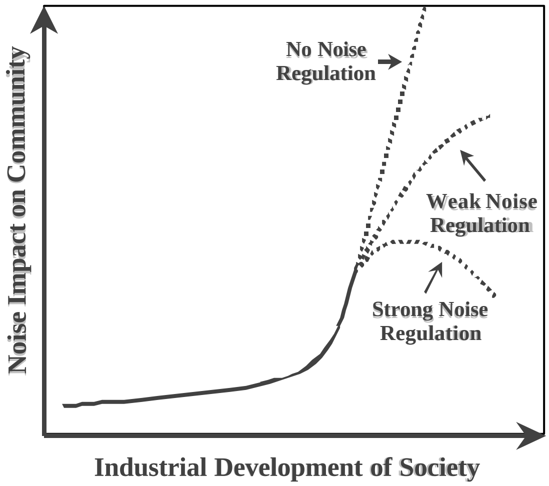

Figure 5.3. Relationship between noise regulation and impact with development (from Hede 1998b)

Policies for noise regulatory standards at the municipal, regional, national and supranational levels are usually determined by the legislatures. The regulatory standards adopted strongly depend on the risk management strategies of the legislatures, and can be influenced by sociopolitical considerations and/or international agreements. Although regulatory standards may be country specific, in general the following issues are taken into consideration:

a. Identification of the adverse public health effects that are to be avoided.

b. Identification of the population to be protected.

c. The type of parameters describing noise and the limit applicable to the parameters.

d. Applicable monitoring methodology and its quality assurance.

e. Enforcement procedures to achieve compliance with noise regulatory standards within a defined time frame.

f. Emission control measures and emission regulatory standards.

g. Immission standards (limits for sound pressure levels).

h. Identification of authorities responsible for enforcement.

i. Resource commitment.

Regulatory standards may be based solely on scientific and technical data showing the adverse effects of noise on public health. But other aspects are usually considered, either when setting standards or when designing appropriate noise abatement measures. These other aspects include the technological feasibility, costs of compliance, prevailing exposure levels, and the social, economic and cultural conditions. Several standards may be set. For example, effect-oriented regulatory standards may be set as a long-term goal, while less-stringent standards are adopted for the short term. As a consequence, noise regulatory standards differ widely from country to country (WHO 1995a; Gottlob 1995).

Noise regulatory standards can set the reference point for emission control and abatement policies at the national, regional or municipal levels, and can thus strongly influence the implementation of noise control policies. In many countries, exceeding regulatory standards is linked to an obligation to develop abatement action plans at the municipal, regional or national levels (low-noise implementation plans). Such plans have to address all relevant sources of noise pollution.

5.7.2. Examples of noise policies

Different countries have adopted a range of policies and regulations for noise control. A number of these are outlined in this section as examples.

Argentina. In Argentina, a national law recently limited the daily 8-h exposure to industrial noise to 80 dB, and it has had beneficial effects on hearing impairment and other hearing disorders among workers. In general, industry has responded by introducing constant controls on noise sources, combined with hearing tests and medical follow-ups for workers. Factory owners have recruited permanent health and safety engineers who control noise, supply advice on how to make further improvements, and routinely assess excessive noise levels. The engineers also provide education in personal protection and in the correct use of ear plugs, mufflers etc.

At the municipal level two types of noise have been considered. Unnecessary noise, which is forbidden; and excessive noise, which is defined for neighbourhood activities (zones), and for which both day and night-time maximum limits have been introduced. The results have been relatively successful in mitigating unwanted noise effects. At the provincial level, similar results have been accomplished for many cities in Argentina and Latin America.

Australia. In Australia, the responsibility for noise control is shared primarily by state and local governments. There are nationally-agreed regulatory standards for airport planning and new vehicle noise emissions. The Australian Noise Exposure Forecast (ANEF) index is used to describe how much aircraft noise is received at locations around an airport (DoTRS 1999). Around all airports, planning controls restrict the construction of dwellings within the 25 ANEF exposure contour and require sound insulation for those within 20 ANEF. Road traffic noise limits are set by state governments, but vary considerably in both the exposure metric and in maximum allowable levels. New vehicles are required to comply with stringent design rules for noise and air emissions. For example, new regulation in New South Wales adopts LAeq as the metric and sets noise limits of 60 dBA for daytime, and 55 dBA for night-time, along new roads. Local governments set regulations restricting noise emissions for household equipment, such as air conditioners, and the hours of use for noisy machines such as lawn mowers.

Europe. In Europe, noise legislation is not generally enforced. As a result, environmental noise levels are often higher than the legislated noise limits. Moreover, there is a gap between long-term political goals and what represents a "good acoustical environment". One reason for this gap is that noise pollution is most commonly regulated only for new land use or for the development of transportation systems, whereas enlargements at existing localities may be approved even though noise limits or guideline values are already surpassed (Gottlob 1995). A comprehensive overview of the noise situation in Europe is given in the Green Paper (EU 1996b), which was established to give noise abatement a higher priority in policy making. The Green Paper outlines a new framework for noise policy in Europe with the following options for future action:

a. Harmonizing the methods for assessing noise exposure, and encouraging the exchange of information among member states.

b. Establishing plans to reduce road traffic noise by applying newer technologies and fiscal instruments.

c. Paying more attention to railway noise in view of the future extension of rail networks.

d. Introducing more stringent regulation on air transport and using economic instruments to encourage compliance.

e. Simplifying the existing seven regulations on outdoor equipment by proposing a Framework Directive that covers a wider range of equipment, including construction machines and others.

Pakistan. In Pakistan, the Environmental Protection Agency is responsible for the control of air pollution nationwide. However, only recently have controls been enforced in Sindh in an attempt to raise public awareness and carry out administrative control on road vehicles producing noise (Zaidi, personal communication).

South Africa. In South Africa, noise control is three decades old. It began with codes of practice issued by the South African Bureau of Standards to address noise pollution in various sectors of the country (e.g. see SABS 1994 1996; and the contribution of Grond in Appendix 2). In 1989, the Environment Conservation Act made provision for the Minister of Environmental Affairs and Tourism to make regulations for noise, vibration and shock (DEAT 1989). These regulations were published in 1990 and local authorities could apply to the Minister to make them applicable in their areas. Later, the act was changed to make it obligatory for all authorities to apply the regulations. However, according to the new Constitution of South Africa of 1996, legislative responsibility for noise control rests exclusively with provincial and local authorities. The noise control regulations will apply to local authorities in South Africa as soon as they are published in the provinces. This will not only give local authorities the power to enforce the regulations, but also place an obligation on them to see that the regulations are enforced.

Thailand. In 1996, noise pollution regulations in Thailand stipulated that not more than 70 dBA LAeq,24h should be allowed in residential areas, and the maximum level of noise in industry should be no more than 85 dBA Leq 8h (Prasansuk 1997).

United States of America. Environmental noise was not addressed as a national policy issue in the USA until the implementation of the Noise Control Act of 1972. This congressional act directed the US Environmental Protection Agency to publish scientific information about noise exposure and its effects, and to identify acceptable levels of noise exposure under various conditions. The Noise Control Act was supposed to protect the public health and well-being with an adequate margin of safety. This was accomplished in 1974 with the publication of the US EPA "Levels Document" (US EPA 1974). It addressed issues such as the use of sound descriptions to describe sound exposure, the identification of the most important human effects resulting from noise exposure, and the specification of noise exposure criteria for various effects. Subsequent to the publication of the US EPA "Levels Document", guidelines for conducting environmental impact analysis were developed (Finegold et al. 1998). The day-night average sound level was thus established as the predominant sound descriptor for most environmental noise exposure.

It is evident from these examples that noise policies and regulations vary considerably across countries and regions. Moves towards global noise policies need to be encouraged to ensure that the world population gains the maximum health benefits from new developments in noise control.

5.7.3. Noise emission standards have proven to be inadequate

Much of the progress towards solving the noise pollution problem has come from advanced technology, which in turn has come about mainly as a result of governmental regulations (e.g. OECD-ECMT 1995). So far, however, the introduction of noise emission standards for vehicles has had limited impact on exposure to transportation noise, especially from aircraft and road traffic noise (Sandberg 1995). In part, this is because changes in human behaviour (of polluters, planners and citizens) have tended to offset some of the gains made. For example, mitigation efforts such as developing quieter vehicles, moving people to less noise-exposed areas, improving traffic systems and direct noise abatement and control (sound insulation, barriers etc.), have been counteracted by increases in the number of roads and highways built, by the number of traffic movements, and by higher driving speeds and the number of kilometers driven (OECD 1991; OECD-ECMT 1995).

Traffic planning and correction policies may diminish the number of people exposed to the very high community noise levels (>70 dB LAeq), but the number exposed to moderately high levels (55-65 dB LAeq) continues to increase in industrialized countries (Stanners & Bordeau 1995). In developing countries, exposure to excessive sound pressure levels (>85 dB LAeq), not only from occupational noise but also from urban, environmental noise, is the major avoidable cause of permanent hearing impairment (Smith 1998). Such sound pressure levels can also be reached by leisure activities at concerts, discotheques, motor sports and shooting ranges; by music played back in headphones; and by impulse noises from toys and fireworks.

A substantial growth in air transport is also expected in the future. Over the next 10 years large international airports may have to accommodate a doubling in passenger movements. General aviation noise at regional airports is also expected to increase (Large & House 1989). Although jet aircraft are expected to become less noisy due to regulation of noise emissions (ICAO 1993), the number of passengers is expected to increase. Increased air traffic movement between 1980 and 1990 is considered to be the main reason for the average 22% increase in the number of people exposed to noise above 67 dB LAeq at German airports (OECD 1993).

5.7.4. Unsustainable trends in noise pollution future policy planning

A number of trends are expected to increase environmental noise pollution, and are considered to be unsustainable in the long term. The OECD (1991) identified the following factors to be of increasing importance in the future:

a. The expanding use of increasingly powerful sources of noise.

b. The wider geographical dispersion of noise sources, together with greater individual mobility and spread of leisure activities.

c. The increasing invasion of noise, particularly into the early morning, evenings and weekends.

d. The increasing public expectations that are closely linked to increases in incomes and in education levels.

Apart from these, increased noise pollution is also linked to systemic changes in business practices (OECD-ECMT 1995). By accepting a just-in-time concept in transportation, products and components are stored in heavy-duty vehicles on roads, instead of in warehouses; and workers are recruited as temporary consultants just in time for the work, instead of as long-term employees.

In addition, the OECD (1991) report forecasts:

a. A strengthening of present noise abatement policies and their applications.

b. A further sharpening of emission standards.

c. A co-ordination of noise abatement measures and transport planning, to specifically reduce mobility.

d. A co-ordination of noise abatement measures with urban planning.

Planners need to know the likely effects of introducing a new noise source, or of increasing the level of an existing source, on the noise pollution in a community. Policy makers, when considering applications for new developmental projects, must take into account maximum levels, continuous equivalent sound pressure levels of both the background and the new noise source, the frequency of noise occurrence and the operating times of major noise sources.

5.7.5. Analysis of the impact of environmental noise

The concept of an environmental noise impact analysis (ENIA) is central to the philosophy of managing environmental noise. An ENIA should be required before implementing any project that would significantly increase the level of environmental noise in a community (typically, greater than a 5dB increase). The first step in performing an ENIA is to develop a baseline description of the existing noise environment. Next, the expected level of noise from a new source is added to the baseline exposure level to produce the new overall noise level. If the new total noise level is expected to cause an unacceptable impact on human health, trade-off analyses should then be performed to assess the cost, technical feasibility and community acceptance of noise mitigation measures. It is strongly recommended that countries develop standardized procedures for performing ENIAs (Finegold et al. 1998; SABS 1998).

Assessment of adverse health effects. In setting noise standards (for example on the basis of these guidelines), the adverse health effects from which the population is to be protected need to be defined. Health effects range from hearing impairment to sleep disturbance, speech interference to annoyance. The distinction between adverse and non-adverse effects sometimes poses considerable difficulties. Even the elaborate definition of an adverse health effect given in Chapter 3 incorporates significant subjectivity and uncertainty. More serious noise effects, such as hearing impairment or permanent threshold shift, are generally accepted as adverse. Consideration of health effects that are both temporary and reversible, or that involve functional changes with uncertain clinical significance, requires a judgement on whether these less-serious effects should be considered when deriving guideline values. Judgements as to the adversity of health effects may differ between countries, because of factors such as cultural backgrounds and different levels of health status.

Estimation of the population at risk. The population at risk is that part of the population in a given country or community that is exposed to enhanced levels of noise. Each population has sensitive groups or subpopulations that are at higher risk of developing health effects due to noise exposure. Sensitive groups include individuals impaired by concurrent diseases or other physiological limitations and those with specific characteristics that makes them more vulnerable to noise (e.g. premature babies; see the contribution of Zaidi in Appendix 2). The sensitive groups in a population may vary across countries due to differences in medical care, nutritional status, lifestyle and demographic factors, prevailing genetic factors, and whether endemic or debilitating diseases are prevalent.

Calculation of exposure-response relationships. In developing standards, regulators should consider the degree of uncertainty in the exposure-response relationships provided in the noise guidelines. Differences in the population structure (age, health status), climate (temperature, humidity) and geography (altitude, environment) can influence the prevalence and severity of noise-related health effects. In consequence, modified exposure-response relationships may need to be applied when setting noise standards.

Assessment of risks and their acceptability. In the absence of distinct thresholds for the onset of health effects, regulators must determine what constitutes an acceptable health risk for the population and select an appropriate noise standard to protect public health. This is also true in cases where thresholds are present, but where it would not be feasible to adopt noise guidelines as standards because of economical and/or technical constraints. The acceptability of the risks involved, and hence the standards selected, will depend on several factors. These include the expected incidence and severity of the potential effects, the size of the population at risk, the perception of related risks, and the degree of scientific uncertainty that the effects will occur at any given noise level. For example, if it is suspected that a health effect is severe and the size of the population at risk is large, a more cautious approach would be appropriate than if the effect were less troubling, or if the population were smaller.

Again, the acceptability of risk may vary among countries because of differences in social norms, and the degree of adversity and risk perception by the general population and stakeholders. Risk acceptability is also influenced by how the risks associated with noise compare with risks from other pollution sources or human activities.

5.7.6. Cost-benefit analysis

In the derivation of noise standards from noise guidelines two different approaches for decision making can be applied. Decisions can be based purely on health, cultural and environmental consequences, with little weight to economic efficiency. This approach has the objective of reducing the risk of adverse noise effects to a socially acceptable level. The second approach is based on a formal cost-effectiveness, or cost-benefit analysis (CBA). The objective is to identify control actions that achieve the greatest net economic benefit, or are the most economically efficient. The development of noise standards should account for both extremes, and involve stakeholders and assure social equity to all the parties involved. It should also provide sufficient information to guarantee that stakeholders understand the scientific and economic consequences.

To determine the costs of control action, the abatement measures used to reduce emissions must be known. This is usually the case for direct measures at the source and these measures can be monetarized. Costs of action should include all costs of investment, operation and maintenance. It may not be possible to monetarize indirect measures, such as alternative traffic plans or change in behaviour of individuals.

The steps in a cost-benefit analysis include:

a. The identification and cost analysis of control action (such as emission abatement strategies and tactics).

b. An assessment of noise and population exposure, with and without the control action.

c. The identification of benefit categories, such as improved health and reduced property loss.

d. A comparison of the health effects, with and without control action.

e. A comparison of the estimated costs of control action with the benefits that accrue from such action.

f. A sensitivity and uncertainty analysis.

Action taken to reduce one pollutant may increase or decrease the concentration of other pollutants. These additional effects should be considered, as well as pollutant interactions that may lead to double counting of costs or benefits, or to disregarding some costly but necessary action. Due to different levels of knowledge about the costs of control action and health effects, there is a tendency to overestimate the cost of control action and underestimate the benefits.

CBA is a highly interdisciplinary task. Appropriately applied, it is a legitimate and useful way of providing information for managers who must make decisions that impact health. CBA is also an appropriate tool for drawing the attention of politicians to the benefits of noise control. In any case, however, a CBA should be peer-reviewed and never be used as the sole and overriding determinant of decisions.

5.7.7. Review of standard setting

The setting of standards should involve stakeholders at all levels (industry, local authorities, non-governmental organizations and the general public), and should strive for social equity or fairness to all parties involved. It should also provide sufficient information to guarantee that the scientific and economic consequences of the proposed standards are clearly understood by the stakeholders. The earlier that stakeholders are involved, the more likely is their co-operation. Transparency in moving from noise guidelines to noise standards helps to increase public acceptance of necessary measures. Raising public awareness of noise-induced health effects (changing of risk perception) also leads to a better understanding of the issues involved (risk communication) and serves to obtain public support for necessary control action, such as reducing vehicle emissions. Noise standards should be regularly reviewed, and revised as new scientific evidence emerges.

5.7.8. Enforcement of noise standards: Low-noise implementation plans

The main objective of enforcing noise standards is to achieve compliance with the standards. The instrument used to achieve this goal is a Low-Noise Implementation Plan (LNIP). The outline of such a plan should be defined in the regulatory policies and should use the tactical instruments discussed above. A typical low-noise implementation plan includes:

a. A description of the area to be regulated.

b. An emissions inventory.

c. A monitored or simulated inventory of noise levels.

d. A comparison of the plan with emissions and noise standards or guidelines.

e. An inventory of the health effects.

f. A causal analysis of the health effects and their attribution to individual sources.

g. An analysis of control measures and their costs.

h. An analysis of transportation and land-use planning.

i. Enforcement procedures.

j. An analysis of the effectiveness of the noise management procedures.

k. An analysis of resource commitment.

l. Projections for the future.

As the LNIP also addresses the effectiveness of noise control technologies and policies, it is very much in line with the Noise Control Assessment Programme (NCAP) proposed recently (Finegold et al. 1999).

5.8. Conclusions on Noise Management

Successful noise management should be based on the fundamental principles of precaution, the polluter pays and prevention. The noise abatement strategy typically starts with the development of noise standards or guidelines, and the identification, mapping and monitoring of noise sources and exposed communities. A powerful tool in developing and applying the control strategy is to make use of modeling. These models need to be validated by monitoring data. Noise parameters relevant to the important sources of noise must be known. Indoor noise exposures present specific and complex problems, but the general principles for noise management hold. The main means for noise control in buildings include careful site investigations, adequate building designs and building codes, effective means for addressing occupant complaints and symptoms, and building diagnostic procedures.

Noise control should include measures to limit the noise at the source, to control the sound transmission path, to protect the receiver's site, to plan land use, and to raise public awareness. With careful planning, exposure to noise can be avoided or reduced. Control options should take into account the technical, financial, social, health and environmental factors of concern. Cost-benefit relationships, as well as the cost-effectiveness of the control measures, must be considered in the context of the social and financial situation of each country. A framework for a political, regulatory and administrative approach is required for the consistent and transparent promulgation of noise standards. Examples are given for some countries, which may guide others in their development of noise policies.

Noise management should:

a. Start monitoring human exposures to noise.

b. Have health control require mitigation of noise emissions. The mitigation procedures should take into consideration specific environments such as schools, playgrounds, homes and hospitals; environments with multiple noise sources, or which may amplify the effects of noise; sensitive time periods, such as evenings, nights and holidays; and groups at high risk, such as children and the hearing impaired.

c. Consider noise consequences when making decisions on transport-system and land-use planning.

d. Introduce surveillance systems for noise-related adverse health effects.

e. Assess the effectiveness of noise policies in reducing noise exposure and related adverse health effects, and in improving supportive "soundscapes."

a. Adopt these Guidelines for Community Noise as long-term targets for improving human health.

g. Adopt precautionary actions for sustainable development of acoustical environments.

6. Conclusions And Recommendations

6.1. Implementation of the Guidelines

The potential health effects of community noise include hearing impairment; startle and defense reactions; aural pain; ear discomfort speech interference; sleep disturbance; cardiovascular effects; performance reduction; and annoyance responses. These health effects, in turn, can lead to social handicap; reduced productivity; decreased performance in learning; absenteeism in the workplace and school; increased drug use; and accidents. In addition to health effects of community noise, other impacts are important such as loss of property value. In these guidelines the international literature on the health effects of community noise was reviewed and used to derive guideline values for community noise. Besides the health effects of noise, the issues of noise assessment and noise management were also addressed. Other issues considered were priority setting in noise management; quality assurance plans; and the cost-efficiency of control actions. The aim of the guidelines is to protect populations from the adverse health impacts of noise.

The following recommendations were considered appropriate:

a. Governments should consider the protection of populations from community noise as an integral part of their policy for environmental protection.

b. Governments should consider implementing action plans with short-term, medium-term and long-term objectives for reducing noise levels.

c. Governments should adopt the health guidelines for community noise as targets to be achieved in the long-term.

a. Governments should include noise as an important issue when assessing public health matters and support more research related to the health effects of noise exposure.

a. Legislation should be enacted to reduce sound pressure levels, and existing legislation should be enforced.

b. Municipalities should develop low-noise implementation plans.

c. Cost-effectiveness and cost-benefit analyses should be considered as potential instruments when making management decisions.

d. Governments should support more policy-relevant research into noise pollution (see section 6.3).

6.2. Further WHO Work on Noise

The WHO Expert Task Force proposed several issues for future work in the field of community noise. These are:

a. The WHO should consider updating the guidelines on a regular basis.

b. The WHO should provide leadership and technical direction in defining future research priorities into noise.

c. The WHO should organize workshops on the application of the guidelines.

d. The WHO should provide leadership and co-ordinate international efforts to develop techniques for the design of supportive sound environments (e.g. 'soundscapes").

e. The WHO should provide leadership for programmes to assess the effectiveness of health-related noise policies and regulations.

f. The WHO should provide leadership and technical direction for the development of sound methodologies for EIAP and EHIAP.

g. The WHO should encourage further investigation into using noise exposure as an indicator of environmental deterioration, such as found in black spots in cities.

a. The WHO should provide leadership, technical support and advice to developing countries, to facilitate the development of noise policies and noise management.

6.3. Research Needs

In the publication entitled "Community Noise", examples of essential research and development needs were given (Berglund & Lindvall 1995). In part, the scientific community has already addressed these issues.

A major step forward in raising public awareness and that of decision makers is the recommendation of the present Expert Task Force to concentrate more **on variables which have monetary consequences. This means that research should consider the dose-response relationships between sound pressure levels and politically relevant variables, such as noise-induced social handicap, reduced productivity, decreased performance in learning, workplace and school absenteeism, increased drug use and accidents.**

There is also a need for continued efforts to understand community noise and its effects on the health of the world population. Below is a list of essential research needs in non-prioritized order. Research priorities may vary over time and by place and capabilities. The main goal in suggesting these research activities is to improve the scientific basis for policy-making and noise management. This will protect and improve the public health with regard to the effects of community noise pollution.

Research related to measurement and monitoring systems for health effects

- Development of a global noise impact monitoring study. The study should be designed to obtain longitudinal data across countries on the health effects on communities of various types of environmental noise. A baseline survey could be undertaken in both developed and developing countries and monitoring surveys conducted every 3-5 years. Since a national map of noise exposure from all sources would be prohibitively expensive, periodic surveys of a representative sample of about 1000 people (using standard probability techniques) could be reliably generalized to the whole population of a country with an accuracy of plus-or-minus 3%. A small number of standard questions could be used across countries to obtain comparative data on the impact of all the main types of noise pollution.

- Development of continuous monitoring systems for direct health effects in critical locations.
- Development of standardized methods for low-cost assessment of local sound levels by measurement or model calculations.
- Development of instruments appropriate for local/regional surveys of people's perceptions of their noise/sound environments.

- Protocols for reliable measurements of high-frequency hearing (8000 Hz and above) and for evaluation of such measures as early biomarkers for hearing impairment/deficits.

Research related to combined noise sources and combined health effects

- Research into the combined health effects of traffic noise, with emphasis on the distribution of sound levels over time and over population sub-environments (time-activity pattern).
- Comprehensive studies on combined noise sources and their combinations of health effects in the 3 large areas of transport (road, rail and aircraft).
- Procedures for evaluating the various health effects of complex combined noise exposures over 24 hours on vulnerable groups and on the general population.
- Methods for assessing the total health effect from noise immission (and also other pollution) in sensitive areas (for example, airports, city centers and heavily-trafficked highways)

Research related to direct and/or long-term health effects (sensitive risk groups, sensitive areas and combined exposures)

- Identification of potential risk groups, including identification of sensitive individuals (such as people with particular health problems; people dealing with complex cognitive tasks; the blind; the hearing impaired; young children and the elderly), differences between sexes, discrimination of risk among age groups, and influence of transportation noise on pregnancy course and on fetal development.

- Studies of dose-response relationships for various effects, and for continuous transportation noise at relatively low levels of exposure and low number of noise events per unit time (including traffic flow composition).
- Studies on the perception of control of noise exposure, genetic traits, coping strategies and noise annoyance as modifiers of the effects of noise on the cardiovascular system, and as causes of variability in individual responses to noise.
- Prospective longitudinal studies of transportation noise that examine physiological measures of health, including standardized health status inventory, blood pressure, neuro-endocrine and immune function.
- Knowledge on the health effects of low-frequency components in noise and vibration.
-

Research related to indirect or after-effects of noise exposure

- Field studies on the effects of exposure to specific sounds such as aircraft noise and loud music, including effects such as noise-induced temporary and permanent threshold shifts, speech perception and misperception, tinnitus and information retrieval.
- Studies on the influence of noise-induced sleep disturbance on health, work performance, accident risk and social life.
- Assessment of dose-response relationships between sound levels and politically relevant variables such as noise-induced social handicap, reduced productivity, decreased performance in learning, workplace and school absenteeism, increased drug use and accidents.
- Determination of the causal connection between noise and mental health effects, annoyance and (spontaneous) complaints in areas such as around large airports, heavy-trafficked highways, high-speed rail tracks and heavy vehicles transit routes. The connections could be examined by longitudinal studies, for example.
- Studies on the impact of traffic noise on recovery from noise-related stress, or from nervous system hyperactivity due to work and other noise exposures.

Research on the efficiency of noise abatement policies which are health based

- Determination of the accuracy and effectiveness of modern sound insulation (active noise absorption), especially in residential buildings, in reducing the long-term effects of noise on annoyance/sleep disturbance/speech intelligibility. This can be accomplished by studying sites that provide data on remedial activities and changes in behavioral patterns among occupants.
- Evaluation of environmental (area layout, architecture) and traffic planning (e.g. rerouting) interventions on annoyance, speech interference and sleep disturbance.
- Comparative studies to determine whether children and the hearing impaired have equitable access to healthier lives when compared with normal adults in noise-exposed areas.

- Development of a methodology for the environmental health impact assessment of noise that is applicable in developing as well as developed countries.

Research into positive acoustical needs of the general population and vulnerable groups

- Development of techniques/protocols for the design of supportive acoustical environments for the general population and for vulnerable groups. The protocols should take into account time periods that are sensitive from physiological, psychological and socio-cultural perspectives.

- Studies to characterize good “restoration areas” which provide the possibility for rest without adverse noise load.

- Studies to assess the effectiveness of noise policies in maintaining and improving soundscapes and reducing human exposures.

Appendix 1 : Bibliographical References

AAP 1997 Noise: A hazard for the fetus and newborn. American Academy of Pediatrics. Committee on Environmental Health. Pediatrics 100: 724-27.

Altena K 1987 Medische gevolgen van lawaai. Report GA-HR-03-01, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu, Den Haag, Netherlands.

ANSI 1994 American National Standard Acoustical Terminology. ANSI S.1.-1994, American National Standards Institute, Inc., New York, NY, USA.

ANSI 1995 American National Standard Bioacoustical Terminology. ANSI S3.20-1995, American National Standards Institute, Inc., New York, NY, USA.

ANSI 1997 Methods for the Calculation of the Speech Intelligibility Index, American National Standard 3.5, American National Standard Institute, New York, NY, USA.

ASTM 1992 Standard Guide for Field Measurement of Airborne Sound Insulation of Building Facades and Facade Elements, ASTM E966, American Society For Testing and Materials, Philadelphia, West Conshohocken, PA, USA.

ASTM 1994a Classification of Rating Sound Insulation, ASTM E413, American Society For Testing and Materials, Philadelphia, PA, USA .

ASTM 1994b Standard Classification for Determination of Outdoor-Indoor Transmission Class, ASTM E1332, American Society For Testing and Materials, Philadelphia, PA, USA.

ASTM 1994c Standard Classification for Determination of Impact Insulation Class (IIC), ASTM E989, American Society For Testing and Materials, Philadelphia, PA, USA.

ASTM 1996 Standard Test Method for Laboratory Measurement of Impact Sound Transmission through Floor-ceiling Assemblies using the Tapping Machine, ASTM E492, American Society For Testing and Materials, Philadelphia, PA, USA.

ASTM 1997 Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements, ASTM E90, American Society For Testing and Materials, Philadelphia, PA, USA .

Axelsson A, Arvidson I, Jerson T 1986 Hearing in fishermen and coastguards. In R.J. Salvi, D. Henerson, R.P. Hamernik and V. Colletti (eds.), Basic and Applied Aspects of Noise-Induced Hearing Loss, pp. 513-20. Plenum Press, New York.

Axelsson A and Prasher DK 1999. Tinnitus: A warning signal to teenagers attending discotheques? Noise & Health 2: 1-2.

Babisch W 1998a Epidemiological studies on cardiovascular effects of traffic noise. In D. Prasher, D. and L. Luxon, L. (eds.) Advances in Noise Series, Vol. I: Biological Effects, pp. 312-327. Whurr Publishers, London, UK.

Babisch W 1998b Epidemiological studies of cardiovascular effects of traffic noise. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 221-229. Noise Effects ’98 PTY Ltd., Sydney, Australia.

Babisch W and Ising H 1989 Zum Einfluss von Musik in Diskotheken auf die Hörfähigkeit von Jugendlichen. Sozial- und Präventivmedizin 34: 239-243.

Babisch W, Ising H, Gallacher JEJ, Sweetnam PM, Elwood PC 1998 The Caerphilly and Speedwell studies, 10 year follow up. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 230-35. Noise Effects ’98 PTY Ltd., Sydney, Australia.

Babisch W, Ising H, Gallacher JE, Sweetnam PM, Elwood PC 1999 Traffic noise and cardiovascular risk: The Caerphilly and Speedwell studies, third phase 10-year follow up. Archives of Environmental Health 54: 210-216.

Beersma DGM and Altena K 1995 Critical evaluation of the 1992 report of a field study of aircraft noise and sleep disturbance. Newsletter of the European Sleep Research Society 1: 5-7.

Bendat JS and Piersol AG 1971 Random Data: Analysis and Measurement Procedures. Wiley, New York, USA.

Beranek LL 1971 Noise and Vibration Control. McGraw Hill, New York, USA.

Beranek LL 1989 Balanced Noise Criterion (NCB) Curves. Journal of the Acoustical Society of America 86: 650-664.

Berglund B 1998 Community noise in a public health perspective In V.C. Goodwin and D.C. Stevenson (eds.) Inter Noise 98. Sound and Silence: Setting the Balance, Vol. 1, pp. 19-24. New Zealand Acoustical Society, Auckland, New Zealand.

Berglund B, Hassmén P, Job RFS 1996 Sources and effects of low-frequency noise. Journal of the Acoustical Society of America, 99: 2985-3002.

Berglund B and Lindvall T (Eds.) 1995 Community Noise. Document prepared for the World Health Organization. Archives of the Center for Sensory Research, 2: 1-195. A reprint of this document with corrections of language and references has been published in 1998. The 1995 document can be addressed on the Internet address www.who.int/peh/.

Berglund B and Nilsson ME 1997 Empirical issues concerning annoyance models for combined community noise. In F. Augustinovicz (ed.) Inter Noise 97. Help Quiet the World for a Higher Quality Life, Vol. 2, pp. 1053-58. Noise Control Foundation, Poughkeepsie, NY, USA.

Berglund B, Berglund U, Lindvall T 1976 Scaling loudness, noisiness and annoyance of community noise. Journal of the Acoustical Society of America 60: 1119-1125.

Berglund B, Berglund U, Lindberg S 1986 Loudness of impulse sound from different weapons. In R. Lutz (ed.) Inter Noise ’86, Vol. II, pp. 815-20. Noise Control Foundation, New York, USA..

Berry BF 1995 Towards a standardised descriptor of impulsive noise caused by low-altitude military aircraft”. In R.J. Bernhard and S. Bolton (ed.) Inter Noise ’95, Vol. 2, pp. 879-884. Noise Control Foundation, Poughkeepsie, NY, USA

Bishop DE and Horonjef RD 1967 Procedures for Developing Noise Exposure Forecast Areas for Aircraft Flight Operations. FAA Report DS-67-10 (August 1967), Washington DC, USA.

Blazier WE 1998 RC Mark II: A refined procedure for rating the noise of heating, ventilating, and air-conditioning (HVAC) systems in buildings. Noise Control Engineering Journal 45: 243-250.

Bradley JS 1978 Predictors of Adverse Human Responses to Traffic Noise. Proceedings of the ASTM Symposium on Community Noise, Kansas City, pp. 108-123.

Bradley JS 1985 Uniform derivation of optimum conditions for speech in rooms. National Research Council, Building Research Note, BRN 239, Ottawa, Canada.

Bradley JS 1986a Predictors of Speech Intelligibility in Rooms. Journal of the Acoustical Society of America 80: 837-845.

Bradley JS 1986b Speech Intelligibility Studies in Classrooms. Journal of the Acoustical Society of America 80: 846-854.

Bradley JS 1986c Optimum Conditions for Speech in Rooms. Proceedings of the 12th International Congress on the Acoustics, Paper E10-5, Toronto, Canada.

Bradley JS 1993 Disturbance Caused by Residential Air Conditioner Noise. Journal of the Acoustical Society of America 93: 1978-1986.
Bradley JS 1994a On dose response curves of annoyance to aircraft noise. In S. Kuwano (Ed.), Inter-Noise 94. Noise Quantity and Quality, Vol 1, pp. 235-38. Noise Control Foundation, Poughkeepsie, NY, USA.
Bradley JS 1994b Annoyance Caused by Constant-Amplitude and Amplitude- Modulated Sounds Containing Rumble. Noise Control Engineering Journal 42: 203-208.
Bradley, J.S. 1996. Determining acceptable limits for aviation noise. In F.A. Hill and R. Lawrence (eds.) Inter Noise 96, Noise Control – The Next 25 Years, Book 5, pp. 2541-46. Institute of Acoustics, St Albans, UK.
Bradley JS, Vaskor JG, Dickinson SM 1979 The Effect of Skewness and Standard Deviation on Sampling Errors for Traffic Noise. Applied Acoustics 12: 397-409.
Broner N and Leventhall HG 1993 A Modified PNdB for Assessment of Low Frequency Noise. Journal of Sound and Vibration 73: 425-444.
Brookhouser PE, Worthington DW, Kelly WJ 1992 Noise-induced hearing loss in children. Laryngoscope 1992; 102: 645-655.
Brown AL 1994 Exposure of the Australian population to road traffic noise. Applied Acoustics, 43: 169-176.
Buchta E 1996 A field study on annoyance caused by shooting noise – Determination of the penalty for various weapon calibers. . In F.A. Hill and R. Lawrence (eds.) Inter Noise 96, Noise Control – The Next 25 Years, Book 5, pp. 2495-2500. Institute of Acoustics, St Albans, UK.
Bullen RB and Hede AJ 1983 Time of Day Corrections in Measures of Aircraft Noise Exposure. Journal of the Acoustical Society of America 73: 1624-1630.
Burns W 1968 Noise and Man. John Murray, London, UK.
Carter NL 1996 Transportation noise, sleep, and possible after-effects. Environment International 22: 105-116.
Carter NL and Hunyor SN 1991 A field study of traffic noise and cardiac arrythmia during sleep. In: Technical Papers: 4th Western Pacific Regional Acoustics Conference, pp. 165-172, Queensland Department of Environment and Heritage, Brisbane, Australia.
Carter NL, Hunyor SN, Crawford G, Kelly D, Smith AJ 1994a Environmental noise and sleep - a study of arousals, cardiac arrhytmia and urinary catecholamines. Sleep 17: 298-307.
Carter NL, Ingham P, Tran K, Huynor S 1994b A field study of the effects of traffic noise on heart rate and cardiac arrhythmia during sleep. Journal of Sound and Vibration, 169, 221-227.
CEC 1992a Towards Sustainability: A European Community Programme of Policy and Action in Relation to the Environment and Sustainable Development. COM (92) 23 Final – Vol. II. Office for Official Publications of the European Communities, Luxembourg.
CEC 1992b The Impact of Transport on the Environment: A Community Strategy for “Sustainable Mobility”. COM (92) 46 Final. Office for Official Publications of the European Communities, Luxembourg..
CEC 1996. Future Noise Policy. European Commission Green Paper. COM(96) 540 Final Office for Official Publications of the European Communities, Luxembourg.
Chakrabarty D, Santra SC, Mukherjee, A 1997: Status of road traffic noise in Calcutta metropolis, India. Journal of the Acoustical Society of America 101: 943-949.
CMD (1997) Taber’s Cyclopedic Medical Dictionary, edition 18, FA Davis Company, Philadelphia.

Cohen S 1980 Aftereffects of stress on human performance and social behavior: A review of research and theory. Psychological Bulletin, 88: 82-108.

Cohen S, Evans GW, Krantz DS, Stokols D 1980 Physiological, motivational, and cognitive effects of aircraft noise on children. American Psychologist 35: 231-243.

Cohen S, Evans GW, Stokols D, Krantz DS 1986 Behavior, Health and Environmental Stress. Plenum Press, New York**.**

Crocker MJ and Price AJ 1975 Noise and Noise Control. Volume I, CRC Press, Cleveland USA.

Daigle GA, Embleton TFW, Piercy JE 1986 Propagation of Sound In the Presence of Gradients and Turbulence Close to the Ground. Journal of the Acoustical Society of America 79: 613-627.

DEAT 1989 Environment Conservation Act (Act No. 73 of 1989) Noise Control Regulations, Ministry of Environmental Affairs and Tourism, Pretoria, South Africa.

DeKoning HW 1987 Setting Environmental Standards. Guidelines for Decision-Making. World Health Organization, Geneva, Switzerland.

DIMD 1985 Dorland's illustrated medical dictionary, 26th edition, Saunders, Philadelphia [etc.], USA

DiMento JS 1981 Making usable information on environmental stressors: Opportunities for the research and policy communities. Journal of Social Issues 37:172-204.

DoTRS 1999 What is an ANEF? Commonwealth of Australia 1999, Department of Transport and Regional Services. Internet address:
http://www.dotrs.gov.au/airports/avenv/noise/anef.htm

Edworthy J 1998 Warning people through noise. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 147-56. Noise Effects ’98 PTY Ltd., Sydney, Australia.

Edworthy J and Adams AS 1996 Warning Design: A Research Perspective. Taylop and Francis, London.

EEA 1995 Europe’s Environment. The Dobris Assessment. D. Stanners, P. Bourdeau (Eds.), European Environment Agency, Copenhagen, Denmark.

Embleton TFW and Piercy JE 1976 Outdoor Sound Propagation Over Ground of Finite Impedance. Journal of the Acoustical Society of America 59: 267-277.

EU 1970 Council Directive on the approximation of the laws of the Member States relating to the permissible sound level and the exhaust system of motor vehicles. Directive 70/157/EEC of 6 February 1970. Official Journal L 42 (23.2.1970), p. 16. Amended by 73/350/EEC of 7.11.1973; Official Journal L 321 (22.11.1973), p. 33. Amended by 77/212/EEC of 8.3.1977; Official Journal L 66 (12.3.1977), p. 33. Amended by 81/334/EEC of 13.4.1981; Official Journal L 131 (18.5.1981), p. 6. Amended by 84/424/EEC of 03.09.1984; Official Journal L 238 (06.09.84) p. 31. Amended by 87/354/EEC of 3/87; Official Journal L 192 (11.07.87) p. 43. Amended by 89/491/EEC of 3/89; Official Journal L 238 (15.08.89) p. 43. Amended by 92/97/EEC of 10.11.92; Official Journal L 371 (19.12.92) p. 1. Amended by 96/20/EEC of 27.03.1996; Official Journal L 92 (13.04.96) p. 23, Brussels, Belgium.

EU 1978 Council Directive on the approximation of the laws of the Member States on the permissible sound level and exhaust system of motorcycles. Directive 78/1015/EEC of 23 November 1978. Official Journal L 349 (13.12.1978), p. 21, Brussels, Belgium. (Directive 78/1015/EEC is superseded by 97/24/EC, see EU 1997).

