ASSESSING INTRUSIVE NOISE AND LOW AMPLITUDE SOUND

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in fulfilment of the requirements for the degree of
Doctor of Philosophy
in Health Science

Massey University
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Institute of Food, Nutrition and Human Health

Ethics Approval

Ethics approval for the trial of instrumentation and methodology for assessing low amplitude sound as a low risk project was received on 18 October 2007. The approval states:

> This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research. If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Professor Sylvia Rumball, Assistant to the Vice-Chancellor (Ethics and Equity), telephone 06 350 5249, email humanethics@massey.ac.nz

ABSTRACT

Annoyance due to relatively high levels of sound and noise, above 50 dB, has been well documented in noise assessment literature. The potential for annoyance or disturbance from low amplitude sound, below 50 dB to the threshold of an individual's hearing, is not as well documented. The thesis presents a new approach to the measurement and assessment of intrusive noise and low amplitude sound. Acoustical and sound quality measures are integrated with measures of loudness, pitch, dissonance and tonality to provide physical measures of sound. Individual amenity is assessed with respect to personal noise sensitivity and personal attitudes to sound in the environment, the environment itself and the perceived qualities of the audible sound. A decision-support methodology to integrate perceived noise with noise performance indicators, annoyance criteria, personal noise sensitivity and amenity is presented. A method for rating intrusive noise is derived. Designs for sound measurement and calibration instrumentation are described. Methods to measure and assess low amplitude sound are presented.

Keywords

annoyance, intrusive-noise, noise-sensitivity, sound-quality, soundscape

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This research developed over time as people asked questions about why it seemed to be so difficult to measure noise. The usual definition that noise is “unwanted sound” is obvious but the definition is so broad that it is meaningless. Hopefully, the research provides useful meaning to the term, and I want to thank friends and colleagues for their time and patience in helping me. In particular, Dr Densil Cabrera for permission to modify PsySound2, the program that provided a solid stepping stone for this research and Brian Cruse, for all his enthusiasm in translating PsySound2 from Mac to Windows format and in coding my new analysis and display routines. Sue and Daniel: thanks for your thoughts and assistance. The permission of Trevor Cox and Andy Moorhouse of Salford University Acoustic Research Centre (Sound Quality Research) to reference their work on sound quality and sample soundfiles is acknowledged with thanks. My special thanks to Dr Ernst Terhardt, Dr Richard Parncutt, Professor BCJ Moore, Dr Rod Nave and Professor Will Hopkins for their permission to reference their respective works.

For those of us who find field work is a great way to spend the day:

Analysis: so many dragons, so few spears

Results: a bat in the bag is worth two in the belfry

And to all those people who over the last 15 years have said “that noise is driving me crazy… can’t you hear it?” Sorry guys, I still can’t hear it so that must mean…

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18 March 2007

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CHAPTER 1: INTRODUCTION

1.1 Sound, music and noise

Environmental sound surrounds us all the time, awake and asleep. It is the music of the world in which we live. Music has discordant notes, as does our environment. When noise intrudes upon the well-being of an individual it can disturb and cause irritation, anxiety and anger. In an ideal world there would be no noise intrusion and therefore no annoyance caused by noise. Unfortunately, this is not an ideal world.

Why do certain sounds disturb one person but not another? Why can some sounds be heard and ignored by one person when the same sound is intensely disturbing to another person? Can this sound be measured or assessed in a meaningful way?

There are no widely accepted answers to these questions, even after more than 40 years of research on noise induced annoyance. This is partly because research since the mid-1960's has emphasised short and long-term measures of community noise exposure to moderate- and high-amplitude road, rail and aircraft noise. Research on the effects of low amplitude sound has generally involved low-frequency noise from sources such as air conditioning within buildings. This work addresses the specific problems with the measurement and assessment of low amplitude sound and intrusive noise as a public health issue.

1.2 Thesis organisation

The objectives, scope, assumptions, methodologies, outcomes and limitations of the work are described in the following sections.

1.2.1 Objectives

The research has three objectives:

1. To explore the research question:
   Is it possible to develop a methodology incorporating a decision support system to integrate perceived noise with noise performance indicators, annoyance criteria and individual noise sensitivity?

2. To explore the research question:
   Can low amplitude sound affecting individuals be measured and assessed in a standard manner?