EU 1980 Council Directive on the limitation of noise emissions from subsonic airplanes. Directive 80/51/EEC of 20 December 1979. Official Journal L 18 (24.01.80) p. 26, Brussels, Belgium.
EU 1984a Council Directive on the approximation of the laws of the Member States relating to the permissible sound power level of compressors. Directive 84/533/EEC of 17 September 1984. Official Journal L 300 (19.11.1984), p. 123. Amended by 85/406/EEC of 11.7.1985. Official Journal L 233 (30.8.1985), p. 11, Brussels, Belgium.
EU 1984b Council Directive on the approximation of the laws of the Member States relating to the permissible sound power level of tower cranes. Directive 84/534/EEC of 17 September 1984. Official Journal L 300 (19.11.1984), p. 123. Amended by 87/405/EEC of 25.6.1987. Official Journal L 220 (8.8.1987) p. 60, Brussels, Belgium.
EU 1984c Council Directive on the approximation of the laws of the Member States relating to the permissible sound power level of welding generators. Directive 84/535/EEC of 17 September 1984. Official Journal L 300 (19.11.1984), p. 142. Amended by 85/407/EEC of 11.7.1985.Official Journal L 233 (30.8.1985), p. 16, Brussels, Belgium.
EU 1984d Council Directive on the approximation of the laws of the Member States relating to the permissible sound power level of power generators. Directive 84/536/EEC of 17 September 1984. Official Journal L 300 (19.11.1984), p. 149. Amended by 85/408/EEC of 11.7.1985. Official Journal L 233 (30.8.1985), p. 18, Brussels, Belgium.
EU 1984e Council Directive on the approximation of the laws of the Member States relating to the permissible sound power level of powered hand-held concrete-breakers and picks. Directive 84/537/EEC of 17 September 1984. Official Journal L 300 (19.11.1984), p. 156. Amended by 85/409/EEC of 11.7.1985. Official Journal L 233 (30.8.1985), p. 20, Brussels, Belgium.
EU 1984f Council Directive on the approximation of the laws of the Member States relating to the permissible sound power level of lawnmowers. Directive 84/538/EEC of 17 September 1984. Official Journal L 300 (19.11.1984), p. 171. 87. Amended by 87/ 252/EEC of 7.4.87. Official Journal L 117 (5.5.1987), p. 22. Amended by 88/80/EEC of 22.3.1988. Official Journal L 81 (26.3.1988), p. 69. Amended by 88/181/EEC of 22.3.1988. Official Journal L 81 (26.3.1988), p. 71, Brussels, Belgium.
EU 1986a Council Directive on the protection of workers from the risks related to exposure of noise at work. Directive 86/188/EEC of 12.5.1986. Official Journal L 137 (24.5.1986), p. 28, Brussels, Belgium.
EU 1986b Council Directive on the limitation of noise emitted by hydraulic excavators, rope-operated excavators, dozers, loaders and excavator-loaders. Directive 86/662/EEC of 22.12.1986 as amended by the Directive of 2.8.1989. Official Journal L 384 (31.12.1986), p. 1; L 253 (30.8.1989), p. 35, Brussels, Belgium.
EU 1986c Council Directive on airborne noise emitted by household appliances. Directive 86/594/EEC of 1.12.1986. Official Journal L 344 (6.12.1986), p. 24, Brussels, Belgium.
EU 1989 Council Directive on the limitation of noise emission from civil subsonic jet aeroplanes. Directive 89/629/EEC of 04 December1989. Official Journal L 363 (12.12.89) p. 27, Brussels, Belgium.
EU 1996a Council Directive to adapt in the light of technical progress Directive 70/157/EEC of 6 February 1970 on the approximation of the laws of the Member States regarding poermissible sound levels and exhaust systems of motor vehicles. Directive 96/20/EC of 27.03.1996. Official Journal L 92 (13.04.96) p. 23, Brussels, Belgium.

EU 1996b b Future Noise Policy – European Commission Green Paper. Report COM (96) 540 final. Commission of the Euopean Communities, Brussels.
EU 1997 Directive on certain components and charractristics of two or three-wheel motor vehicles. Directive 97/24/EC of the European Parliament and of the Council of 17 June 1997. Official Journal L 226 1997, Brussels, Belgium.
Evans GW 1998 Motivational consequences of exposure to noise. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects '98), Vol. 1, pp. 311-320. Noise Effects '98 PTY Ltd., Sydney, Australia.
Evans GW and Lepore SJ 1993 Non-auditory effects of noise on children: A critical review. Children's Environments 10: 31-51.
Evans GW and Maxwell L 1997 Chronic noise exposure and reading deficits. Environment and Behavior 29: 638-656.
Evans GW, Hygge S, Bullinger M 1995 Chronic noise and psychological stress. Psychological Science 6: 333-338.
Evans GW, Bullinger M, Hygge S 1998 Chronic noise exposure and physiological response: A prospective study of children living under environmental stress. Psychological Science 9: 75-77.
Faiz A, Sinha, K, Wals, M and Valma, A 1990: Automotive air pollution: Issues and options for developing countries. WPS 492, World Bank, Washington, USA.
Falkemark G 1997 Trafikpolitiken, makten och miljön [Traffic politics, power and the environment]. I H.B. Andersson (Red.), Trafik och miljö [Traffic and the Environment]. Kommunikationsforskningsberedningen [Swedish Transport and Communications Research Board], Stockholm, Sweden.Fechter LS 1999 Mechanisms of ototoxicity by chemical contaminants: Prospects for intervention. Noise and Health, 2: 10-27.
Fidell S and Jones G 1975 Effects of cessation of late night on an airport community. Journal of Sound and Vibration, 42:411-427.
Fidell S, Barber, DS, Schultz TJ 1991 Updating a dosage-effect relationship for the prevalence of annoyance due to general transportation noise. Journal of the Acoustical Society of America 89: 221-233.
Fidell S, Pearsons K, Tabachnick B, Howe R, Silvati L, Barber DS 1995a Field study of noise-induced sleep disturbance. Journal of the Acoustical Society of America 98 (2 PART 1): 1025-1033.
Fidell S, Howe R, T Tabachnick BG, Pearsons KS, Sneddon MD 1995b Noise-induced sleep disturbance in residences near two civil airports. NASA Contractor Report 198252, NASA Langley Research Center, Hampton VA, USA.
Fidell S, Howe R, Tabachnick B, Pearsons K, Silvati L, Sneddon M, Fletcher E 1998 Field studies of habituation to change in night-time aircraft noise and of sleep motility measurement methods. BBN Report 8195, BNN Systems and Technologies Corporation, Canogan Park, California, USA.
Fidell S, Pearsons K, Howe R et al. 1994 Noise-induced sleep disturbance in residential settings. BNN Report 7932. BNN Systems and Technologies Corporation, Canoga Park, California, USA.
Fields JM 1986 Cumulative Airport Noise Exposure Metrics: An Assessment of Evidence for Time-of-Day Weightings. US FAA Report, DOT/FAA/EE-86/10, United States Federal Aviation Administration, Washington D.C., USA.

Fields JM 1990 A quantitative summary of non-acoustical variables' effects on reactions to environmental noise. In: Noise Con 90, pp. 303-308. Noise Control Foundation, Poughkeepsie, NY, USA.

Fields JM 1993 Effects of personal and situational variables on noise annoyance in residential areas. Journal of the Acoustical Society of America 93: 2753-2763.

Fields JM 1994 A Review of an Updated Synthesis of Noise/Annoyance Relationships. NASA Contractor Report 194950, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, USA.

Fields JM 1998 Reactions to environmental noise in an ambient noise context in residential areas. Journal of the Acoustical Society of America 104: 2245-2260.

Fields JM, de Jong RG, Brown AL, Flindell IH, Gjestland T, Job RFS, Kurra S, Lercher P, Schuemer-Kors A, Vallet M, Yano M 1997 Guidelines for reporting core information from communicy noise reaction surveys. Journal of Sound and Vibration 206: 685-695.

Fields JM, de Jong RG, Flindell IA, Gjestland T, Job R.S, Kurra S, Schuemer-Kors,A, Lercher P, Vallet M, Yano T 1998 Recommendation for shared annoyance questions in noise annoyance surveys. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects '98.), Vol. 1, pp. 481-86. Noise Effects '98 PTY Ltd., Sydney, Australia.

Finegold LS, Harris CS, von Gierke HE 1994. Community annoyance and sleep disturbance: Updated criteria for assessing the impacts of general transportation noise on people. Noise Control Engineering Journal, 42: 25-30.

Finegold LS, von Gierke HE, McKinley RL, and Schomer PD 1998 Addressing the effectiveness of noise control regulations and policies In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects '98), Vol. 2, pp. 719-24. Noise Effects '98 PTY Ltd., Sydney, Australia.

Finegold LS, von Gierke HE, Schomer PD, Berry BF 1999 Proposal for monitoring worldwide noise exposure and assessing the effectiveness of noise exposure policies and noise control technologies. In: J. Cuschieri, S. Glegg, Yan Yong (eds.) Internoise 99 – The 1999 International Congress on Noise Control Engineering, 6-8 December 1999, Fort Lauderdale, Florida, USA, pp. 1917-1922.

Finke H-O 1980 Akustische Kennwerte für die Messung und Beurteilung von Gerauschimmissionen und deren Zusammenhang mit der subjektiven Gestörtheit. Dissertation of Technical University, Braunschweig, Germany.

Flindell IH and Stallen, PJM 1999 Non-acoustical factors in evnrionmental noise. Noise and Health 3: 11-16.

Florentine M, Buus S, Poulsen T 1996. Temporal integration of loudness as a function of level. Journal of the Acoustical Society of America, 99, 1633-44.

Ford RD 1987 Physical assessment of transportation noise. In P.M. Nelson (ed.) Transportation Noise Reference Book. Butterworth, London, UK.

Franks JH 1998 Preventing noise-induced hearing loss: A perspective view from the next millennium. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects '98.), Vol. 1, pp. 11-16. Noise Effects '98 PTY Ltd., Sydney, Australia..

Freeman K 1984 Mental Health and the Environment. Churchill Livingstone, London, UK.

French NR and Steinberg JC 1947 Factors governing the intelligibility of speech sounds. Journal of the Acoustical Society of America 19:90-119.

Gjestland T, Liasjo K, Granoien I, Fields JM 1990 Response to Noise Around Oslo Airport Fornebu. ELAB-RUNIT Report No. STF40 A90189, Trondheim, Norway.

Globus G, Friedmann J, Cohen H, Pearsons SK, Fidell S 1974 The effects of aircraft noise on sleep electrophysiology as recorded in the home. In: Noise as a Public Health Problem. US Environmental Protection Agency, Report EPA 550/9-73.008, pp. 587-591, Washington DC, USA.
Goldstein M 1994 Low-frequency components in complex noise and their perceived loudness and annoyance. Arbete & Haelsa 1994: 2 (Work and Health; Scientific Journal of the National Institute of Occupational Health, Solna, Sweden).
Gottlob D 1995 Regulations for community noise. Noise/News International, December 1995, pp.223-236.
Griefahn B 1977 Long-term exposure to noise. Aspects of adaptation, habituation and compensation. Waking and Sleeping, 1:383-386.
Griefahn B 1990a Präventivmedizinische Vorschläge für den nächtlichen Schallschutz [Proposal for protection against noise during night from the point of view of preventive medicine]. Zeitschrift für Lärmbekämpfung 37: 7-14.
Griefahn B 1990b Sleeping in noisy environments: effects, limits and preventative measures. In: JA Horne (ed) Sleep 1990, pp. 391-93, Pontenagel Press, Bochum, Germany.
Griefahn B, Mehnert P, Moehler U, Schuemer-Kohrs A, Schuemer R 1996 Design of a field study on the effects of railway noise and road traffic noise. In F.A. Hill and R. Lawrence (eds.) Inter Noise 96. Noise Control – The Next 25 Years, Book 4, pp. 2183-88. Institute of Acoustics, St Albans, UK.
Griefahn B, Deppe C, Mehnert P, Moog R, Moehler U, Schuemer R 1998 What nighttimes are adequate to prevent noise effects on sleep? In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 2, pp. 445-450. Noise Effects ’98 PTY Ltd., Sydney, Australia.
Griffiths ID 1983 Review of Community Response to Noise. In G. Rossi, (ed.), Noise as a Public Health Problem, Vol. 2, pp. 1031-1047. Milano, Italy: Centro Ricerche e Studi Amplifon.
Guski R 1987 Lärm–Wirkungen unerwünschter Geräusche. Huber, Bern, Switzerland.
Haines M, Stansfeld SA, Job RFS, Berglund B 1998 Chroinic aircraft noise exposure and child cognitive performance and stress. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 329-336. Noise Effects ’98 PTY Ltd., Sydney, Australia.
Hall FL, Birnie SE, Taylor SM, Palmer JE 1981 Direct Comparison of Community Response to Road Traffic Noise and to Aircraft Noise. Journal of the Acoustical Society of America 70: 1690-1698.
Hall FL, Taylor SM, Birnie SE 1985 Activity interference and noise annoyance. Journal of Sound and Vibration 103: 237-252.
Halpern D 1995 Mental Health and the Built Environment. More than Bricks and Mortar? Taylor and Francis Ltd, London, UK.
Hanner P and Axelsson A 1988 Acute acoustic trauma. Scandinavian Audiology 17: 57-63.
Harris CM 1991 Handbook of Acoustical Measurements and Noise Control. Mc Graw Hill, New York, USA.
Hasan S and Beg MHA 1994 Noise induced hearing loss in industrial workers of Karachi. Pakistan Journal of Otolaryngology 10: 200-205.
Hasan S and Zaidi SH 1997 The prevalence of noise induced hearing loss in industrial (textile) workers of Karachi. Thesis, University of Karachi, Karachi, Pakistan.

HCN 1994 Noise and Health. Publication No. 1994/15E, Health Council of the Netherlands, The Hague, Netherlands.
HCN 1997 Assessing noise exposure for public health purposes. Publication no. 1997/23E, Health Council of the Netherlands, Rijswijk, Netherlands.
Hede A 1998a Environmental noise regulation: A public policy perspective. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 2, pp. 687-96. Noise Effects ’98 PTY Ltd., Sydney, Australia.
Hede, A 1998b: Towards a normative model of public policy for environmental noise, Acoustics Australia, 26, 95-100.
Hellström PA, Dengerink HA, Axelsson A 1992 Noise levels from toys and recreational articles for children and teenagers. British Journal of Audiology, 26: 267-270.
Hetu Rand Fortin M 1995 Potential risk of hearing damage associated with exposure to highly amplified music. Journal of the American Academy of Audiology 6: 378-386.
Hobson JA 1989 Sleep. Scientific American Library, W.H. Freeman and Co, New York, NY, USA.
Holmes G, Singh B.R. and Theodore L. 1993. Handbook of environmental management and technology. Wiley, New York.
Horne JA, Pankhurst FL, Reyner LA, Hume K, Diamond ID 1994 A field study of sleep disturbance: Effects of aircraft noise and other factors on 5,742 nights of actimetrically monitored sleep in a large subject sample. Sleep 17: 146-159.
House ME 1987 Measurement and Prediction of Aircraft Noise. In P.M. Nelson (ed.) Transportation Noise Reference Book, Butterworth, London.
Houtgast T 1981 The Effect of Ambient Noise on Speech Intelligibility in Classrooms. Applied Acoustics 14: 15-25.
Houtgast T and Steeneken, HJM. 1983. Experimental verification of the STI: A valid basis for setting indoor noise level criteria. In G. Rossi (ed.), Noise as a Public Health Problem. Vol. 1, pp. 477-487, Centro Ricerche e Studi Amplifon, Milano, Italy.
Houtgast T and Steeneken JM 1985 A Review of the MTF Concept in Room Acoustics and Its Use for Estimating Speech Intelligibility in Auditoria. Journal of the Acoustical Society of America 77: 1069-1077.
Humes LE, Dirks DD, Bell TS, Ahlstrom C, Kincaid GE 1986 Application of the Artic-ulation Index and the Speech Transmission Index to the recognition of speech by normal-hearing and hearing-impaired listeners. Journal of Speech Hearing Research, 29:447-462.
Hygge S, Evans GW, Bullinger M 1996 The Munich airport noise study: Cognitive effects on children from before to after the change over of airports. In F.A. Hill and R. Lawrence (eds.) Inter Noise 96. Noise Control – The Next 25 Years, Vol. 5, pp. 2189-92. Institute of Acoustics, St Albans, UK.
Hygge S, Jones DM, Smith AP 1998 Recent developments in noise and performance. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 321-28, Noise Effects ’98 PTY Ltd., Sydney, Australia.
ICAO 1993 International Standards and Recommended Practices: Environmental Protection. Annex 16, Volume I: "Aircraft Noise". Annex 16 (Chapter 2 and 3) to the Convention on International Civil Aviation. International Civil Aviation Organization, [Air Navigation (Noise Certification) Order 1990 -Statutory Instrument 1514], Montreal, Canada.
IEC 1979 Sound Level Meters. IEC Publication 651, International Electrotechnical Commission, Geneva, Switzerland.

IEC 1988 Sound system equipment, part 16: The objective rating of speech intelligibility in auditoria by the RASTI method. IEC Publication 268-/6, International Electrotechnical Commission, Geneva, Switzerland.

IEH 1997. The Non-Auditory Effects of Noise. IEH Report R10, Institute for Environment and Health, Leicester, UK.

Irle M 1975 Is aircraft noise harming people? In M. Deutsch and H.A. Hornstein (eds.), Applying Social Psychology, pp. 115-138, Erlbaum, Hillsdale, NJ. USA.

Ising H and Günther T 1997 Interaction between noise-induced stress and magnesium losses: relevance for long-term health effects. In F. Augustinovicz (ed.), Inter Noise 97. Help Quiet the World for a Higher Quality Life, Vol. 2, pp. 1099-1104. Noise Control Foundation, Poughkeepsie, NY, USA.

Ising H, Babisch W, Kruppa B 1998 Acute and chronic noise stress as cardiovascular risk factors. Federal Environmental Agency, Berlin, Germany.

Ising H, Babisch W, Gandert J, Scheuermann B 1988 Hörschäden bei jugendlichen Berufs-anfängern aufgrund von Freizeitlärm und Musik. Zeitschrift für Lärmbekämpfung, 35:35-41.

Ising H, Hanel J, Pilgramm M et al. 1994 Gehörschadensrisiko durch Musikhören mit Kopfhörern. Hals-Nasen-Ohren 1994; 42:764-8.

ISO 1975a Acoustics-Method for Calculating Loudness Level. ISO-532-1975 (E), International Organization for Standardization, Geneva, Switzerland.

ISO 1975b Acoustics-Preferred Frequencies for Measurements. International Standard ISO 266-1975 (E), International Organization for Standardization, Geneva, Switzerland

ISO 1978 Laboratory Measurement of Airborne Sound Insulation of Building Elements – Part V, Field Measurements of Airborne Sound Insulation of Façade Elements and Facades", International Standard ISO-140/V, International Organization for Standardization, Geneva, Switzerland.

ISO 1982 Acoustics – Description and measurement of environmental noise – Part 1: Basic quantities and procedures. International Standard ISO 1996-1, International Organization for Standardization, Geneva, Switzerland.

ISO 1987a Acoustics-Normal Equal Loudness Contours. International Standard ISO 226-1-1987 (E), International Organization for Standardization, Geneva, Switzerland.

ISO 1987b Acoustics – Description and measurement of environmental noise – Part 3: Application to noise limits. International Standard ISO 1996-3:1987(E), International Organization for Standardization, Geneva, Switzerland.

ISO 1990 Acoustics–Determination of occupational noise exposure and estimation of noise-induced hearing impairment. International Standard ISO 1999, International Organization for Standardization, Geneva, Switzerland.

ISO 1994 Quality systems -- Model for quality assurance in production, installation and servicing. International Standard ISO 9002, International Organization for Standardization, Geneva, Switzerland.

ISO 1995 Laboratory Measurement of Airborne Sound Insulation of Building Elements – Part III: Laboratory Measurements of Airborne Sound Insulation of Building Elements. International Standard ISO-140/III, International Organization for Standardization, Geneva, Switzerland .

ISO 1996a Acoustics – Rating of Sound Insulation in Buildings and of Building Elements – Part 1: Airborne Sound Insulation. International Standard ISO 717-1, International Organization for Standardization, Geneva, Switzerland.

ISO 1996b Environmental management systems - specification with guidance for use. International Standard ISO 14001, International Organization for Standardization, Geneva, Switzerland.

ISO 1996c Environmental management systems - general guidelines on principles, systems and supporting techniques. International Standard ISO 14004, International Organization for Standardization, Geneva, Switzerland.

ISO 1998 Measurement of Sound Insulation In Buildings and of Building Elements – Part VI: Laboratory Measurements of impact sound insulation of floors. International Standard ISO-140/VI, International Organization for Standardization, Geneva, Switzerland.

Jansen G 1986 Zur “erheblichen Belästigung” und “Gefährdung” durch Lärm. Zeitschrift für Lärmbekämpfung 33:2-7.

Jansen G 1987 Verkehrslärmwirkungen bei besonderen Personengruppen. Zeitschrift für Lärmbekämpfung 34: 152-156.

Jansen G 1998 Health concepts and noise effects. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 2, pp. 697-702. Noise Effects ’98 PTY Ltd., Sydney, Australia.

Jansen G and Gottlob D 1996 Requirements for the protection against outdoor noise in various countries with respect to standardization and regulations. In F.A. Hill and R. Lawrence (eds.) Inter Noise 96. Noise Control – The Next 25 Years, Book 6, pp. 3343-3346. Institute of Acoustics, St Albans, UK.

Jenkins LM, Tarnopolsky A, Hand DJ 1981 Psychiatric admissions and aircraft noise from London Airport: Four-year, three hospitals' study. Psychological Medicine 11: 765-782.

Job RFS 1988 Community response to noise: A review of factors influencing the relationship between noise exposure and reaction. Journal of the Acoustical Society of America 83: 991-1001.

Job RFS 1993 Psychological factors of community reaction to noise. In M. Vallet (ed.) Noise as a Public Health Problem, Vol. 3, pp. 48-59, INRETS - Institut National de REcherche sur les Transports et leur Sécurité, Arcueil, France.

Job RFS 1996 The influence of subjective reactions to noise on health effects of the noise. Environment International 22: 93-104.

Kabuto M and Suzuki S 1976 A trial measurement of individual noise exposure by time-zone in a day. Japanese Journal of Industrial Health, 18: 17-22.

Kabuto M, Ohtsuka R, Suzuki S 1978 Measurement and evaluation of individual noise exposure level of Tokyo metropolitan commuters in railroad cars above ground and in subways. Japanese Journal of Public Health, 2: 59-63.

Kageyama T, Kabuto M, Nitta H, Kurokawa Y, Taira K, Suzuki S, Takemoto T 1997 A populations study on risk factors for insomnia among adult Japanese women: A possible effect of road traffic volume. Sleep 20: 963-971.

Kastka J, Buchta E, Ritterstaedt U, Paulsen R, Mau U 1995 The long term effect of noise protection barriers on the annoyance response of residents. Journal of Sound and Vibration, 184: 823-852.

Katz J. (ed.) 1994 Handbook of Clinical Audiology. Fourth edition, Williams and Wilkins Baltimore, ML, USA.

Kerry G, Lomax C, and James DJ 1997 Assessment and Relevance of methods for calculating onset rate of low altitude flight noise. In F. Augustinovicz (ed.), Inter Noise 97. Help Quiet the World for a Higher Quality Life, vol. 3, pp. 1227-30. Noise Control Foundation, Poughkeepsie, NY, USA.

Kjellberg A, Goldstein M, and Gamberale F 1984 An Assessment of dBA for Predicting Loudness and Annoyance of Noise Containing Low Frequency Components. Journal of Low Frequency Noise and Vibration 3: 10-16.

Klæboe R, Kolbenstvedt M, Lercher P, and Solberg S 1998 Changes in noise reactions– Evidence for an area-effect? In V.C. Goodwin and D.C. Stevenson (eds.) Inter Noise 98. Sound and Silence: Setting the Balance, Vol. 2, pp. 1133-36. New Zealand Acoustical Society, Auckland, New Zealand.

Koelega HS (ed.) 1987 Environmental Annoyance: Characterization, Measurement, and Control. Elsevier, Amsterdam, Netherlands.

Kremer L 1950 Die Wissenschaftliche Grundlagen der Raumakustik. Band III, Hirzel Verlag, Leipzig

Kryter KD 1959 Scaling Human Reaction to the Sound from Aircraft. Journal of the Acoustical Society of America 31: 1415-1429.

Kryter KD 1994 The Handbook of Noise and Hearing. Academic Press, San Diego, CA, USA.

Kutscheidt E 1989 Rechtsprobleme bei der Bewertung von Geräuschimmissionen. Neue Zeitschrift für Verwaltungsrecht 3:193-199.

Kuwano S, Namba S, and Mizunami T 1998 The effect of noise on the effort to sleep. In V.C. Goodwin and D.C. Stevenson (eds.) Inter Noise 98. Sound and Silence: Setting the Balance, Vol. 2, pp. 1083-1086. New Zealand Acoustical Society, Auckland, New Zealand.

Lara Sáenz A and Stephens RWB (eds.) 1986 Noise Pollution. Wiley, Chichester, UK.

Lambert J and Vallet M 1994 Study Related to the Preparation of a Communication on a Future EC Noise Policy. INRETS LRN Report No. 9420, INRETS - Institut National de REcherche sur les Transports et leur Sécurité, Bron, France.

Lang J 1986 Assessment of noise impact on the urban environment, A study on noise prediction models, Environmental Health Series 9, Regional Office for Europe, World Health Organization, Copenhagen, Denmark.

Lang J 1995 Noise abatement regulations and strategies. In: Noise - Selected presentations of an Informal Regional Consultation Meeting on Noise Pollution, 2-5 September 1991, Amman, Jordan, Eastern Mediterranean Regional Office, Regional Centre for Environmental Health Activities (CEHA), Amman, Jordan.

Lang WW 1999 Is noise policy a global issue, or is it a local issue? In: J. Cuschieri, S. Glegg, Yan Yong (eds.) Internoise 99 – The 1999 International Congress on Noise Control Engineering, 6-8 December 1999, Fort Lauderdale, Florida, USA, pp. 1939-1943.

Large JB and House ME 1989 The effect on aviation noise of the single European market. In G.C. Maling, Jr. (ed.), Inter-Noise 89, Vol. 1, pp. 695-700, Noise Control Foundation, Poughkeepsie, NY, USA.

Lazarus H 1990 New methods for describing and assessing direct speech communication under disturbing conditions. Environment Inernational 16: 373-392.

Lazarus H 1998 Noise and communication: The present state. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 157-162. Noise Effects ’98 PTY Ltd., Sydney, Australia.

Lercher P 1996 Environmental noise and health: An integrated research perspective. Environment International 22: 117-129.

Lercher P 1998a Context and coping as moderators of potential health effects in noise-exposed persons. In D. Prasher and L. Luxon, (Eds.), Advances in Noise Series. Vol. I: Biological Effects, pp. 328-335, Whurr Publishers, London, UK.

Lercher P 1998b Deviant dose-response curves for traffic noise in “sensitive areas”? In V.C. Goodwin and D.C. Stevenson (eds.) Inter Noise 98. Sound and Silence: Setting the Balance, Vol. 2, pp. 1141-1144. New Zealand Acoustical Society, Auckland, New Zealand.

Lercher P, Stansfeld SA, Thompson SJ 1998 Non-auditory health effects of noise: Review of the 1993-1998 period. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 213-220. Noise Effects ’98 PTY Ltd., Sydney, Australia.

Lindemann HE, van der Klaauw MM, Platenburg-Gits FA 1987 Hearing acuity in male adolescents at the age of 17 – 23 years. Audiology 26: 65-78.

Lindvall T and Radford EP (eds.) 1973 Measurement of annoyance due to exposure to environmental factors. Environmental Research 6:1-36.

London Charter 1999 Charter on Transport, Environment and Health. Final version prepared following the Fourth Preparatory Meeting on “Transport, enviroment and Health, Vienna, 15-17 March 1999. EUR/ICP/EHCO 02 02 05/9 Rev.4 - 09009 – 16 June 1999. Regional Office for Europe, European Centre for Environment and Health, Rome Division, World Health Organization, Rome, Italy. Internet address: http://www.who.it/london_conference/teh.htm.

Lutman ME and Haggard MP (eds.) 1983 Hearing Science and Hearing Disorders. Academic Press, London, UK.

Mage, D and Walsh, M 1998: Case studies from cities around the world. In: Urban Traffic Pollution, eds. D. Schwela and O. Zali, E & Spon, London, UK.

Maschke C 1992 Der Einfluss von Nachtlärm auf den Schlafverlauf und die Katecholaminenausscheidung. Technische Universität, Berlin, Germany.

Maschke C, Arndt D, Ising H, et al. 1995 Nachtfluglärmwirkungen auf Anwohner. DFG-Forschungsbericht Gr. 452/8-2. Gustav Fischer Verlag, Stuttgart, Germany.

Miedema HME 1987 Annoyance from Combined Noise Sources. In H. S. Koelega (ed.), Environmental Annoyance: Characterization, Measurement and Control, pp. 313-320, Elsevier, Amsterdam, The Netherlands.

Miedema HME 1993 Response Functions for Environmental Noise. In M. Vallet (ed.) Noise as a Public Health Problem, Vol. 3, pp. 428-433, INRETS - Institut National de Recherche sur les Transports et leur Sécurité, Arcueil Cedex, France.

Miedema HME 1996 Quantification of Annoyance Caused by Environmental Noise and Odor. TNO, Leiden, Netherlands.

Miedema HME, Vos H 1998 Exposure response functions for transportation noise. Journal of the Acoustical Society of America 104: 3432-3445.

Miller JD 1978 General psychological and sociological effects of noise. In E.C. Carterette and M.P. Friedman (eds.), Handbook of Perception. Vol. VI: Hearing (pp. 641-676). Academic Press, New York NZ, USA.

Moehler U Community response to railway noise: A review of social surveys. Journal of Sound and Vibration 120: 321-332.

Molino JA 1974 Equal aversion levels for pure tones and 1/3 octave bands of noise. Journal of the Acoustical Society of America 55: 1285-1289.

National Environment Board of Thailand 1990 Air and noise pollution in Thailand 1989, Bangkok.

NRC-CNRC 1994 NEF Validation Study. (2) Review of Aircraft Noise and its Effects. Contract Report A-1505.5 (Final). Institute for Research in Construction, Ottawa, Canada.
OECD 1991 Fighting Noise in the 1990's. Organisation for Economic Co-operation and Development, Paris, France.
OECD 1993 Environmental Data Compendium. Organisation for Economic Co-operation and Development, Paris, France.
OECD-ECMT. 1995. Urban Travel and Sustainable Development. European Conference of Ministers of Transport, Organisation for Economic Co-operation and Development, Paris, France.
Öhrström E 1993a Research on noise and sleep since 1988: Present state. In M. Vallet (ed.), Noise as a Public Health Problem, Vol. 3, pp. 331-338, INRETS - Institut National de REcherche sur les Transports et leur Sécurité, Arcueil, France.
Öhrström, E. 1993b. Effects of low levels of road traffic noise during night. . In M. Vallet (ed.), Noise as a Public Health Problem, Vol. 3, pp. 359-366, INRETS - Institut National de REcherche sur les Transports et leur Sécurité, Arcueil, France.
Öhrström E 1997 Effects of exposure to railway noise–A comparison between areas with and without vibration. Journal of Sound and Vibration 205, 555-560.
Öhrström E, Björkman M 1988 Effects of noise-disturbed sleep–A laboratory study on habituation and subjective noise sensitivity. Journal of Sound and Vibration 122: 277-290.
Öhrström E, Skånberg AB1996 A field survey on effects of exposure to noise and vibrations from railway traffic. Part I: Annoyance and activity disturbance effects. Journal of Sound and Vibration 193: 39-47.
Ollerhead JB, Jones CJ, Cadoux RE, Woodley A, Atkinson BJ, Horne JA, Pankhurst F, Reyner L, Hume KI, Van F, Watson A, Diamond I, Egger P, Holmes D, McKean J 1992 Report of a Field Study of Aircraft Noise and Sleep Disturbance. Department of Transport, London, UK.
Pankhurst FL and Horne JA 1994 The influence of bed partners on movement during sleep. Sleep 17: 308-315.
Passchier-Vermeer W 1991 Noise from toys and the hearing of children. NIPG-TNO Report 91.032, TNO Institute of Preventive Health Care, Leiden, Netherlands.
Passchier-Vermeer W 1993 Noise and Health. The Hague: Health Council of the Netherlands. [Publication No A93/02E, review prepared by TNO Institute of Preventive Health Care, Leiden]
Passchier-Vermeer W 1994 Sleep disturbance due to night-time aircraft noise. Leiden: TNO-PG Report 94.077, TNO Institute of Preventive Health Care, Leiden, Netherlands.
Passchier-Vermeer, W 1996. Effects of noise and health. Chapter 3 of a report on Noise and Health prepared by a committee of the Health Council of The Netherlands. Noise/News International: 137-150.
Passchier-Vermeer W and Rövekamp AJM 1985 Verband tussen gehoorschade en de sociale handicap door een verminderd hoorvermogen bij groepen personen die tijdens hun werk aan lawaai zijn geëxponeerd. In: Passchier-Vermeer W, et al. Preventie gehoorschade door lawaai.Voordrachten ter gelegenheid van het 10-jarig jubileum van NVBA, pp.185-202. NIPG-TNO Institute of Preventive Health Care, Leiden, Netherlands.
Passchier-Vermeer W and Zeichart K Vibrations in the living environment. TNO-PG Report 98.030, TNO Institute of Preventive Health Care, Leiden, Netherlands.
Passchier-Vermeer W, Vos H, Steenbekkers JHM 1998 Popmusic through headphones and hearing loss. Report 98.036, TNO Institute of Preventive Health Care, Leiden, Netherlands.

Paulsen R and Kastka J 1995 Effects of combined noise and vibration on annoyance. Journal of Sound and Vibration 181: 295-314.
Pearsons KS 1998 Awakening and motility effects of aircraft noise. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 2, pp. 427-32. Noise Effects ’98 PTY Ltd., Sydney, Australia.
Pearsons KS, Barber DS, Tabachnick BG, Fidell S 1995 Predicting noise-induced sleep disturbance. Journal of the Acoustic Society of America 97: 331-338.
Pearsons KS 1996 Recent field studies in the United States involving the disturbance of sleep from aircraft noise. In F.A. Hill and R. Lawrence (eds.) Inter Noise 96. Noise Control – The Next 25 Years, Book 5, pp. 2271-2276. Institute of Acoustics, St. Albans, UK.
Persson K and Björkman M 1988 Annoyance due to Low Frequency Noise and the Use of the dBA Scale. Journal of Sound and Vibration 127: 491-497.
Plomp R 1986 A signal to noise ratio model for the speech-reception threshold of the hearing impaired. Journal of Speech and Hearing Research 29: 146-152.
Prasanchuk S (1997) Noise pollution. Its effect on health and hearing – Thailand as a case study. Presentation at the PDH Informal Consultation on the Prevention of Noise-induced Hearing Loss, 28-30 October 1997, WHO/PDH/98.5. World Health Organization, Geneva.
Razi MS, Jafer S, Hillier V, Zaidi SH, Newton V 1995 Causes of bilateral hearing loss in school children. Pakistan Journal of Otolaryngology 11: 68-86.
Reyner LA and Horne JA 1995 Gender- and age-related differences in sleep determined by home-recorded sleep logs and actimetry from 400 adults. Sleep 18: 127-134.
Ronnebaum T Schulte-Fortkamp B Weber R 1996 Synergetic effects of noise from different sources: a literature study. In F.A. Hill and R. Lawrence (eds.), Inter Noise 96. Noise Control – – The Next 25 Years, Vol. 6, pp. 2241-2246. Institute of Acoustics, St. Albans, UK.
SABS 1994 Code of practice for the measurement and rating of environmental noise with respect to annoyance and speech communication (third revision). South African Bureau of Standards publication No. 0103, Pretoria, South Africa.
SABS 1996 Code of practice for calculating and predicting road traffic noise. South African Bureau of Standards publication No. 0210, Pretoria, South Africa.
SABS 1998 Code of practice for methods for environmental noise impact assessments. South African Bureau of Standards publication No. 0328, Pretoria, South Africa.
Salter L 1988 Mandated Science: Science and Scientists in the Making of Standards. Kluwer, Dordrecht, Netherlands.
Sandberg U (ed.) 1995 The effects of regulations on road vehicle noise. Report by the International Institute of Noise Control Engineering Working Party, Noise News International 6: 85-113.
Sandberg U 1999 Abatement of traffic, vehicle and tire/road noise – the global perspective. In: J. Cuschieri, S. Glegg, Yan Yong (eds.) Internoise 99 – The 1999 International Congress on Noise Control Engineering, 6-8 December 1999, Fort Lauderdale, Florida, USA, pp. 37-42.
Sargent JW and Fothergill LC 1993 The noise climate around our homes. Information Paper 21/93, Building Research Establishment, Garston, UK.
Scharf B 1970 Critical bands. In J.V.Tobias (ed.), Foundations of Modern Auditory Theory, Vol. 1, pp. 157-202. Academic Press, New York, NY, USA.
Scharf B and Hellman R 1980 How Best to Predict Human Response to Noise on the Basis of Acoustic Variables. In J.V. Tobias, G. Jansen andW.D. Ward (eds.) Noise as a Public Health Problem, ASHA Report no. 10, pp. 475-487, Rockville, ML, USA.

Schulz TJ 1978 Synthesis of Social Surveys on noise annoyance. Journal of the Acoustical Society of America, 64: 377-405.

Schwela D 1998. WHO Guidelines on Community Noise. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 2, pp. 475-480. Noise Effects ’98 PTY Ltd., Sydney, Australia.

Smith AW 1998 The World Health Organisation and the prevention of deafness and hearing impairment caused by noise. Noise and Health 1: 6-12.

Smith AP 1990 Noise, performance efficiency and safety. International Archive of Occupational and Environmental Health 62: 1-5.

Smoorenburg GF 1998 Effects of impulse noise on man. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects ’98), Vol. 1, pp. 1-10, Noise Effects ’98 PTY Ltd., Sydney, Australia.

Smoorenburg GF and Goldstein-Brouwers WG 1986 Spreaakverstaan in relatie tot het toonaudiogram bij slechthorendheid ten gevolge van lawaai. IZF-TNO Report 1986 C-17, Soesterberg, Netherlands.

Stanners D and Bordeau P (Eds.) 1995 Europe’s Environment the Dobris Assessment. Noise and radiation, pp.359-374, European Environment Agency, Copenhagen, Denmark.

Stansfeld SA 1992 Noise, noise sensitivity and psychiatric disorder: Epidemiological and psychological studies. Psychological Mededicine, Monograph Suppl. 22, Cambridge University Press, Cambridge, UK.

Stansfeld SA, Gallacher J, Babisch W, Shipley S 1996. Road traffic noise and psychiatric disorder: prospective findings from the Caerphilly Study. British Medical Journal 313: 266-267.

Stevens SS 1972 Perceived level of noise by Mark VII and decibels (E). Journal of the Acoustical Society of America 51: 575-601.

Struwe F, Jansen G, Schwarze S, Schwenzer C, Nitzsche M 1996 Untersuchung von Hörgewohn-heiten und möglichen Gehörrisiken durch Schalleinwirkungen in der Freizeit unter beson-derer Berücksichtigung des Walkman-Hörens. Düsseldorf: Institut für Arbeitsmedizin der Heinrich-Heine-Universität. In B. Babissch , G. Bambach, H. Ising, B. Kruppa, P. Plath, E. Rebentisch, F. Struwe Gehörgefährdung durch laute Musik und Freizeitlärm, pp. 44 - 154. Institut für Wasser-, Boden- und Lufthygiene des Umweltbundesamtes, Berlin, Germany.

Tafalla RJ and Evans GW 1997 Noise, physiology and human performance: The potential role of effort. Journal of Occupational Health Psychology 2: 148-155.

Tempest W (ed.) 1985 The Noise Handbook. Academic Press, London, UK.

ten Wolde T 1998 European Commission’s future noise policy. In V.C. Goodwin and D.C. Stevenson (eds.) Inter Noise 98. Sound and Silence: Setting the Balance, Vol. 3, pp. 1719-1722. New Zealand Acoustical Society, Auckland, New Zealand.

Thiessen GJ 1978 Disturbance oif sleep by noise. Journal of the Acoustical Society of America, 64: 216-222.

Thompson SJ 1996 Non-auditory health effects of noise: an updated review. In F.A Hill and R. Lawrence (eds.) Inter Noise 96. Noise Control – The Next 25 Years, Vol. 4, pp. 2177-2182. Institute of Acoustics, St. Albans, UK.

UNCED 1992 Agenda 21. United Nations Conference on Environment and Development, Conches, Switzerland.

US EPA. 1974. Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. Report EPA 550/9-74.004, US Environmental Protection Agency, Washington DC, USA.

Vallet M 1996 Charactéristiques et indicateurs de la gene due au bruit des avions. Synthèse. INRETS LRN Report No. 29, Institut National de REcherche sur les Transports et leur Sécurité, Arcueil, France.

Vallet M 1998 Sleep disturbance by noise: Recent orientations. In N.L. Carter and R.F.S. Job (eds.) Noise as a Public Health Problem (Noise Effects '98),, Vol. 2, pp. 421-26, Noise Effects '98 PTY Ltd., Sydney, Australia.

Vallet M and Vernet I 1991 Night aircraft noise index and sleep research results. In A. Lawrence (ed.), Inter-Noise 91. The Cost of Noise, Vol. 1, pp. 207-210. Noise Control Foundation, Poughkeepsie, NY, USA.

Vallet M, Gagneux J-M, Clairet JM, Laurens JF, Letisserand D 1983 Heart rate reactivity to aircraft noise after a long-term exposure. In G. Rossi (ed.), Noise as a Public Health Problem, Vol. 2, pp. 965-971, Centro Richerche e Studi Amplifon, Milano, Italy.

van den Berg M 1996 Noise management in the Netherlands. Noise and Vibration, September 1996, 11-12.

van Hees O 1992 Gehoorafwijkingen bij beroepsmusici. Thesis, GUA, Amsterdam, Netherlands.

Vaskor JG, Dickinson SM, Bradley JS 1979 Effect of Sampling on the Statistical Descriptors of Traffic Noise. Applied Acoustics 12: 111-124.

Vernon JA, Moller AR (Eds.) 1995 Mechanisms of Tinnitus. Allyn and Bacon, Needham Heights, Ma, USA.

von Gierke HE 1975 Noise – How Much is Too Much? Noise Control Engineering Journal 5: 24-34.

von Gierke HE and Harris CS 1987 Annoyance Response to Military Flight Operations and the Development of Standard Criteria for Community Annoyance. In H.S. Koelega (ed.), Environmental Annoyance, Characterization, Measurement and Control, pp. 257-269, Elsevier, Amsterdam, The Netherlands.

Vos, J 1992 Annoyance caused by simultaneous impulse, road-traffic and aircraft sounds: a quantitative model. Journal of the Acoustical Society of America 91: 3330-45.

Vos J 1996 Annoyance caused by impulse sounds produced by small, medium-large, and large firearms. In F.A Hill and R. Lawrence (eds.) Inter-Noise 96. Noise Control – The Next 25 Years, Book 5, pp. 2231-36. Institute of Acoustics, St. Albans, UK.

Warren CHE 1972 The sonic boom exposure effects 1.2: The sonic boom–generation and propagation. Journal of Sound and Vibration 20: 485-497.

WCED 1987 Our Common Future. World Commission on Environment and Development The Brundtland Commission, Oxford University Press, Oxford UK.

Westman JC and Walters JR 1981 Noise and stress. A comprehensive approach. Environmental Health Perspectives 41: 291-309.

WHO 1980a Noise. Environmental Health Criteria Document No. 12. World Health Organization, Geneva, Switzerland.

WHO 1980b. Glossary on Air Pollution. WHO Regional Office of Europe, Series No. 9, World Health Organization, Copenhagen, Denmark.

WHO 1993 The Environmental Health Criteria Document on Community Noise. Report on the Task Force Meeting, Düsseldorf, Germany, 24-28 November 1992. WHO Regional Office for Europe, Report EUR/HFA Target 24, World Health Organization, Copenhagen, Denmark.

WHO 1994 Assessing human health risks of chemicals: Derivation of guidance values for health-based exposure limits. Environmental Health Criteria No. 170, World Health Organization, Geneva, Switzerland.

WHO 1995a Concern for Europe's Tomorrow – Health and the Environment in the WHO European Region. WHO European Centre for Environment and Health. Wissenschaftliche Verlagsgesellschaft, Stuttgart, Germany.

WHO 1995b Noise - Selected presentations of an Informal Regional Consultation Meeting on Noise Pollution, 2-5 September 1991, Amman, Jordan, Eastern Mediterranean Regional Office, Regional Centre for Environmental Health Activities (CEHA), Amman, Jordan.

WHO 1998 Air Management Information System. AMIS CD ROM, 2nd edition. World Health Organization, Geneva, Switzerland.

Zaidi SH 1998 Current status and future trends of deafness and hearing impairment in the Tropics. Pakistan Journal of Otolaryngology 14: 38-45.

Zaidi SH 1999 An epidemiological study of hearing impairment in the Himalayan territories of Pakistan. Hearing International Newsletter 8: 1-4.

Zeichart K 1998 Kombintorische Wirkungen von Bahnlärm und Bahnerschütterungen. Zeitschrift für Lärmbekämpfung 45: 7-16.

Zwicker E 1960 Ein Verfahren zur Berechnung der Lautstärke. Acustica 10: 304-308.

Zwicker E 1989 On the dependence of unbiased annoyance on loudness. In G. Maling Jr. (ed.) Inter Noise 89, Vol. 2, pp. 809-14. Noise Control Foundation, Poughkeepsie, NY, USA. .

Appendix 2 : Examples Of Regional Noise Situations

REGION OF THE AMERICAS

Latin America (Guillermo Fuchs, Argentina).

As more and more cities in Latin America surpass the 20 million inhabitants mark, the noise pollution situation will continue to deteriorate. Most noise pollution in Latin American cities comes from traffic, industry, domestic situations and from the community. Traffic is the main source of outdoor noise in most big cities. The increase in automobile engine power and lack of adequate silencing results in LAeq street levels >70 dB, above acceptable limits. Vehicle noise has strong low-frequency peaks at ~13 Hz, and at driving speeds of 100 Km/h noise levels can exceed 100 dB. The low-frequency (LF) noise is aerodynamic in origin produced, for example, by driving with the car windows open. Little can be done to mitigate these low-frequency noises, except to drive with all the windows closed. Noise exposure due to leisure activities such as carting, motor racing and Walkman use is also growing at a fast rate. Walkman use in the street not only contributes to temporary threshold shifts (TTS) in hearing, but also endangers the user because they may not hear warning signals Construction sites, pavement repairs and advertisements also contribute to street noise, and noise levels of 85–100 dB are common.

The Centro de Investigaciones Acústicas y Luminotécnicas (CIAL) in Córdoba, Argentina has investigated noise pollution in both the field and in the laboratory. The most noticeable effect of excessive urban noise is hearing impairment, but other psychophysiological effects also result. For example, tinnitus resulting from sudden or continuous noise bursts, can produce a TTS of 20–30 dB, and prolonged exposures can result in permanent threshold shifts (PTS). By analyzing sound spectra down to a few Hertz, and at levels of up to 120 dB, discrete frequencies and bands of infrasound were found which damage hearing. With LF sounds at levels of 120 dB, TTS resulted after brief exposure, and PTS after only 30 min of exposure. The effects of noise on hearing can be especially detrimental to children in schools located downtown. Field studies in Córdoba city schools located near streets with high traffic density showed that speech intelligibility was dramatically degraded in classrooms that did not meet international acoustical standards. This is a particularly worrying problem for the younger students, who are in the process of language acquisition, and interferes with their learning process.

In general, community noise in Latin America remains above accepted limits. Particularly at night, sleep and rest are affected by transient noise signals from electronically amplified sounds, music and propaganda. Field research was carried out in four zones of Buenos Aires, to determine the effects of urban noise on the well-being, health and activities of the inhabitants. The effects of confounding variables were taken into consideration. It was concluded that night-time noise levels in downtown Buenos Aires were barely lower than daytime levels. The results showed that sleep, concentration, communication and well-being were affected in most people when noise levels exceeded those permitted by international laws. The reactions of the inhabitants to protect themselves from the effects of noise varied, and included changing rooms, closing windows and complaining to authorities.

Individual responses to noise also vary, and depend on factors such as social, educational and economic levels, individual sensibility, attitudes towards noise, satisfaction with home or neighborhood, and cognitive and affective parameters. For example, at CIAL, two pilot studies were carried out with a group of adolescents to determine the influence of environmental conditions on the perception of noise. When music was played at very high sound levels (with sound peaks of 119 dBA) in a discotheque, judged to be a pleasant environment, the subjects showed less TTS than when exposed to the same music in the laboratory, which was considered to be an unpleasant environment.

At the municipal level Argentinean Ordinances consider two types of noises: unnecessary and excessive. Unnecessary noises are forbidden. Excessive noises are classified according to neighboring activities and are limited by maximum levels allowed for daytime (7 am to 10 pm) and night-time (10 pm to 7 am). This regulation has been relatively successful, but control has to be continuous. Similar actions have been prescribed at the provincial level in many cities of Argentina and Latin America. Control efforts aimed at reducing noise levels from individual vehicles are showing reasonably good improvements. However, many efforts of municipal authorities to mitigate noise pollution have failed because of economic, political and other pressures. For example, although noise control for automobiles has shown some improvement, efforts have been counteracted by the growth in the number and power of automobiles.

CIAL has designed both static and dynamic tests that can be used to set annual noise control limits. For roads and freeways where permitted speeds are above 80 Km/h, CIAL has also designed barriers which protect buildings lining the freeways. Considerable improvements have been obtained using these barriers with noise reductions of over 20 dB at buildings fronts. The most common types of barrier are concrete slabs or wooden structures, made translucent or covered with vegetation. Planted vegetation does not act as an efficient noise shield for freeway noise, except in cases of thick forest strips. In several cities, CIAL also designed ring roads to avoid heavy traffic along sensitive areas such as hospitals, schools and laboratories.

Efforts have not been successful in reducing the noise pollution from popular sports such as carting, motorboating and motocross, where noise levels can exceed 100 dB. In part, this is because individuals do not believe these activities can result in hearing impairment or have other detrimental effects, in spite of the scientific evidence. Argentinean and other Latin American authorities also have not been successful in reducing the sound levels from music centres, such as discotheques, where sound levels can exceed 100 dB between 11 pm and 6 am. However, public protest is increasing and municipal authorities have been applying some control. For instance, in big cities, discotheque owners and others are beginning to seek advice on how to isolate their businesses from apartment buildings and residential areas. Some improvements have been observed, but accepted limits have not yet been generally attained.

United States of America (Larry Finegold)

Noise Exposure.

In the United States, there have only been a few major attempts to describe broad environmental noise exposures. Early estimates for the average daily exposure of various population groups were reported in the U.S. Environmental Protection Agency's *Levels Document* (US EPA 1974), but these were only partially verified by subsequent large-scale measurements. Another EPA publication the same year provided estimates of the national population distribution as a function of outdoor noise level, and established population density as the primary predictor of a community's noise exposure (Galloway et al. 1974). Methodological issues that need be considered when measuring community noise, including both temporal and geographic sampling techniques, have been addressed by Eldred (1975). This paper also provided early quantitative estimates of noise exposure at a variety of sites, from an isolated spot on the North rim of the Grand Canyon to a spot in downtown Harlem in New York City. Another nationwide survey focused on exposure to everyday urban noises, rather than the more traditional approach of measuring exposure to high-level transportation noise from aircraft, traffic and rail (Fidell 1978). This study included noise exposure and human response data from over 2 000 participants at 24 sites.

A comprehensive report, *Noise In America: The Extent of the Problem,* included estimates of occupational noise exposure in the US in standard industrial classification categories (Bolt, Beranek & Newman, Inc. 1981). A more recent paper reviewed the long-term trends of noise exposure in the US and its impact over a 30-year time span, starting in the early 1970's. The focus was primarily on motor vehicle and aircraft noise, and the prediction was for steadily decreasing population-weighted day-night sound exposure (Eldred 1988). However, it remains to be seen whether the technological improvements in noise emission, such as changing from Chapter 2 to Chapter 3 aircraft, will be offset in the long run by the larger carriers and increased operations levels that are forecast for all transportation modes. Although never implemented in its entirety, a comprehensive plan for measuring community environmental noise and associated human responses was proposed over 25 years ago in the US (Sutherland et al. 1973).

Environmental Noise Policy in the United States

One of the first major breakthroughs in developing an environmental noise policy in the United States occurred in 1969 with the adoption of the National Environmental Policy Act (NEPA). This Congressional Act mandated that the environmental effects of any major development project be assessed if federal funds were involved in the project. Through the Noise Control Act (NCA) of 1972, the U.S. Congress directed the US Environmental Protection Agency (EPA) to publish scientific information about the kind and extent of all identifiable effects of different qualities and quantities of noise. The US EPA was also requested to define acceptable noise levels under various conditions that would protect the public health and welfare with an adequate margin of safety. To accomplish this objective, the 1974 US EPA *Levels Document* formally introduced prescribed noise descriptors and prescribed levels of environmental noise exposure. Along with its companion document, *Guidelines for Preparing Environmental Impact Statements on Noise,* which was published by the U.S. National Research Council in 1977, the

Levels Document has been the mainstay of U.S. environmental noise policy for nearly a quarter of a century. These documents were supplemented by additional Public Laws, Presidential Executive Orders, and many-tiered noise exposure guidelines, regulations, and Standards. Important examples include *Guidelines for Considering Noise in Land Use Planning and Control*, published in 1980 by the US Federal Interagency Committee on Urban Noise; and *Guidelines for Noise Impact Analysis*, published in 1982 by the US EPA.

One of the distinctive features of the US EPA *Levels Document* is that it does not establish regulatory goals. This is because the noise exposure levels identified in this document were determined by a negotiated scientific consensus and were chosen without concern for their economic and technological feasibility; they also included an additional margin of safety. For these reasons, an A-weighted Day-Night Average Sound Level (DNL) of 55 dB was selected in the *Levels Document* as that required to totally protect against outdoor activity interference and annoyance. Land use planning guidelines developed since its publication allow for an outdoor DNL exposure in non-sensitive areas of up to 65 dB before sound insulation or other noise mitigation measures must be implemented. Thus, separation of short-, medium- and long-term goals allow noise-exposure goals to be established that are based on human effects research data, yet still allow for the financial and technological constraints within which all countries must work.

The US EPA's Office of Noise Abatement and Control (ONAC) provided a considerable amount of impetus to the development of environmental noise policies for about a decade in the US. During this time, several major US federal agencies, including the US EPA, the Department of Transportation, the Federal Aviation Administration, the Department of Housing and Urban Development, the National Aeronautics and Space Administration, the Department of Defense, and the Federal Interagency Committee on Noise have all published important documents addressing environmental noise and its effects on people. Lack of funding, however, has made the EPA ONAC largely ineffective in the past decade. A new bill, the *Quiet Communities Act* has recently been introduced in the U.S. Congress to re-enact and fund this office (House of Representatives Bill, H.R. 536). However, the passage of this bill is uncertain, because noise in the US, as in Europe, has not received the attention that other environmental issues have, such as air and water quality.

In the USA there is growing debate over whether to continue to rely on the use of DNL (and the A-Weighted Equivalent Continuous Sound Pressure Level upon which DNL is based) as the primary environmental noise exposure metric, or whether to supplement it with other noise descriptors. Because a growing number of researchers believe that "Sound Exposure" is more understandable to the public, the American National Standards Institute has prepared a new Standard, which allows the equivalent use of either DNL or Sound Exposure (ANSI 1996). The primary purpose of this new standard, however, is to provide a methodology for modeling the Combined or Total Noise Environment, by making numerical adjustments to the exposure levels from various noise sources before assessing their predicted impacts on people. A companion standard (ANSI 1998) links DNL and Sound Exposure with the current USA land use planning table. The latter is currently being updated by a team of people from various federal government agencies and when completed should improve the capabilities of environmental and community land-use planners. These documents will complement the newly revised ANSI standard on acoustical terminology (ANSI 1994).

To summarize progress in noise control made in the USA in the nearly 25 years since the initial national environmental noise policy documents were written, the Acoustical Society of America held a special session in Washington, D.C. in 1995. The papers presented in this special session were then published as a collaborative effort between the Acoustical Society of America and the Institute of Noise Control Engineering (von Gierke & Johnson 1996). This document is available from the Acoustical Society of America, as are a wide range of standards related to various environmental noise and bioacoustics topics from the ANSI.

A document from the European Union is now also available, which includes guidelines for addressing noise in environmental assessments (EU 1996). Policy documents from organizations such as ISO, CEN, and ICAO have shown that international cooperation is quite possible in the environmental noise arena. The ISO document, entitled *Acoustics - Description and Measurement of Environmental Noise* (ISO 1996), and other international standards have already proven themselves to be invaluable in moving towards the development of a harmonized environmental noise policy. The best way to move forward in developing a harmonized environmental noise policy is to take a look at the various national policies that have already been adopted in many countries, including those both from the European member states and from the USA, and to decide what improvements need to be made to the existing policy documents. A solid understanding of the progress that has already been achieved around the world would obviously provide the foundation for the development of future noise policies.

Implementation Concepts and Tools

Development of appropriate policies, regulations, and standards, particularly in the noise measurement and impact assessment areas, is a necessary foundation for implementing effective noise abatement policies and noise control programs. A well-trained cadre of environmental planners will be needed in the future to perform land-use planning and environmental impact analysis. These professionals will require both a new generation of standardized noise propagation models to deal with the Total Noise Environment, as well as sophisticated computer-based impact analysis and land-use planning tools.

A more thorough description of the current noise environment in major cities, suburbs, and rural areas is needed to support the noise policy development process. A new generation of noise measurement and monitoring systems, along with standards related to their use, are already providing considerable improvement in our ability to accurately describe complex noise environments. Finally, both active and passive noise control technologies, and other noise mitigation techniques, are rapidly becoming available for addressing local noise problems. Combined with a strong public awareness and education program, land-use planning and noise abatement efforts certainly have the potential to provide us with an environment with acceptable levels of noise exposure.

References

ANSI 1994 American National Samerican Standard Acoustical Terminology. American National Standard S1. American National Standards Institute, New York, NY, USA.

ANSI 1996)Quantities and Procedures for Description and Measurement of Environmental Sound - Part 4: Assessment and Prediction of Long-Term Community Response. American National Standard S12.9-Part 4, American National Standard Institute, New York, NY, USA.
ANSI 1998 Quantities and Procedures for Description and Measurement of Environmental Sound - Part 5: Sound Level Descriptors for Determination of Compatible Land Use. American National Standard S12.9-Part 5, American National Standard Institute, New York, NY, USA.
Bolt, Beranek, Newman, Inc. (BBN) 1981 Noise in America: The extent of the problem. Cambridge, MA, USA.
Eldred km 1975 Assessment of community noise. Noise Control Engineering Journal 3: 88-95.
Eldred km 1988 Noise at the year 2000. In Proceedings of the Fifth International Congress on Noise as a Public Health Problem (B. Berglund et al., eds.). Stockholm: Swedish Council for Building Research.
Fidell S (1978) Nationwide urban noise survey. Journal of the Acoustical Society of America 64: 198-206.
Galloway W, Eldred K, and Simpson M 1974 Population distribution of the United States as a function of outdoor noise. US Environmental Protection Agency Report No. 550/9-74-009. Washington, D.C., USA.
Schori JR, McGatha EA (1973) A real-world assessment of noise exposure. Sound and Vibration 12: 24-30.
Sutherland LC, Braden, MH, and Colman R 1973 A programme for the measurement of environmental noise in the community and its associated human response. Vols. I and II. Report No. DOT-TST-74-5, Washington, D.C.: Department of Transportation, Office of Noise Abatement.
US EPA 1974 Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. EPA/ONAC Report 550/9-74-004, U.S. Environmental Protection Agency, Washington, D.C., USA.
von Gierke HE, Johnson LC 1996 Noise Control - Where Do We Stand Today? Noise Control Engineering Journal.

AFRICAN REGION

South Africa (Etienne Grond, South Africa)

Introduction

Cultural and developmental levels diverge greatly in South Africa, and the country can be divided into a first world sector, a developing sector and a third world sector. This contributes to huge variations in both the awareness of noise pollution and in population exposure to noise pollution. Noise-related health problems will in all probability show the same large variations.

Legal requirements

Noise control in South Africa has a history dating back about three decades. Noise control began with codes of practice issued by the South African Bureau of Standards (SABS) to address noise pollution in different sectors. Since then, Section 25 of the Environment Conservation Act (Act 73 of 1989) made provision for the Minister of Environmental Affairs and Tourism to regulate noise, vibration and shock at the national level. These regulations were published in 1990 and local authorities could apply to the Minister to make them applicable in their areas of jurisdiction. However, a number of the bigger local authorities did not apply for the regulations since they already had by-laws in place, which they felt were sufficient. By the middle of 1992 only 29 local authorities had applied the regulations and so the act was changed to make it obligatory for all authorities to apply the regulations. However, by the time the regulations were ready to be published, the new Constitution of South Africa came into effect and this listed noise control as an exclusive legislative competence of provincial and local authorities. This meant that the national government could not publish the regulations. However, provincial governments have agreed to publish the regulations in their respective areas. The regulations will apply to all local authorities as soon as they are published in the provinces, and will give local authorities both the power and the obligation to enforce the regulations.

The Department of Environmental Affairs and Tourism also published regulations during 1997 to make Environmental Impact Assessments mandatory for most new developments, as well as for changes in existing developments. This means that any impact that a development might have on its surrounding environment must be evaluated and, where necessary, the impact must be mitigated to acceptable levels. The noise control regulations also state that a local authority may declare a “controlled area,” which is an area where the average noise level exceeds 65 dBA over a period of 24 h period. This means that educational and residential buildings, hospitals and churches may not be situated within such areas.

Occupational noise exposure is regulated by the Department of Manpower, under the Occupational Health and Safety Act (Act 85 of 1993). These regulations states that workers may not be exposed to noise levels of higher than 85 dBA and that those exposed to such levels must make use of equipment to protect their hearing. The problem, however, is that most workers tend not to make use of the provided equipment, either because the equipment is not comfortable, or because they are not aware of the risks high noise levels pose to their hearing. A further problem is that small industries often do not supply the workers with the necessary equipment, or supply inferior equipment that is less costly.

Codes of practice

The codes of practice issued by the SABS were for the most part replaced by IEC (International Electrotechnical Commission) standards and adopted as SABS ISO codes of practice. They are still being used in South Africa and are regularly updated. A relevant list can be found in the references. The SABS has also published a number of recommended practices (ARP). These include the ARP 020: “Sound impact investigations for integrated environmental management” that is currently being upgraded to a code of practice. Such codes of practice can be referred to as requirements in legislation and will be known as SABS 0328: “Methods for environmental noise impact assessments.” The codes of practice published in South Africa cover hearing protection; measurement of noise; occupational noise; environmental noise; airplane noise; and building acoustics, etc.

Courses

Local authorities responsible for applying regulations published by the Department of Environmental Affairs and Tourism must employ a noise control officer who has at least three years tertiary education in engineering, physical sciences or health sciences, and who is registered with a professional council. Alternatively, a consultant with similar training may be employed. Most of the universities in South Africa provide the relevant training, with at least part of the training in acoustics. Universities and technical colleges also provide a number of special acoustics courses. Over the last couple of years awareness of environmental conservation has expanded dramatically within the academic community, and most universities and colleges now have degree courses in environmental management. At the very least, these courses include a six-month module in acoustics, and usually also include training in basic mathematics; the physics of sound; sound measuring methodologies; and noise pollution.

Community awareness and exposure to noise pollution

This topic should be discussed with respect to three separate population sectors: the first-world sector (developed), the developing sector and the third-world sector (rural).

Developed sector

This sector of the population is more-or-less as developed as their European and American counterparts. They have been exposed to noise pollution for a considerable time and, for the most part, are aware of the health consequences of high noise levels. People in this group are also aware of the existence of legal measures by which noise pollution can be addressed. Not surprisingly, most of the complaints and legal action regarding noise pollution are received from this group. Information about noise-related health problems is very limited, but because this group is highly aware of the risks posed by high noise levels, future studies will probably show that people in this category have the fewest health problems. The majority of people in this group are less exposed to high noise levels at work, and they live in more affluent neighborhoods with large plots and separating walls. Their houses tend to be built with materials that are noise reducing. They also live further away from major noise-producing activities, such as highways, airports and large industries.

Developing sector

This sector of the population has the greatest exposure to high noise levels, both at home and in the workplace. Overall, they are relatively poor and cannot afford to live in quiet areas, or afford large plots or solid building materials. A large component of this sector resides in squatter communities where building are made of any material available, from plastic to corrugated sheets and wood. The buildings are right next to each other and there is almost no noise attenuation between residencies.

People in this category usually live close to major access routes into the cities, because they make use of public transportation and taxis to get to their places of work. Often, too, they live close to their places of work, which are usually big industries with relatively high levels of noise pollution. These people usually work in high noise areas, and because of their lack of awareness of the effects of high noise levels, often do not make use of available hearing protection equipment. Because of a lack of funds, these people also cannot get out of high noise areas and go to recreational areas for relaxation and lower noise levels. Not much information is available on the adverse health problems in this sector. However, workers in this sector should undergo regular medical examinations and the results can be obtained from the industries involved.

Rural sector

As the name suggests, people in this sector live in rural surroundings and for the most part are not subjected to noise levels that could be detrimental to their health. However, they are almost totally unaware of the risks posed by high noise levels. Some of these people work on farms and work with machinery that emits relatively high noise levels, but because of their lack of awareness they do not make use of hearing protection equipment. One advantage they do have is that they return to homes in quiet surroundings and their hearing has a chance to recover. To date, no studies have been carried out to determine the state of their hearing and it would be impossible to state that they have no health problems related to high noise levels.

References

Environment Conservation Act (Act No. 73 of 1989) Noise Control Regulations, Ministry of Environmental Affairs and Tourism, Pretoria, South Africa.

Relevant SABS codes of practice:

SABS 083-1996. The measurement and assessment of occupational noise for hearing conservation purposes.

SABS 0103-1994. The measurement and rating of environmental noise with respect to annoyance and speech communication (third revision).

SABS 0115-1974. The measurement of noise and the determination of disturbance from aeroplanes for certification purposes.

SABS 0117-1974. The determination and limitation of disturbance around an aerodrome due to noise from aeroplanes (Amendment no 1 - 1984).

SABS 0205-1986. The measurement of noise emitted by motor vehicles in motion.

SABS 0210-1996. Calculating and predicting road traffic noise (Amendment no 1 - 1997).

SABS 0211-1987. The measurement of noise inside motor vehicles.

SABS 0218/1-1988. Acoustical properties of buildings Part 1: The grading of buildings according to their airborne-sound insulation properties (under revision).

SABS 0218/2-1988. Acoustical properties of buildings Part 2: The assessment of building plans and buildings with respect to their acoustical properties (under revision).

SABS 0234-1991. Determination of sound power levels of multi-source industrial plants for the evaluation of the sound pressure levels in the environment - Engineering method (Incorporating ISO 8297:1994).

ARP 020-1992. Sound impact investigations for integrated environmental management. (To be superseded and replaced by SABS 0328: Methods for environmental noise impact assessments).

EASTERN MEDITERRANEAN REGION (Shabih H. Zaidi)

Scope

In the Eastern Mediterranean region some countries have highly developed industries, while others have none. In other cases, the agricultural economy is inseparably mixed with high-technology industries, such as the oil industry, which can be seen in nearly the whole of the Arabian Peninsula. Other examples of where agriculture and industry are intertwined can be seen in Pakistan, Jordan and Egypt. The main focus of this paper is community noise, but because industry is so widely distributed, some discussion of industrial noise is inevitable. The scope of this paper is to document the available scientific data on community noise in the WHO Regional Office of the Eastern Mediterranean (EMRO) region, including preventive strategies, legislation, compensation and future trends.

Sources of Noise Pollution

Sources of noise pollution in the Eastern Mediterranean region include noise from transportation, social and religious activities, building and civil works, roadside workshops, mechanical floor shops and others. During civil works and building booms, noise levels in all countries of the Eastern Mediterranean region could easily reach 85dBA during the daytime over an 8 h work period. In Pakistan, unprotected construction work goes on at all times of the day and night and uses outdated machinery; and the noise is compounded by workers shouting. On a typical building site noise levels reach 90–100 dBA.

In Karachi, the main artery for daily commuters is a long road that terminates at the harbor. In the densest area of this road there are a hundred small and large mechanical workshops, garages, metal sheet workers, dent removers, painters, welders and repair shops, all of which create a variety of noises. In the middle of this area at the Tibet Centre the LAeq,8h is 90dBA (Zaidi 1989). A similar picture is seen elsewhere in cities like Lahore, Peshawar, etc. Fortunately, the same is not true for other newly built cities in the EMRO region, such as Dubai, or Tripoli, where strict rules separate industrial zones from residential areas.

A special noise problem is Karachi harbour. This port serves the whole of Pakistan as well as Afghanistan and several Asian states, such as Kyrgyzstan, Kazakhstan and Uzbekistan. The noise level at the main wharf of Karachi Port ranges between 90–110 dBA on any given day. Other special sources of noise are the Eastern Mediterranean airports, and indeed most of the airports in the Middle East. Most northbound air traffic originates in Pakistan, Dubai, Sharjah etc. and flights usually depart after midnight so as to arrive in Europe during the daytime. A study is currently underway in Karachi to identify the damage caused by these nocturnal flights to those living under the flight path (SH Zaidi, GH Shaikh & AN Zaidi, personal communication).

Sadly, violence has become part of Eastern culture and is a significant source of noise pollution. Wars generate a lot of noise, and although noise-induced hearing loss is a secondary issue compared with the killing, after the wars many people are hearing impaired. This has been seen following conflicts in Balochistan, Peshawar and Afghanistan, where perforated ear drums, profound hearing loss and stress-related psychosomatic illnesses are common in the refugee camps. The noise levels during a recent mass demonstration in Karachi, which included the firing of automatic weapons, reached 120 dBA at a distance of 50 m from the scene.

The Effects of Noise on Health

There is good evidence that environmental noise causes a range of health effects, including hearing loss, annoyance, cardiovascular changes, sleep disturbance and psychological effects. Although the health effects of noise pollution have not been documented for the entire EMRO region, data are available for Pakistan and can be used to illustrate the general problem. In this report, noise exposure is mainly expressed as LAeq,24h values.

Noise-induced hearing loss (NIHL).

It is believed that exposure to environmental noise in the EMRO countries is directly related to the living habits, economic prosperity and outdoor habits of people. It has been estimated that no more than 5% of the people are exposed to environmental sound levels in excess of 65dBA over a 24-h period. Similarly, for indoor noise, it is believed that the average family is not exposed to sound levels in excess of 70 dBA over a 24-h period. However, it is difficult to generalize for all countries in the EMRO region, because of ancient living styles and different cultural practices, such as taking siestas between 13:00–16:00 and stopping work at 20:00.

Exposure to noise while travelling to schools, offices or workplaces may vary tremendously between cities in the region. In Karachi, for example, traffic flow is undisciplined, erratic and irrational, with LAeq,8h values of 80–85 dBA. In Riyadh, by contrast, traffic flow is orderly with LAeq levels of 70 dBA during a normal working day. In Karachi, noise levels show significant diurnal variation, reaching levels in excess of 140 dB during the peak rush hour at around 5.00 p.m. (Zaidi 1989). At the Tibet Centre, located at a busy downtown junction, noise levels were 60–70 dB at 9 am, but reached levels in excess of 140 dB between 5-7 p.m. A study conducted on a day that transportation workers went on strike established that road traffic is the most significant source of noise pollution in this city: in the absence of buses, rickshaws, trucks and other public vehicles the LAeq level declined from 90dB to 75dB (Zaidi 1990). Motor engines, horns, loud music on public buses and rickshaws generate at least 65% of the noise in Karachi (Zaidi 1997; Shams 1997). Rickshaws can produce noise levels of 100–110 dBA and do not have silencers. On festive occasions, such as national holidays or political rallies, motorbikes running at high speeds along the Clifton beach in Karachi easily make noise exceeding 120 dBA. (Zaidi 1996).

Another study conducted at 14 different sites in Karachi showed that, in 11 of the sites, the average noise level ranged between 79–80 dB (Bosan & Zaidi 1995). The maximum noise levels at all these sites exceeded 100 dB. Speech interference, measured by the Preferred Speech Interference Level and the Articulation Index, was significant (Shaikh & Rizvi 1990). The study results indicated that two people facing each other at a distance of 1.2 m would have to shout to be intelligible; and the Articulation Indexes demonstrated that communication was unsatisfactory. Of perhaps greater concern are the results of a survey of 587 males between the ages of 17 and 45 years old, who worked as shopkeepers, vehicle drivers, builders and office assistants. Audiograms showed that 14.6% of the subjects had significant hearing impairment at 3 000–4 000 Hertz (Hasan et al., 2000).

Noise pollution from leisure activities can vary from country to country in the EMRO region. The Panthans in northern Pakistan, for example, like to shoot in the air on festive occasions, such as weddings, without using any noise protection devices. A minimum of 1 000 shots are fired on such occasions; and at a traditional tribal dance called the 'Khattak" the noise level recorded during a particularly enthralling performance in a sports arena was 120dBA. The hunting of wild boar is a common sport in the hinterlands of Sindh. With the rifle shots and the noise made by the beaters, noise levels can easily reach 110 –120 dBA. In some EMRO countries, the younger crowd has taken up the Western habit of listening to Pop music for many hours. Discos and floorshows are confined to a few countries, such as Egypt. Open-air concerts are usually held in stadiums. The noise level recorded at a particularly popular concert was 130 dBA at a distance of 20 m from the stage and 35 m from the amplifiers.

In a study of road traffic at 25 different sites in Peshawar, the third most populous city in Pakistan, 90 traffic constables were taken as cohorts to investigate the extent of NIHL. Of these, 50 did not have any previous history of noise exposure and were taken as controls. Detailed evaluation and audiological investigations established that constables exposed to a noise level of 90 dBA for 8 hours every day suffered from NIHL. Compared to the control subjects, the constables had significant hearing impairment at 3 000 Hz, measured by Pure Tone Audiometry (Akhter 1996).

A similar study of traffic constables in Karachi showed that 82.8% of the constables suffered from NIHL (Itrat & Zaidi 1999). The study also showed that 33.3% of rickshaw drivers, and 56.9% of shopkeepers who worked in noisy bazaars, had hearing impairment. If these findings can be extrapolated to the total populations, there are 1 566 traffic constables (out of a total of 1 890 constables), and 4 067 rickshaw drivers (out of a total of 12 202 drivers) who suffer from NIHL. As has been reported by other researchers, the study also found evidence of acclimatization in the subjects: following an initial, rapid decline, hearing loss stabilized after prolonged noise exposure.

Annoyance.

The citizens of Karachi commonly complain that noise causes irritability and stress. The main sources have been identified as traffic noise, industrial noise and noise generated by human activity. Unfortunately no data are available for the level of annoyance caused by noise exposure in the EMRO region. From limited research around the world, it can be estimated that 35–40% of employees in office buildings are seriously annoyed by noise at sound levels in excess of 55–60 dBA. In countries such as Pakistan, Iran, Jordan and Egypt that level is often seen in most offices. Annoyance is a non-tangible entity and cannot be quantified scientifically. It is a human reaction and perhaps its parameters could include irritability, apprehension, fear, anger, frustration, uneasiness, apathy, chaos and confusion. If such are the parameters, then on a scale of 0–10, with 10 being the greatest annoyance, many EMRO countries could easily score 6 or higher.

Effects of noise on sleep and the cardiovascular system.

In the Eastern Mediterranean region no specific data are available on the effects of noise on sleep or the cardiovascular system. However, factory workers, traffic constables, rickshaw drivers and shopkeepers frequently complain about fatigue, irritability and headaches; and one of the most common causes of poor performance in offices is sleep disturbance. The rising incidence of tinnitus in cities like Karachi is also related to noise exposure, and tinnitus itself can lead to sleep deprivation. Although the effects of noise on the cardiovascular system have been well documented for other countries (Berglund & Lindvall 1995), data are lacking for the EMRO region. However, the prevalence of cardiovascular diseases are on the rise in the EMRO countries, particularly hypertension. While most of the increase in these diseases is due to a rich diet and lack of exercise, the relationship between noise and cardiovascular changes is worth investigating.

The risk to unborn babies and newborns.

Although evidence from other countries indicates that noise may damage the hearing of a fetus, there are no data from the EMRO countries to confirm this. With newborn babies, however, noise from incubators is a major cause of hearing loss in the EMRO region, particularly as 20–27% of them are born underweight (Razi et al. 1995). Once exposed to noise in an incubator, the chances of hearing impairment rapidly rises compared with cohorts in developed countries. Several other factors have also been identified as causing deafness and hearing impairment in newborns in the Eastern Mediterranean region (Zaidi 1998; Zakzouk et al. 1994). They are:

a. Discharge from the ears.

b. Communicable infections.

c. Ototoxicity.

d. Noise.

e. Consanguinity.

f. Iodine deficiency.

Noise Control

Although noise control legislation exists in several EMRO countries, it is seldom enforced, particularly in Pakistan and some neighboring countries. Noise control begins with education, public awareness and the appropriate use of media in highlighting the effects of noise. In Calcutta, for instance, public orientation and mass media mobilization have produced tangible results, and this can easily be done in other countries. Three strategies have been devised for noise control, all of which are practicable in EMRO region countries. They are control at the source, control along the path and control at the receiving end.

There are many ways noise can be controlled at the source. For example, most of the equipment and machinery used in EMRO countries is imported from the West. Noise control could begin by importing quieter machinery, built with newer materials like ceramics or frictionless parts. And at the local level, the timely replacement of parts and proper maintenance of the machines should be carried out. Vehicles like the rickshaw should be banned, or at least be compelled to maintain their silencers, and all vehicles must be put to a road worthiness test periodically. This already occurs in some EMRO countries, but not all. Horns, hooters, music players and other noise making factors must also be controlled. The use of amplifiers and public address systems should also be banned, and social, leisure and religious activities should be restricted to specific places and times.

Along the sound path, barriers can be used to control noise. There are three kinds of barriers available, namely, space absorbers made out of porous material, resonant absorbers and panel absorbers. Architects, for example, use hollow blocks of porous material. The air gaps between building walls not only keep the buildings cool in hot weather, but also reduce the effects of noise. Ceilings and roofs are often treated with absorbent material. In large factories, architects use corrugated sheets and prefabricated material, which are helpful in reducing noise levels. In Pakistan, some people use clay pots in closely ranked positions on rooftops to reduce the effect of heat as well as noise. For civic works and buildings, special enclosures, barriers and vibration controlling devices should be used. Public halls, such as cinemas, mosques and meeting places should have their walls and floors carpeted, and covered with hangings, mats etc. An effective material is jute, which is grown in many countries, mainly Bangladesh, and it is quite economical. Some of the old highways and most of the busy expressways need natural noise barriers, such as earth banks, trees and plants.

References.

Akhter NH 1996 Noise induced hearing loss in traffic police constables of Peshawar. Journal of College of Physicians and Surgeons Pakistan 6: 265-268.

Berglund B and Lindvall T 1995 Community Noise. Archives of the Centre for Sensory Research, volume 2, issue 1, pp. 56,57. Stockholm University and Karolinska Institute, Stockholm.

Bosan Altaf, Zaidi SH Nobel Tracy 1995 The problem of noise, Pakistan Journal of Otolaryngology 11, 128-131.

Hasan S, Zaidi AN, Tahira S, Zaidi SH 2000 Audiological profile of NIHLin IMPACT Ear Camps. Pakistan Journal of Oto-Rhino-Laryngology, in print.

Itrat J, Zaidi SH 1999 Deafness in Pakistan, Pakistan Journal of Otolaryngology 15: 78-83.

Razi MS, Jaffer S, Hillier V, Zaidi SH, Newton V 1995 Causes of bilateral hearing loss in school children. Pakistan Journal of Otolaryngology 11: 68-86.

Shams ZI 1997 The hazards of noise pollution. Daily Dawn, 30th September 1997.

Shaikh GH, Rizvi SSH 1987 Road transport in Karachi city. Pakistan Journal of Science and research, 30: 197.

The environmental protection agency Sindh. The study of noise pollution in Karachi. Executive Report. Karachi Pakistan. ACE (pvt.) Ltd. Karachi.

Zaidi SH 1989 Noise level and the sources of noise pollution in Karachi. Journal of Pakistan Medical Association, 39: 62-65.

Zaidi SH 1990 Noise level in Karachi on a transporter's strike day. Journal of Pakistan Medical Association, 40: 299-300.
Zaidi SH 1996 Noise Ototoxicity. Pakistan Journal of Otolaryngology, 12: 194.
Zaidi SH 1997 Noise induced hearing loss in Pakistan. Hearing International, 6: 12-13.
Zaidi SH 1998 The causes of deafness and Hearing Impairment in the Tropics: Keynote speech delivered at the Centennial Congress of Liverpool School of Tropical Medicine in Sept 1998. Pakistan Journal of Otolaryngology 14: 102-107.
Zakzouk SM, Bafaqeh SA, Al-Mahmmod H, Essa A 1994 Demographic factors and hearing impairment in Saudi Arabian Children., Journal of Laryngology and Otology 108: 294-298.