3. To consequently establish a methodology to assess low amplitude intrusive noise with respect to an individual.

1.2.2 Scope

The scope of the research program is:

1. Limited to the development of sound and noise measurement and assessment methodologies for individuals rather than communities within a New Zealand context.

2. Defined by reference to literature reviews and investigation work undertaken by myself.

3. Limited by the availability of commercial hardware and software.

1.2.3 Research Assumptions

Two fundamental assumptions were made at the commencement of the research:

1. It was assumed that noise could be measured and assessed for a potentially affected individual.

2. It was assumed that a methodology or methodologies could be developed to identify the character of low amplitude environmental sound and low amplitude intrusive noise.

1.2.4 Research Methodologies

The research methodologies involved the development of a multi-disciplinary approach to noise as a public health issue. The overall approach chosen incorporated scientific and administrative techniques to:

1. Identify research concerns.

   One fundamental issue was to define the terms in which the research is undertaken. Definition is addressed in the work following a review of significant relevant literature dealing with the scientific basis of sound and noise, human response to sound, human sensitivity to noise, actual field work, acoustical measurement methods and instrumentation, sound propagation, and sound quality methods of assessment and analysis. There is no measurement or assessment protocol for low amplitude intrusive noise and few readily available instruments that will record and analyse low amplitude sound.

2. Develop noise perception methodologies

   Noise exposure methodologies exist in national and international standards but there are no methodologies available to “split-out” noise from low amplitude sound. This is a critical issue, as a fundamental issue is to establish the nexus between “unreasonable noise and a reasonable person” and “reasonable noise and an unreasonable person”. Consequently, for this work, new definitions for intrusive noise have been developed to quantify and qualify different levels of noise exposure and adverse effects from noise. New measurement and assessment protocols for low amplitude sound and intrusive noise are presented.

3. Attitudinal and acoustical studies

   The work references attitudinal and acoustical studies undertaken by myself or to which I have an appropriate relationship. My study and analysis methods were drawn from standard methods described further in this work. Acoustical studies are presented as measures of audible sound and inferences made of the degree of intrusiveness based on interviews with affected persons. Pilot studies were undertaken in a community affected by wind farms and compared to an urban population unaffected by wind turbine sound. Wind farms are a unique source of potential adverse noise due to their low amplitude and special audible characteristics. The methods of measurement, analysis and assessment developed from this research are brought forward to the development of the decision methodologies for perceived noise and the measurement of low amplitude sound.

4. Developing measurement and assessment methodologies

   The measurement methodologies utilised existing technology to complete most of the work but low amplitude sound is difficult to measure and record even with professional instrumentation. Measurement instrumentation for sound and noise analysis is relatively expensive, complex to use and capable of considerable variation in application. This limits instrumentation availability to relatively few individuals. Inexpensive alternative instrumentation was developed that supports measurement of low amplitude sound. The instrumentation is described in this work.

   With instrumentation available two issues with noise investigation are addressed: 1) how to measure and assess the sound environment, and; 2) how to measure and assess intrusive noise that may sit "inside" the overall sound environment. This returns to the definitions of intrusive sound and noise as an individual is the only person who can determine if a sound is noise to that person. The work presents a process to allow an individual measure and assess low amplitude sound and noise.

1.2.5 Research Constraints

Constraints to the research were primarily due to-

1. Budget - The cost of the research was supported only by personal funding.
2. The limited availability of sound analysis instrumentation and sound quality analysis software required for significant portions of this work.

CHAPTER 2: INDIVIDUAL AND COMMUNITY ATTITUDES TO NOISE

2.1 Introduction

> Each of us is different. ... And at the centre of our uniqueness is the human brain. Each of these is - to the anatomist at least - discernibly different from every other in some and often hundreds of structural features; and its functioning is - to the analytical psychologist - likewise different. The consequence is simple, but inescapable: each of us has an own world. The framework and the ordering, and the manifold organization, that we impose on our experience, is as a whole ours alone and ultimately unique. Quite literally, we create our own realities.
>
> Brosnahan F., *Seeing, Saying, Thinking, 2007*