SOUTH-EAST ASIAN REGION. (Sudhakar B. Ogale)

Introduction

The ability to hear sound is a sensory function vital for human survival and communication. However, not all sounds are wanted. Unwanted sounds, for which the term "noise" is normally used, often originate from human activities such as road traffic, rail traffic, aircraft, discos, electric power generators, festivals, firecrackers and toys. In general, however, data on noise pollution in South east Asian countries are not available. For example, there are no comprehensive statistical data regarding the incidence and etiology of hearing impairment. Consequently, it is difficult to estimate the exact percentage of the population affected by community noise.

Excessive noise is the major contributor to many stress conditions. It reduces resistance to illness by decreasing the efficiency of the immune system, and is the direct cause of some gastrointestinal problems. Noise also increases the use of drugs, disturbs sleep and increases proneness to accidents. An increased incidence of mental illness and hospital admissions, increases in absenteeism from work and lethargy from sleep disturbance all result from noise pollution and cause considerable loss of industrial production.

Noise Exposure in India

India is rapidly becoming industrialized and more mechanized, which directly affects noise levels. However, no general population study regarding the magnitude of the noise problem in India has been performed.

Road Traffic Noise

Exposure. A study by the Indian Institute of Road Traffic (IRT) reported that Delhi was the noisiest city in India, followed by Calcutta and Bombay (IRT 1996; Santra & Chakrabarty 1996). The survey examined whether road-traffic noise affected people with respect to annoyance, sleep disturbance, interference with communication and hearing impairment. It showed that 35% of the population in four major cities have bilateral sensory neural hearing loss at noise emission levels above 82 dBA. This is of particular concern in light of a second study, showing that LAeq,24h levels at 24 kerbside locations in Calcutta were 80–92 dBA (Chakrabarty et al. 1997) The mean noise emission levels of four different vehicle categories are presented in Table A2.1.

Table A2.1: Mean noise emission levels of vehicles

Type of vehicle	Mean sound pressure level
2 wheelers (motor cycle)	82 dBA
3 wheelers (auto rickshaw)	87 dBA
Motor car (taxi, private cars)	85 dBA
Heavy vehicles (trucks)	92 dBA

Control Measures. Only recently has noise pollution been considered an offence in India, under the Environmental (Protection) Act 1986. Several measures are being taken to reduce traffic-noise exposure. These include:

a. Planting trees, shrubs and hedges along roadsides.

b. Mandatory, periodic vehicle inspections by road traffic control.

c. Reintroduction of silent zones, such as around schools, nursing homes and hospitals that face main roads.

d. Regulation of traffic discipline, and a ban on the use of pressure horns.

e. Enforcement of exhaust noise standards.

f. Mandating that silencers be effective in three-wheeled vehicles.

g. The use and construction of bypass roads for heavy vehicles.

h. Limiting night-time access of heavy vehicles to roads in residential neighbourhoods

i. Installation of sound-proof windows.

j. Proper planning of new towns and buildings.

Air Traffic Noise

Many airports were originally built at some distance from the towns they served. But due to growing populations and the lack of space, buildings are now commonly constructed alongside airports in India.

Exposure. A survey revealed that aircraft produced a high level of noise during take-off, with sound pressure levels of 97–109 dBA for the Airbus, and 109 dBA for Boeing aircraft (SB Ogale, unpublished observations). During landing, the aircraft produced a sound pressure level of 108 dBA. Although exposure to aircraft noise is considered to be less of a problem than exposure to traffic noise, the effects of air-traffic noise are similar to those of road traffic, and include palpitations and frequent awakenings at night.

Control measures. The use of ear muffs must be made obligatory at the airport. This can reduce noise exposure to a safe level. An air-traffic control act should also enforce the use and introduction of low-noise aircraft, and mandate fewer night-time flights.

Rail Traffic Noise

Very little attention has been paid to the problems of railway noise.

Exposure. In Bombay, where the majority of residential buildings are situated on either side of railway tracks, residents are more prone to suffer from acoustic trauma. More than 14% of the population in Bombay suffer from sleep disturbances during night, due to high-speed trains and their whistling. A study on surface railways (SB Ogale, unpublished observations) revealed that platform noise was 71–73 dBA in the morning and 78–83 dBA in the evening. The noise from loudspeakers mounted in the platform was 87–90 dBA. At a distance of 1 m from the engine, the whistle noise was 105–108 dBA for a train with an electric engine, up to 110 dBA for a train with diesel engine and 118 dBA for steam engine trains. Vacuum brakes produced noise levels as high as 95 dBA. This suggests that unprotected railway staff on platforms are at risk of permanent noise induced hearing loss.

Festival noise

Festival noise in India was first surveyed in Bombay in late 1970, during the Ganpati festival period. A similar study (Santra et al. 1996) was conducted soon after in Calcutta at the Durga Pooja festival during evening hours (18:00–22:00). The music from loudspeakers produces sound pressure levels of more than 112 dBA. During the festival period the residents experienced a noisy environment for 8–10 h at a stretch, with noise level of 85–95 dBA. This level is above the 80 dBA limit set by WHO for industrial workers exposed to noise for a maximum period of 8 hours.

Control measures. In a religious country, it is politically difficult to restrict religious music, even in the interests of public health. A ban on all music from loudspeakers after 22:00 would decrease the sound pressure levels to below the permissible legal limit. A preventive programme is advocated to measure noise levels with sound level metres.

Fire crackers and toy weapons noise

Exposure. A study conducted by Gupta & Vishvakarma (1989) at the time of Deepawali, an Indian festival of fireworks, determined the auditory status of 600 volunteers from various age groups, before and after exposure to firecrackers. The study also measured the acoustical output of representative samples of toy weapons and firecrackers, and the noise intensity level at critical spectator points. The average sound level at a distance of 3 m from the noise source was 150 dBA, exceeding the 130 dBA level at which adults are at risk for hearing damage. On average, 2.5% of the people surveyed during Deepawali had persistent sensory neural hearing loss of 30 dBA, with those in the 9–15 year old age group being most affected.

Control Measures. A judicious approach in the manufacture and use of toy weapons and firecrackers is encouraged, in addition to legal restraints. Fireworks should be more a display of light, rather than sound.

Generator Noise

Diesel generators are often used in India to produce electric power. Big generators produce sound pressure levels exceeding 96 dBA (SB Ogale, unpublished observations).

Conclusions

No comprehensive statistical data are available for community noise in India, however, the main sources of environmental noise are road traffic, air traffic, rail traffic, festivals, firecrackers and diesel generators. The adverse effects of noise are difficult to quantify, since tolerance to noise levels and to different types of noise varies considerably between people. Noise intensity also varies significantly from place to place. It should also be noted that noise data from different countries are often not obtained by the same method, and in general models have been used which are based on data from a limited number of locations. Noise control measures could be taken at several levels, including building design, legal measures, and educating the people on the health dangers of community noise. In India, what is needed now is noise control legislation and its strict enforcement, if a friendly, low-noise environment is to be maintained.

Noise Exposure in Indonesia

According to a report by the WHO, the noise exposure and control situation in Indonesia is as follows (Dickinson 1993).

Exposure. No nationwide data are available for Indonesia. However, during the last three decades there has been rapid growth in transportation, industry and tourism in Indonesia.

Control Measures. With the large majority of people having little income, protection of the physical environment has not been a first-order priority. The following recommendations have been made with respect to community noise (Dickinson 1993):

a. The cities of Indonesia have relatively large populations and each provincial government will need the staff and equipment to monitor and manage the environment.

b. Sound level meters with noise analysis computer programmes should be purchased.

c. Training courses and adequate equipment should be provided.

d. Noise management planning for airports should be promoted.

e. Reduction measures should be taken for road-traffic noise.

Noise Exposure in Bangladesh

Exposure. In Bangladesh no authentic statistical data on the effects of community noise on deafness or hearing impairment are available (Amin 1995).

Control Measures. Governments have meager resources, a vast population to contend with and high illiteracy rates; consequently, priorities are with fighting hunger, malnutrition, diseases and various man-made and natural calamities. The governments are unable to give the necessary attention towards the prevention, early detection and management of noise disabilities in the country. Close cooperation is needed between the national and international organizations, to exchange ideas, skills and knowledge (Amin 1995).

Noise Exposure in Thailand

Exposure. Noise from traffic, construction, and from factories and industry has become a big problem in the Bangkok area. The National Environmental Board of Thailand was set up two decades ago and has been active in studying the pollution problems in Thailand. Indeed, a committee on noise pollution control was set up to study the noise pollution in Bangkok area and its surroundings. Although regulations and recommendations were made for controlling various sources of noise, the problem was not solved due to a lack of public awareness, the difficulty of proving that noise had adverse effects on health and hearing, and the difficulty of getting access to control noise. A general survey revealed that 21.4% of the Bangkok population is suffering from sensory neural hearing loss (Prasanchuk 1997). Noise sources included street noise, traffic noise, industrial noise and leisure noise.

Control Measures. In 1996, regulations for noise pollution control set LAeq,24h levels at 70 dBA for residential areas, and less than 50 dBA to avoid annoyance. The National Committee on Noise Pollution Control has been asked to study the health effects of noise in the Bangkok area and its surroundings, and determine whether these regulations are realistic and feasible.

References.

Amin 1995 Community Noise. Proceedings of the International Symposium on Deafness and Hearing Impairment in Developing Countries, Manchester, 6-8 July 1995.
Chakrabarty D, Santra SC, Mukherjee A, Roy B, Das P 1997 Status of road traffic noise in Calcutta metropolis, India. Journal of the Acoustical Society of America 101: 943-949
Dickinson P (1993) Noise assessment and management in Indonesia. Report SEA/EH 461, Regional Office for South-East Asia, World Health Organization, New Delhi, India.
Gupta D, Vishvakarma SK. 1989 Toy weapons and fire crackers. Laryngoscope 99: 330-334.

IRT 1996 Indian Council of Medical Research Bulletin Vol. 26, No. 8, August 1996, New Delhi.
Prasanchuk S (1997) Noise pollution. Its effect on health and hearing – Thailand as a case study. Presentation at the PDH Informal Consultation on the Prevention of Noise-induced Hearing Loss, 28-30 October 1997, WHO/PDH/98.5. World Health Organization, Geneva, Switzerland.
Santra SC, Chakrabarty D 1996 Need for rationalization of noise standards in Indian perspectives. Presented at the First National Workshop on Development and Use of Environmental Reference Materials, 14-16 February 1996, Central Pollution Control Board, New Delhi.
Santra SC, Chakrabarty D, Mukherjee A, Roy B 1996 Noise status of Calcutta metropolis. A resume. Man and Environment, Annual Report, pp. 19-22.

WESTERN PACIFIC REGION.

In this section, information on noise pollution and control will be given for three countries in the Western Pacific Region, namely Australia, the People's Republic of China and Japan. From a noise pollution point of view China may be viewed as a developing country, whereas Japan and Australia, with their high level of industrialization, represent developed countries.

Australia (Andrew Hede & Michinori Kabuto)

Exposure. Australia has a population of 18 million with the majority living in cities that have experienced increasing noise pollution from a number of sources. The single most serious source of noise is road traffic, although in major cities such as Sydney, Melbourne and Perth, large communities are exposed to aircraft noise as well. Other important sources of noise pollution are railway noise and neighbourhood noise (including barking dogs, lawn mowers and garbage collection). A particular problem in Australia is that the climate encourages most residents to live with open windows, and few houses have effective noise insulation.

A study of road-traffic noise was conducted at 264 sites in 11 urban centres with populations in excess of 100 000 people (Brown et al. 1994). Noise was measured one metre from the façade of the most exposed windows and at window height. From the results, it was estimated that over 9% of the Australian population is exposed to LA10,18h levels of 68 dB or greater, and 19% of the population is exposed to noise levels of 63 dB or greater. In terms of LAeq values for daytimes, noise exposure in Australia is worse than in the Netherlands, but better than in Germany, France, Switzerland or Japan.

Control. In the mid-1990's, when a third runway was built at Sydney Airport, the government funded noise insulation of high-exposed dwellings. Increasingly, too, major cities are using noise barriers along freeways adjacent to residential communities. In most states barriers are mandatory for new freeways and for new residential developments along existing freeways and major motorways. There has been considerable testing of noise barriers by state agencies, to develop designs and materials that are cost effective.

Brown AL et al. (1994) Exposure of the Australian Population in Road Traffic Noise. Applied Acoustics 43: 169-176.
OECD (1991) Fighting Noise in the 1990's. Organization for Economic Cooperation and Development, Paris, France.

China (Chen Ming)

Introduction

Urban noise pollution has become a contemporary world problem. Urban noise influences people's living, learning and working. People exposed to noise feel disagreeable and cannot concentrate on work. Rest and sleep are also disturbed. People exposed to high-intensity noise do not hear alarm signals and cannot communicate with each other. This can result in injury and, indeed, with the modernization of China, construction accidents related to noise are increasing. According to statistics for several cities in China, including Beijing, Shanghai, Tientsin and Fuzhou, the proportion of total accidents that were noise related was 29.7% in 1979, 34.6% in 1980, 44.8% in 1981 and 50% in 1990. It is therefore very important to control noise pollution in China.

Long-term exposure to urban environmental noise can lead to temporary hearing loss (assessed by temporary threshold shift), permanent hearing loss (assessed by permanent threshold shift) or deafness. Microscopy studies have shown that in people exposed to noise for long periods, hair cells, nerve fibers and ganglion cells were absent in the cochleae, especially in the basal turns. The primary lesion is in the 8–10 mm region of the cochlea, which is responsible for detecting sound at a frequency of 4 000 Hz. People chronically exposed to noise may first complain about tinnitus and, later on, about hearing loss. This is especially true for patients who have bilateral hearing loss at 4 000 Hz, but who have relatively good hearing other frequencies. Non-auditory symptoms of noise include effects on the nervous system, cardiovascular system and blood system. These symptoms were rarely observed in China in the past, but today more and more people complain about hearing damage and non-auditory physiological effects.

Urban environmental noise has thus become a common concern of all members of society. A key to resolving the complex noise issue lies in the effective control of urban noise sources. Control measures include reducing noise at its source, changing noise transmission pathways, building design, community planning and the use of personal hearing protection.

Urban environmental noise sources can be divided into industrial noise, traffic noise, building architecture noise and community district noise sources. Only the last three types are of concern here.

Traffic Noise

There are four sources of traffic noise: road traffic, railway transport, civil aviation and water transport; of these, road traffic is the main source of urban noise. The sound emission levels of heavy-duty trucks are 82–92 dBA and 90–100 dBA for electric horns; air horns are even worse, with sound emission levels of 105–110 dBA. Most urban noise from automobiles is in the 70–75 dB range, and it has been estimated that 27% of all complaints are about traffic noise. When a commercial jet takes off, speech communication is interrupted for up to 1 km on both sides of the runway, but people as far away as 4 km are disturbed in their sleep and rest. If a supersonic passenger plane flies at an altitude of 1 500 m, its sound pressure waves can be heard on the ground in a 30–50 km radius.

Building Noise

As a result of urban development in China, construction noise has become an increasingly serious problem. It is estimated that 80% of the houses in Fuzhou were built in the past 20 years. According to statistics, the noise from ramming in posts and supports is about 88 dB and the noise from bulldozers and excavators is about 91 dB, 10 m from the equipment. About 98% of industrial noise is in the 80–105 dB range, and it is estimated that 20% of all noise complaints is about industrial noise.

Community Noise

The main sources of community noise include street noise, noise from electronic equipment (air conditioners, refrigerators, washing machines, televisions), music, clocks, gongs and drums. Trumpets, gongs, drums and firecrackers, in particular, seriously disturb normal life and lead to annoyance complaints.

In conclusion, urban noise pollution in China is serious and is getting worse. To control noise pollution, China has promulgated standard sound values for environmental noise. These are summarized in table A2.2.

Table A2.2: LAeq standard values in dB for environmental noise in urban areas.

Applied area	day	night
Special residential quarters[1]	45	35
Residential and cultural education area[2]	50	40
Type 1 mixed area[3]	55	45
Type 2 mixed area[4] or commercial area	60	50
Industrial area	65	55
Arterial roads[5]	70	55

1 Special residential quarters: quiet residential area
2 Residential and cultural education area: residential quarters, cultural, educational offices
3 Type 1 mixed area: mixture of commercial area and residential quarters
4 Type 2 mixed area: mixture of industrial area, commercial area, residential quarters and others
5 Roads with traffic volume of more than 100 cars per hour

The peak sound levels for frequent noises emitted during the night-time are not allowed to exceed standard values by more than 10 dBA. Single, sudden noises during the night-time are not allowed to exceed standard values by more than 15dBA.

References

Liu Tian Gi et al.: Noise pollution and control. Environmental protection. Chemical industrial publishing company 1996, 6. First publication P137-154.
National environmental protection leader group. GB 3096-82. Urban environmental noise

standard. The national standard of the People's Republic of China. 1982, 8, 1.
Feng Gen Quan: The main result of field investigation for industrial continuous noise. Foreign Medicine. Otorhinolaryngology. 1978, 2:12.
Beijing Medical Quarantine Station: The investigation analysis of the noise hazard condition in nine provinces and cities. The noise work investigation cooperation group in nine provinces and cities (internal material). 1982.
Cheng Ming: The diagnostic criteria of occupational deafness and experience of hearing conservation in China. Noise as public health problem. New advance in noise research, part 1. Swedish Council for building research. Stockholm, Sweden 1990, pp. 137-44.

Japan (Michinori Kabuto)

Environmental Quality Standards

Noise standards for both general and roadside areas were set in Japan in 1967, through the "Basic Law for Environmental Pollution." This law was updated in September 1999. Each standard is classified according to the type of land use and the time of day. In ordinary residential areas, the night-time standard is 45 dB LAeq, but in areas that require even lower noise exposure, such as hospitals, this is lowered to 40 dB LAeq. In contrast, the daytime levels for commercial and industrial areas is as high as 60 dBA. Standards for roadside areas are 70 dB LAeq for daytime and 65 dB LAeq for nighttime. Between 1973–1997 noise standards for aircraft noise, super-express train noise and conventional railway train noise were also implemented. Standards for aircraft noise were set in terms of the weighted equivalent continuous perceived noise level (WECPNL). For residential areas, the WECPNL standard is 70 dBA, and is 75 dBA for areas where it is necessary to maintain a normal daily life.

For super-express trains, the Environmental Agency required noise levels to be below 75 dBA in densely populated residential areas, such as along the Tokaido and Sanyo Shinkansen lines, as well as in increasingly populated areas, such as along the Tohoku and Joetsu Shinkansen lines. The standards were to be met by 1990, but by 1991 this level had been achieved at only 76% of the measuring sites on average. Noise countermeasures included the installation of new types of sound-proof walls, and laying ballast mats along densely populated stretches of the four Shinkansen lines. Noise and vibration problems can also result from conventional trains, such as occurred with the opening of the Tsugaru Strait and Seto Ohashi railway lines in 1988. Various measures have since been taken to address the problems.

Complaints About Community Noise.

In Japan, complaints to local governments about environmental problems have been summarized annually and reported by Japan Environmental Agency. Thirty-seven percent of all complaints was due to factory (machinery) noise; 22% to construction noise; 3% to road traffic noise; 4% to air traffic noise; 0.8% to rail traffic noise; 9% to night-time business; 6% to other commercial activities; 2.5% to loudspeaker announcements; 9% to domestic noise; and 8% was due to miscellaneous complaints.

Sources of Noise Exposure and their Effects

Road-traffic noise. The number of automobiles in Japan has increased from 20 million in 1971 to 70 million in 1994, a 3.5-fold increase. One-third of this increase was due to heavy-duty vehicles. Since 1994, out of a total of 1 150 000 km of roads in Japan, only 29 930 km have been designed according to noise regulations. According to 1998 estimates by the Environmental Agency, 58% of all roads passed through residential areas. Daytime noise limits were exceeded in 92% of all cases, and night-time limits were exceeded in 87% of all cases. The study also estimated that 0.5 million houses within 10 m of the roads were exposed to excessive traffic noise. In a recent lawsuit, the Japanese Supreme Court ruled that people should be compensated when exposed to night-time noise levels exceeding 65 dB Laeq. This would apply to people living alongside 2 000 km of roads in Japan.

A recent epidemiological study examined insomnia in 3 600 women living in eight different roadside areas exposed to night-time traffic. Insomnia was defined as one or more of the following symptoms: difficulty in falling asleep; waking up during sleep; waking up too early; and feelings of sleeplessness one or more days a week over a period of at least a month. The data were adjusted for confounding variables, such as age, medical care, whether the subjects had young children to care for, and sleep apnea symptoms. The results showed that the odds ratio for insomnia was significantly correlated with the average night-time traffic volume for each of the eight areas and suggested that insomnia could be attributed solely to night-time road traffic.

From the most noisy areas in the above study 19 insomnia cases were selected for a further in-depth examination. The insomnia cases were matched in age and work with 19 control subjects. Indoor and outdoor sound levels during sleep were measured simultaneously at 0.6 s intervals. For residences facing roads with average night-time traffic volume of 6 000 vehicles per hour, the highest sound levels observed were 78–93 dBA. The odds ratios for insomnia in each of the quartiles for LAmax,1min; L50,1min; L10,1min and LAeq,1min generally showed a linear trend and ranged between 1 (lowest quartile) and 6–7 (highest quartile). It was concluded that insomnia was likely to result when night-time indoor LAeq, 1min sound levels exceeded 30 dBA.

Air-traffic noise At the larger Japanese airports (Osaka, Tokyo, Fukuoka), jet airplanes have rapidly increased in number and have caused serious complaints and lawsuits from those living nearby. Complaints about jet-fighter noise are also common from residents living in the vicinity of several U.S. airbases located in Japan. In the case of Kadena and Futemma airbases on Okinawa, a recent study by the Okinawa Prefecture Government suggested that hearing loss, child misbehaviour and low birth-weight babies were possible health effects of the noise associated with these bases (RSCANIH 1997). Using measurements taken in 1968 during the Vietnam War, it was estimated that the WECPNL was 99–108 dBA at the Kadena village fire station. Similar WECPNL estimates of 105 dBA were also obtained for Yara (Kadena-cho) and Sunabe (Chatan-cho) bases. These levels correspond to a LAeq,24h value of 83 dB, and are of serious concern in light of recommendations by the Japan Association of Industrial Health that occupational noise exposure levels should not exceed 85 dB for an 8-h work day if hearing loss is to be avoided.

Audiogrammes of subjects living in areas surrounding Kadena airport indicated that they had progressive hearing loss at higher frequencies. Eight subjects had hearing impairment in the 3–6 kHz range, which strongly suggested that the hearing loss was due to excessive noise exposure. Since the examiners confirmed the subjects had not been exposed to repeated intense noise at their residences or workplaces, the most likely cause of their hearing loss was the intense aircraft noise during take-offs, landings and tune-ups at Kadena airport.

The effects of noise were examined in children from nursery schools and kindergartens in towns surrounding Kadena airport. The children were scored with respect to seven variables: cold symptoms, emotional instability, discontentment-anxiety, headache-stomachache, passivity, eating problems and urination problems. Confounding factors, such as sex, age, birth order, the number of parents living together, the mother's age when the child was born, reaction to noise and the extent of noise exposure, were taken into account. The results showed that children exposed to noise had significantly more problems with respect to their behaviour, physical condition, character and reaction to noise, when compared to a control group of children that had not been exposed to airport noise. This was especially true of for children exposed to a WECPNL of 75 or more. Thus, small children acquire both physical and mental disorders from chronic exposure to aircraft noise.

Chronic exposure to aircraft noise also affects the birth-weight of children. The birth-weights of infants were analyzed using records from 1974 to 1993 in the Okinawa Prefecture. Confounding factors such as the mother's age, whether there were single or multiple embryos, the child's sex, and the legitimacy of the child were considered. The results showed that 9.1 % of all infants born in Kadena-cho, located closest to Kadena airport, had low birth-weights. This was significantly higher than the 7.6 % rate seen in other municipalities around Kadena and Futemma airfields, and much higher than the 7 % rate in cities, towns and villages on other parts of Okinawa Island.

Rail-traffic noise. Commuter trains and subway cars expose Tokyo office workers to much higher noise levels than do other daily activities (Kabuto & Suzuki 1976). Exposure to indoor noise may vary according to railway line or season (there are more open windows in good weather), but the levels range from 65–85 dBA. In general, these values exceeded the LAeq,24h level of 70 dBA for auditory protection (US EPA 1974).

Neighbourhood noise. Neighbourhood noise, including noise from late-night business operations, noise caused by loudspeaker announcements, and noise from everyday activities, have accounted for approximately 39% of all complaints about noise in recent years. At present, noise controls for late-night business operations have been enforced by ordinances in 39 cities and prefectures, and in 42 cities for loudspeaker announcements.

References

Japan Environmental Agency Government of Japan (1994): Quality of the Environment in Japan 1994, Global Environment Department, Environment Agency, Tokyo.

Kabuto M and Suzuki S (1976) A trial measurement of individual noise exposure by time zone in a day. Japanese Journal of Industrial Health, 18:17-22.

Kabuto M, Ohtsuka R, Suzuki S (1978) Measurement and evaluation of individual noise exposure level of Tokyo metropolitan commuters and railroad cars above ground and in subways. Japanese Journal of Public Health 2: 59-63.

Kageyama, T., Kabuto, M. Nitta H, Kurokawa Y, Taira K, Suzuki S, Takemoto T (1974): A population study on risk factors for insomnia among adult Japanese women: A possible effects of road traffic volume. Sleep 20: 963-971.

RSCAINH (1997) Summary of the Interim Report of the Field Study on Public Health around U.S. Bases in Okinawa, Research Study Committee of Aircraft Noise Influences to Health, Okinawa Prefecture Government, Okinawa Public Health Association.

US EPA (1974) information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. Rep. No. 550/9-74.004.

Appendix 3 : Glossary

Acoustic	Pertaning to sound or to the sense of hearing (CMD 1997)
Acoustic dispersion	Change of speed of sound with frequency (ANSI 1994)
Acoustic trauma	Injury to hearing by noise, especially loud noise (CMD 1997)
Adverse effect	(of noise:) A change in morphology and physiology of an organism which results in impairment of functional capacity or impairment of capacity to compensate for additional stress or increase in susceptibility to the harmful effects of other environmental influences. This definition includes any temporary or long term lowering of physical, psychological or social functioning of humans or human organs (WHO 1994)
Annoyance	A feeling of displeasure associated with any agent or condition known or believed by an individual or a group to be adversely affecting them" (Lindvall and Radford 1973; Koelega 1987). Any sound that is perceived as irritating or a nuisance (ANSI 1995)
Anxiety	A feeling of apprehension, uncertainty, and fear without apparent stimulus, and associated with physiological changes (tachycardia, sweating, tremor, etc.) (DIMD 1985). A vaguer feeling of apprehension, worry, uneasiness, or dread, the source of which is often nonspecific or unknown to the individual (CMD 1997).
Audiometry	Testing of the hearing sense (CMD 1997). Measurement of hearing, including aspects other than hearing sensitivity (ANSI 1995)
Auditory	Pertaining to the sense of hearing (CMD 1997)
Auditory threshold	Minimum audible sound perceived (CMD 1997)
A-weighting	A frequency dependent correction that is applied to a measured or calculated sound of moderate intensity to mimick the varying sensitivity of the ear to sound for different frequencies

Ambient noise	All-encompassing sound at a given place, usually a composite of sounds from many sources near and far (ANSI 1994)
Articulation index	Numerical value indicating the proportion of an average speech signal that is understandable to an individual (ANSI 1995)
Bel	Unit of level when the base of the logarithm is ten, and the quantities concerned are proportional to power; unit symbol B (ANSI 1994)
Cardiovascular	Pertaining to the heart and blood vessels (DIMD 1985)
Cochlea	A winding cone-shaped tube forming a portion of the inner ear. It contains the receptor for hearing (CMD 1997)
Cognitive	Being aware with perception, reasoning, judgement, intuition, and memory (CMD 1997)
Community noise	Noise emitted from all noise sources except noise at the industrial workplace (WHO 1995a)
Cortisol	A glucocortical hormone of the outer layer of the adrenal gland (CMD 1997)
Critical health effect	Health effect with lowest effect level
C-weighting	A frequency dependent correction that is applied to a measured or calculated sound of high intensity to mimick the varying sensitivity of the ear to sound for different frequencies
dB	Decibel, one-tenth of a bel
dBA	A-weighted frequency spectrum in dB, see A-weighting
dBC	C-weighted frequency spectrum in dB, see C-weighting
dBlin	Unweighted frequency spectrum in dB
Decibel	Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power; unit symbol dB (ANSI 1994)

Ear plug	Hearing protector that is inserted into the ear canal (ANSI 1994)
Ear muff	Hearing protector worn over the pinna (external part) of an ear (ANSI 1994)
Effective perceived noise level	Level of the time integral of the antilogarithm of one tenth of tone-corrected perceived noise level over the duration of an aircraft fly-over, the reference duration being 10 s (ANSI 1994)
Emission	(of sounds). Sounds generated from all types of sources
Epinephrine	A hormone secreted by the adrenal medulla (inner or central portion of an organ) in response to stimulation of the sympathetic nervous system (CMD 1997)
Equal energy principle	Hypothesis that states that the total effect of sound is proportional to the total amount of sound energy received by the ear, irrespective of the distribution of that energy in time
Equivalent sound pressure level	Ten times the logarithm to the base ten of the ratio of the time-mean-square instantaneous sound pressure, during a stated time interval T, to the square of the standard reference sound pressure (ANSI 1994)
Exposure-response curve	Graphical representation of exposure-response relationship
Exposure-response relationship	(With respect to noise:) Relationship between specified sound levels and health impacts
Frequency	For a function periodic in time, the reciprocal of the period (ANSI 1994)
Frequency-weighting	A frequency dependent correction that is applied to a measured or calculated sound (ANSI 1994)
Gastro-intestinal	Pertaining to the stomach and intestines (CMD 1997)
Hearing impairment, hearing loss	A decreased ability to perceive sounds as compared which what the individual or examiner would regard as normal (CMD 1997)
Hearing threshold	For a given listener and specified signal, the minimum (a) sound pressure level or (b) force level that is capable of

	evoking an auditory sensation in a specified function of trials (ANSI 1994)
Hertz	Unit of frequency, the number of times a phenomenon repeats itself in a unit of time; abbreviated to Hz
Hysteria	A mental disorder, usually temporary, presenting somatic (pertaining to the body) symptoms, stimulating almost any type of physical disease. Symptoms include emotional instability, various sensory disturbations, and a marked craving for sympathy (CMD 1997)
Immission	Sounds impacting on the human ear.
Impulsive sound	Sound consisting of one or more very brief and rapid increases in sound pressure
Incubator	An enclosed crib, in which the temperature and humidity may be regulated, for care of premature babies (CMD 1997)
Isolation, insulation	(With respect to sound:) Between two rooms in a specified frequency band, difference between the space-time average sound presssure levels in the two enclosed spaces when one or more sound sources operates in one of the rooms (ANSI 1994). (With respect to vibrations:) Reduction in the capacity of a system to respond to excitation, attained by use of resilient support (ANSI 1994).
Ischaemic Heart Disease	Heart disease due to a local and temporary deficiency of blood supply due to obstruction of the circulation to a part (CMD 1997)
Loudness level	Of a sound, the median sound pressure level in a specified number of trials of a free progressive wave having a frequency of 1000 Hz that is judged equally loud as the unknown sound when presented to listeners with normal hearing who are facing the source; unit phon (ANSI 1994)
Level	Logarithm of the ratio of a quantity to a reference quantity of the same kind; unit Bel (ANSI 1994)
Maximum sound level	Greatest fast (125 milliseconds) A-weighted sound level, within a stated time interval (ANSI 1994)

Mental Health	The absence of identifiable psychiatric disorder according to current norms (Freeman 1984). In noise research, mental health covers a variety of symptoms, ranging from anxiety, emotional stress, nervous complaints, nausea, headaches, instability, argumentativeness, sexual impotency, changes in general mood and anxiety, and social conflicts, to more general psychiatric categories like neurosis, phychosis and hysteria (Berglund and Lindvall 1995).
Morphological	Pertaining to the science of structure and form of organisms without regard to function (CMD 1997)
Nausea	An unpleasant sensation usually preceding vomiting (CMD 1997)
Neurosis	An emotional disorder due to unresolved conflicts, anxiety being its chief characteristic (DIMD 1985)
Noise	Undesired sound. By extension, noise is any unwarranted disturbance within a useful frequency band, such as undesired electric waves in a transmission channel or device (ANSI 1994).
Noise induced temporary threshold shift	Temporary hearing impairment occurring as a result of noise exposure, often phrased temporary threshold shift (adapted from ANSI 1994)
Noise induced permanent threshold shift	Permanent hearing impairment occurring as a result of noise exposure, often phrased permanent threshold shift (adapted from ANSI 1994)
Noise level	Level of undesired sound
Norepinephrine	A hormone produced by the adrenal medulla (inner or central portion of an organ), similar in chemical and pharmacological properties to epinephrine, but chiefly a vasoconstrictor with little effect on cardiac output (CMD 1997)
Oscillation	Variation, usually with time, of the magnitude of a quantity with respect to a specified reference when the magnitude is alternately greater and smaller than the reference (ANSI 1994)

Ototoxic	Having a detrimental effect on the organs of hearing (CMD 1997)
Paracusis	Any abnormality or disorder of the sense of hearing (CMD 1997)
Pascal	Unit of pressure, equal to one newton per square meter, abbreviated to Pa
Peak sound pressure	Greatest absolute instantaneous sound pressure within a specified time interval (ANSI 1994)
Peak sound pressure level	Level of peak sound pressure with stated frequency weighting, within a specified time interval (ANSI 1994)
Perceived noise level	Frequency-weighted sound pressure level obtained by a stated procedure that combines the sound pressure levels in the 24 one-third octave bands with midband frequencies from 50 Hz to 10 kHz (ANSI 1994)
Permanent threshold shift, permanent hearing loss	Permanent increase in the auditory threshold for an ear (adapted from ANSI 1995) (see also: noise induced permanent threshold shift)
Presbyacusia, presbycusis	The progressive loss of hearing ability due to the normal aging process (CMD 1997)
Psychiatric disorders	Mental disorders
Psychosis	Mental disturbance of a magnitude that there is a personality disintegration and loss of contact with reality (CMD 1997)
Psychotropic drug	A drug that affects psychic function, behaviour or experience (CMD 1997)
Reverberation time	Of an enclosure, for a stated frequency or frequency band, time that would be required for the level of time-mean-square sound pressure in the enclosure to decrease by 60 dB, after the source has been stopped (ANSI 1994)
Sensorineural	Of or pertaining to a sensory nerve; pertaining to or affecting a sensory mechanism and/or a sensory nerve (DIMD 1985)

Signal	Information to be conveyed over a communication system (ANSI 1994)
Signal-to-noise ratio	Ratio of a measure of a signal to the same measure of the noise (ANSI 1995) (see also: noise –in its extended meaning)
Silencer	Duct designed to reduce the level of sound; the sound-reducing mechanisms may be either absorptive or reactive, or a combination (ANSI 1994)
Sound absorption	Change in sound energy into some other form, usually heat, in passing through a medium or on striking a surface (ANSI 1994)
Sound energy	Total energy in a given part of a medium minus the energy that would exist at that same part with no sound waves present (ANSI 1994)
Sound exposure	Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event (ANSI 1994)
Sound exposure level	Ten times the logarithm to the base ten of the ratio of a given time integral of squared, instantaneous A-weighted sound pressure, over a stated time interval or event, to the product of the squared reference sound pressure of 20 micropascals and reference duration of one second (ANSI 1994)
Sound intensity	Average rate of sound energy transmitted in a specified direction at a point through a unit area normal to this direction at the point considered (ANSI 1994)
Sound level meter	Device to be used to measure sound pressure level with a standardized frequency weighting and indicated exponential time weighting for measurements of sound level, or without time weighting for measurement of time-average sound pressure level or sound exposure level (ANSI 1994)
Sound pressure	Root-mean-square instantaneous sound pressure at a point, during a given time interval (ANSI 1994), where the *instantaneous* sound pressure is the total instantaneous pressure in that point minus the static pressure (ANSI 1994)

Sound pressure level	Ten times the logarithm to the base ten of the ratio of the time-mean-square pressure of a sound, in a stated frequency band, to the square of the reference sound pressure in gases of 20 :Pa (ANSI 1994)
Sound reduction index	Single-number rating of airborne sound insulation of a partition (ANSI 1994)
Sound transmission class	Single-number rating of airborne sound insulation of a building partition (ANSI 1994)
Speech interference level	One-fourth of the the sum of the band sound pressure levels for octave-bands with nominal midband frequencies of 500, 100, 2000 and 4000 Hz (ANSI 1994)
Speech intelligibility	That property which allows units of speech to be identified (ANSI 1995)
Speech perception	Psychological process that relates a sensation caused by a spoken message to a listener's knowledge of speech and language (ANSI 1995)
Speech comprehension	(a) Highest level of speech perception. (b) Knowledge or understanding of a verbal statement (ANSI 1995)
Speech transmission index	Physical methgod for measuring the quality of speech-transmission channels accounting for nonlinear distortions as well as distortions of time (ANSI 1995)
Stereocilia	Nonmotile protoplasmic projections from free surfaces on the hair cells of the receptors of the inner ear (CMD 1997)
Stress	The sum of the biological reactions to any adverse stimulus, physical, mental or emotional, internal or external, that tends to disturb the organism's homeostasis (DIMD 1985)
Temporary threshold shift, temporary hearing loss	Temporary increase in the auditory threshold for an ear caused by exposure to high-intensity acoustic stimuli (adapted from ANSI 1995) (see also: noise induced temporary threshold shift).
Tinnitus	A subjective ringing or tinkling sound in the ear (CMD 1997). Otological condition in which sound is perceived by

	a person without an external auditory stimulation. The sound may be a whistling, ringing, buzzing, or cricket type sounds, but auditory hallucinations of voices are excluded (ANSI 1995).
Vibration	Oscillation of a parameter that defines the motion of a mechanical system (ANSI 1994)

For references see Appendix A.