The observation by Brosnahan captures the essential conflict between individual noise response and community noise response. Individuals vary whereas community noise exposure guidelines imply that "we" are all alike in our response to noise. This has significant effect in the way noise is measured, assessed and managed. Sound and noise are often used to describe the same thing, but they are not the same. Audible sound is anything that can be heard by a person. The audibility of a sound can be graduated, and different methods of assessment applied, in order to predict the level of acceptance a particular sound or noise may have on an individual or within a community. The significant difference between sound and noise is the adverse emotional response that is the major characteristic of noise. Noise is a characteristic that may, or may not, exist in audible sound. Noise is the audible unwanted part of a sound and is generally specific to a person (either real or notional) at a specific time and place. When noise intrudes upon the well-being of an individual it can disturb and cause irritation, anxiety and anger. For instance, the quality of a person's home environment, and the intrinsic and extrinsic relationships that person has with that environment is significantly influenced by the character of noise intruding onto the home and the perceived amenity of the immediate environment.

Kryter (1985, p. 124-125) developed the definition of *noisiness* by reference to noise as 'unwanted sound'. Unwanted sound, he wrote, comes in two general classes of 'unwantedness':

> One category carries … information about the source of the sound that the listener has learned to associate with some unpleasantness not due to the sound per se, but due to some other attribute of the source…
>
> Unwanted sound in the second category annoys a listener because of the physical content of the sound per se and not because of the meaning, if any, of the noise.

As reported by Job et al. (1999a, 1999b) noise exposure may produce various health disadvantages, amongst them negative reactions (e.g., dissatisfaction, annoyance). Noise management legislation, codes and guidelines are made based on predicting the effects of a given noise exposure. The United States Environmental Protection Agency USEPA (1974) published the "Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety" based on the knowledge and instrumentation available at the time. The guidelines have had far reaching effect and have been referenced in one form or another world-wide. The recommended levels identified to protect public health and welfare for a large number of situations (USEPA 1974, p. 1) were established as an outdoor level of 55 dB day-night level (DNL) and 45 dB DNL indoors. Both levels are A-frequency weighted. Implicit in the guidelines, however, is the knowledge that a proportion of the population will be disturbed by noise levels held to be "acceptable" for the majority of the population. Similarly, people sensitive to noise are not catered for by the guidelines.

Annoyance is not a measure of noise either. It is the outcome or response to noise. Schultz, in *Community Noise Rating* (1982, p. 2) records that the proliferation of noise ratings

> …have stemmed from the desire that they should in some sense mirror the extraordinarily complex working of the human ear and brain, without being any more complicated than necessary for the immediate problem at hand.

Further, (1982, p. 3) he states ‘Thus, we look for ways to measure certain physical properties of community noise exposure that are closely connected with people’s subjective judgment’.

Common simple acoustical measures, while a good starting point, have limited application explaining why or how a person responds to a sound. This is evident, for example, in the subjective responses of people when asked about their likes or dislikes in music. The intensity of the music’s sound only partly explains an individual’s responses, as they are generally defined in more subjective terms; for example, through perceptual reactions and emotional weightings. The presence of a noise and its subjective perception are identified within this methodology by an individual through a personal noise sensitivity questionnaire (Anderson, 1971). A person gives emotional weighting to noise heard and it is this highly variable weighting that is identified as an individual’s sensitivity and potential for annoyance to noise. The techniques of sound quality measurement provide a partial analogy for sensitivity. The hearing response of an individual is an important consideration when assessing intrusive noise. In this context hearing response includes not only the person’s physical hearing response but emotional response also.

A sound, for example, may or may not be pleasurable or it may have a warning content that is, or is not, acceptable to the listener. There is intrusion by degree, where a sound may be acceptable for a short while but after a certain length of time becomes noise. Most often intrusion is negative, but there can be occasions when an intrusive sound has a positive or beneficial effect. The information content within the sound becomes the determining factor. For a sound to become noise it must, therefore, possess characteristics that are not solely due to the “loudness” of the sound. Various measures, such as dB ratings, loudness, audibility and perceived noise levels deal with physical aspects of average human response to sound (Kryter, 1985). Non-acoustical variables, however, have considerable effect on an individual’s emotional responses to noise. These responses can include annoyance, anger, and fear and constitute the effects of noise intrusion.

2.2 Attitudinal surveys

Attitudinal surveys present a methodology to assess individual and community response to sound and noise. Borsky (1970, pp. 219-227) proposed a model to understand the variability of the responses to noise. The model, in use today, has 4 phases-

1. Perception or awareness of noise;
2. Activities affected or interrupted;
3. Annoyance or hostility resulting from interruption;
4. Complaints resulting from this annoyance.

The first three phases have been utilised in this work. The complaints mechanism is not considered further. Kryter (1970, pp. 69-84), Stevens (1970, pp. 114-128) and Young (1970, pp. 45-58; pp. 129-150) established fundamental concepts and definitions for the evaluation of noise. McKennell (1970, pp. 228-244) established a relationship between noise complaints and community action. Stevens (1970, pp. 120-121) summarized the central issue in the debate over the use of an acceptable criterion to use to assess noise; that is, 'loudness' or 'noisiness' by saying ‘There is little hope that acceptability can be measured in any useful sense when meaning and context are allowed to change’. This work presents a methodology to standardise the meaning and context of low amplitude sound and noise and to assist in the determination of acceptable sound.

During the late 1970's the USEPA commissioned acoustical and social survey design manuals that present the “baseline” state of knowledge (USEPA 1981a, 1981b, 1981c, 1981d). Prior to the publication of these guidelines the USEPA commissioned studies into acoustical measures and measures of acceptability of noise (Scharf Hellman & Bauer, 1977; Sharp et al., 1977; Scharf & Hellman, 1979). These guidelines have been referenced in the development of the surveys for this research.

Schultz (1978) synthesised the key characteristics of social surveys from a comprehensive range of surveys completed by others over the period 1961 - 1971. Key elements of the conclusions made by Schultz have been studied by other researchers but it wasn’t until 1998 that Fields (1998b, 1998c); Fields et al. (1998d) reported proposed procedures to standardize key elements of an attitudinal survey. In 2001 Fields published an updated catalogue of 521 social surveys. The work of Fields presents the current state-of-the art for attitudinal - social surveys. The logic of an *attitudinal survey* is that the selected households collectively will represent the population as a whole. Each household in the population has an equal chance or probability of being chosen for interviewing. By taking care to geographically disperse the sample over the region, the distribution of the household characteristics will approximate the distribution of the characteristics of the population as a whole. The detailed survey is designed so the sample should have defined margin of error, with a significance level of 5 percent being common. It has been observed by this author that standard attitudinal surveys are often restricted to respondents aged 18 or over. The reason or reasons for this are not clear. Draft International standard ISO/DTS 15666 *"Acoustics – Assessment of noise annoyance by means of social and socio-acoustic surveys"* does not prescribe any age limit for the questions on annoyance. While an age restriction is possibly suitable for marketing purposes this degree of bias is unacceptable in environmental noise investigations as a significant proportion of the potentially exposed population would be excluded. Fields (1998e) reported on the "Survey-Design Guideline Project" that had as its brief the creation of guidelines for the design of combined acoustical/social surveys of residents' responses to environmental noise.

Three survey objectives have been identified by Fields (1988e, p. 10):

- A "basic" survey to measure existing noise levels and annoyance responses within limited geographical areas
- Developing dose/response relationships for planning or comparisons to determine how noise level affects reactions in a population or to enable comparisons between the reactions in a specific study population and that of people generally or specific other studies
- Understanding factors affecting responses and to measure the effect of other, non-noise, factors on responses to the primary noise source

2.3 Noise exposure surveys

When an attitudinal survey to assess a person's individual reaction to noise is associated with an acoustical survey it is termed a "socio-acoustic survey". This type of survey is the most useful. The ISO 15666 format does not incorporate localised noise surveys whereas the USEPA survey methods (1981a, 1981b, 1981c, 1981d) recommended attitudinal and acoustical surveys complement each other. Historically, however, attitudinal surveys did not have co-ordinated acoustical surveys. Most of the surveys can not, therefore, be used to assess intrusive noise or its effects on individuals.

Exposure to noise is most often measured on the basis of noise levels outdoors and interpolated for an assessment of effects indoors. This approach, however, has been questioned by Berry (1998, p. 628). Interior sound levels vary depending on the area of openings to the exterior and the construction of the floors, walls and roof/ceiling of the building. Noise exposure predictions for outdoor assessments are made on the basis of simple noise monitoring routines that take into account noise from a range of different sources. The prediction methodologies reflect the idea that community noise can be reduced to a series of relationships between measures of general annoyance, health risk assessment and noise exposure metrics, as presented by the USEPA (USEPA, 1974) for example. The technique of using a single descriptor/metric is widely used. The technique has the benefit of being relatively inexpensive to undertake and analyse for meaningful results but the approach is flawed as it does not identify the character of the sound. Fields (1998c) has identified the care that must be taken in undertaking a community noise survey investigating the relationships between measures of general annoyance, health risk assessment and noise exposure metrics. The comprehensive approach of the USEPA (1974, 1981b) must, therefore, be treated with caution for individual assessment.