Appendix 4 : Acronyms

AAP	American Academy of Pediatrics
AI	Articulation Index
AMIS	Air Management Information System (WHO, Healthy Cities)
ANEF	Australian Noise Exposure Forecast
ANSI	American National Standard Institute, Washington DC, USA
ASCII	American Standard Code for Information Interchange
ASHA	American Speech-Language-Hearing Association, Rockville, MD, USA
ASTM	American Society for Testing and Materials, West Conshohocken, PA, USA
CEN	Comité Européen de Normalisation, Brussels, Belgium (European Committee for Standardization)
CFR	Code of Federal Regulations (United States)
CIAL	Centro de Investigaciones Acústicas y Luminotécnicas, Córdoba, Argentina (Centre of acoustical and light-technical investigations)
CMD	Cyclopedic Medical Dictionary
CNRC	Conseil National de Recherches du Canada (National Research Council)
COPD	Chronic Obstructive Pulmonary Disease
CSD	Commission for Sustainable Development
CSIRO	Commonwealth Scientific and Industrial Research Organization
CVS	Cardiovascular System
DNL	Day-Night Average Sound Level (United States)
EC DG	European Commission Directorate General
ECE	Economic Commission for Europe
ECMT	European Conference of Ministers of Transport
EHIAP	Environmental Health Impact Assessment Plan
EIAP	Environmental Impact Assessment Plan
EMRO	WHO Regional Office of the Eastern Mediterranean
ENIA	Environmental Noise Impact Analysis
EPNL	Effective Perceived Noise Level measure
EU	European Union
FAA	Federal Aviation Administration (United States)
FFT	Fast Fourier Transform technique
GIS	Geographic Information System
Hz	Hertz, the unit of frequency
ICAO	International Civil Aviation Organization
ICBEN	International Commission on the Biological Effects of Noise
IEC	International Electrotechnical Commission
ILO	International Labour Office, Geneva, Switzerland
INCE	Institute of Noise Control Engineering of the United States of America
INRETS	Institut National de REcherche sur les Transports et leur Sécurité, Arcueil, France (National Research Institute for Transport and their Safety)
ISO	International Standards Organization
I-INCE	International Institute of Noise Control Engineering
L10	10 percentile of sound pressure level

L50	Median sound pressure level
L90	90-percentile of sound pressure level
LA	Latin America
LAeq,T	A-weighted equivalent sound pressure level for period T
LAmax	Maximum A-weighted sound pressure level in a stated interval
L_{dn}	Day and night continuous equivalent sound pressure level
Leq,T	Equivalent sound pressure level for period T
LEQ(FLG)	Descriptor used for aircraft noise (Germany)
LNIP	Low Noise Implementation Plan
Lp	Sound pressure level
MTF	Modulation Transfer Function
NASA	National Aeronautics and Space Administration (United States)
NC	Noise Criterion
NCA	Noise Control Act (United States)
NCB	Balanced Noise Criterion procedure system
NEF	Noise Exposure Forecast
NEPA	National Environmental Policy Act (United States)
NGO	Non Governmental Organization
NIHL	Noise Induced Hearing Loss
NIPTS	Noise Induced Permanent Threshold Shift
NITTS	Noise Induced Temporary Threshold Shift
NNI	Noise and Number Index
NR	Noise Rating
NRC	National Research Council (United States, Canada)
OECD	Organisation for Economic Co-operation and Development, Paris, France.
ONAC	Office of Noise Abatement and Control of the US EPA
OSHA	Occupational Safety and Health Administration
Pa	Pascal, the unit of pressure
PAHO	Pan American Health Organization
PHE	Department for Protection of the Human Environment, WHO, Geneva
PNL	Perceived Noise Level
PSIL	Preferred Speech Interference Level
PTS	Permanent Threshold Shift
RASTI	Rapid Speech Transmission Index
RC	Room Criterion
SABS	South African Bureau of Standards
SEL	Sound Exposure Level
STC	Sound Transmission Class
STI	Speech Transmission Index
TTS	Temporary Threshold Shift
UK	United Kingdom
UN	United Nations
UNCED	United Nations Conference on Environment and Development (Rio de Janeiro, June 1992)
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe

UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
US EPA	United States Environmental Protection Agency
USA	United States of America
WCED	World Commission on Environment and Development (Brundtland Commission)
WECPNL	Weighted Equivalent Continuous Perceived Noise Level
WHO	World Health Organization
WWF	World Wildlife Fund

Appendix 5 : Equations and other technical information

Basic acoustical measures

Sound Pressure Level

The time-varying sound pressure will completely define a sound in a given location. The sound pressure range is wide within which human listeners can receive (10^{-5} - 10^{2} N/m^{2}). Therefore, it is practical to measure sound pressure level on a logarithmic scale. Sound intensity level is defined as 10 times the logarithm (to the base 10) of the ratio of the sound intensity of a target sound to the sound intensity of another (reference) sound. Sound intensity is proportional to the squared sound pressure because the static mass density of the sound medium as well as the speed of sound in this medium are invariant. The sound pressure level (L_p) of a sound may be expressed as a function of sound pressure (p) and is, thus, possible to measure:

$$L_p = 10 \log_{10} (p/p_{ref})^2$$

For the purpose of measuring sound pressure level in a comparative way, the reference pressure, p_{ref}, has an internationally agreed value of $2 \cdot 10^{-5}$ N/m^{2} (earlier 20 μPa). Sound pressure level is then expressed in decibel (dB) relative to this reference sound.

Sound Pressure Level of Combined Sounds

Whereas sound intensities or energies or pressures are additive, non-correlated time-varying sound pressure levels have first to be expressed as mean square pressure, then added, and then transferred to a sound pressure value again. For example, if two sound sources are combined, each of a sound pressure level of 80 dB, then the sound pressure level of the resulting combined sound will become 83 dB:

$$L_p = 10 * \log_{10} (10^8 + 10^8) = 10 * \log_{10} (2 * 10^8) = 10 * (\log_{10} 2 + \log_{10} 10^8) = 10 * (0.3 + 8) = 83$$

It is only sounds with similar sound pressure levels that when combined will result in a significant increase in sound pressure level relative to the louder sound. In the example given above, a doubling of the sound energy from two sources will only result in a 3-dB increase in sound pressure level. For two sound sources that emit non-correlated time-varying sound pressures, this represents the maximum increase possible. The sound pressure level outcome, resulting from combining two sound pressure levels in dB, is displayed in Figure A.5.1.

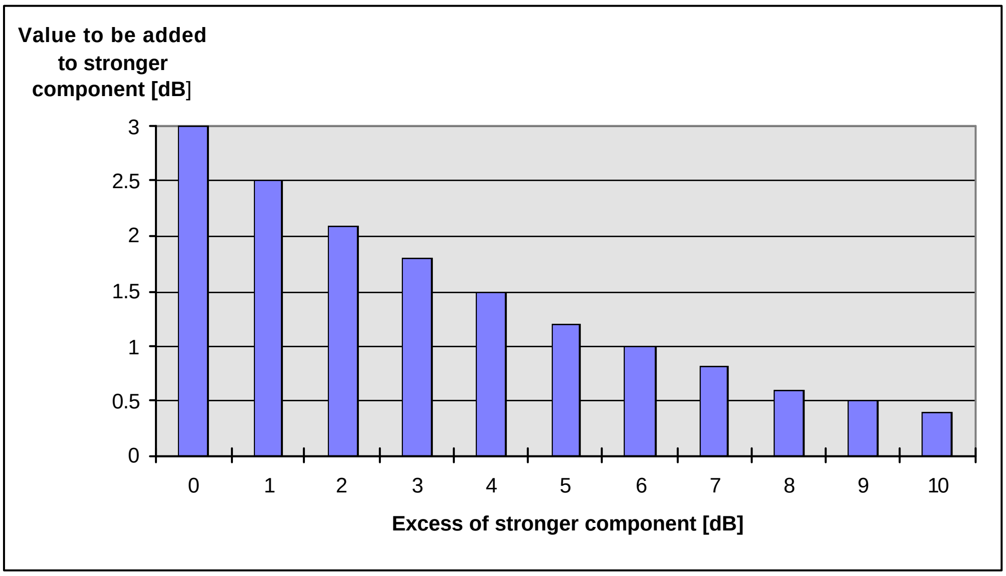

Figure A.5.1: Estimate of combined sound levels

Equivalent Continuous Sound Pressure Level

Average sound pressure level is determined for a time period of interest, T, which may be an interval in seconds, minutes, or hours. This gives a dB-value in Leq that stands for equivalent continuous sound pressure level or simply sound level. It is derived from the following mathematical expression in which A-weighting has been applied:

.

$$L_{Aeq,T} = 10 \log_{10}\{(1/T) \int_0^T 10^{L_p(t)/10}\, dt\} \text{ [dBA]}$$

Because the integral is a measure of the total sound energy during the period T, this process is often called "energy averaging". For similar reasons, the integral term representing the total sound energy may be interpreted as a measure of the total noise dose. Thus, Leq is the level of that steady sound which, over the same interval of time as the fluctuating sound of interest, has the same mean square sound pressure, usually applied as an A-frequency weighting. The interval of time must be stated.

Sound exposure level

Individual noise events can be described in terms of their sound exposure level (SEL). SEL is defined as the constant sound level over a period of 1 s that would have the same amount of energy as the complete noise event (Ford 1987). For a single noise event occurring over a time interval T, the relationship between SEL and LAeq,T is,

$$SEL = L_{Aeq,T} + 10 \log_{10} (T/T_0)$$

In this equation T_0 is 1 s.

Day and night continuous sound pressure level

There are different definition in different countries. One definition is (von Gierke 1975; Ford 1987):

L_{dn} = LAeq,16h + LAeq,8h – 10 dBA

Where LAeq,16h is the day equivalent sound pressure level and LAeq,8h is the night equivalent sound pressure level.

Sound Transmission into and within buildings

An approximate relationship between sound reduction index (*R*), the frequency (*f*), the mass per unit area of the panel (*m*) in kg/m^2, and the angle of incidence (*q*) is given by

$R(q) = 20 \log\{f\, m\, \mathrm{COS}(q)\} - 42.4$, (dB)

This relationship indicates that the sound reduction index will increase with the mass of a panel and with the frequency of the sound as well as varying with the angle of incidence of the sound. It is valid for limp materials but is a good approximation to the behaviour of many real building materials at lower frequencies.

The sound reduction index versus frequency characteristics are usually complicated by a coincidence dip which occurs around the frequency where the wavelength of the incident sound is the same as the wavelength of bending waves in the building façade material. The frequency at which the coincidence dip occurs is influenced by the stiffness of the panel material. Thicker, and hence stiffer materials, will have coincidence dips that are lower in frequency than less stiff materials. Figure A.5.2 plots measured sound reduction index values versus frequency for 4 mm thick glass and illustrates the coincidence dip for this glass at a frequency centered just above 3 kHz.

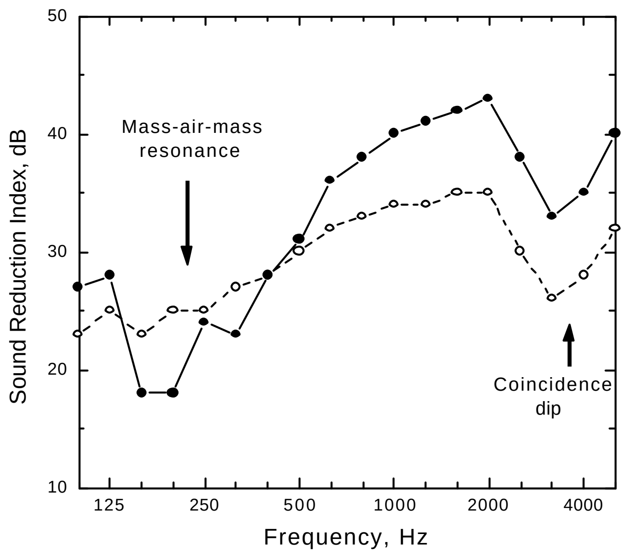

Figure A.5.2: Sound reduction index versus frequency for single and double layers of 4 mm glass (air separation 13 mm).

As also illustrated in Figure A.5.2 for two layers of 4 mm glass, the low frequency sound reduction can be severely limited by the mass-air-mass resonance. This resonance is due to the combination of the masses of the two layers and the stiffness of the enclosed air space. As the Figure A.5.2 example shows, this resonance can often dramatically reduce the low frequency sound reduction of common double window constructions.

The sound reduction of various building constructions can be calculated as the difference between the average sound levels in the two rooms ($L_1 - L_2$) plus a correction involving the area of the test panel (S) in m^2 and the total sound absorption (A) in m^2 in the receiving room,

$$R = L_1 - L_2 + 10 \log\{S/A\} \quad [\text{dB}].$$

For outdoor-to-indoor sound propagation, the measured sound reduction index will also depend on the angle of incidence of the outdoor sound as well as the position of the outdoor measuring microphone relative to the building façade,

$$R = L_1 - L_2 + 10 \log\{4S\ COS(q)/A\} + k \quad [\text{dB}].$$

When the outdoor incident sound level L_1 is measured with the outdoor microphone positioned against the external façade surface, measured incident sound pressures will be 6 dB higher due to pressure doubling. This occurs because the incident sound and reflected sound arrive at the microphone at the same time. If the external microphone is located 2 m from the façade, there will not be exact pressure doubling but an approximate doubling of the measured sound energy corresponding to a 3 dB increase in sound level. The table below indicates the appropriate values of k to be used in the above equation, depending on the location of the outdoor microphone, to account for sound reflected from the façade.

k = 0, dB	L_1 does not include reflected sound.
k = -3, dB	L_1 measured 2 m from façade and includes reflected energy.
k = -6, dB	L_1 measured at the façade surface and includes pressure doubling effect.

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Wind turbine audibility and noise annoyance in a national U.S. survey: Individual perception and influencing factors

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Wind turbine audibility and noise annoyance in a national U.S. survey: Individual perception and influencing factors

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With results from a nationwide survey sponsored by the U.S. Department of Energy, factors that affect outdoor audibility and noise annoyance of wind turbines were evaluated. Wind turbine and summer daytime median background sound levels were estimated for 1043 respondents. Wind turbine sound level was the most robust predictor of audibility yet only a weak, albeit significant, predictor of noise annoyance. For each 1 dB increase in wind turbine sound level ($L_{1h\text{-}max}$), the odds of hearing a wind turbine on one's property increased by 31% [odds ratio (OR): 1.31; 95% CI (confidence interval): 1.25–1.38] and the odds of moving to the next level of annoyance increased by 9% (OR: 1.09; 95% CI: 1.02–1.16). While audibility was overwhelmingly dependent on turbine sound level, noise annoyance was best explained by visual disapproval (OR: 11.0; 95% CI: 4.8–25.4). The final models correctly predict audibility and annoyance level for 80% and 62% of individuals, respectively. The results demonstrate that among community members not receiving personal benefits from wind projects, the Community Tolerance Level of wind turbine noise for the U.S. aligns with the international average, further supporting observations that communities are less tolerant of wind turbine noise than other common environmental noise sources at equivalent A-weighted sound levels. https://doi.org/10.1121/1.5121309

[SF] Pages: 1124–1141

I. INTRODUCTION

Wind turbine noise can cause annoyance (WHO, 2018), reduce social acceptance of wind energy, create conflict and negative experiences in local communities, and result in delayed or derailed wind projects (Rand and Hoen, 2017). Thus, if wind turbines continue to add to the mix of energy generation as is projected (Rogelj *et al.*, 2018), understanding the factors that lead to audibility and noise annoyance could help improve the compatibility between wind projects and their surrounding communities.

Some of the first researchers to study wind turbine noise with larger upwind wind turbines (>500 kW) were Pedersen and Persson Waye (2004), who found that noise annoyance was due not only to the sound level category of wind turbine noise, but also to subjective factors such as perception of wind turbine appearance and self-reported noise sensitivity. Since then, several other studies have investigated the association between wind turbine sound and noise annoyance and/or audibility (Table I). While these studies used different approaches and metrics, a common theme emerged: factors specific to individuals, such as self-reported noise sensitivity, visual impressions, and concerns about physical safety, were often more highly correlated with noise annoyance than a single sound level metric's representation (numerical or categorical) of wind turbine sound levels.

Endpoints of interest in most noise-related dose-response studies are often explored through the binary lens of "Highly Annoyed" and "Not Highly Annoyed" individuals (Miedema and Vos, 1998). This classification provides a polarized categorization of reactions throughout the surrounding population (Schultz, 1978). Further, the Community Tolerance Level (CTL) provides a method for comparing community response to specific noise sources (Fidell *et al.*, 2011; Schomer *et al.*, 2012; Michaud *et al.*, 2016b). The CTL is defined as the long-term day-night sound level (DNL) at which 50% of the population is considered Highly Annoyed by a noise source. CTL has been used to propose that wind turbine noise elicits higher levels of annoyance at equivalent sound levels compared to railway, aircraft, and road traffic sources (Michaud *et al.*, 2016b).

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TABLE I. Summary of prior studies of community response to wind turbine sound.

Study	Number of respondents	Country	Wind Turbine Sound Level Quantification	Included Measurable Variables[a]	Included Subjective Variables	Modeled Metric	Background Sound Included	Adjusted to Long Term Metric
Pedersen and Persson Waye (2004)	351	Sweden	Modeled	No	Yes	L_{eq} at 8 m/s	No	No
Pedersen and Persson Waye (2007)	754	Sweden	Modeled	Yes	Yes	L_{eq} at 8 m/s	No	No
van den Berg *et al.* (2008) and Pedersen *et al.* (2009)	725	Netherlands	Modeled	Yes	Yes	L_{eq} at 8 m/s	No but used rural classification of area in regression model	L_{den}
Janssen *et al.* (2011)	1820	Sweden, Netherlands	Modeled	Yes	Yes	L_{eq} at 8 m/s	No	L_{den}
Pawlaczyk-Łuszczyńska *et al.* (2015)	361	Poland	Modeled with some verification	No	Yes	L_{eq}	No	L_{den}
Kuwano *et al.* (2014)	747 nearby, 332 distant	Japan	Measurements to create a model	No	Yes	$L_{eq,n}$	Yes, but not in regression model	No
Magari *et al.* (2014)	62	U.S.	Measured	Yes	Yes	L_{eq}	No	No
Michaud *et al.* (2016a, 2016b)	1238	Canada	Modeled with some verification	Yes	Yes	L_{annual}	Yes, but not in regression model	DNL
This study	1025	U.S.	Modeled	Yes	Yes	$L_{1h\text{-}max}$	Yes, summer daytime L_{50}	DNL

[a]Modeled independent non-personal variables that can be directly observed, other than sound, such as wind turbine characteristics and participation.

Previous studies of wind turbine noise annoyance are set out in Table I. In most, wind turbine sound level was modeled. Each study used different modeling parameters and averaging times, making comparisons difficult (Old and Kaliski, 2017). Although each provided some estimate of long-term sound levels in the form of annual DNL or L_{den} (day-night-evening level), they do not appear to have been based on a full accounting of site-specific meteorology. Long-term sound levels are affected by meteorological conditions that affect sound propagation, such as wind shear (change in wind speed with height above ground), wind direction, turbulence intensity, and temperature profile (Ingard, 1953). Long-term sound levels are also affected by changes in sound emissions from the source (sound power), which for wind turbines are primarily a function of wind speed (van den Berg, 2008; Keith *et al.*, 2016b). To this end, the present study evaluated the impact of long-term meteorology with a variable representing average atmospheric stability and a sound level adjustment variable based on site-specific wind speed distribution.

Given the European Union Environmental Noise Directive (Directive 2002/49/EC), European researchers have tended to use the long-term metric, L_{den}. In contrast, this study uses $L_{1h\text{-}max}$ as the primary metric because it is a more practical regulatory metric in the U.S. that can be accurately assessed in the field and through modeling.

In addition to sound level metrics, prior studies have not typically assessed wind turbine characteristics as predictors of wind turbine audibility or annoyance. Rotor diameter and hub height may influence feelings of encroachment, visibility, and general intrusiveness, and may also have an impact on sound characteristics, such as amplitude modulation (van Kamp and van den Berg, 2017). Blade tip speeds can affect the characteristic sound produced by a wind turbine and its sound power (Arakawa *et al.*, 2005). Wind turbines with elevated low-frequency noise emissions may be audible at greater distances than other wind turbines, potentially resulting in increased noise annoyance (Hongisto *et al.*, 2017; Møller and Pedersen, 2011). This study evaluates the effects of several wind turbine characteristics on outdoor audibility and noise annoyance.

Moreover, prior studies did not account for the theory that individuals will self-sort among communities based on their valuation of local amenities and disamenities offered by those communities (Tiebout, 1956). Applied to wind turbine development, the theory suggests that individuals who move in after the construction of a wind project are more likely to accept its auditory and visual effects than those who have lived near the project site prior to the wind turbine development (Firestone *et al.*, 2018). For respondents who lived in the area at the time of construction, experiences with project development and associated public engagement are relevant: one's prior attitude manifests expectations that may set the course of one's perception of a particular project, which is evaluated in this study.

The masking of background sound and its effect on self-reported audibility and noise annoyance have not been widely studied over a large population because a consistent approach to the estimation of background sound over a wide area is lacking in most countries. Environmental sources may mask wind turbine sound, rendering the turbines inaudible or less audible (Nelson, 2007). Masking also changes the characteristics of the sound, for example, by reducing amplitude modulation at a receiver (RSG *et al.*, 2016). Thus, it is reasonable to hypothesize that for a given level of wind turbine sound, increasing background sound would reduce the audibility and noise annoyance of wind turbine sound.

In contrast to noise annoyance, audibility has been found to be more dependent on objective variables. Pedersen *et al.* (2009), the only study in Table I that evaluated audibility discretely, found that noticing wind turbine sound was correlated with sound pressure level, turbine visibility, and a categorical representation of whether the location was rural with a main road (as opposed to without one). Economic benefits or whether the receptor was in a built-up area were not associated with noticing wind turbine sound. Pedersen *et al.* (2009) did not extend the audibility analysis to additional independent variables; the present study addresses this gap by analyzing wind turbine audibility in the context of the range of factors mentioned above.

This study, sponsored by the U.S. Department of Energy (DOE), through the Lawrence Berkeley National Laboratory, is an analysis of how sound level, objective characteristics, and subjective measures influence wind turbine audibility and noise annoyance amongst wind turbine neighbors throughout the U.S. The research question is addressed by considering the implications of the effects of meteorology and averaging times/metrics on wind turbine sound level, turbines characteristics, residency in the area prior to the wind project, subjective factors, and background sound levels. It is based on a national mail, internet, and phone survey of wind project neighbors and part of a multi-faceted research effort.[1]

II. METHODS

A. Study approach

This study utilizes survey data, modeled wind turbine sound levels, an estimate of background sound levels, and other external variables to assess the acoustic and attitudinal impact of wind turbine noise in the U.S.

The structure of the analysis presented here differs from most previous studies in that the prediction of noise annoyance is done in two parts. First, the analysis focuses on factors that affect audibility of wind turbines outside one's home. Second, for those respondents who indicated wind turbine audibility on their property, factors that contributed to the level of noise annoyance were evaluated. This approach recognizes an important distinction: those who cannot hear wind turbines will not be directly annoyed by wind turbine noise.

This study also estimates a dose-response relationship between sound pressure level category and wind turbine noise annoyance using the CTL. The CTL results are best used to compare the dose-response of these U.S. respondents to those in other countries and other environmental noise sources.

B. Sampling

A dataset of modern wind turbines installed through 2014 guided the determination of the potential homes to be surveyed.[2] Turbines were considered "modern" if they were at least 111 m in total height (hub height plus rotor radius) and held a nameplate capacity of 1.5 MW or greater, which resulted in 29 848 turbines in 604 projects. From 1.29×10^6 homes in the U.S. located 8 km or less from a modern wind turbine, an initial random sample of 43 041 homes was drawn. The location of the homes was confirmed using two different geolocation services; only residences that agreed between the two sources (within 0.4 km) were retained. Geodetic distance from each residence to its nearest turbine was determined using the "Geonear" (Picard, 2010) function in Stata, which finds nearest neighbors between sets of locations by calculating the geodetic distance between pairs of *X*/*Y* coordinates using the Haversine equation on a reference ellipsoid (Vincenty, 1975). Geographical position accuracy and phone record matching decreased the sample to 15 455 addresses.

To ensure a sample that was representative of the full population of individuals living near turbines in the U.S., the sample was stratified by project size (greater or less than 10 turbines) and distance to the nearest wind turbine (0–0.8, 0.8–1.6, 1.6–4.8, and 4.8–8 km). The final set of records was drawn from each project-size/distance strata to ensure adequate samples within each strata. Oversampling occurred at 15 discrete wind project sites where sound modeling was initially planned. These sites were selected to provide a diversity of turbine manufacturers, geographies, project sizes, median background sound levels, population densities, and topographies. Finally, to ensure adequate dispersion of homes across the country, four projects that included a disproportionately large fraction of the sample were deliberately under-sampled.

A total of 7845 records were ultimately loaded for phone sampling and a total of 6000 records were prepared for the mail/internet survey. The mail/internet survey included 750 phone non-responding homes and 5250 records that did not have matching phone numbers or were excluded because of locational disagreement as noted above. The mail/internet survey generally followed Dillman *et al.* (2014), with an introductory letter, which included a web address and unique web PIN, a second mailing with a paper survey, and a reminder postcard. There were no differences between the multi-modal survey instruments other than those necessitated by the mode.

C. Survey instrument

The instrument comprised a 50-question survey[3] that sought information regarding the following:

- Respondents' present attitude toward the nearby project and their attitude prior to construction;
- Participation in and perceived fairness of the project's planning and siting process;
- Relationship to the local wind project (e.g., turbines on property, compensation, number of turbines visible, and ability to hear turbines from property and inside home);
- Perceptions of and reactions to the project (e.g., appearance, landscape changes, turbine sounds, shadow flicker, lighting);
- Background information (e.g., length of residence, awareness of project development, place attachment, noise sensitivity, and acute and chronic stress);

- General attitudes toward sources of electricity, climate change, and wind energy's effectiveness at combating it; and
- Demographic information.

Portland State University's Survey Research Lab conducted telephone surveys[4] and administered follow-on internet and mail surveys. The phone survey occurred in March and April of 2016 with mail/internet surveys following through July of 2016. All respondents who completed the survey were entered into a drawing to win one of four $500 gift cards. Individuals contacted were not informed that the survey would inquire into audibility and sound annoyance. Rather, they were informed of the more general purpose of the survey—that is, to "understand [the] experiences, perceptions, and opinions" of wind turbine neighbors (see footnote 4).

The research team received a total of 875 phone responses out of 3114 resolved (not to be called back because they completed the survey, asked to never be called back, or refused to take part) and 6332 eligible (resolved plus, e.g., reached voice mail or was asked to call back) phone numbers. Response rates for the phone survey were 13.8% for "eligible" numbers and 28.1% for "resolved" numbers. Nonresponse phone survey follow-up calls averaged 6.3 calls/number; residences closer to wind turbines were prioritized for follow-up calls to ensure the sample size for this cohort was adequate. The research team also received 483 web and 347 mail responses out of a total of 4637 eligible addresses (accounting for undeliverable mail, etc.), resulting in a response rate for the mail/web survey of 17.9%. All mail/web respondents received two mail invitations in addition to the actual mail survey. In general, response rates were consistently higher for residences closer to the turbines, potentially indicating greater interest in the survey. The maximum response rate (25%) was observed from the mail/web survey for residences within 0.8 km of the nearest turbine.[5] A total of 1705 responses were obtained from near 250 wind projects.

Of the 1705 responses, 621 responses were located within 0.8 km of a wind turbine and another 500 responses were between 0.8 and 1.6 km. In the context of projects operating in the U.S. at the time, responses were well distributed across the country, with the majority located in the midwestern U.S. (Fig. 1). For this study, sound levels were predicted for 1043 respondents living in the vicinity of 61 projects (435 within 0.8 km of a wind turbine and 293 between 0.8 and 1.6 km).

D. Response interpretation

1. Assessment of wind turbine audibility

Respondents were asked, "Have you ever heard sound from the wind project," to which they could respond "Yes," "No," or "Don't know." If they answered yes, they were then asked, "Can you hear sound from the wind project when you are on your property, but outside your home?" Finally, respondents answering in the affirmative were asked if they could hear the turbines, "…in your home?" Using these responses, a respondent's wind turbine audibility is characterized as "Cannot Hear," "On Property," or "In Home." Outdoor audibility on the respondent's property was

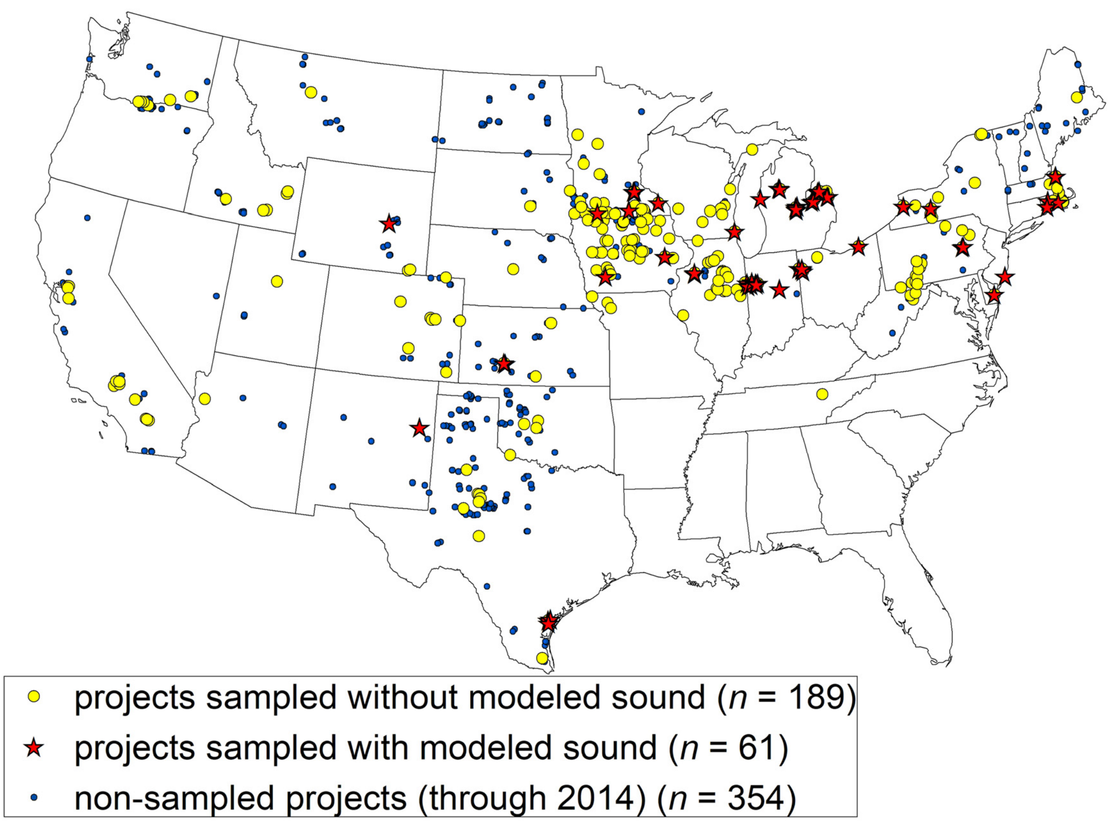

FIG. 1. (Color online) Wind power projects in the U.S., highlighting those surveyed and modeled for this study. Sound was modeled at 24% of the sampled projects, representing 61% of respondents.

chosen as the first endpoint tested because only outdoor sound level was modeled.

2. Assessment of respondent noise annoyance

Prior to inquiring about annoyance, the survey prefaced respondents with the following statement: "The next set of questions asks about any effects the local wind project has had on you. For these questions, think about the experiences you have had over the past year." Then, respondents were asked, "To what extent do you feel annoyed by each of the following effects of the local wind project?" Four effects were listed: "Change to the landscape," "Wind turbine lighting," "Shadow flicker," and "Sound of the wind project." For each effect, the possible responses were 1 = "Not at all," 2 = "Slightly," 3 = "Somewhat," 4 = "Moderately," and 5 = "Very." This study only considered the indicated annoyance to "Sound of the wind project," i.e., noise annoyance. For analysis as a dependent variable, the three middle reactions, Slightly, Somewhat, and Moderately, were combined into one category ("Mildly") to represent respondents who elicited a mild negative reaction to wind turbine noise. This resulted in three annoyance categories: "Not at all," "Mildly," and "Very." Reported noise annoyance was only considered valid in this study for respondents who also reported hearing wind turbines on their property (see Sec. IV C for further discussion).

3. Formulation of additional variables from survey responses

A single three-level categorical variable was formulated to describe a respondent's participation in (or relationship with) their local project. By convention, project participants are compensated in some way for the project, e.g., lease payments for hosting a turbine. This study compares respondents who did not participate in their local project (non-participants), respondents who were compensated for hosting a turbine on their property (host and compensated), and respondents who were compensated but did not host a turbine (compensated). Wind project neighbors receiving compensation without hosting a wind turbine may have granted the wind project easements for project infrastructure (e.g., roads, powerlines), leased land to the developer (e.g., substations), or consented to a "good neighbor agreement" (NYSERDA, 2017). Monetary compensation levels for wind turbine hosts were considerably higher than for non-hosts.[6]

Additional survey responses were formed into variables describing the respondent and some personal attributes. The variable "move-in" distinguishes those who moved in after construction and respondents who lived in the area prior to the wind project. A respondent's "prior attitude" toward the local wind project prior to construction was included with a positive, negative, and neutral group. Note that in the presence of subjective variables, prior attitude subsumes the move-in variable, as these variables contain mutually exclusive groups of respondents. Noise sensitivity was assessed as a five-level ordered categorical variable based on the survey responses (i.e., Not at all, Slightly, Somewhat, Moderately, and Very), with "Not at all noise sensitive" as the omitted reference level. Last, a "like look" variable was assigned to respondents based on whether or not they liked the appearance of the local wind project or were neutral.

4. Assessment of CTL (dose-response analysis)

Although the survey instrument deviated from ISO/TS 15666 (2003), which is discussed in Sec. IV C, respondents who indicated they were "Very Annoyed" were regarded as being Highly Annoyed.[7] The percentage of Highly Annoyed respondents by sound level category was calculated for two groups: all respondents and only non-participants, resulting in two distinct CTLs.

E. Additional data collection

Survey responses were supplemented with additional attributes, which included wind turbine data, sound levels, meteorology, and site characteristics.

1. Wind turbine data

Wind turbine data were obtained via the U.S. Wind Turbine Database (Hoen *et al.*, 2018), including coordinates, model, maximum power output, hub height, rotor diameter, and tip speed (Table II). Attributes for the wind turbine nearest to each respondent were assigned for the regression analysis.

Apparent sound power levels for wind turbines in this study were collected by octave band to the extent they were available. For wind turbines without available spectral data, spectra were estimated based on the reported overall A-weighted level as proposed by Keith *et al.* (2016a). These estimates were used for 5% of the turbines included in the sound propagation models, representing about 15% of respondents. Additionally, the C-to-A ratio of the turbine closest to each respondent was assigned to that respondent, which is the overall C-weighted sound power level of the wind turbine minus the overall A-weighted sound power level. The greater the C-to-A ratio, the greater the proportion of low-frequency sound generated by the wind turbine relative to the full spectrum. The C-to-A ratio is reported with an asterisk ("*") in this work due to the lack of data below the 63 Hz octave band.[8]

2. Wind turbine sound levels

The level of wind turbine sound is one of the most important variables in the study. The authors chose to model wind turbine sound using the $L_{1h\text{-}max}$ metric: the maximum

TABLE II. Descriptive statistics of distinct wind turbines included in the sound propagation models ($n = 38$ unique turbines).

	Minimum	Maximum	Mean	SD
Hub Height (m)	70	100	85.9	9.1
Rotor Diameter (m)	77	117	90.8	8.9
Turbine Capacity (MW)	1.5	2.5	1.8	0.3
Rotor Tip Speed (m/s)	61.8	87.4	75.7	7.1
Turbine Sound Power (dBA)	103.1	109.1	105.2	1.5
C-to-A Sound Power Ratio*	7.5	14.9	10.3	2.2

A-weighted 1 h equivalent continuous average wind turbine sound level at each receptor that is reasonably expected under normal operating conditions. The $L_{1h\text{-}max}$ is a common regulatory metric in the U.S. (Fowler *et al.*, 2013). Since long-term averages are also useful for understanding ongoing exposure to wind turbine sound, this study includes annualized sound power correction and mean inverse Obukhov length (as a proxy for temperature profile) (Kaliski *et al.*, 2018a) as factors that influence long-term sound emissions and propagation effects, respectively.

Sound propagation modeling was performed according to ISO 9613-2 (ISO, 1996) as implemented in CadnaA version 4.6 (Datakustik®, 2016) software to predict $L_{1h\text{-}max}$ at each respondent's home. All wind turbines within 8 km of each receiver were considered to be operating at maximum sound output with no noise-reduced operations (NROs). Sound levels were calculated at 4 m above ground level. To account for atmospheric absorption (ISO 9613-1, 1993), the temperature and humidity were set at 10 °C and 70%, respectively. The ground type was represented as half hard/half porous ($G = 0.5$), except for large bodies of water ($G = 0$). Buildings and foliage attenuation were not included. Two decibels were added to the model results to account for remaining manufacturer sound power and propagation uncertainty (Bowdler *et al.*, 2009, RSG *et al.*, 2016, Kaliski *et al.*, 2018b).

Sound propagation modeling was undertaken at 30 wind projects to generate a large sample size and provide a broad diversity of projects. To account for other nearby wind projects that could affect the sound levels at respondent homes, each sound propagation model included any wind project within 8 km of a respondent. Respondents living within 8 km of the additional projects were also added to the sound propagation models, if applicable. This way, 61 distinct wind projects, totaling 3267 turbines (26 different makes and models) were modeled for 1043 respondent homes, 1025 of which indicated whether they could hear or not hear wind turbines on their property.

3. Annualized sound levels

While $L_{1h\text{-}max}$ is the representation of equivalent wind turbine sound levels used in the regression models,[9] the effect of long-term wind turbine sound power emissions is also included through a variable called "DNL correction" (DNL* minus $L_{1h\text{-}max}$, calculated for each respondent). Hourly simulations of turbine sound power output were generated using project-level hub-height wind speed obtained from the NREL Wind Toolkit (NREL, 2018) in conjunction with turbine sound power output curves and project-level capacity factors. Hourly data from 2007 to 2012 were processed for locations geographically central to each included wind project. DNL was calculated by applying a 10-dB penalty during the night (22:00 to 07:00) (ANSI, 2013). The approximate day-night level ("DNL*") was on average 3.6 dB [standard deviation (SD) = 1.2] higher than $L_{1h\text{-}max}$. The average annual equivalent sound level was 3.5 dB (SD = 1.4) less than $L_{1h\text{-}max}$. The asterisk (*) in DNL* denotes that the sound level metric is not a true DNL, in that it does not account for conditions when atmospheric stability and wind direction are less favorable for sound propagation, or any NROs at the modeled projects. As a result, the DNL* is the upper bound of the *actual* DNL for long-term outdoor wind turbine sound.

4. Background sound levels

Estimated background sound levels were obtained from the U.S. National Park Service (NPS) mapping of A-weighted median ambient daytime summer sound levels (L_{50}) of the U.S. (National Park Service, 2014). The maps were generated using statistical relationships between ambient sound level and biogenic, geospatial, and anthropogenic surface characteristics (Mennitt *et al.*, 2014). The L_{50} is calculated by the NPS in a 270-m grid across the U.S. The median deviation of measured versus modeled sound levels was reported to be 3.1 dB at natural sites and 1.7 dB at urban sites (Mennitt *et al.*, 2014). Note that there are many measures that can be made to quantify background sound, including different seasons, times of day, and sound level metrics. Presently, only summer daytime L_{50} is available from the NPS as a comprehensive representation of overall background sound. This background L_{50} provides a consistent and *relative* measure of background sound amongst the study participants.

F. Data analysis techniques

1. Regression models

This analysis differentiates a respondent's experience with and response to wind turbine noise through sound levels and other covariates using two sets of models. First, the factors contributing to wind turbine audibility outdoors were assessed ($n = 749$). Adding variables in succession, three models are presented, with each building on the previous: a Basic model (sound levels, project participation, demographic variables, and stratification variables); an Observable model (adding variables than can be directly measured); and a Subjective model (adding variables describing respondent personal experience). Then, wind turbine noise annoyance *among respondents who could hear the wind turbines on their property* was tested following the same procedure with the same covariates ($n = 407$).

Although respondents out to 8 km were sampled and included in the sound propagation models, only respondents located within 5 km of the nearest turbine were included in the regression models due to few respondents being able to hear the wind turbines beyond 5 km. Only three respondents out of 132 living farther than 5 km from a turbine indicated turbine audibility or noise annoyance on their property, nearly resulting in a singular condition for this distance bin. Moreover, given that maximum short-term wind turbine sound levels were modeled well below 20 dB at 5 km from the nearest wind turbine, including respondents from distances greater than 5 km would not have been useful in predicting noise annoyance. Respondents without resolved survey responses forming the independents variables (i.e., missing values) were excluded from the regression analysis.

No data weighting was applied to the regression models but controlling variables were included to account for unequal probability of selection given sampling strategy/strata and to address differential response rates by gender, age, and education.[10] To test the robustness of the unweighted regression approach, a weighted[11] regression, in which the sample was weighted to account for census tract demographics and survey stratification, was run for comparison. Although there were some minor differences in the significance of some variables with the weighted model, there were no substantive differences in the conclusions.

Covariates were selected based on those that were necessitated by sampling (demographics, sample stratification), factors that previous research has shown to be significant (wind turbine related or not), wind turbine characteristics, simulated long-term equivalent wind turbine sound power level correction (with DNL nighttime penalty), and long-term atmospheric stability. Selected variables were not eliminated from the model on the basis of insignificance, as systematically removing nonsignificant variables biases *p*-values and standard errors low and coefficients high (Heinze and Dunkler, 2017; Harrell, 2001). The fact that a specific variable is not significant in the presence of covariates may, in itself, be a result to be interpreted. Variables were only eliminated from the model if multicollinearity was found or for lack of data.[12] If multicollinearity was found, the authors sought to replace the variable with a similar representation or drop it altogether.

In Table III, descriptive statistics of all variables in the models, grouped into functional classification groups, are provided for the survey sample ($n = 1705$) and the subsample of respondents with modeled sound ($n = 1025$).

2. Statistical methodology

a. Regression model formulation. The audibility models used binary logistic regression to estimate the probability that a respondent hears the turbines on their property, while the noise annoyance models applied an ordinal logistic model for three response levels (Not at all Annoyed<Mildly Annoyed<Very Annoyed). The regression analyses were implemented using the R software environment (R Core Team, 2018; Harrell, 2018).