The effects of noise, especially relatively high levels of noise, are well known and quantified; whereas the effects of low levels of noise are not as well documented, but are real none-the-less. Standard noise measures, such as LAeq, deal quite well with noise exposure but more specialised measurements are needed for assessing intrusive noise events. Noise exposure is generally measured over a 24-hour (or longer) time period and is related to the community at large, rather than individuals. This clearly illustrates the problem an individual has in assessing the measure of a particular noise, which may occur for only a very short period of time (a reversing alarm on a vehicle, for example), in terms of noise exposure or personal effect. On the other hand, the number of people in a community annoyed by noise from transportation is related to relatively long-term noise exposure level from road, rail and/or aircraft.

Socio-acoustic surveys on noise annoyance are conducted by researchers to assess the magnitude of environmental noise and to develop suitable noise ratings for community noise exposure. A closely linked outcome is that, from a measurement of the physical characteristics of community noise, it is possible to predict the community's subjective response to the noise. The reliability of the prediction methods is being challenged by the work of Berry (Hoare Lea Acoustics, 2006) by drawing attention to the potential sources of error. A typical survey would address one particular source of noise from, for example, aircraft over-flight or road traffic. The general procedure is to subdivide a neighbourhood known to be significantly impacted by the noise in question into smaller local areas. The local areas are more or less uniformly exposed to the 'principal' noise but are affected to varying degrees to other sources of noise as well.

Ambient sound levels vary significantly day by day and hour by hour at the same location and individual location prediction is still an inexact art-form even when the noise source is from a "single" well-defined source. For the same level of exposure some people are nearly oblivious to the noise, some experience varying degrees of annoyance, and some are extremely disturbed. The subjective responses do not depend upon the level of noise but on a range of factors including the degree of acceptance of the noise source. These responses indicate the necessity for locality-specific noise management within communities.

2.4 Individual sensitivity to noise

In *Dracula*, Bram Stoker (1897) identifies the subjective nature of emotional reactions to the same sound. For example, in the following excerpts, the varying emotional responses of Jonathan Harker, Harker’s coach horses and Count Dracula to the howling of wolves in the distance are described:

> Then, far off in the distance, from the mountains on each side of us began a louder and a sharper howling, that of wolves, which affected both the horses and myself in the same way. For I was minded to jump from the calèche and run, whilst they reared again and plunged madly, so that the driver had to use all his great strength to keep them from bolting. In a few minutes, however, my own ears got accustomed to the sound, and the horses so far became quiet that the driver was able to descend and to stand before them. (Chapter 1)
>
> *and*
>
> … but as I listened I heard as if from down below in the valley the howling of many wolves. The Count's eyes gleamed, and he said: "Listen to them, the children of the night. What music they make!" Seeing, I suppose, some expression in my face strange to him, he added, "Ah, sir, you dwellers in the city cannot enter into the feelings of the hunter." (Chapter 2)

The effect of the wolves howling on Harker illustrates the feelings people often experience in response to strange sounds, such as disturbance, annoyance and fear. The description of the wolves suggests that the sound of their howling, being far-off in the distance, is not loud, yet it is audible to Harker and the horses. Initially, Harker and the horses perceive the howling negatively but, after a short while, they become accustomed to the sound. It is possible to infer that their initial reaction was one of fear. The Count, however, has a different reaction to the howling of wolves, and this is one of immediate pleasure. To the Count, the sound of the wolves howling is music.

As observed by Stoker, personality factors significantly influence reactions to noise. Negative reactions to noise may include dissatisfaction, annoyance, anger, frustration, disappointment, and/or distress. Reaction is generally regarded as an important effect of noise exposure and has been examined in community surveys; for example Fields (1998a), Hatfield et al. (2001a), Hatfield (2001b), Hatfield et al. (2001c), Job (1988), Job et al. (1996a), Job et al. (1998), Job & Hatfield (2001), Job & Hatfield (2006). Everyone, at some time, will be aware of the disturbing and annoying effects of noise. Attitudinal survey questionnaires, however, do not investigate the reasons why an individual is disturbed by noise.

Individual amenity is evaluated with respect to personal noise sensitivity, personal and cultural expectations and attitudes to noise in the environment and habituation effects. Noise intrusion, as a personality variable, is dependent on noise sensitivity. Methods of assessment of individual sensitivity to noise have not been as well developed as community social surveys, with few methodologies readily available.

Zimmer and Ellermeier also found that noise sensitivity is a stable personality trait (1997, p. 163) reflecting attitudes towards a wide range of noises and is a trait (1997, p. 169) that contributes to the level of perceived annoyance. They present the concept of *noise sensitivity* (1999, p. 295) to explain the considerable difference in noise tolerance across individuals when noise exposure is controlled. The importance of noise sensitivity assessment, as a measure of human response, is the strong association between noise sensitivity and annoyance. Noise sensitivity is stated as being the only personal background variable investigated to have a significant effect on annoyance. Addressing the question of whether individual differences in noise sensitivity are related to differences in auditory functioning they conclude (1999, p. 301) that:

> It turned out that groups of participants exhibiting 'low' vs 'high' noise sensitivity (LEF) were indistinguishable on the basis of absolute thresholds, intensity discrimination, simple auditory reaction time, or power-function exponents for loudness.

Miedema and Vos (2003, p. 1498) reported that noise sensitivity has a strong influence on annoyance and is independent of the noise exposure. They also found (p. 1503) that noise sensitivity alters reactions such as self-reported sleep disturbance attributed to noise:

> Noise sensitivity has at most a very weak (positive) relationship with noise exposure, which cannot explain the strong influence of noise sensitivity on effects such as noise annoyance. Noise sensitivity changes the influence of noise exposure on noise annoyance, and does not (only) have an additive effect, i.e., it affects the rate at which annoyance increases when the noise exposure gets higher. It also alters reactions other than noise annoyance, such as self-reported sleep disturbance attributed to noise, as well as reactions to other environmental conditions, such as odour. The above results

> suggest that noise sensitive subjects have a predisposition to discriminate environmental conditions and evaluate them. This predisposition is weaker or lacking in persons who are not sensitive to noise.

Job (1999a, p. 2) has observed that: ‘Sensitivity to noise in general … may be overlaid with sensitivity to particular noise sources… such that reaction to a combined noise source would involve a complex interplay of noise sensitivities.’ In an earlier paper Job (1988, p. 991) stated that-

> Only a small percentage (typically less than 20%) of the variation in individual reaction is accounted for by noise exposure.
>
> Variables, such as attitude to the noise source and sensitivity to noise, account for more variation in reaction than does noise exposure.

Personal noise sensitivity questionnaires such as the LEF Questionnaire by Zimmer and Ellermeier (1997, 1998, 1999) and that developed by Weinstein (1978) - and the discussion on Weinstein’s noise sensitivity rating by Luz (2005) - are presented for the assessment of individual noise sensitivity. Noise annoyance reactions are directly affected by a person’s sensitivity to noise. The LEF noise sensitivity questionnaire is designed to relate perceptual, cognitive, affective and behavioural responses to noise in the context of everyday life, recreation, health, sleep, communication, work and noise in general.

The Weinstein study (1978) investigated differences among individuals (students) in their initial reactions to noise and in their ability to adapt to noise over a longer period of time. Their results suggested that sensitivity to noise is a personal attribute that permits predictions of reactions to environments encountered for the first time. Luz (2005) has presented a score process from Weinstein. In discussing the Weinstein’s Noise Sensitivity Scale, Luz (p. 15) states-

> Weinstein’s scale is designed to capture sensitivity to different noise sources. This design is consistent with research showing that people who are more annoyed than the general population by one source of noise will be more annoyed by another source of noise.

Luz (p. 14) summarises the significant aspects of noise sensitivity and quotes, in part, psychiatrist Dr Stephen Stansfeld (1992) as saying:

> In summary, noise sensitivity may be comprised of two elements. Noise is important to noise-sensitive people who attend to noise more, discriminate between noises more, and tend to find noises more threatening and out of their control than people who are not sensitive to noise. Secondly, because of negative affinity, they react to noises more than less sensitive people, and may adapt to noises more slowly. This may result in a greater expression of annoyance to noises than in less sensitive people…

Luz (p. 17) observes that noise sensitive individuals do not hear better than non-noise sensitive individuals, and they don’t experience a sound as any louder than non-noise sensitive:

> What does distinguish the noise sensitive from their non-noise sensitive neighbours is an inability to “turn-off” their response to low intensity sounds.
>
> *and*
>
> Surveys have found that the incidence of noise sensitivity to vary between 22% and 30%, so it is safe to say that you have a 1 in 5 chance of being noise sensitive.