For ease of interpretation, the regression model coefficients are presented as odds ratios (ORs), calculated as $\exp(\beta)$, where β represents the coefficient of interest. ORs, a measure of effect size, are a common form of reporting logistic regression coefficients and indicate the effect of a one-unit increase in a continuous covariate or a change in levels of a categorical covariate on the odds of experiencing the dependent variable in question. For instance, an OR of 1.15 indicates that for a one-unit increase in sound levels, a respondent would have a 15% increase in the odds of being able to hear the wind turbines. Unity is the no-effect value and values less than 1 indicate that the odds decrease with increasing values of the covariate. In ordinal logistic regression, the interpretation of the OR is similar: it is the change in the odds of having a higher value of the response variable.

Variance inflation factors (VIFs) test for collinearity in the models (James *et al.*, 2017). A VIF of 1.0 indicates that there is no correlation. Typically, a VIF above 4 deserves a closer look. This study employs a conservative maximum VIF of 2.5 for independent variable inclusion.

b. Variable importance. The relative importance of each variable is characterized using change in Akaike Information Criteria (ΔAIC; Harrell, 2018). This represents the effect on the model fit when that variable is removed from the regression. Higher ΔAIC values signify stronger predictors. For categorical variables, the ΔAIC measure is particularly useful in that it shows the strength of the whole variable as opposed to the individual model coefficients.

c. Model accuracy. The overall fit of the model is measured with several indicators: leave-one-out cross-validation (LOOCV), area under the receiver operating curve (AUC), and Nagelkerke's R^2 (R_N^2). These are described below.

In LOOCV, the regression model is estimated repeatedly leaving out one case (i.e., respondent; Geisser, 1993). Then, the predicted outcome for the omitted case is compared to the actual outcome for that respondent. The goal is to see if the model correctly predicts the case that was "left out." The results of the validation are expressed as the proportion of outcomes that are correctly predicted for each level of the response variable. In addition to the proportion of correct predictions, the LOOCV can also be summarized by the multiclass area under the receiver operating characteristic curve (Hand and Till, 2001), which is a measure of model fit obtained by comparing the LOOCV predicted responses to the observed responses (Robin *et al.*, 2011). The AUC ranges from 0.5 for a model with no predictive ability to a maximum of 1.0 for a model with perfect predictive ability (Fawcett, 2006).

Nagelkerke's R^2 is a "pseudo-R^2" and is used as an index of overall model quality (Nagelkerke, 1991). It is calculated as a measure of the improvement of the log-likelihood of the model compared to that of a null model and is designated here as R_N^2.

3. CTL (dose-response analysis)

Responses were weighted and grouped into 5 dB categories using DNL*. Proportions of Highly Annoyed respondents were calculated for each sound level category for respondents with resolved audibility and noise annoyance ($n = 1023$) and for the subset of respondents who were not compensated for the project ($n = 818$). The percentage of Highly Annoyed responses in each sound level category was then fit to a dose-response relationship, as shown in Eq. (1) (Fidell *et al.*, 2011),

$$\text{Percent Highly Annoyed} = 100\mathrm{e}^{-\left[1/\left(10^{(\mathrm{DNL}-\mathrm{CTL}+5.306)/10}\right)^{0.3}\right]}, \quad (1)$$

where the CTL represents the DNL at which half of the population is considered Highly Annoyed. The key difference between an analysis of Highly Annoyed individuals for calculating of the CTL and the Very Annoyed endpoint tested in the regression models is that the CTL dose-response

TABLE III. Distribution of modeled variables among subsets of survey response data by count and descriptive statistics: mean, mean and SD, or distribution of responses (%). The modeled sound level dataset is very similar in proportions and means to the full survey sample.

				Full Sample			
				All Respondents ($n = 1705$)		Modeled Sound ($n = 1025$)	
Group	Variable Name	Type[a]	Variable Description (Units or Reference Level[b] and Order)	n	Mean (SD)	n	Mean (SD)
Dependent	Annoyance[c]	O	[Cannot Hear] < **Not at all Annoyed** < Mildly Annoyed < Very Annoyed	[53] / **21** / 17 / 9		[52] / **22** / 17 / 9	
	Audibility	B	0 = Cannot hear turbine on property, 1 = Can hear turbine on property	1682	0.46	1025	0.48
Demographic	Female	B	0 = not female, 1 = female	1686	0.53	1016	0.55
	Age	C	Respondent age, years	1667	58 (15)	1004	58 (15)
	College	B	0 = no college degree, 1 = college degree	1686	0.48	1014	0.48
	White	B	0 = not white, 1 = white	1678	0.9	1010	0.89
	Income	C	Median income of survey selected census categories (×$10 000)	1479	7.4 (5.2)	893	7.2 (5.1)
Stratification	Dominant	B	0 = not under-sampled, 1 = under-sampled due to population distribution	1705	0.07	1025	0.09
	Discrete	B	0 = not over-sampled, 1 = over-sampled for initial sound modeling	1705	0.33	1025	0.53
	Project size[d]	B	0 = small project (10 turbines or less), 1 = large project (>10 turbines)	1705	0.64	1025	0.6
	# of turbines	C	Number of turbines in local project	1705	49 (52)	1025	50 (57)
Relationship	Project participation[c]	Ca	**Non-participant**/Compensated (not host)/Host and Compensated	1661	81 / 12 / 5	998	80 / 12 / 5
Sound Level	Wind turbine	C	Wind turbine sound level ($L_{1h\text{-}max}$)			1025	36.7 (10.5)
	Background L_{50}	C	Median summer daytime sound level (L_{50}) (dBA)	1687	40.9 (5)	1025	41.9 (5.1)
Site Conditions	Atm. Stability	C	Atmospheric stability (mean long-term inverse Obukhov Length)			1025	0.004 (0.015)
	DNL correction	C	Adjustment to DNL using long-term wind turbine sound power emission			1025	3.47 (1.2)
Turbine Specifications	C-to-A ratio*	C	Turbine sound power C-to-A ratio (no data below 63 Hz octave band) (dB)			1025	10.1 (1.8)
	Rotor diameter	C	Rotor diameter (m)	1693	88.4 (9)	1020	89.5 (9.2)
	Hub height	C	Hub height (m)	1693	84 (8.5)	1020	85 (9.2)
	Tip speed	C	Rotor tip speed at full output capacity (m/s)			1025	77 (6.3)
Individual	Turbine view	B	0 = Cannot see turbine, 1 = Can see turbine	1647	0.8	995	0.8
	Move-in	B	0 = Resident prior to project, 1 = Move-in after project was built	1639	0.23	988	0.22
Subjective	Prior attitude[c]	Ca	**Neutral** / Negative / Positive / Move-in after	1639	41 / 10 / 26 / 23	988	42 / 9 / 28 / 22
	Noise sensitive	O	**Not at all** < Slightly < Somewhat < Moderately < Very	1694	23 / 31 / 22 / 15 / 8	1020	25 / 32 / 21 / 14 / 8
	Like look (visual)[c]	Ca	**Neutral** / No / Yes	1646	14 / 25 / 61	990	14 / 24 / 63

[a]Variable type: C = continuous, B = binary, Ca = categorical, O = ordinal.
[b]Reference level in bold.
[c]Percentages may not add to 100 due to rounding; Prior attitude combines with the mutually exclusive move-in variable for 100%.
[d]Not included in regression models due to multicollinearity with variables of interest (mostly background sound level); actual number of turbines in a project was used in its place.

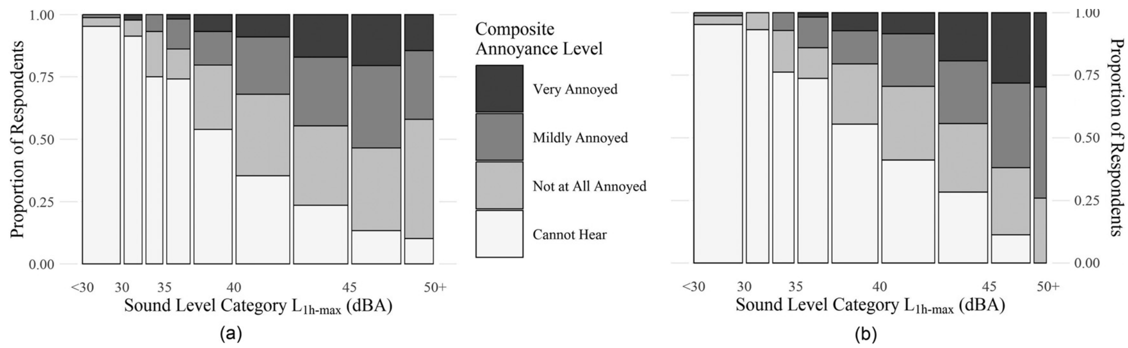

FIG. 2. Composite annoyance: distribution of outdoor audibility and annoyance level by sound level category for (a) all respondents ($n = 747$; two respondents who indicated wind turbine audibility but did not provide an annoyance level are excluded from the plot) and (b) for only non-participants ($n = 591$; two respondents who indicated wind turbine audibility but did not provide an annoyance level are excluded from the plot). Bar widths are proportional to the number of respondents in each exposure category. Each bar represents a grouping of 2.5 dBA, except for the top sound level category, which includes respondents with modeled sound levels greater than or equal to 47.5 dBA.

analysis includes all respondents with resolved audibility, while the Very Annoyed regression analysis tested noise annoyance only among respondents for whom wind turbines were audible on their property.

III. RESULTS

A. Sound levels and survey results

The composite distribution of wind turbine audibility and noise annoyance among respondents is presented together in Fig. 2. Figure 2 shows that wind turbine audibility and noise annoyance both increase with sound level category. Below 40 dBA $L_{1h\text{-}max}$, over half of the respondents indicated that they were unable to hear the turbines on their property and less than 20% expressed some noise annoyance, i.e., they were Mildly or Very Annoyed. At 45 dBA and above, about half of the respondents reported that they were annoyed by wind turbine noise. A comparison of Figs. 2(a) and 2(b) reveals that in wind turbine noise categories above 45 dBA, project participants reported less audibility and annoyance than non-participants. Furthermore, all non-participants with a modeled wind turbine sound level of 47.5 dBA $L_{1h\text{-}max}$ or greater reported hearing wind turbine noise on their property.

Table IV expands on the distribution of responses and sample characteristics by sound level category. It reveals the following:

- Larger projects (more turbines) were associated with higher sound level categories (Spearman's $\rho = 0.47$).
- Average background sound levels tended to be lower in higher wind turbine sound level categories.[13]
- College education, whether a respondent identified as white, and income were strongly associated with audibility but less so with noise annoyance.
- About 90% of respondents within 5 km could see wind turbines from their property.
- Higher sound level categories were significantly associated with higher rates of negative visual perceptions (except above 50 dBA).[14]
- More than 2/3 of respondents with wind turbine sound levels above 40 dB could hear the turbines on their property. Of these, about 2/3 also reported hearing turbines in their home.
- Among respondents who reported hearing wind turbines on their property, the annoyance level was statistically significant with respect to sound level category only when project participants were excluded from the analysis.

Further analysis reveals that there was a significant association between noise annoyance level and hearing wind turbines inside the home (Chi-squared test, $p < 0.001$). However the directionality of the association is important: while respondents who reported hearing wind turbine noise in their home were not necessarily Very Annoyed by the noise (27% of respondents who reported hearing wind turbine noise in their home found it very annoying), nearly all respondents who were Very Annoyed by the noise also reported hearing wind turbine noise in their home (72 out 73 Very Annoyed responses).

B. Regression model results

Three successive models are presented for testing the multivariable relationships between respondent audibility and noise annoyance: the Basic variables model, the Observable variables model, and the Subjective variables model. Each model includes the variables contained in the preceding iteration.

1. Audibility

Wind turbine sound level was the strongest predictor of wind turbine audibility (Table V). Background sound levels also had a significant effect, albeit in the opposite direction. With project participation, sound levels, and controlling variables accounted for, wind turbine audibility outdoors was predicted correctly 80% of the time. Adding in observable quantities was found to improve the R_N^2 from 0.54 to 0.58. Although age, atmospheric stability, DNL correction, rotor tip speed, turbine view from property, and move-in after construction of the local project were significant, the overall ability of the model to correctly predict audibility remained unchanged (i.e., 80% of responses predicted correctly). Finally, adding in the subjective variables did not improve audibility predictions; no subjective variables were significant. Thus, wind turbine sound level is the most important

TABLE IV. Sample characteristics as a function of wind turbine sound level category. Each variable was assessed for significant variability across sound level categories. Categorical (and binary) variables were assessed with Pearson's chi-squared test and continuous variables were assessed with one-way ANOVA. The distribution of characteristics across exposure categories is shown for the audibility dataset ($n = 749$). Only overall values (and p-values) are included for each variable in the context of the annoyance dataset ($n = 407$). Lastly, noise annoyance is assessed across sound level categories for all respondents and only non-participants.

		Sound Level Category						Audibility		Annoyance	
Variable Name	Statistic	<30	[30–35)	[35–40)	[40–45)	[45–50)	[50 +	Overall	*p*-value	Overall	*p*-value
Sample size	*n*	82	90	143	244	177	13	749		407	
Distance (km)	Mean (SD)	2.9 (1.1)	2 (0.9)	1.3 (0.5)	0.8 (0.3)	0.5 (0.2)	0.2 (0.1)	1.2 (0.9)	<0.001	0.8 (0.4)	<0.001
	Min–Max	1.2–4.8	0.9–4.6	0.5–3.2	0.3–1.6	0.2–1.1	0.1–0.4	0.1–4.8		0.1–4.2	
Female	%	41	54	56	59	51	38	54	0.067	54	0.445
Age	Mean (SD)	61 (15)	60 (15)	57 (14)	58 (14)	58 (15)	61 (17)	59 (15)	0.433	57 (14)	0.349
College	%	68	50	56	37	45	31	47	<0.001	45	0.146
White	%	82	87	90	92	97	100	91	<0.001	96	0.017
Median income[a]	*n*: Mean (SD)	71: 8.5 (5.2)	82: 7.5 (5)	130: 6.7 (4.8)	220: 6.5 (4.6)	156: 8.3 (5.6)	11: 10.8 (6.6)	672: 7.4 (5.1)	<0.001	365: 7.6 (5.1)	0.022
Dominant project	%	12	14	15	9	3	0	10	0.002	4	0.318
Discrete project	%	41	41	42	56	60	54	51	0.002	54	0.023
# of Turbines	Mean (SD)	15.7 (34.1)	31.3 (45.7)	40.3 (51.7)	59.6 (57.4)	87.6 (60)	104.3 (84.2)	55 (59)	<0.001	70 (59)	<0.001
	Min–Max	1–152	1–152	1–193	1–222	1–222	1–222	1–222		1–222	
Project Participation **No**/Comp./Host comp.	%[b]	100/0/0	97/3/0	94/6/0	77/20/4	55/30/15	31/15/54	79/15/6	<0.001	68/25 /7	<0.001
Background L_{50} (dBA)	Mean (SD)	45.2 (5.2)	44 (5)	42.2 (4.9)	41.3 (4.1)	40.5 (2.6)	40.6 (2.6)	42 (4.5)	<0.001	40.4 (3.1)	<0.001
	Min–Max	32.9–52.2	33.3–52.2	33.3–52.2	32.3–52.2	36.5–52.2	38.5–46	32.3–52.2		32.9–52.2	
Turbine view	%	56	79	87	96	99	100	89	<0.001	98	0.132
Move-in after	%	30	23	22	20	19	8	21	0.23	16	0.757
Prior attitude: **Neutral**/Neg./Pos./ Move-in after	%[b]	41/4/24/30	48/6/23/23	48/7/23/22	39/10/32/20	32/13/36/19	31/0/62/8	40/9/30/21	0.006	39/13/32/16	0.304
Noise sensitive: Not at all to Very	%[b]	30/28/18/13/10	17/38/23/14/8	25/37/17/11/9	23/32/22/14/9	37/26/21/11/5	15/46/15/15/8	27/32/20/12/8	0.249	26/31/22/13/8	0.399
Like look of wind project: **Neutral** / No / Yes	%[b]	17/1 /72	14/18/68	19/20/61	13/27/61	6/32/61	8/8/85	13/24/63	<0.001	11/32/57	0.088
Hear on property	%	4	17	38	69	88	92	54	<0.001	100	
Hear in home	%	2	8	20	41	64	69	35	<0.001	64	0.019
Annoyance sample	*n*	3	15	54	169	154	12			407	0.577
Annoyance levels[c]	%[b]	67/33/0	73/20/7	54/33/13	46/36/19	44/36/21	58/33/8			47/35/18	
Annoyance sample (non-participants only)	*n*	3	14	49	120	88	4			278	0.011
Annoyance levels[c]	%[b]	67/33/0	79/21/0	51/35/14	45/34/21	28/40/32	25/75/0			42/36/22	

[a]Median income of survey selected census categories (×$10 000).
[b]Percentages may not add to 100 due to rounding.
[c]Dependent variable tested in Noise Annoyance model. Noise Annoyance levels = Not at all Annoyed/Mildly Annoyed/Very Annoyed.

TABLE V. Audibility model results. For each variable included in each model, the OR, its 95% CI, and ΔAIC value are provided. ORs that are bolded and underlined denote statistical significance ($p < 0.05$).

($n = 749$)		BASIC			OBSERVABLE			SUBJECTIVE	
Nagelkerke R^2		0.54			0.58			0.60	
AUC		0.80			0.79			0.80	
Maximum VIF		1.72			2.36			2.30	
Proportion Predicted Correctly									
Cannot Hear		0.74			0.73			0.74	
Hear on Prop.		0.86			0.86			0.86	
Total Proportion Correct		0.80			0.80			0.80	
Variable	**OR**	**(95% CI)**	**ΔAIC**	**OR**	**(95% CI)**	**ΔAIC**	**OR**	**(95% CI)**	**ΔAIC**
Female	1.01	(0.68, 1.49)	−2	1.00	(0.66, 1.49)	−2	0.95	(0.63, 1.45)	−2
Respondent age	0.99	(0.98, 1.01)	0	**0.99**	(0.97, 1[a])	2	0.99	(0.97, 1.001)	1
College	**1.52**	(1.001, 2.29)	2	1.46	(0.95, 2.23)	1	1.37	(0.88, 2.12)	0
White	1.41	(0.63, 3.17)	−1	1.62	(0.67, 3.92)	−1	1.52	(0.63, 3.69)	−1
Dominant project	**0.42**	(0.18, 0.98)	2	**0.40**	(0.16, 0.96)	2	**0.39**	(0.16, 0.98)	2
Discrete project	0.77	(0.5, 1.19)	−1	**0.61**	(0.37, 0.99)	2	**0.60**	(0.37, 0.996)	2
Number of turbines in project	1.00	(0.99, 1.002)	−1	1.00	(0.995, 1.003)	−2	1.00	(0.995, 1.003)	−2
Project participation (Non-participant[b])			19			19			16
– Compensated: not a host	**2.01**	(1.01, 4.01)		1.73	(0.85, 3.55)		**2.14**	(1.03, 4.43)	
– Compensated: turbine host	**0.20**	(0.09, 0.45)		**0.17**	(0.07, 0.38)		**0.22**	(0.09, 0.52)	
Wind turbine sound level ($L_{1h\text{-}max}$)	**1.32**	(1.26, 1.38)	131	**1.31**	(1.25, 1.38)	111	**1.31**	(1.25, 1.38)	103
Summer daytime background L_{50}	**0.88**	(0.83, 0.94)	13	**0.91**	(0.85, 0.98)	5	**0.93**	(0.86, 0.99)	3
Atmospheric stability[c]				**1.02**	(1.002, 1.04)	3	**1.02**	(1.003, 1.04)	3
DNL correction				**1.35**	(1.07, 1.71)	4	**1.38**	(1.09, 1.75)	5
Sound power C-to-A ratio*				0.96	(0.82, 1.12)	−2	0.96	(0.82, 1.13)	−2
Rotor diameter				0.98	(0.96, 1.01)	0	0.98	(0.96, 1.01)	0
Turbine hub height				0.99	(0.96, 1.02)	−1	0.99	(0.96, 1.02)	−1
Rotor tip speed				**1.08**	(1.03, 1.14)	9	**1.08**	(1.03, 1.13)	8
View of turbine from property				**3.87**	(1.52, 9.85)	6	**4.27**	(1.66, 10.94)	7
Move-in after construction				**0.56**	(0.34, 0.94)	3			
Prior attitude (Neutral)[b]									2
– Negative							2.10	(0.83, 5.35)	
– Positive							0.85	(0.5, 1.44)	
– Move-in after construction							0.57	(0.32, 1)	
Noise sensitive (Not at all)[b]									−4
– Slightly							1.27	(0.74, 2.19)	
– Somewhat							1.71	(0.92, 3.16)	
– Moderately							1.34	(0.65, 2.78)	
– Very							2.14	(0.88, 5.18)	
Like look of wind project (Neutral)[b]									2
– No							1.34	(0.65, 2.78)	
– Yes							2.14	(0.88, 5.18)	

[a]Value rounds to 1 at 3 significant digits yet is indeed less than 1 (p-value = 0.04).
[b]Compared to reference level; ΔAIC represents importance of the variable as a whole.
[c]Atmospheric stability (mean inverse Obukhov length) is scaled by 1000 in the model to improve interpretation of results.

predictor of audibility, with a ΔAIC score almost an order of magnitude higher than the next highest covariate: a 1 dB increase in wind turbine sound level is associated with an increase in the odds of hearing the local wind project by 31% [OR 1.31; *95% Confidence Interval* (*CI*): 1.25–1.38]. For additional context, a 3 dB increase in wind turbine sound level translates to an increase in the odds of hearing the local wind project by a factor of 2.3 (95% CI: 2.14–2.38).

Project participation was the second most important factor for predicting audibility. The odds of hearing wind turbines were 2.1 (95% CI: 1.03–4.43) times higher for those who were compensated without hosting a turbine than for non-participants (Table V). However, turbine hosts had lower odds (OR: 0.22; 95% CI: 0.09–0.52) than non-participants of hearing wind turbines on their property. The lower audibility among wind turbine hosts is counterintuitive and is discussed in Sec. IV B.

Although much less important than sound levels and project participation, several other independent variables were significant factors in determining wind turbine audibility. Faster tip speeds were associated with increased audibility: the OR indicates that an increase of 1 m/s in tip speed is associated with an increase in the odds of hearing the local wind project by 8% (OR: 1.08; 95% CI: 1.03–1.13). Increases in long-term wind turbine sound power emissions relative to the maximum reported sound power level (DNL correction) and atmospheric stability, as well as being able to see the turbine from one's property, were significantly associated with increased odds of hearing the local wind project on one's property. Higher background sound levels were significantly associated with decreased odds of hearing wind turbines on one's property (OR: 0.93; 95% CI: 0.86–0.99).

2. Noise annoyance

While significant in all three Noise Annoyance models, sound levels were not the dominant predictor of the response variable (Table VI). In the Basic Noise Annoyance model, wind turbine sound level, background L_{50}, and project participation were significant. Project participation was the most important variable, decreasing the odds of being annoyed by wind turbine noise by 86% if hosting (OR: 0.14; 95% CI: 0.06–0.35) and 58% if not hosting (OR: 0.42; 95% CI: 0.27–0.68). However, the R_N^2 of this first model was just 0.12, with no Very Annoyed responses predicted by the cross-validation procedure.

In the Observable model, rotor diameter (OR: 1.03; 95% CI: 1.004–1.06) and move-in after construction (OR: 0.37; 95% CI: 0.21–0.66) became significant in addition to the previous variables, which resulted in a modest increase in R_N^2 to 0.17. The Observable model was still only able to

TABLE VI. Noise Annoyance model results. For each variable included in each model, the OR, its 95% CI, and ΔAIC value are provided. ORs that are bolded and underlined denote statistical significance ($p < 0.05$).

($n = 407$)		BASIC			OBSERVABLE			SUBJECTIVE	
Nagelkerke R²		0.12			0.17			0.56	
AUC		0.61			0.61			0.78	
Maximum VIF		1.35			2.02			2.23	
Proportion Predicted Correctly									
Not at all		0.75			0.64			0.83	
Mildly		0.38			0.40			0.38	
Very		0.00			0.04			0.52	
Total Proportion Correct		0.48			0.45			0.62	
Variable	**OR**	**(95% CI)**	**ΔAIC**	**OR**	**(95% CI)**	**ΔAIC**	**OR**	**(95% CI)**	**ΔAIC**
Female	0.90	(0.61, 1.32)	−1	0.87	(0.59, 1.29)	−1	**0.60**	(0.39, 0.94)	3
Respondent age	1.00	(0.98, 1.01)	−2	0.99	(0.98, 1.01)	−1	0.99	(0.97, 1.003)	1
College	1.00	(0.67, 1.49)	−2	1.10	(0.73, 1.64)	−2	0.96	(0.6, 1.51)	−2
White	2.52	(0.74, 8.53)	−1	2.98	(0.77, 11.52)	0	1.52	(0.37, 6.34)	−2
Dominant project	2.62	(0.89, 7.72)	1	**3.46**	(1.12, 10.71)	2	3.39	(0.95, 12.1)	2
Discrete project	0.92	(0.6, 1.39)	−2	0.94	(0.59, 1.48)	−2	1.11	(0.65, 1.89)	−2
Number of turbines in project	1.00	(0.997, 1.005)	−2	1.00	(0.997, 1.004)	−2	1.00	(0.99, 1.003)	−2
Project participation (Non-participant[a])			22			21			−1
– Compensated: not a host	**0.42**	(0.27, 0.68)		**0.43**	(0.27, 0.7)		0.90	(0.52, 1.57)	
– Compensated: turbine host	**0.14**	(0.06, 0.35)		**0.14**	(0.06, 0.36)		0.42	(0.15, 1.19)	
Wind turbine sound level ($L_{1h\text{-}max}$)	**1.08**	(1.03, 1.14)	10	**1.08**	(1.02, 1.14)	8	**1.09**	(1.02, 1.16)	5
Summer daytime background L_{50}	**0.90**	(0.84, 0.97)	7	**0.89**	(0.82, 0.97)	6	0.92	(0.84, 1.01)	1
Atmospheric stability[b]				0.99	(0.97, 1.01)	−1	0.98	(0.96, 1.01)	0
DNL correction				0.94	(0.75, 1.19)	−2	1.25	(0.95, 1.65)	1
Sound power C-to-A ratio*				1.01	(0.88, 1.15)	−2	0.96	(0.83, 1.11)	−2
Rotor diameter				**1.03**	(1.004, 1.06)	3	**1.04**	(1.01, 1.07)	5
Turbine hub height				1.02	(0.99, 1.04)	−1	0.99	(0.96, 1.02)	−2
Rotor tip speed				0.98	(0.94, 1.02)	0	1.00	(0.95, 1.05)	−2
View of turbine from property				0.46	(0.1, 2.15)	−1	0.44	(0.08, 2.39)	−1
Move-in after construction				**0.37**	(0.21, 0.66)	10			
Prior attitude (Neutral)[a]									13
– Negative							0.97	(0.48, 1.96)	
– Positive							**0.45**	(0.25, 0.8)	
– Move-in after construction							**0.24**	(0.12, 0.48)	
Noise sensitive (Not at all)[a]									14
– Slightly							**2.24**	(1.19, 4.2)	
– Somewhat							**2.57**	(1.3, 5.08)	
– Moderately							**2.98**	(1.33, 6.66)	
– Very							**8.49**	(3.33, 21.6)	
Like look of wind project (Neutral)[a]									81
– No							**11.0**	(4.8, 25.4)	
– Yes							0.49	(0.23, 1.05)	

[a]Compared to reference level; ΔAIC represents importance of the variable as a whole.
[b]Atmospheric stability (mean inverse Obukhov length) is scaled by 1000 in the model to improve interpretation of result.

predict 4% of Very Annoyed respondents, with 45% of responses correctly predicted overall. In the Subjective model, the addition of subjective variables resulted in a considerable increase in model performance ($R_N^2 = 0.56$). The Subjective model was able to correctly predict 52% of the Very Annoyed responses (total proportion correct of 0.62). All newly added variables (i.e., prior attitude, noise sensitive and like the look were statistically significant and had the highest ΔAIC values. Although project participation was the most important variable in the Basic and Observable and Noise Annoyance models, accounting for subjective variables rendered project participation status insignificant. Background L_{50} also lost significance once subjective variables were added.

The strongest correlates with noise annoyance were subjective factors (including self-reported noise sensitivity). Visual impression (like the look) was the most important factor (OR: 11; 95% CI: 4.8–25.4) in predicting noise annoyance with an ΔAIC of 81 compared to 14 for the next most important variable (noise sensitive). Respondents who reported the highest level of noise sensitivity had 8.5 times higher odds of moving to the next level of annoyance compared to respondents who reported no noise sensitivity (OR 8.49, 95% CI: 3.33–21.6) and about 3 times the odds of moving to the next level of annoyance compared to the middle three levels of self-reported noise sensitivity. While having prior positive attitude was important in the model, having had a negative attitude was not significantly different from the reference (neutral) group (OR: 0.97; 95% CI: 0.48–1.96). This may be due to the strong association between negative attitude and negative visual impressions: 73% of respondents with negative prior attitudes toward the project also reported that they did not like the look. In the absence of like the look, all levels of prior attitude, including negative attitude, were significant (results not shown).

The addition of the subjective variables had a notable effect on the importance of project participation in the Noise Annoyance models. Wind project participation was the strongest predictor ($\Delta AIC > 20$) until subjective variables were included in the regression. No wind turbine hosts reported being Very Annoyed by wind turbine noise. In contrast, 13 out of 113 respondents who were compensated without hosting a turbine reported being Very Annoyed by wind turbine noise. Survey responses revealed strong relationships between project participation and perceptions of the wind project,[15] which may explain the change in importance of project participation upon the addition of the subjective variables.

Alongside subjective variables, wind turbine sound levels, turbine rotor diameter, identifying as female, and move-in after were significant in the final Noise Annoyance model. A 1 dB increase in wind turbine sound level was found to be associated with an increase in the odds of moving to the next level of annoyance by 9% (OR: 1.09; 95% CI: 1.02–1.16). For context, a 3 dB increase in wind turbine sound level translates to a 28% increase in the odds of moving to the next annoyance level (95% CI: 1.20–1.36). Increased wind turbine rotor diameters were associated with greater noise annoyance: for each 1 m increase in rotor diameter, the odds of moving to the next level of noise annoyance increased by 4% (OR: 1.04; 95% CI: 1.01–1.07). Also, females had lower odds of moving to the next annoyance level than males (OR: 0.60; 95% CI: 0.39–0.94), signifying that when subjective factors were accounted for, females had lower odds of moving to the next level of noise annoyance than males.

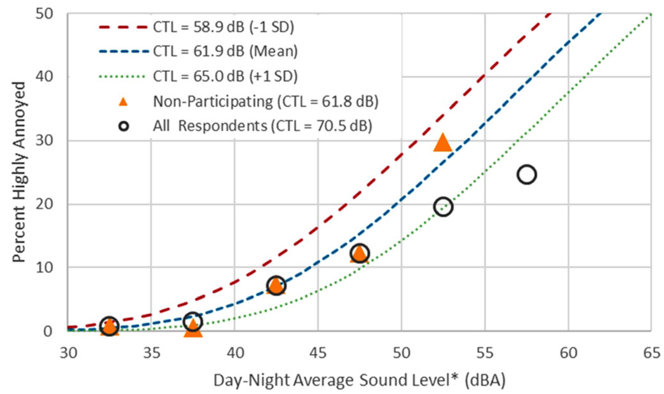

FIG. 3. (Color online) The percent Highly Annoyed for each sound level category represents the response of the population living near wind turbines in the U.S. (the data are weighted). Results are binned in 5 dB DNL* increments. The points for non-participating respondents exclude respondents who were compensated or hosted wind turbines on their property; the datasets diverge above the 45 to 50 dB sound level category. CTL curves for 58.9 and 65 dB are the ±1 SD exposure response for wind turbine noise as reported in Michaud *et al.* (2016b).

C. Dose-response analysis

Figure 3 depicts the percent Highly Annoyed by sound level category for the entire study sample and for those who were not project participants. The data are plotted alongside the ranges of wind turbine CTL calculated by Michaud *et al.* (2016b). When project participants were included, the rate of increase of the percentage of Highly Annoyed individuals decreased above 50 dBA (DNL*) and no longer followed the third-order polynomial trend. From this study, the CTL was estimated to be 61.8 dB when project participants were excluded from the calculation and 70.5 dB when project participants were included (CTLs for unweighted data are similar: 60.8 dB for non-project participants and 68.0 dB for all respondents). The mean CTL among six studies in Europe and Canada was 61.9 dB (Michaud *et al.*, 2016b), so the value calculated in the U.S. (for non-participants) falls near the international average.

IV. DISCUSSION

A. Dependent variable design

Separating the prediction of audibility from that of noise annoyance distinguishes the various factors that contribute to reaction to wind turbine noise. Audibility is largely a function of wind turbine sound level, while alternatively, noise annoyance from audible sound is largely a function of subjective factors (though wind turbine sound level is also a significant factor). Residents who are unable to perceive a community noise source and those that notice a community noise—but express no annoyance toward the sound—represent two separate groups of individuals with distinct experiences; they should not be treated as one. Regardless, the range of R_N^2 and the predictive characteristics of the models (i.e., poor prediction of noise annoyance without subjective variables) presented in this work show good agreement with prior literature performing similar analyses, albeit with slightly different response variables (e.g., Michaud *et al.*, 2016b).

B. Factors influencing wind turbine audibility and noise annoyance

The long-term average sound level is useful for comparing to other dose-response studies and for considering long-term exposure to wind turbine sound, but many jurisdictions often use short-term sound levels to set standards (Fowler *et al.*, 2013). This study helps bridge that gap by using the $L_{1h\text{-}max}$ as the primary sound level metric in regressions yet also calculating a long-term sound level metric (i.e., DNL) to compare to other studies. The dose-response analysis reveals that wind turbine noise annoyance in the U.S. (among the population not receiving personal benefits from the local project) is comparable to the international average CTL calculated by Michaud *et al.* (2016b) and thus supports the assertion that wind turbines are more annoying than other community noise sources at similar long-term sound pressure levels. When project participants were included in the dose-response relationship, the community became more tolerant of wind turbine noise, particularly at higher sound levels, which parallels results found by van den Berg *et al.* (2008).

This study showed that background sound levels affected the audibility of wind turbines, which is most likely due to the masking of wind turbine sound by other sources (Nelson, 2007). Using partially masked loudness (Zwicker and Fastl, 2007) to calculate the "residual" loudness of wind turbine noise in contrasting ambient soundscapes, Nelson showed that perceived loudness of wind turbine noise is a function of the character of the existing background sound. Background sources can include natural sounds (e.g., wind, water, foliage, and insects) and anthropogenic sounds (e.g., transportation, agriculture, and industry) that vary considerably with time and place. Therefore, the masking provided by background sound and its impact on wind turbine audibility is often difficult to accurately quantify in absolute terms (Hathaway and Kaliski, 2006). Thus, caution is in order for using this research as the basis to create regulatory limits relative to background sound levels.

Atmospheric conditions can produce substantial changes in sound levels experienced from a given community noise sources at a given location (Kaliski *et al.*, 2018a). Projects sited in areas with more stable atmospheric conditions (on average) and higher long-term wind turbine sound emissions (relative to short-term levels) were significantly associated with increased audibility. However, these factors had no influence on noise annoyance, which suggests that the $L_{1h\text{-}max}$ is just as suitable for predicting noise annoyance as long-term averages. Modeling the $L_{1h\text{-}max}$ using simple parameters eliminates the problems of comparing results between researchers that use different methodologies to calculate long-term averages and avoids the larger uncertainties related to modeling sound levels over a typical year for every unique respondent.

Although the C-A ratio is a good indicator of the relative low-frequency content present in a sound, the results of this study indicate that the relative low-frequency dominance of nearby wind turbines did not have a significant effect on either audibility or noise annoyance. That is, with overall sound levels accounted for, wind turbines with higher C-A ratios did not significantly result in higher audibility or noise annoyance in the regression models. This finding supports the observation by Leventhall (2003) that the C-A ratio is not a suitable predictor for annoyance. However, in this study, the caveat remains that the C-A ratio was only tested with data down to the 63 Hz octave band due to poor availability of low-frequency spectral data on turbines sound powers tested prior to 2012.

In the presence of the covariates assessed, project size was found to have no significant effect on either audibility or noise annoyance. However, a significant trend of increasing project size with increasing sound level category existed in the sample, which the authors believe to be related to the expansive footprint of larger projects in rural areas where respondents may receive sound from multiple nearby turbines. Project size is not significant in the regression models perhaps because the variability accounted for by project size is better explained by wind turbine sound levels. That is, according to the Baron and Kenny (1986) criteria, wind turbine sound level is the "mediator" variable through which the effect of project size is realized.

Whether a turbine can be viewed from a property has been found in other studies to affect noise annoyance (Pedersen and Pernilla, 2008; van den Berg *et al.*, 2008). In this study, turbine visibility is a significant variable in the Audibility model: the odds of hearing wind turbines were 4.3 (95% CI: 1.66–10.9) times higher for respondents who could see a turbine from their property. However, as in Michaud *et al.* (2016b), this study found that the effect on noise annoyance was not significant.

The regression models showed that those who move in after a wind project is constructed had 44% lower odds of hearing the wind turbines (Table V) and 63% lower odds of being annoyed by their sound compared to prior residents (Table VI). In general, those who moved in after wind development were less annoyed by wind turbine noise than those who lived in the area prior to the project being built. This aligns with Tiebout's (1956) original theory that suggests that "sorting" will encourage more supportive (and therefore, less-negative) individuals to move into the community. As we did not sample those individuals who moved out, we cannot say whether or not they voted with their feet due to audibility and noise annoyance. Firestone *et al.* (2018) suggest that existing residents may have been more likely to express negative attitudes toward a project than those who moved in afterward because some of them may have been negatively affected by the process leading to permitting, had negative experiences with the developer, or perceived a negative change in the landscape. However, Firestone *et al.* (2018) also found that the opposite was true if residents perceived the development process to be open, transparent, and inclusive. In this study, compared to respondents who were neutral toward the project prior to construction, a positive prior attitude significantly decreased the odds of noise annoyance; negative prior attitudes were significantly associated with increased noise annoyance, but only when visual impressions were excluded from the model.

Previous studies on wind turbine noise have identified subjective factors as important drivers of noise annoyance. Self-reported noise sensitivity and whether a respondent feels that the wind turbines mar the landscape have been found to increase noise annoyance from wind turbines (Pawlaczyk-Łuszczynska *et al.*, 2014; Pedersen and Persson Waye, 2004; Michaud *et al.*, 2016b). Consistent with those findings, the Noise Annoyance model including subjective variables in this study shows that both variables have a significant effect on noise annoyance, with visual effect (appearance) as the most important for noise annoyance. However, the direction of causation for this effect is not known: it is not possible to determine whether someone is more likely to be annoyed by wind turbine noise because they object to wind turbines visually or whether noise annoyance has led them to have a negative association with the visual aspects of the wind turbines. In other words, one cannot determine whether these effects are re-enforcing, or whether they are endogenous—that is, jointly determined.

This study categorized respondents who received personal benefits from their local wind project as those hosting a wind turbine on their property and those who were not. The regression model results demonstrate that these two groups of project participants are significantly different. In regard to wind turbine audibility, the Audibility model established that non-hosting participants had the highest odds of hearing wind turbines on their property, while wind turbine hosts had the lowest odds. The lower odds of audibility among wind turbine hosts is a nonintuitive result, given that hosts, on average, had the highest wind turbine sound levels in the sample.[16] The unexpected result could be due to the relatively small sample size of hosts ($n=43$), but outliers that could have disproportionately affected the results were not apparent. Alternatively, the authors speculate that as the oldest[17] group of the "project participation" variable, age-induced hearing loss may have contributed to the lower odds of wind turbine audibility among hosts.[18] In regard to noise annoyance, in the absence of subjective variables, wind turbine hosts had lower odds of moving to the next level annoyance than both non-participants and participants not hosting wind turbines.

Among project participants in this study, participants not hosting wind turbines on their property generally held more negative attitudes and perceptions toward the project than wind turbine hosts. Negative impressions among non-hosts may be due to compensation itself as a validation of a specific negative impact of the project or a missed opportunity for additional revenue from the project. Neighbor agreements (compensation for impacts, such as noise) and variances (monetary waivers for deviations from land-use regulations) are formal admissions of local impacts (NYSERDA, 2017). Also, since hosting a turbine was more lucrative than not hosting one (see footnote 6), non-hosts may have been disappointed that they missed out on an income opportunity, if, for example, the final wind turbine array layout did not include a wind turbine on their property.

C. Study limitations

Although the degree of regularity of audibility was not established by the survey instrument, the audibility of wind turbine noise tested in this study was formulated based on questions implying a present stimulus ("Can you…hear," i.e., "Are you able to…hear") and thus relies on the respondent's interpretation of the question. Moreover, the survey did not assess if a respondent had normal hearing.

The survey did not explicitly inquire about the location where respondents experienced the reported noise annoyance (i.e., at home or elsewhere in the community). To provide confidence in assessing noise annoyance at one's residence, the less than 3% of respondents who were unable to hear wind turbines on their property that reported at being at least Slightly Annoyed by wind turbine noise were excluded from the Noise Annoyance model in this study. These respondents may have been exposed to wind turbine noise at a location that did not correspond to their residence or they may have indicated noise annoyance without any exposure. Limiting the tested noise annoyance response to those who reported hearing wind turbines on their property increased the likelihood of predicting annoyance for the location where sound was modeled.

The survey instrument's method of assessing annoyance level deviated from the ISO/TS 15666 (2003), "Acoustics—Assessment of noise annoyance by means of social and socio-acoustic surveys," because noise annoyance was not the only research effort involved (see footnote 1) and consistency in the response scale throughout the multipurpose survey was of greater importance. The result is that the assignment of Highly Annoyed was based on the authors' interpretation of the survey responses.

While the overall response rate was higher for respondents living closer to wind turbines, selection bias was not found (see footnote 5). Moreover, given that the study focused on modeled sound level rather than distance *per se*, individuals living closest (i.e., within 1.6 km) were most valuable to this study. Selection bias, if found, would be concerning if those who lived closer to wind turbines responded at lower rates than those who lived farther away.

Field measurements to validate the sound propagation modeling were not performed due to budgetary constraints and impracticality. Meaningful measurements would have required wind turbine operational data to inform the expected sound power level as well as precise meteorological data to understand the propagation conditions. Likewise, field measurements would have required cooperation from wind turbine project operators to shut down wind turbines so that background sound could be assessed and subtracted from the measurements.

V. CONCLUDING REMARKS

The factors that affect wind turbine audibility and noise annoyance are distinct: wind turbine sound level is the strongest predictor of audibility while more experiential and psychological variables, such as visual perception, self-reported noise sensitivity, and prior attitude/move-in after, were the strongest predictors of noise annoyance in this study. The results suggest that wind turbine noise annoyance is mostly an expression of personal experience and visual perceptions rather than an objective response to wind turbine sound level. Increasing summer daytime median background sound levels were significantly associated with decreased audibility and noise annoyance, but the effect was relatively small (and insignificant for noise annoyance once subjective variables were considered). For respondents not receiving personal benefits from their local wind project, the estimated CTL for wind turbine noise in this study (60.8 dB) is consistent with research results from other countries, validating the notion that communities are less tolerant of wind turbines than other environmental noise sources at the same long-term A-weighted sound level.

Several avenues of future research could help further explain wind turbine audibility and noise annoyance:

- The simulation of long-term sound level emissions in this study considered neither the frequency of unstable atmospheric conditions nor the percent of time a respondent is downwind from the local project (the amount of time downwind from a source is known to affect sound levels received from wind turbines; RSG *et al.*, 2016). Fully accounting for these would produce a more accurate estimation of site-specific DNL. Most dose-response studies do not simulate the effect of changing sound propagation conditions throughout a year, using only a fixed constant to go from a single modeled (or monitored) sound level to a long-term average. This is a drawback that should be addressed in future studies using long-term sound metrics.
- In the regression model, inverse Obukhov length and long-term wind turbine sound power emissions relative to the maximum reported sound power level were significant predictors of audibility. Thus, several sound level-related metrics, as opposed to a single sound level, may provide a better understanding of objective wind turbine sound exposure. Further research on wind turbine audibility could consider additional variables such as wind shear and turbulence, which have been postulated to affect the level of amplitude modulation from wind turbines (Renewable UK, 2013).
- The authors encourage, where possible, a more holistic definition of annoyance response to be considered that includes perception (i.e., audibility), personal evaluation of the noise (i.e., self-reported annoyance), and symptoms (stress indicators, health effects, sleep impacts). See Pohl *et al.* (2018) and Michaud *et al.* (2016c).
- The survey results indicated that most Very Annoyed individuals could hear the wind turbine in their home. Further research is needed to understand the mechanisms that permit hearing sound in one's home (e.g., home construction or window type) and whether improvements to sound insulation or sound masking can consistently be used to reduce wind turbine audibility and noise annoyance, and if they supersede the correlations with subjective variables found in this study.
- The effects of physical wind turbine characteristics should be further investigated. Increases in wind turbine rotor diameter correspond to an increase in tip speed absent a decrease in rotor speed. Therefore, as wind turbines get larger, higher levels of audibility and noise annoyance may occur.

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[1]A summary of the overall project can be found at https://emp.lbl.gov/projects/wind-neighbor-survey.

[2]U.S. Wind Turbine Data accessible here: https://eerscmap.usgs.gov/uswtdb/.

[3]See supplementary material at https://doi.org/10.1121/1.5121309 for mail-based survey instrument.

[4]Introductory telephone script: "Hello, my name is <fill in name> and I'm calling from Portland State University on behalf of the U.S. DOE. We're conducting a survey of people living near wind power projects throughout the United States to better understand their experiences, perceptions, and opinions. The survey is completely voluntary and confidential. It should take about 15 to 20 minutes and you can skip any item you don't want to answer or stop the survey at any time. Is now a good time to do the survey?"

[5]Nonresponse bias was examined through the influence of the two dependent variables (wind turbine audibility and noise annoyance) by comparing the responses of "late responders"—those who responded only after being contacted by telephone and not responding and then being contacted by mail and offered the opportunity to respond by mail or online—to those who responded to a single mode of contact. In each case, whether the data were unweighted, weighted but not with regard to distance, or fully weighted, the means between the two populations were not statistically significantly different from one another. Likewise, bias from response type was not found: the response modes (mail/phone/internet) were tested as an independent variable in the regression models and never approached significance. As a result, response type was excluded from the regression analysis.

[6]Responses from the survey indicate that wind turbine hosts, on average, were compensated at levels 3 to 4 times that of non-hosts. Some respondents hosted multiple turbines on their property (37% hosted one turbine, 54% hosted two to four turbines, with the remaining 9% hosting more than four). The maximum number of turbines hosted by a single landowner was 12. All but one host indicated that they received annual payments, while 33% of hosts also received an initial lump sum payment. Eighty-five percent of respondents who were compensated without hosting received annual payments, 25% of whom also received a lump sum; the other 15% were provided a lump sum payment only.

[7]The second highest response category in the survey, "Moderately Annoyed," does not elicit a clear language interpretation as Highly Annoyed. The approach taken here *appears* to be consistent with Schultz's interpretation of a 1975 Swedish survey (Rylander *et al.*, 1976) that associated Highly Annoyed only with the Very Annoyed responses.

[8]Turbine sound power data were only consistently available down to the 63 Hz octave band. Sound power below this frequency is scarce because in the 2002 version of IEC 61400-11, the standard for measuring wind turbine, sound power did not require testing at the 31.5 Hz octave band or below. In the revised IEC 61400-11 (2012) standard, the procedure requires testing down to the 20 Hz 1/3 octave band.

[9]Short-term ($L_{1h\text{-}max}$) and long-term (DNL) sound level metrics produced nearly identical results in the regression models (results not shown).

[10]Sampling stratification for oversampling close to turbines (distance bin) and categorical project size were not included in the models due to multicollinearity with variables of interest (mostly wind turbine sound levels and background L_{50}, respectively). However, these sample strata are represented in the models through independent variables (modeled sound level, as a proxy for distance; the number of turbines in a project replaced categorical project size). Model results and conclusions were similar when using the prescribed sample strata, but variances were higher for affected variables (VIF > 3).

[11]As described in Firestone *et al.* (2018), the weighting followed the method known as "iterative raking" or "sample balancing" (Battaglia *et al.*, 2009; Deming, 1943). Sample weights were prepared for over- and under-sampling based on differential response rates by gender, age, and education using American Community Survey (2014) census tract level household and demographic data. Unlike the weights used by Firestone *et al.* (2018), the weighting here did not correct for over- and under-sampling based on the respondents' distance to the nearest turbine because modeled wind turbine sound pressure level is overwhelmingly related to distance from a wind turbine (Pearson's $r = -0.84$) and is thereby accounted for in the models.

[12]Respondent income was not included in the regression models due to missing data (>10% of final sample). This approach was tested by running the same models presented here with the addition of the respondent income variable. Although there were some minor differences in the significance of some variables, respondent income was never statistically significant and the conclusions derived from the model were practically identical.

[13]Background sound level is a corollary of the rural character of an area and is thus strongly related to population density (Pearson's $r = 0.69$, $p < 0.001$). There is a significant relationship between the number of turbines in a project and background sound level (Pearson's $r = -0.45$, $p < 0.001$), as well as the number of turbines and wind turbine sound level (Pearson's $r = 0.41$, $p < 0.001$). This suggests a general trend that for larger projects, which are often sited in more rural areas, higher wind turbine sound levels are common with lower background sound levels.

[14]Thirteen respondents had modeled wind turbine sound levels above 50 dBA. Of these 13 respondents, 69% were turbine hosts or otherwise compensated. The highest modeled $L_{1h\text{-}max}$ was 55.2 dBA at a turbine host's residence; the lowest was 40.2 dBA.

[15]Fifteen percent of project participants had a negative visual perception of the local project, of which approximately 90% were compensated without hosting a turbine. A similar relationship was found between project participants and prior project attitudes: five percent of project participants had negative prior attitudes toward the project, over 90% of which was expressed by project participants that did not host a turbine.

[16]In this study, the average (and SD of) modeled wind turbine sound pressure level are as follows: non-participants ($n = 591$): 38.3 dBA (7); compensated without hosting ($n = 113$): 44.2 dBA (3.8); compensated and hosting a turbine ($n = 43$): 47.5 dBA (3.1).

[17]Respondents who hosted a wind turbine were the oldest group, with a mean age of 63.1 years. On average, wind turbine hosts were 6.2 years older than respondents who were compensated without hosting a turbine and 4.6 years older than non-participants.

[18]For wind turbine hosts, increasing age was significantly associated with decreased wind turbine audibility [one-way analysis of variance (ANOVA), $p = 0.02$], while wind turbine sound level was not significantly associated with audibility (one-way ANOVA, $p = 0.27$). The significant univariate association between age and audibility did not hold for respondents who were compensated without hosting a wind turbine nor for non-participants. However, wind turbine sound level was significantly correlated with audibility for non-participants (one-way ANOVA, $p < 0.001$) and project participants not hosting a turbine (one-way ANOVA, $p = 0.002$), as expected.

ANSI (**2013**). ANSI/ASA S1.1-2013, *Acoustical Terminology* (American National Standards Institute, New York).

Arakawa, C., Fleig, O., Iida, M., and Shimooka, M. (**2005**). "Numerical approach for noise reduction of wind turbine blade tip with Earth simulator," J. Earth Simulator **2**, 11–33, available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.494.9766&rep=rep1&type=pdf.

Baron, R., and Kenny, D. (**1986**). "The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations," J. Person. Soc. Psychol. **51**(6), 1173–1182.

Battaglia, M. P., Izrael, D., Hoaglin, D. C., and Frankel, M. R. (**2009**). "Practical considerations in raking survey data," Survey Practice **2**, 1–10.

Bowdler, D., Bullmore, A., Davis, B., Hayes, M, Jiggins, M., Leventhall, G., and McKenzie, A. (**2009**). "Prediction and assessment of wind turbine noise," Acoust. Bull. **34**(2), 35–37.

DataKustik® GmbH (**2016**). "CadnaA version 4.6," software for emission protection, available at www.datakustik.com (Last viewed October 1, 2018).

Deming, W. E. (**1943**). *Statistical Adjustment of Data* (Wiley, New York, NY).

Dillman, D. A., Smyth, J. D., and Christian, L. M. (**2014**). *Internet, Phone, Mail, and Mixed-Mode Surveys: The Tailored Design Method* (John Wiley & Sons, Hoboken, NJ).

Fawcett, T. (**2006**). "An introduction to ROC analysis," Pattern Recog. Lett. **27**, 861–874.

Fidell, S., Mestre, V., Schomer, P., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2011**). "A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure," J. Acoust. Soc. Am. **130**, 791–806.

Firestone, J., Hoen, B., Rand, J., Elliott, D., Hübner, G., and Pohl, J. (**2018**). "Reconsidering barriers to wind power projects: Community engagement, developer transparency and place," J. Environ. Policy Plan. **20**, 370–386.

Fowler, K., Koppen, E., and Matthis, K. (**2013**). "International legislation and regulations for wind turbine noise," in *Proceedings of the Fifth International Meeting on Wind Turbine Noise, INCE Europe*, Denver, CO.

Geisser, S. (**1993**). *Predictive Inference* (Chapman and Hall, New York, NY).

Hand, D., and Till, R. (**2001**). "A simple generalization of the area under the ROC curve for multiple class classification problems," Mach. Learn. **45**, 171–186.

Harrell, F. E., Jr. (**2001**). *Regression Modeling Strategies: With Applications to Linear Models, Logistic Regression, and Survival Analysis*, 1st ed. (Springer-Verlag, New York).

Harrell, F. E., Jr. (**2018**). "rms: Regression modeling strategies," R package version 5.1-2, available at https://CRAN.R-project.org/package=rms (Last viewed October 11, 2018).

Hathaway, K., and Kaliski, K. (**2006**). "Assessing wind turbines against relative noise standards," in *Proceedings of InterNoise2006*, Honolulu, HI.

Heinze, G., and Dunkler, D. (**2017**). "Five myths about variable selection," Transplant Int. **30**: 6–10.

Hoen, B. D., Diffendorfer, J. E., Rand, J. T., Kramer, L. A., Garrity, C. P., and Hunt, H. E. (**2018**). United States wind turbine database. U.S. geological survey, American Wind Energy Association, and Lawrence Berkeley National Laboratory data release: USWTDB V1.2, available at https://eerscmap.usgs.gov/uswtdb (Last viewed October 1, 2018).

Hongisto, V., Oliva, D., and Keränen, J. (**2017**). "Indoor noise annoyance due to 3-5 megawatt wind turbines—An exposure-response relationship," J. Acoust. Soc. Am. **142**, 2185–2196.

IEC 61400-11 Ed. 2.0 (**2002**). "Wind turbine generator systems— Part 11: Acoustic noise measurement techniques" (International Electrotechnical Commission, Geneva, Switzerland). Withdrawn November 2012.

IEC 61400-11 Ed. 3.0 (**2012**). "Wind turbine generator systems—Part 11: Acoustic noise measurement techniques" (International Electrotechnical Commission, Geneva, Switzerland).

Ingard, U. (**1953**). "A review of the influence of meteorological conditions on sound propagation," J. Acoust. Soc. Am. **25**, 405–411.

ISO 9613-1 (**1993**). "Acoustics. Attenuation of sound during propagation outdoors. Part 1: Calculation of the absorption of sound by the atmosphere" (International Organization for Standardization, Geneva, Switzerland).

ISO 9613-2 (**1996**). "Acoustics. Attenuation of sound during propagation outdoors. Part 2: General method of calculation" (International Organization for Standardization, Geneva, Switzerland).

ISO/TS-15666 (**2003**). "Acoustics—Assessment of noise annoyance by means of social and socio-acoustic surveys" (International Organization for Standardization, Geneva, Switzerland).

James, G., Witten, D., Hastie, T., and Tibshirani, R. (**2017**). *An Introduction to Statistical Learning*, 8th ed. (Springer Science+Business Media, New York).

Janssen, S. A., Vos, H., Eissess, A. R., and Pedersen, E. (**2011**). "A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources," J. Acoust. Soc. Am. **130**, 3746–3753.

Kaliski, K., Bastasch, M., and O'Neal, R. (**2018b**). "Regulating and predicting wind turbine sound in the U.S.," in *Proceedings of InterNoise 2018, Institute of Noise Control Engineering*, Chicago, IL.

Kaliski, K., Haac, T. R., Brese, D., Duncan, E., Reiter, D., Williamson, R., Pratt, G., Salomons, E., Wayson, R., McDonald, J., Zimmerman, J., Snyder, J., and Hastings, A. (**2018a**). NCHRP Research Report 882: How Weather Affects the Noise You Hear from Highways. TRB, National Research Council, Washington, DC.

Keith, S. E., Feder, K., Voicescu, S. A., and Soukhovtsev, V. (**2016a**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**, 1431–1435.

Keith, S. E., Feder, K., Voicescu, S. A., and Soukhovtsev, V. (**2016b**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**, 1436–1442.

Kuwano, S., Yano, T., Kageyama, T., Sueoka, S., and Tachibana, H. (**2014**). "Social survey on wind turbine noise in Japan," Noise Control Engr. J. **62**, 503–520.

Leventhall, Geoff. (**2003**). "A review of published research on low frequency noise and its effects," Department for Environment, Food and Rural Affairs (United Kingdom).

Magari, S., Smith, C. E., Shciff, M., and Rohr, A. C. (**2014**). "Evaluation of community response to wind turbine-related noise in Western New York State," Noise Health. **16**, 228–239.

Mennitt, D., Sherrill, K., and Fristrup, K. (**2014**). "A geospatial model of ambient sound pressure levels in the contiguous United States," J. Acoust. Soc. Am. **135**, 2746–2764.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T., Villeneuve, P. J., Russel, E., Koren, G., and van den Breg, F. (**2016c**). "Self-reported and measured stress related responses associated with exposure to wind turbine noise," J. Acoust. Soc. Am. **139**, 1467–1479.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B., Weiss, S., and van den Berg, F. (**2016a**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**, 1443–1454.

Michaud, D. S., Keith, S. E., Feder, K., Voicescu, S. A., Marro, L., Than, J., Guay, M., Bower, T., Denning, A., Lavigne, E., Whelan, C., Janssen, S. A., Leroux, T., and van den Berg, F. (**2016b**). "Personal and situational variables associated with wind turbine noise annoyance," J. Acoust. Soc. Am. **139**, 1455–1466.

Miedema, H. M. E., and Vos, H. (**1998**). "Exposure-response relationships for transportation noise," J. Acoust. Soc. Am. **104**, 3432–3445.

Møller, H., and Pedersen, C. S. (**2011**). "Low-frequency noise from large wind turbines," J. Acoust. Soc. Am. **129**(6), 3727–3744.

Nagelkerke, N. (**1991**). "A note on a general definition of the coefficient of determination," Biometrika **78**, 691–692.

National Park Service (**2014**). "Data store: Project code 2217356, geospatial sound modeling," U.S. National Park Service, Department of the Interior, available at https://irma.nps.gov/DataStore/Reference/Profile/2217356 (Last viewed October 11, 2018).

Nelson, D. (**2007**). "Perceived loudness of wind turbine noise in the presence of ambient sound," in *Proceedings of the Second International Meeting on Wind Turbine Noise, INCE Europe*, Lyon, France.

NREL (**2018**). "Wind integration national dataset toolkit," National Renewable Energy Laboratory (NREL), U.S. Department of Energy, available at https://www.nrel.gov/grid/wind-toolkit.html (Last viewed October 11, 2018).

NYSERDA (**2017**). "Land Agreements—NYSERDA," New York State Energy Research and Development Authority, available at https://www.nyserda.ny.gov/-/media/Files/Publications/Research/Biomass-Solar-Wind/NY-Wind-Energy-Guide-3.pdf (Last viewed July 1, 2019).

Old, I., and Kaliski, K. (**2017**). "Wind turbine noise dose response—comparison of recent studies," in *Proceedings of Wind Turbine Noise 2017*, Institute of Noise Control Engineering, Rotterdam, Netherlands.

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamosjska-Daniszewska, M., and Waszkowska, M. (**2015**). "Annoyance related to wind turbine sound," Arch. Acoust. **39**, 89–102.

Pawlaczyk-Łuszczyńska, M., Zaborowski, K., Dudarewicz, A., Zamosjska-Daniszewska, M., and Waszkowska, M. (**2014**). "Response to noise generated by wind farms in people living in nearby areas," in *Proceedings of Noise-Con 2014*, Institute of Noise Control Engineering, Fort Lauderdale, Florida.

Pedersen, E., and Pernilla, L. (**2008**). "The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines," J. Environ. Psychol. **28**, 379–389.

Pedersen, E., and Persson Waye, K. (**2004**). "Perception and annoyance due to wind turbine noise—a dose-response relationship," J. Acoust. Soc. Am. **116**, 3460–3470.

Pedersen, E., and Persson Waye, K. (**2007**). "Wind turbine noise, annoyance and self-reported health and well-being in different living environments," Occ. Environ. Med. **64**, 480–486.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in The Netherlands," J. Acoust. Soc. Am. **126**, 634–643.

Picard, R. (**2010**). "GEONEAR: Stata module to find nearest neighbors using geodetic distances, Statistical Software Components S457146," Boston College Department of Economics.

Pohl, J., Gabriel, J., and Hübner, G. (**2018**). "Understanding stress effects of wind turbine noise—The integrated approach," Energy Policy **112**, 119–128.

Rand, J., and Hoen, B. (**2017**). "Thirty years of North American wind energy acceptance research: What have we learned?," J. Energy Res. Soc. Sci. **29**, 135–148.

R Core Team (**2018**). "R: A language and environment for statistical computing," R Foundation for Statistical Computing, Vienna, Austria, available at https://www.R-project.org/ (Last viewed October 11, 2018).

RenewableUK. (**2013**). "Wind turbine amplitude modulation: Research to improve understanding as to its cause and effect." Available at https://www.renewableuk.com/resource/collection/4E7CC744-FEF2-473B-AF2B-135FF2AA3A43/ruk_wind_turbine_amplitude_modulation_dec_2013_v2_(1).pdf (Last viewed May 14, 2019).

Robin, X., Turck, N., Hainard, A., Tiberti, N., Lisacek, F., Sanchez, J.-C., and Müller, M. (**2011**). "pROC: An open-source package for R and S+ to analyze and compare ROC curves," BMC Bioinfor. **12**, 77.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., and Vilariño, M. V. (**2018**). "Mitigation pathways compatible with 1.5 °C in the context of sustainable development," in *Global Warming of 1.5 °C*, available at https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf.

RSG, Epsilon Associates, Inc., and Northeast Wind. (**2016**). "Massachusetts study on wind turbine acoustics," Massachusetts Clean Energy Center and Department of Environmental Protection, available at http://files.masscec.com/research/wind/MassCECWindTurbinesAcousticsStudy.pdf (Last viewed October 11, 2018).

Rylander, R., Sorensen, S., and Kajland, A. (**1976**). "Traffic noise exposure and annoyance reactions," J. Sound Vib. **47**, 237–242.

Schomer, P., Mestre, V., Fidell, S., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2012**). "Role of community tolerance level (CTL) in predicting the prevalence of the annoyance of road and rail noise," J. Acoust. Soc. Am. **131**, 2772–2786.

Schultz, T. J. (**1978**). "Synthesis of social surveys on noise annoyance," J. Acoust. Soc. Am. **64**, 377–405.

Tiebout, C. (**1956**). "A pure theory of local expenditures," J. Political Econ. **64**(5) 416–424.

van den Berg, F. (**2008**). "Criteria for wind farm noise: Lmax and Lden," *Euronoise 2008*, Paris, France (June 29–July 4), pp. 4043–4048.

van den Berg, F., Pedersen, E., Bouma, J., and Bakker, R. (**2008**). "Windfarm perception: Visual and acoustic impact of wind turbine of wind turbine farms on residents," Report FP6-2005-Science-and-Society-20. University of Groningen, Groningen, The Netherlands and University of Gothenburg, Gothenburg, Sweden.

van Kamp, I., and van den Berg, F. (**2017**). "Health effects related to wind turbine sound, including low-frequency sound and infrasound," Acoust. Australia **46**, 31–57.

Vincenty, T. (**1975**). "Direct and inverse solutions of geodesics on the ellipsoid with application of nested equations," Survey Rev. **22**(176), 88–93.

WHO Europe. (**2018**). "Environmental noise guidelines for the European region," World Health Organization Regional Office for Europe, available at http://www.euro.who.int/en/health-topics/environment-and-health/noise/environmental-noise-guidelines-for-the-european-region (Last viewed October 11, 2018).

Zwicker, E., and Fastl, H. (**2007**). *Psychoacoustics, Facts and Models*, 3rd ed. (Springer-Verlag, Berlin).

Personal and situational variables associated with wind turbine noise annoyance

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Personal and situational variables associated with wind turbine noise annoyance

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The possibility that wind turbine noise (WTN) affects human health remains controversial. The current analysis presents results related to WTN annoyance reported by randomly selected participants (606 males, 632 females), aged 18–79, living between 0.25 and 11.22 km from wind turbines. WTN levels reached 46 dB, and for each 5 dB increase in WTN levels, the odds of reporting to be either very or extremely (i.e., highly) annoyed increased by 2.60 [95% confidence interval: (1.92, 3.58), $p < 0.0001$]. Multiple regression models had R^2's up to 58%, with approximately 9% attributed to WTN level. Variables associated with WTN annoyance included, but were not limited to, other wind turbine-related annoyances, personal benefit, noise sensitivity, physical safety concerns, property ownership, and province. Annoyance was related to several reported measures of health and well-being, although these associations were statistically weak ($R^2 < 9\%$), independent of WTN levels, and not retained in multiple regression models. The role of community tolerance level as a complement and/or an alternative to multiple regression in predicting the prevalence of WTN annoyance is also provided. The analysis suggests that communities are between 11 and 26 dB less tolerant of WTN than of other transportation noise sources.

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I. INTRODUCTION

One of the most widely studied responses to environmental noise is community annoyance. There is a large body of social and socio-acoustical research spanning over 50 years which relates to the impact of noise on individuals and communities. Studies using socio-acoustic surveys have consistently shown an association between long-term average noise levels and the prevalence of reporting a high level of noise annoyance. The "*highly annoyed*" classification refers to a social survey question on noise annoyance with a

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response in the top 27%–29% on an anchored numerical scale or in the top two categories on a five point adjectival scale (Schultz, 1978), hereafter referred to as annoyance. The R^2 for models of WTN annoyance as a function of calculated long-term energy equivalent noise level alone varies from study to study, although it is often below 20%, confirming that the expression of annoyance is influenced by more than noise levels alone (Job, 1988). Long-term noise annoyance, and more specifically the change in the percentage of a community reporting to be highly annoyed by noise, has been utilised as a health endpoint in environmental assessments (Michaud *et al.*, 2008a). The support for this is partially based on the possible association between high annoyance and other health effects (Niemann *et al.*, 2006; World Health Organization, 2011). The World Health Organization (WHO) has recently quantified the burden of disease associated with long term high annoyance towards environmental noise (WHO, 2011). Several studies have found statistical associations between high degrees of annoyance toward noise and self-reported health effects that include, but are not limited to, migraines, heart disease, diabetes, and hypertension (Basner *et al.*, 2014; Michaud *et al.*, 2008b; Niemann *et al.*, 2006), with these associations also reported in wind turbine studies (Pawlaczyk-Łuszczyńska *et al.*, 2014; Pedersen *et al.*, 2009). Annoyance need not be part of the causal chain to account for the aforementioned associations with health effects; rather, it may act as an intermediary variable between exposure and health (European Network on Noise and Health, 2013).

In comparison to the scientific literature that exists for other sources of environmental noise, there are few peer-reviewed field studies that have investigated the community response to modern wind turbines (Kuwano *et al.*, 2014; Krogh *et al.*, 2011; Mroczek *et al.*, 2012; Nissenbaum *et al.*, 2012; Pawlaczyk-Łuszczyńska *et al.*, 2014; Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009; Shepherd *et al.*, 2011; Tachibana *et al.*, 2012). The studies that have been conducted to date differ in terms of their design and evaluated endpoints. Common features include reliance upon self-reported endpoints, modeled levels of wind turbine noise (WTN), and/or proximity to wind turbines as the explanatory variable for the observed community response. Despite the small number of unique epidemiological studies published in the peer-reviewed wind turbine literature, the association between calculated WTN and self-reported community annoyance has been one of the more robust observations. A general conclusion from these studies is that annoyance increased with increasing WTN levels (or reduced proximity to wind turbines) (Shepherd *et al.*, 2011) and that over and above WTN levels, the exposure-response relationship was influenced by attitudes towards wind turbines, economic incentives and population density (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009).

The present paper provides two multiple regression models for WTN annoyance. In the first *unrestricted* model, the purpose was to assess the variables that, in addition to WTN levels, have the strongest overall association with WTN annoyance. As such, there was no *a priori* exclusion of variables that may be viewed as a response to wind turbine operations (e.g., window closing behaviour, annoyance towards shadow flicker, hearing the wind turbines, etc.). Variables are selected only on the basis of the strength of their statistical association with WTN annoyance. In contrast, a second *restricted* model of community annoyance is also presented wherein, with the exception of WTN exposure, the aforementioned variables, which may be considered to more likely reflect a reaction to wind turbine operations, are not considered in the model, regardless of their statistical association with annoyance. This restricted model may yield information that could serve to identify annoyance mitigation measures, over and above a reduction in WTN levels.

Even with a restricted analysis, complex multiple regression models do not readily afford comparisons to other studies that may not have considered the same variables. The Appendix provides a more parsimonious analysis that permits the prediction of WTN annoyance by calculating community tolerance to WTN. An assessment based on community tolerance readily permits comparisons between *all* field studies. The only requirement is that each study must document the exposure-response relationship between the prevalence of high annoyance and increasing noise levels.

II. METHODS

A. Sample design

1. Target population, sample size and sampling frame strategy

The study design, target population, final sample size, allocation of participants as well as the sampling strategy has been described by Michaud *et al.* (2013) and Michaud *et al.* (2016b). Briefly, the study locations were drawn from areas in southwestern Ontario (ON) and Prince Edward Island (PEI) where there were a sufficient number of dwellings within the vicinity of wind turbine installations. There were 2004 potential dwellings identified from the ON and PEI sampling regions, which included 315 and 84 wind turbines, respectively. All turbines had three pitch controlled rotor blades (∼80 m diameter) upwind of the tower. The wind turbine electrical power outputs ranged between 660 kW to 3 MW (average 2.0 ± 0.4 MW). Turbine hub heights were predominantly 80 m. All identified dwellings within approximately 600 m from a wind turbine and a random selection of dwellings between 600 m and 11.22 km were selected, from which one person per household between the ages of 18 and 79 years was randomly chosen to participate. Several factors influenced the determination of the final sample size, including having adequate statistical power (Michaud *et al.*, 2016b; Michaud *et al.*, 2016c) to assess the study objectives, and the time required for collection of data, as influenced by factors such as the length of the interview and the time needed to collect the physical measures.

This study was approved by the Health Canada and Public Health Agency of Canada Review Ethics Board (Protocols #2012–0065 and #2012–0072).

B. Calculating wind turbine and nighttime background sound pressure levels at dwellings

A detailed description of the approach applied to sound pressure level modeling [including background nighttime sound pressure (BNTS) levels] is presented separately (Keith *et al.*, 2016a,b). Briefly, sound pressure levels were estimated at each dwelling using both ISO 9613-1 (ISO, 1993) and ISO 9613-2 (ISO, 1996) as incorporated in the commercial software CadnaA version 4.4 (Datakustik®, 2014). The calculations included all wind turbines within a radius of 10 km, and were based on manufacturers' octave band sound power spectra at 8 m/s standardized wind speed and favourable sound propagation conditions. The few dwellings beyond this distance were assigned the same calculated WTN value as dwellings at 10 km. The manufacturers' data were verified for consistency using on-site measurements of wind turbine sound power (Keith *et al.*, 2016a). Unless otherwise stated, all decibel references are A-weighted.

The BNTS levels were calculated according to the Alberta noise regulations [Alberta Utilities Commission (AUC), 2013], which estimates ambient noise levels in rural and suburban environments. Estimated levels can range from 35 to 51 dB, based on dwelling density and calculated distance to heavily travelled roads or rail lines. In ON, road noise for the six lane concrete 401 Highway was calculated using the U.S. Traffic Noise Model (United States Department of Transportation, 1998) module in the CadnaA software. This value was used if it exceeded the Alberta noise estimate (Keith *et al.*, 2016b).

C. Data collection

1. Questionnaire

A detailed description of the questionnaire development, including content, pilot testing, administration, and the approaches used to enhance participation, have been described in detail by Michaud *et al.* (2013), Michaud *et al.* (2016b), and Feder *et al.* (2015). The questionnaire included modules on basic demographics, noise annoyance, wind turbine perceptions (including concern for physical safety), health effects, quality of life, sleep quality, perceived stress, lifestyle behaviours, and prevalence of chronic diseases (Statistics Canada, 2014).

The official title of the study, *Community Noise and Health Study* (CNHS), was used throughout all data collection phases as a means of masking the true intent of the study, which was to assess the association between wind turbines and health. This approach is commonly used in epidemiological studies to avoid a disproportionate contribution from any group that may have distinct views towards the study subject, such as wind turbines. At multiple times of the day, 16 Statistics Canada trained interviewers conducted in-person home interviews including physical measures data collection between May 2013 and September 2013, in southwestern ON and PEI. Potential participants were informed that the purpose of the survey was to investigate community noise and the potential impact on health. Once a roster of all adults, 18 to 79 years, living in the dwelling was compiled, a computer algorithm selected one adult per dwelling. No substitution was permitted under any circumstances. Participants were not compensated for their participation.

2. Defining "highly" annoyed

Annoyance toward WTN, road traffic, aircraft and rail noise was assessed using the five-point adjectival scale as per ISO/TS (ISO, 2003a) after it was confirmed that the noise source of interest was audible (Michaud *et al.*, 2016b). For each source of noise heard, participants were then asked to respond to the following question "*Thinking about the last year or so, when you are at home, how much does noise from [SOURCE] bother, disturb or annoy you?*" Participants were asked to select one of the following response categories: "*not at all*," "*slightly*," "*moderately*," "*very*," or "*extremely*." Participants that reported they did not hear a particular source of noise were classified into a "*Do not hear*" group and retained in the analysis. The analysis of annoyance was performed after collapsing the response categories into two groups (i.e., "*highly annoyed*" and "*not highly annoyed*"). As per ISO/TS (ISO, 2003a), participants reporting to be either "*very*" or "*extremely*" annoyed were treated as "*highly annoyed*" in the analysis. Consistent with Pedersen *et al.* (2009), the "*not highly annoyed*" group was comprised of participants who did not hear the source or indicated that they were "*not at all*," "*slightly*," and "*moderately*" annoyed by the source. A similar approach was used for the assessment of highly sleep disturbed and highly concerned for physical safety from having wind turbines in the area.

D. Statistical methodology

The analysis for categorical outcomes closely follows the description as outlined in Michaud *et al.* (2013), which provides a summary of the pre-data collection study design, and objectives, as well as proposed data analysis. Final A-weighted WTN categories were defined as follows: {<25; [25–30); [30–35); [35–40); and [40–46]}. As a first step to develop the best predictive model for WTN annoyance, univariate logistic regression models were carried out with WTN category as the exposure of interest, adjusted for province and a predictor of interest. It should be emphasized that variables considered in the univariate analysis have been previously demonstrated to be related to the modeled endpoint and/or considered by the authors to conceptually have a potential association with the modeled endpoint. The analysis of each variable only adjusts for WTN category and province, therefore interpretation of any individual relationship must be made with caution.

Multiple logistic regression models to identify variables associated with WTN annoyance were developed using stepwise regression with a 20% significance entry criterion for predictors (based upon univariate analyses) and a 10% significance criterion to remain in the model. The stepwise regression was carried out in three different ways: (1) the base model included exposure to WTN category and province, (2) the base model included exposure to WTN category, province, and an adjustment for participants who reported receiving personal benefit from having wind turbines in the area, and (3) the base model included exposure to WTN category and province, conditioned on those who reported receiving no personal benefit. In all models, WTN category was treated as a continuous variable. The current model aimed to identify variables that have the strongest overall association with annoyance.

All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. Since the interaction was not statistically significant for any of the regression models, province was treated as a confounder in the models with associated adjustments, as required. In cases when cell frequencies were small (i.e., <5) in logistic regression models, exact tests were used as described in Agresti (2002) and Stokes *et al.* (2000). The Nagelkerke pseudo R^2 and Hosmer-Lemeshow (H-L) *p*-value were reported for all logistic regression models.

Statistical analysis was performed using Statistical analysis system version 9.2 (SAS Institute Inc., 2014). A 5% statistical significance level was implemented throughout unless otherwise stated. In addition, Bonferroni corrections were made to account for all pairwise comparisons to ensure that the overall Type I (false positive) error rate was less than 0.05.

III. RESULTS

A. Wind turbine sound pressure levels at dwellings, response rates, and sample characteristics

Calculated outdoor sound pressure levels reached 46 dB. Calculations are representative of typical worst case long term (1 year) average WTN levels. Of the 2004 potential dwellings, 1570 addresses were considered to be valid dwellings, from which 1238 occupants agreed to participate in the study (606 males, 632 females). This produced a final calculated response rate of 78.9%. The 434 dwellings that were found to be out-of-scope was anticipated based on previous surveys carried out in rural Canadian areas and on Census data forecasting a higher out-of-scope dwelling rate in PEI compared to ON. A characterisation of the out-of-scope locations is provided in Michaud *et al.* (2016b).

The study sample was found to be relatively homogenous with some minor differences found with respect to age, employment, type of home and home ownership. Self-reported prevalence of illnesses, chronic diseases, noise sensitivity and reporting to be highly sleep disturbed in any way for any reason were all found to be statistically equivalent across WTN categories (Michaud *et al.*, 2016b).

B. Effects of WTN on annoyance

The analysis of self-reported annoyance towards several features associated with wind turbines (i.e., visual impacts, shadow flicker, vibrations, and blinking lights) in relation to WTN levels has been presented in a separate paper by Michaud *et al.* (2016b). In addition to reporting the prevalence of annoyance toward WTN in general, Michaud *et al.* (2016b) also provided an analysis of the WTN annoyance as a function of location (indoors, outdoors), time of day (morning, afternoon, evening, nighttime), and season (summer, fall, winter, spring). The focus of the current analysis is the characterization of the variables that are related to WTN annoyance in general, hereafter referred to as WTN annoyance.

1. Univariate analysis of variables related to WTN annoyance

The base model included WTN category and province as explanatory variables with regard to WTN annoyance. The Nagelkerke pseudo R^2 for this model was 12% (see supplemental material[1]). The R^2 was less than 10% with only WTN levels in the model.

Variables related to WTN annoyance after accounting for WTN level and province in the logistic regression models are presented in the supplemental material.[1] Some of the notable variables that were related to WTN annoyance in these univariate analyses included property ownership, household complaint regarding WTN, noise sensitivity, perceived stress, self-reported sleep disturbance, annoyance with other wind turbine features (e.g., blinking lights), window closing behaviour, and concern for physical safety from having wind turbines in the area (see supplemental material[1]). Many of the self-reported illnesses (e.g., migraines, tinnitus, dizziness, chronic pain, etc.) were statistically related to WTN annoyance; however, chronic conditions that were reported to have been diagnosed by a health care professional tended to not be related to WTN annoyance (see supplemental material[1]).

The relationship between WTN annoyance and the three validated modules incorporated in the study questionnaire: WHOQOL-BREF (Skevington *et al.*, 2004; WHOQOL Group, 1998), Perceived Stress Scale (PSS) (Cohen *et al.*, 1983), and the Pittsburgh Sleep Quality Index (PSQI) (Buysse *et al.*, 1989) was assessed in the CNHS. Decreased quality of life, higher perceived stress and scores on the PSQI were all associated with higher odds of reporting to be highly annoyed by WTN (see supplemental material[1]).

Modeled BNTS levels ranged between 35 and 61 dB in the sample (Keith *et al.*, 2016b). Average BNTS was highest in the WTN group [30–35) dB and lowest in areas where modeled WTN levels were between 40 and 46 dB. BNTS level was not significantly associated with WTN annoyance and the odds of WTN annoyance did not change as a function of BNTS level. Furthermore, after accounting for BNTS levels, WTN annoyance was still significantly associated with WTN levels ($p < 0.0001$) (see supplemental material[1]).

2. Multiple logistic regression model for WTN annoyance

As noted in Sec. II D, variables considered in the multiple regression model had to be significant at the 20% level and be conceptually related to WTN annoyance. Table I provides a summary of the variables that met these conditions.

The final multiple logistic regression models for the three approaches listed in the statistical methodology section yielded similar results. The predictive strength of the three final models was close to 60%. For these reasons, only the results from the first unrestricted multiple logistic regression model are shown in Table II.

WTN annoyance was strongly related to closing bedroom windows to reduce noise during sleep when WTN was identified as the source. Even after adjusting for the other variables in the final model, those who closed their window

TABLE I. Variables conceptually related to WTN annoyance and statistically significant at the 20% level.

Variable	p-value
Income	0.182
Property ownership[a]	0.007
Personal benefit[a]	<0.0001
At least 1 turbine on property	0.003
Complaint about wind turbine noise	<0.0001
Number of years turbines audible	0.090
Sensitivity to noise[a]	<0.0001
Audible WTN	<0.0001
Audible road traffic[a]	0.150
Ability to see turbines from property[a]	0.153
Visual annoyance to wind turbines	<0.0001
Annoyance with blinking lights	<0.0001
Shadow flicker annoyance	<0.0001
Notice vibrations during turbine operations	<0.0001
Annoyance to vibrations/rattles	<0.0001
Concerned about physical safety[a]	<0.0001
Bedroom window type[a]	0.011
Bedroom on quiet side[a]	0.125
Calculated volume of bedroom (1000 ft^3)[a]	0.049
Closing bedroom window to block outside noise during sleep	<0.0001
Closure of bedroom window due to road traffic	0.123
Closure of bedroom window due to wind turbines	<0.0001
Migraines	<0.0001
Dizziness	<0.0001
Tinnitus	<0.0001
Chronic pain	<0.0001
Medication for high blood pressure	0.191
Diagnosed sleep disorder	0.115
Restless leg syndrome	0.023
Self-reported sleep disturbance	<0.0001
Rated quality of life	0.016
Score on PSQI (categorical and range 0–21)	<0.0001
Physical Health domain (range 4–20)	<0.0001
Psychological domain (range 4–20)	0.049
Environment domain (range 4–20)	<0.0001
Perceived Stress Scale (range 0–37)	0.014

[a]Tested in the restricted multiple regression model.

due to WTN had 8 times higher odds of being annoyed by WTN compared to those who did not need to close their window for this reason. In all three models, this variable was the first factor to enter the multiple logistic regression model and the corresponding Nagelkerke R^2 in the base models increased from approximately 11% to 41%. The variables that added the remaining 17% to the R^2 included, but were not limited to, other wind turbine related annoyances (i.e., blinking lights on the nacelle of the wind turbines, visual impact, and vibrations), noise sensitivity, concern about physical safety from having wind turbines in the area, and self-reported sleep disturbance over the last year.

It was also of interest to develop a model of community annoyance restricted to the variables from Table I that are not likely to reflect a reaction to wind turbine operations. Such a model may yield information that could serve to identify annoyance mitigation measures, which are over and above a reduction in WTN levels. Variables that were considered included, but were not limited to, type of dwelling, facade type, property ownership, type of windows, bedroom location within dwelling, self-reported size of bedroom (e.g., volume), presence of air conditioner in the dwelling, visibility of wind turbines from anywhere on the property, other noise sources that the participant reported hearing (e.g., road traffic, railway, aircraft), receiving personal benefits, concern for physical safety associated with having wind turbines in the area, noise sensitivity, and BNTS levels. Income was not considered for inclusion in the restricted regression model because it would have reduced the sample size from 1129 to 968. Furthermore, income was not statistically significant in the unrestricted multiple regression model. Although the variables considered were different from the unrestricted model, the same stepwise procedure as explained in Sec. II D was carried out to develop the restricted multiple logistic regression model.

Table III presents the results for the final restricted multiple logistic regression model where personal benefits was considered for entry into the model. Variables that entered the final model and were associated with higher odds of being annoyed to WTN included concern for physical safety from having wind turbines in the area, noise sensitivity, personal benefits, window type, dwelling ownership, and audibility of road traffic. Participants with a high concern for their physical safety had 14 times higher odds of being annoyed by WTN [95% confidence interval (CI): (7.71, 26.96)]. Participants who did not receive personal benefits had 12 times higher odds of being annoyed by WTN [95% CI: (1.66, 94.25)]. Participants reporting to have single and double pane windows in their bedroom had statistically similar odds of being highly annoyed to WTN ($p = 0.742$); and both had lower odds of being annoyed to WTN compared to those with triple pane windows ($p < 0.03$, in both cases). Participants who did not hear road traffic ($p = 0.026$) had higher odds of being highly annoyed to WTN. The final model had an R^2 of 40% (Table III).

IV. DISCUSSION

The community response to WTN reported in this study was found to be statistically related to A-weighted WTN levels. In other words, the prevalence of reporting to be very or extremely (i.e., highly) annoyed by WTN increased from 2.1% to 13.7% when sound pressure levels were below 30 dB compared to [40–46] dB, respectively. Although statistically significant, the association between WTN levels and annoyance was found to be rather weak ($R^2 = 9\%$). The R^2 substantially improved after considering annoyance due to other wind turbine related features such as the visual impact of wind turbines, the blinking lights on the nacelle used to alert aircraft, and the perception of vibrations during wind turbine operations. The self-reported high concern about physical safety from having wind turbines in the area was found to be significantly related to WTN annoyance. This finding is reminiscent of the general observation from community noise research that fear of a noise source may be the most important non-acoustic variable related to annoyance (Fields, 1993; Miedema and Vos, 1998). van den Berg *et al.* (2015) also

TABLE II. Multiple logistic regression model (unrestricted) for WTN annoyance.

Variable	Groups in variable[a]	Multiple logistic regression model ($n = 934$, $R^2 = 0.58$,[c] H-L,[d] $p = 0.702$)		Order of entry into model: R^2 at each step
		OR(CI)[b]	p-value	
WTN (dB)[e]	Continuous	2.38 (1.42, 3.99)	0.001	Base: 0.11[f]
Province	ON/PEI	4.98 (1.15, 21.58)	0.032	Base: 0.11[f]
Closure of bedroom window due to wind turbines	Yes/no	8.45 (3.67, 19.46)	<0.0001	Step 1: 0.41
Annoyance with blinking lights	High/low	3.26 (1.40, 7.56)	0.006	Step 2: 0.50
Annoyance with vibrations/rattles	High/low	3.99 (1.22, 13.07)	0.023	Step 3: 0.52
Visual annoyance to wind turbine	High/low	2.77 (1.22, 6.29)	0.015	Step 4: 0.53
Self-reported sleep disturbance[g]	High/low	2.93 (1.27, 6.77)	0.012	Step 5: 0.55
Closure of bedroom window due to road traffic	Yes/no	0.42 (0.17, 1.05)	0.063	Step 6: 0.56
Sensitivity to noise	High/low	2.11 (0.97, 4.59)	0.061	Step 7: 0.57
Concerned about physical safety	High/low	2.56 (1.08, 6.07)	0.033	Step 8: 0.57
Complaint about wind turbines	Yes/no	3.22 (0.85, 12.20)	0.085	Step 9: 0.58

[a]Where a reference group is not specified it was taken to be the last group.
[b]Odds ratio (OR) and 95% confidence interval (CI) based on logistic regression model; an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c]The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable.
[d]H-L: Hosmer-Lemeshow test, $p > 0.05$ indicates a good fit.
[e]WTN level is treated as a continuous scale in the logistic regression model, giving an overall OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.
[f]Note that the results of the base model differ from the supplemental material (see footnote 1) and Table III due to sample size differences.
[g]Evaluates the magnitude of reported sleep disturbance for any reason over the previous year while at home.

reported that self-reported worry about a noise source was strongly correlated to noise annoyance from that source.

Noise sensitivity was found to be a significant predictor of WTN annoyance in the current study—a finding that is consistent with previously published community noise research (Guski, 1999; Miedema and Vos, 2003), including WTN studies (Janssen *et al.*, 2011). Despite the influence that concern for physical safety and noise sensitivity seem to have on WTN annoyance, the variable found to have the strongest association with annoyance was identifying wind turbines as the source of noise that led to window closing because it was disturbing sleep. In fact, the R^2 increased from 11% to 41% when this variable entered the final model. This is an observation that requires careful interpretation because sleep disturbance (of any kind) was not found to be related to WTN exposure in the current study

TABLE III. Multiple logistic regression model (restricted) for WTN annoyance.

Variable	Groups in variable[a]	Multiple logistic regression model ($n = 1129$, $R^2 = 0.40$,[c] H-L,[d] $p = 0.480$)		Order of entry into model: R^2 at each step
		OR(CI)[b]	p-value	
WTN (dB)[e]	Continuous	2.84 (1.96, 4.11)	<0.0001	Base: 0.11[f]
Province	ON/PEI	3.46 (1.32, 9.10)	0.012	Base: 0.11[f]
Concerned about physical safety	High/low	14.42 (7.71, 26.96)	<0.0001	Step 1: 0.28
Sensitivity to noise	High/low	5.54 (3.12, 9.84)	<0.0001	Step 2: 0.34
Personal benefit	No/yes	12.49 (1.66, 94.25)	0.014	Step 3: 0.37
Bedroom window type	Single pane	0.17 (0.04, 0.79)	0.024	Step 4: 0.38
	Double pane	0.21 (0.07, 0.63)	0.006	
	Triple pane	Reference		
Property ownership	Own/rent	5.89 (1.19, 29.06)	0.030	Step 5: 0.40
Audible road traffic	No/yes	2.08 (1.09, 3.95)	0.026	Step 6: 0.40

[a]Where a reference group is not specified it was taken to be the last group.
[b]Odds ratio (OR) and 95% confidence interval (CI) based on logistic regression model; an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c]The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable.
[d]H-L: Hosmer-Lemeshow test, $p > 0.05$ indicates a good fit.
[e]WTN level is treated as a continuous scale in the logistic regression model, giving an overall OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.
[f]Note that the results of the base model are different from the supplemental material (see footnote 1) and Table II due to sample size differences.

sample (Michaud *et al.*, 2016c). It is conceivable that closing the window may be an expression of the annoyance toward WTN and/or a coping strategy that protects against sleep disturbance. When closing the window reduces the indoor WTN level and hence improves sleep, this action may conceivably explain the absent association between WTN levels and sleep disturbance.

In the restricted model, variables not expected to be a direct response to wind turbine operations were considered. The rationale for such a model was that it could identify factors that may serve to diminish the annoyance response, over and above a reduction in levels of WTN exposure. The finding that concern for physical safety due to the presence of wind turbines in the area was a significant predictor of annoyance in both the unrestricted and restricted models is informative. This suggests that actions (e.g., education, community consultation) which aim to address this concern during the planning stages of a wind project may also serve to reduce community annoyance toward WTN. Noise sensitivity as a personality trait has long been known to influence the response to community noise (Job, 1988) and it is therefore not surprising that this variable was found to be associated with WTN annoyance.

In the unrestricted model, personal benefit was not retained, although this was likely due to the small number of participants in this category (i.e., 110). Indeed, in the restricted model, personal benefit was found to be statistically significant, although the increase in R^2 was rather modest (3%). Taken together with Pedersen *et al.* (2009), these findings would support initiatives that facilitate direct or indirect personal benefit among participants living within a community in close proximity to wind power projects. There was a significant effect related to window type in the current study that remained in the final model, but nevertheless appears to be counter-intuitive when considering the reduction in noise annoyance that has been reported as a result of noise insulation programs (Amundsen *et al.*, 2013; Asensio *et al.*, 2014). The odds of reporting to be highly annoyed by WTN were higher among participants who self-reported that they had triple pane windows in their bedroom. A tentative explanation for this finding could be that installing these types of windows may be a coping strategy among those who are more highly annoyed by noise. However, the potential influence this action may have on annoyance over time cannot be accounted for in the current study because no information was gathered about the time they were installed.

The possibility that elevated background noise may influence community annoyance has been reviewed by Fields (1993) with the general conclusion that the vast majority of studies reviewed indicated that ambient noise levels have no impact on community annoyance. However, wind turbines were not among the sources reviewed by Fields (1993). Certainly, there is some evidence that the association between WTN levels and annoyance is stronger in areas that are classified as quiet, compared to those classified as noisy (Bakker *et al.*, 2012; Pedersen *et al.*, 2010a,b). It has been recommended that sound levels are adjusted by up to 10 dB when estimating the prevalence of annoyance in areas where there may be a greater expectation of peace and quiet (ANSI, 1996; ISO, 2003c). In the current study, there was a tendency for BNTS levels to be slightly higher in areas where WTN levels (and therefore the prevalence of annoyance) were lower. For this reason, it is difficult to reconcile what influence, if any, BNTS had on WTN annoyance in the current study. A more appropriate assessment of the potential influence that BNTS levels may have on WTN annoyance requires a sufficient sample size in areas with similar WTN levels in the presence of varying BNTS levels. Future research in this area may clarify the influence of background noise on the overall community response to WTN, which could prove to be an important consideration in an urban planning context where it may inform decisions regarding wind turbine siting.

In the univariate analysis the odds of reporting to be highly annoyed by WTN were almost 4 times higher (95% CI: 1.17, 19.41) among participants who heard the wind turbines for 1 year or more compared to those who heard it for less than 1 year (see supplemental material[1]). Unfortunately, the limited breakdown for the audibility categories was dictated by sample size and there may be added value to having a more refined history of WTN audibility. Nevertheless, if this finding is corroborated in future research it would support sensitisation rather than habituation/adaptation with prolonged exposure to WTN.

Some discussion on the potential link between health effects and WTN annoyance is warranted. Long-term high annoyance, as a measure of community response to noise is considered to be a health effect by the World Health Organization (WHO, 1999, 2011) and has been associated with other health effects (Michaud *et al.*, 2008b; Niemann *et al.*, 2006; Pawlaczyk-Łuszczyńska, 2014; Pedersen *et al.*, 2009). This is consistent with the current findings demonstrating that participants who reported being highly annoyed by WTN were more likely to report migraines, dizziness, tinnitus, chronic pain, and restless leg syndrome (see supplemental material[1]). In addition, self-reporting to be highly sleep disturbed for any reason and rating overall quality of life as either "*very poor*" or "*poor*" were also related to WTN annoyance. Higher scores on the PSS and PSQI were likewise found to be related to WTN annoyance. Finally, hair cortisol concentrations, systolic and diastolic blood pressure were significantly higher among the participants that reported to be highly annoyed by WTN (Michaud *et al.*, 2016a). These associations between annoyance and other health effects/indicators need to be interpreted cautiously for a number of reasons. First, none of these associations were related to calculated WTN levels. Second, the R^2 in any of the reported or measured health effects was very low (i.e., $<7\%$), which demonstrates the dominance of other factors. Finally, WTN annoyance was never retained in the final multiple regression models developed for stress, sleep, or quality of life outcomes (Michaud *et al.*, 2016b; Michaud *et al.*, 2016a; Feder *et al.*, 2015). Rubin *et al.* (2014) recently reviewed studies examining symptoms related to modern technology (including wind turbines) and found that health symptoms were more commonly reported among participants who were more anxious, worried, concerned, or annoyed by a source they perceived to be a health risk. The authors suggested that annoyance may promote changes in physiology, behaviour, self-monitoring or enhance recall bias (Rubin *et al.*, 2014). Despite an incomplete understanding of the mechanisms through which annoyance may impact health, or vice versa, it is nevertheless relevant that there were observed associations between long-term high annoyance toward WTN and several self-reported and measured endpoints, which included elevated hair cortisol concentrations and blood pressure. Collectively, these findings support efforts aimed at mitigating community annoyance that may be associated with new wind power projects and concomitant changes in community noise levels.

V. CONCLUDING REMARKS

The complex relationship that exists between community annoyance and noise is a well-established phenomenon that has been further illustrated in the current study. This study found that the R^2 for the model with only WTN levels was merely 9% and that any efforts aimed at mitigating the community response to WTN will profit from considering other factors associated with annoyance. Although the final models had R^2's of up to 58%, their predictive strength for WTN annoyance was still rather limited. It has been shown in previous studies that trust or misfeasance with source authorities, community engagement in project development in addition to community expectations, all have an influence on community annoyance (Guski, 1999). There is also strong support for considering attitudinal factors (Job, 1988; Pawlaczyk-Łuszczyńska, 2014; Pedersen *et al.*, 2009). The relative importance of these and many other unknown factors will fluctuate across different communities. This makes it exceedingly difficult, if not impossible, to fully account for their influence on annoyance in any given community. Recently, it has been demonstrated that predicting the prevalence of annoyance to transportation noise can be much more effectively achieved using a simple one-parameter model. The analysis in the Appendix extends this methodology to WTN annoyance.

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APPENDIX: ESTIMATING COMMUNITY TOLERANCE LEVEL FOR WIND TURBINE NOISE EXPOSURE

The multiple regression models presented in the current paper demonstrate that the R^2 for the prevalence of high annoyance to wind turbine noise (WTN) exposure using a long term energy average (LAeq) alone is less than 10%. Although this increases substantially after consideration is given to several non-LAeq parameters, the predictive strength still only reaches approximately 60%. This makes it difficult to compare the prevalence of WTN annoyance to other socio-acoustic surveys and offers little confidence in estimating the prevalence of annoyance using only LAeq. Fidell *et al.* (2011) demonstrated that the wide scatter in the prevalence of aircraft noise annoyance within and between studies can be effectively accounted for with a simple model that includes only one single variable parameter, a "Community Tolerance Level" or CTL. For a detailed description of the CTL model the reader should refer to Fidell *et al.* (2011). The CTL model is based on well-accepted assumptions that in a homogenous community the prevalence of annoyance will be low or non-existent at very low sound pressure levels, and that it will increase monotonically with increasing sound pressure levels. For aircraft noise, the rate of increase in annoyance can be effectively estimated using a loudness function (i.e., sound pressure raised to the power of 0.3) and the assumption that annoyance increases monotonically with increasing sound pressure levels as shown in Eq. (A1) (Fidell *et al.*, 2011),

$$\%HA = 100\ \exp\left(-(1/[10^{(DNL-CTL+5.306)/10}]^{0.3})\right). \quad \text{(A1)}$$

The CTL in Eq. (A1) adjusts the horizontal position of the transition function on the abscissa. The value of the CTL was obtained statistically using maximum likelihood estimation, which is a suitable approach to obtain estimates for binary data (i.e., being highly annoyed compared to not being highly annoyed). Schomer *et al.* (2012) recently demonstrated that the CTL model can also be applied to road and rail noise.

1. Calculating annual average day-night sound level (DNL) from wind turbine noise studies

Determination of CTL requires the yearly average DNL. In the current study, the yearly averaged WTN DNL was calculated at each dwelling by taking into account the effect of wind speed on the WTN sound power level (Keith *et al.*, 2016b). Wind turbine electrical power output in 10 min periods was used to derive the associated sound power. The day-night sound power level was then estimated by adding 10 dB to levels that occurred between 10 p.m. and 7 a.m. and the resulting 52 560 values were averaged over a 1 year period. At each dwelling, corrections were based on the wind park associated with the closest wind turbine. The correction applied to the sound pressure level at each dwelling was the difference between the nominal 8 m/s WTN sound power level and the yearly average day-night WTN sound power level. As described by Keith *et al.* (2016b), WTN sound pressure levels at each dwelling had been calculated for nominal 8 m/s wind speed (i.e., wind speed at 10 m height under standardised conditions according to IEC, 2012). For the few cases where operational data were not available, wind speed data were obtained from the closest wind turbines for which data were available.

For Pedersen's studies (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2009) the DNL was estimated by adding 4.7 dB to the 8 m/s LAeq data (van den Berg, 2008; Janssen *et al.*, 2011). Based on van den Berg (2008), DNL was assumed to be approximately equal to LDEN. In a Japanese study by Kuwano *et al.* (2014) the DNL was estimated by adding 6 dB to the measured nighttime average sound pressure level (Yano, 2015).

Not all studies in this area could be included in the current analysis because not all research designs permitted an estimate of high annoyance as a function of DNL. This was either because an equivalent to the percentage highly annoyed could not be estimated and/or the analysis of annoyance was estimated without an exposure metric that could readily be converted to DNL (e.g., distance only).

2. Applying CTL to WTN annoyance

In comparison to the large databases available for transportation noise, there are relatively few socio-acoustic surveys related to WTN annoyance. Nevertheless, the data that are currently available suggests that the loudness function in the CTL model provides an effective prediction of WTN annoyance. After converting all noise metrics to DNL, CTL can be used to quantify the differences between exposure-response relationships. By convention, the value of the CTL is the DNL from Eq. (A1) where 50% of the community would be highly annoyed. It would appear from the plots presented in Fig. 1 that the CTL model provides a reasonable fit to the available data from six field studies. It would be difficult to find a loudness function that has better

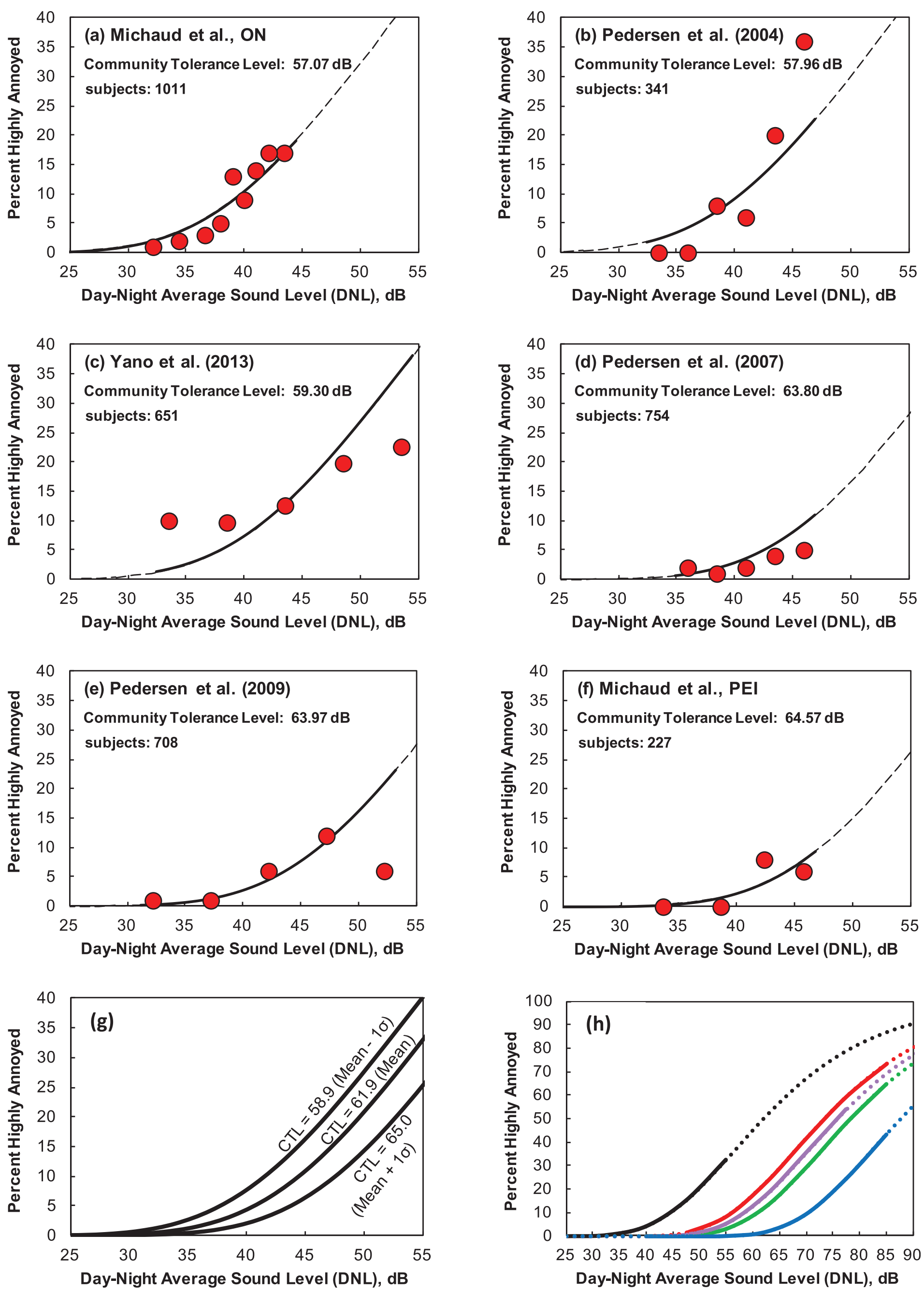

FIG. 1. Panels (a)–(f) show the best fit for the available field studies of wind turbine noise and the prevalence of high annoyance to Eq. (A1). (g) Exposure-response relationship for the prevalence of high annoyance with wind turbine noise exposure in communities of average, +1 standard deviation, and −1 standard deviation tolerance for wind turbine noise exposure. (h) Exposure-response relationship in communities with average tolerance for the prevalence of high annoyance with wind turbine noise (leftmost line, black online), aircraft noise (second line from left, red online), rail noise with high vibration (middle line, purple online), road traffic noise (right of middle line, green online), and rail noise without vibration (rightmost line, blue online).

TABLE IV. Prevalence of high annoyance in communities with an average tolerance. CTL_{50} for WTN (61.9 dB), aircraft noise (73.3 dB), road traffic noise (78.3 dB), rail noise with vibrations (75.8 dB), and rail noise without heavy vibrations (87.8 dB).

	Noise source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	1	0	0	0	0
40	4	0	0	0	0
45	11	1	0	0	0
50	21	3	1	2	0
55	33	9	3	5	0
60	45	18	9	13	1
65	57	29	18	23	4
70	67	42	29	36	9
75	76	54	42	48	19
80	82	65	54	60	30
85	87	73	65	69	43

agreement. The CTL for WTN ranges from 57.1 to 64.6 DNL with the grand mean of 62 and a standard deviation of 3. The calculated prevalence of WTN annoyance as a function of DNL for communities that are 1 standard deviation above and below the grand mean is provided in Tables IV–VI.

In the CNHS, the prevalence of high annoyance was nearly non-existent among the 110 participants that reported to receive personal benefit from having wind turbines in the area. This was found to have a negligible impact on CTL (~1 dB) and for this reason they were retained in the plots shown in Fig. 1.

Quantifying WTN with an A-weighted metric has become a source of debate because wind turbines are a known source of low frequency noise (LFN) that may be undermined with an A-weighted filter. If LFN were the cause of annoyance, the loudness function would be expected to be steeper because the perception of loudness increases more rapidly once low frequencies become audible (ISO, 2003b). The only fit that would be improved with a steeper loudness function is Pedersen and Persson Waye (2004). In contrast, the data from Yano *et al.* (2013) would seem to require a shallower curve and the remaining studies can all be approximated with the same loudness function used for aircraft, road, and rail (Fidell *et al.*, 2011; Schomer *et al.*, 2012). Therefore, based on the field studies that are currently available the argument can be made that the change in high annoyance due to WTN is not driven by LFN and is effectively approximated by a long-term A-weighted metric.

TABLE V. Prevalence of high annoyance in communities 1 standard deviation less tolerant. CTL_{50} for WTN (58.9 dB), aircraft noise (66 dB), road traffic noise (73.2 dB), rail noise with vibrations (72.3 dB), and rail noise without heavy vibrations (83.8 dB).

	Noise Source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	1	0	0	0	0
35	3	0	0	0	0
40	8	1	0	0	0
45	16	5	1	1	0
50	28	12	3	4	0
55	40	22	9	11	1
60	53	34	18	21	2
65	64	47	29	33	7
70	73	58	42	46	16
75	80	68	54	57	27
80	85	76	65	67	39
85	89	83	74	76	52

TABLE VI. Prevalence of high annoyance in communities 1 standard deviation more tolerant. CTL_{50} for WTN (64.9 dB), aircraft noise (80.3 dB), road traffic noise (83.4 dB), rail noise with vibrations (79.3 dB), and rail noise without heavy vibrations (91.8 dB).

	Noise Source				
DNL	WTN	Aircraft	Road	Rail + vib.	Rail − vib.
20	0	0	0	0	0
25	0	0	0	0	0
30	0	0	0	0	0
35	0	0	0	0	0
40	2	0	0	0	0
45	6	0	0	0	0
50	14	0	0	0	0
55	25	2	1	2	0
60	38	6	3	7	0
65	50	14	8	15	1
70	61	24	17	26	5
75	71	37	29	38	12
80	78	49	42	50	22
85	84	61	54	62	34

3. Using CTL to make source comparisons

With the CTL calculated, direct comparisons can be made to other noise sources. The corresponding overall average CTL values for aircraft, road, rail with vibration and rail without vibration are 73.3, 78.3, 75.8, and 87.8 DNL, respectively (Fidell *et al.*, 2011; Schomer *et al.*, 2012). This can be interpreted to mean that, on average, communities are about 11 dB less tolerant of WTN than of aircraft noise, 16 dB less tolerant of WTN than of road traffic noise, 14 dB less tolerant of WTN than of rail noise accompanied with high vibrations, and 26 dB less tolerant of WTN than of rail noise without vibrations. Confidence in these source differences will increase as future studies in this area produce additional estimates for the relationship between WTN levels and the prevalence of high annoyance.

4. Conclusions

The advantage of using the CTL model over multiple regression is that CTL provides a quantification in decibels for the differences between data sets that may originate from different communities and/or reflect responses to different noise sources. However, this approach does not identify the origins of the non-acoustic determinants of annoyance. By contrast, the multiple regression models have the advantage of identifying and quantifying non-DNL factors that are associated with individual differences in annoyance. For reflections on the advantages and disadvantages of the CTL model and multiple regressions, see Janssen and Vos (2011) and Fidell *et al*. (2011). The reality faced by jurisdictions that govern community noise policy is that they may never fully understand the myriad of reasons why communities may differ in their annoyance at comparable noise exposure levels. An assessment based on CTL side-steps the need for this type of speculation. The analysis presented here is obviously based on a limited number of field studies, and supports only preliminary conclusions. Nonetheless, further systematic collection and analysis of the relationship between WTN exposure and the prevalence of high annoyance can test and strengthen the current conclusions.

[1]See supplemental material at http://dx.doi.org/10.1121/1.4942390 for the univariate analysis results.

Agresti, A. (**2002**). *Categorical Data Analysis*, 2nd ed. (Wiley, New York).

Alberta Utilities Commission (AUC) (**2013**). "Rule 012-Noise Control," http://www.auc.ab.ca/acts-regulations-and-auc-rules/rules/Pages/Rule012.aspx (Last viewed 11/24/2014).

American National Standards Institute (ANSI) (**1996**). *S12.9-1996, Quantities and Procedures for Description and Measurement of Environmental Sound—Part 4: Noise Assessment and Predication of Long-Term Community Response* (American Standards Association, New York).

Amundsen, A. H., Klæboe, R., and Aasvang, G. M. (**2013**). "Long-term effects of noise reduction measures on noise annoyance and sleep disturbance: The Norwegian facade insulation study," J. Acoust. Soc. Am. **133**(6), 3921–3928.

Asensio, C., Recuero, M., and Pavón, I. (**2014**). "Citizens' perception of the efficacy of airport noise insulation programmes in Spain," Appl. Acoust. **84**, 107–115.

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., and Bouma, J. (**2012**). "Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress," Sci. Total Environ. **425**, 42–51.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., and Stansfeld, S. (**2014**). "Auditory and non-auditory effects of noise on health," Lancet **383**(9925), 1325–1332.

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., and Kupfer, D. J. (**1989**). "The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research," Psych. Res. **28**, 193–213.

Cohen, S., Kamarck, T., and Mermelstein, R. (**1983**). "A global measure of perceived stress," J. Health Soc. Behav. **24**(4), 385–396.

DataKustik® GmbH (**2014**). "CadnaA version 4.4," software for emission protection, www.datakustik.com (Last viewed 11/24/2014).

European Network on Noise and Health (ENNAH) (**2013**). "Final Report," edited by J. Lekaviciute, S. Kephalopoulos, S. Stansfeld, and C. Clark, Inspra Italy: European Commission Joint Research Centre Scientific and Policy Report, Report No. EUR 25809 EN.

Feder, K., Michaud, D. S., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T. J., Lavigne, E., Whelan, C., and van den Berg, F. (**2015**). "An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines," Environ. Res. **142**, 227–238.

Fidell, S., Mestre, V., Schomer, P., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2011**). "A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure," J. Acoust. Soc. Am. **130**(2), 791–806.

Fields, J. M. (**1993**). "Effect of personal and situational variables on noise annoyance in residential areas," J. Acoust. Soc. Am. **93**(5), 2753–2763.

Guski, R. (**1999**). "Personal and social variables as co-determinants of noise annoyance," Noise Health **1**(3), 45–56.

International Electrotechnical Commission (IEC) (**2012**). IEC-61400-11 Ed. 3.0, *Wind Turbine Generator Systems–Part 11: Acoustic Noise Measurement Techniques* (IEC, Geneva).

ISO (**1993**). ISO 9613-1, *Acoustics. Attenuation of Sound During Propagation Outdoors. Part 1: Calculation of the Absorption of Sound by the Atmosphere* (International Organization for Standardization, Geneva).

ISO (**1996**). ISO 9613-2, *Acoustics. Attenuation of Sound During Propagation Outdoors. Part 2: General Method of Calculation* (International Organization for Standardization, Geneva).

ISO (**2003a**). ISO/TS-15666, *Acoustics—Assessment of Noise Annoyance by Means of Social and Socio-Acoustic Surveys* (International Organization for Standardization, Geneva).

ISO (**2003b**). ISO 226:2003, *Acoustics—Normal Equal-Loudness Level Contours*, 2nd ed. (International Organization for Standardization, Geneva).

ISO (**2003c**). ISO 1996-1:2003(E), *Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 1: Basic Quantities and Assessment Procedures* (International Organization for Standardization, Geneva).

Janssen, S., Vos, H., Eisses, A. R., and Pedersen, E. (**2011**). "A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources," J. Acoust. Soc. Am. **130**(6), 3746–3753.

Job, R. F. S. (**1988**). "Community response to noise: A review of factors influencing the relationship between noise exposure and reaction," J. Acoust. Soc. Am. **83**, 991–1001.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016a**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.

Keith, S. E., Feder, K., Voicescu, S., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016b**). "Wind turbine sound pressure level calculations at dwellings," J. Acoust. Soc. Am. **139**(3), 1436–1442.

Krogh, C. M. E., Gillis, L., Kouwen, N., and Aramini, J. (**2011**). "WindVOiCe, a self-reporting survey: Adverse health effects, industrial wind turbines, and the need for vigilance monitoring," Bull. Sci. Technol. Soc. **31**(4), 334–345.

Kuwano, S., Yano, T., Kageyama, T., Sueoka, S., and Tachibana, H. (**2014**). "Social survey on wind turbine noise in Japan," Noise Control Eng. J. **62**(6), 503–520.

Michaud, D. S., Bly, S. H. P., and Keith, S. E. (**2008a**). "Using a change in percent highly annoyed with noise as a potential health effect measure for projects under the *Canadian Environmental Assessment Act*," Can. Acoust. **36**(2), 13–28.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Bower, T., Villeneuve, P., Russell, E., Koren, G., and van den Berg, F. (**2016a**). "Self-reported and measured stress related responses associated with exposure to wind turbine noise," J. Acoust. Soc. Am. **139**(3), 1467–1479.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016b**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Guay, M., Denning, A., Murray, B. J., Weiss, S. K., Villeneuve, P., van den Berg, F., and Bower, T. (**2016c**). "Effects of wind turbine noise on self-reported and objective measures of sleep," SLEEP **39**(1), 97–109.

Michaud, D. S., Keith, S. E., Feder, K., Soukhovtsev, V., Marro, L., Denning, A., McGuire, D., Broner, N., Richarz, W., Tsang, J., Legault, S., Poulin, D., Bryan, S., Duddeck, C., Lavigne, E., Villeneuve, P. J., Leroux, T., Weiss, S. K., Murray, B. J., and Bower, T. (**2013**). "Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: Social survey and sound level modelling methodology," Noise News Int. **21**, 14–27.

Michaud, D. S., Keith, S. E., and McMurchy, D. (**2008b**). "Annoyance and disturbance of daily activities from road traffic noise in Canada," J. Acoust. Soc. Am. **123**(2), 784–792.

Miedema, H. M., and Vos, H. (**1998**). "Exposure-response relationships for transportation noise," J. Acoust. Soc. Am. **104**(6), 3432–3445.

Miedema, H. M., and Vos, H. (**2003**). "Noise sensitivity and reactions to noise and other environmental conditions," J. Acoust. Soc. Am. **113**(3), 1492–1504.

Mroczek, B., Kurpas, D., and Karakiewicz, B. (**2012**). "Influence of distances between places of residence and wind farms on the quality of life in nearby areas," Ann. Agr. Environ. Med. **19**(4), 692–696.

Niemann, H., Bonnefoy, X., Braubach, M., Hecht, K., Maschke, C., Rodrigues, C., and Röbbel, N. (**2006**). "Noise-induced annoyance and morbidity results from the pan-European LARES study," Noise Health **8**(31), 63–79.

Nissenbaum, M. A., Aramini, J. J., and Hanning, C. D. (**2012**). "Effects of industrial wind turbine noise on sleep and health," Noise Health **14**(60), 237–243.

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., and Waszkowska, M. (**2014**). "Evaluation of annoyance from the wind turbine noise: A pilot study," Int. J. Occup. Med. Environ. Health **27**(3), 364–388.

Pedersen, E., and Persson Waye, K. (**2004**). "Perception and annoyance due to wind turbine noise—A dose-response relationship," J. Acoust. Soc. Am. **116**(6), 3460–3470.

Pedersen, E., and Persson Waye, K. (**2007**). "Wind turbine noise, annoyance and self-reported health and wellbeing in different living environments," Occup. Environ. Med. **64**(7), 480–486.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in the Netherlands," J. Acoust. Soc. Am. **126**(2), 634–643.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2010a**). "Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound," Energ. Pol. **38**(5), 2520–2527.

Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2010b**). "Why is wind turbine noise so poorly masked by road traffic noise?," in *Proceedings of INTERNOISE, 39th Congress of Noise Control Engineering*, Lisbon, Portugal, June 13–16, 2010.

Rubin, G. J., Burns, M., and Wessely, S. (**2014**). "Possible psychological mechanisms for 'wind turbine syndrome.' On the windmills of your mind," Noise Health **16**(69), 116–122.

SAS Institute Inc. (**2014**). *SAS (Statistical Analysis System) Software package Version 9.2* (SAS Institute, Cary, NC).

Schomer, P., Mestre, V., Fidell, S., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2012**). "Role of community tolerance level (CTL) in predicting the prevalence of the annoyance of road and rail noise," J. Acoust. Soc. Am. **131**(4), 2772–2786.

Schultz, T. J. (**1978**). "Synthesis of social surveys on noise annoyance," J. Acoust. Soc. Am. **64**(2), 377–405.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., and Hill, E. M. (**2011**). "Evaluating the impact of wind turbine noise on health-related quality of life," Noise Health **13**(54), 333–339.

Skevington, S. M., Lotfy, M., and O'Connell, K. A. (**2004**). "The World Health Organization's WHOQOL-BREF quality of life assessment: Psychometric properties and results of the international field trial—A report from the WHOQOL group," Qual. Life Res. **13**(2), 299–310.

Statistics Canada (**2014**). "Community noise and health study," http://www.statcan.gc.ca/daily-quotidien/141106/dq141106c-eng.htm (Last viewed 11/6/2014).

Stokes, M. E., Davis, C. S., and Koch, G. G. (**2000**). "Categorical data analysis using the SAS system," 2nd ed. (SAS Institute, Cary, NC).

Tachibana, H., Yano, H., Sakamoto, S., and Sueoka, S. (**2012**). "Synthetic research program on wind turbine noise in Japan," in *Proceedings of INTERNOISE, 41st Congress of Noise Control Engineering*, New York, NY, August 19–22, 2012, pp. 8505–8514.

United States Department of Transportation (**1998**). FHWA Traffic Noise Model®, technical manual (Federal Highway Administration, Washington, DC).

van den Berg, F. (**2008**). "Criteria for wind farm noise: Lmac and Lden," in *Proceedings of Acoustics '08*, Paris, June 29–July 4, 2008, pp. 4043–4048.

van den Berg, F., Verhagen, C., and Uitenbroek, D. (**2015**). "The relation between self-reported worry and annoyance from air and road traffic," Int. J. Environ. Res. Public Health **13**(3), 2486–2500.

World Health Organization (WHO) (**1999**). *Guidelines for Community Noise*, edited by B. Berglund, T. Lindvall, and D. H. Schwela (World Health Organization, Geneva).

WHO (**2011**). *Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe*, edited by L. Fritschi, A. L. Brown, R. Kim, D. Schwela, and S. Kephalopolous (World Health Organization, Regional Office for Europe, Bonn).

WHOQOL Group (**1998**). "Development of the World Health Organization WHOQOL-BREF quality of life assessment," Psychol. Med. **28**(3), 551–558.

Yano, T. (**2015**). (personal communication).

Yano, T., Kuwano, S., Kageyama, T., Sueoka, S., and Tachibana, H. (**2013**). "Dose-response relationships for wind turbine noise in Japan," in *Proceedings of INTERNOISE, 42nd International Congress and Exposition on Noise Control Engineering*, Innsbruck, Austria, September 15–18, 2013, pp. 4591–4598.