One criticism of the Weinstein scale is that it combines noise exposure with noise sensitivity questions. The scale has been adapted by Kishikawa et al. (2006) from the original scale to a subjective sensitivity scale which focuses more tightly on individual noise sensitivity. The LEF questionnaire with its multidimensional analysis has led to the Noise-Sensitivity-Questionnaire or “NoiSeQ” (Schütte et al. 2007, p. 9-24). NoiSeQ assigns question items to five subscales: leisure, work, habitation, communication and sleep. The design of the questionnaire allows a value for global noise sensitivity as well as the subscales. The reliability of the questionnaire is reviewed (Sandrock, Schütte & Griefahn 2007, p. 8-14) with the conclusion that the subscales work, sleep and communication allow reliable classifications. The leisure and habitation subscales require extra questions in order to improve reliability. It is concluded that NoiSeQ is an appropriate method for noise sensitivity analysis and has the additional benefit of being able to be referenced to the standard environmental questionnaires presented in this work.

2.5 Influence of other factors on personal reaction to noise

In addition to the consideration of noise sensitivity to the variability in individual response to noise there are the influences of various factors, for example: behavioural coping strategies (Schulte-Fortkamp 1996, p. 2353); habituation (Schulte-Fortkamp 1996, p. 2353), (Namba & Kuwano 1988, 2000); temporal factors (Namba & Kuwano 1997); frame of reference (Namba & Kuwano 2000); perception (Miedema & Vos 2003, p. 1499), and; synergetic effects from different combined noise sources (Ronnebaum, Schulte-Fortkamp & Weber 1997, p. 171). There does not appear to be any difference between males and females with respect to noise sensitivity. There is some evidence, however, that women may evaluate sound in a different way to men (Hellbrück 1991, p. 238). Women may have a lower hearing threshold and a lower uncomfortable loudness level and may judge sounds higher than men. The variation appears to be from the assessment methodologies: the findings are relevant if category scales are used but there is no difference between men and women if magnitude estimation is used. Hellbrück considers any variance to be an artifact of the assessment methodologies.

Temporal factors, or the duration of a noise, are important in the assessment of noise in sound. The assessment methods recommended by Namba and Kuwano (1997, p. 465) comprise three temporal durations:

> (1) short-term noise: When the duration of a noise is shorter than 1 second, the duration and envelope patterns were found to have a significant effect on the loudness and timbre. A dynamic model of hearing…was found to be applicable to the evaluation of various short-term noises.
> (2) level fluctuating noise: When the noise is longer than 1 sec, the loudness is not integrated, but averaged. The mean energy model can be applied to the evaluation of level fluctuating sounds.
> (3) long-term noise: In the case on long term noise, it would be necessary to take various factors into consideration such as the relation between short-term and long-term-term evaluation, and the interaction among noise sources. By comparing the overall and instantaneous impressions using the method of continuous judgment by category, it would be expected to find factors which determine the overall impression of the long-term noise.

In relation to the subjective assessment of noise Namba and Kuwano (2000, pp. 35, 36) have concluded that two factors apply to the subjective assessment of noise:

> (1) The application of an appropriate physical index that shows good correspondence with subjective impressions in order to predict the effect of noise. They suggest magnitude estimation as a good method and comment that there is good correlation between mean energy level LAeq and loudness of level fluctuating sounds.
> (2) The measurement of the degree of disturbance-effect of noise and to determine noise criteria.

In addition, Namba and Kuwano (2000) conclude that cultural and social factors as well as physical properties of the sounds have an effect on noise evaluation. A person's cultural expectations and experiences have a significant role in that person's response to noise. Acceptance of noise has strong correlation to environmental, social and economic factors (Altena 1987; Johnson & Button 1997; Lambert, Kail & Quinet 1998). People with differing standards of living have different expectations from their environment and people who have habituated to a relatively noisy environment can find it hard to adjust to a relatively quiet environment. The expectations of segments of society with respect to a noise-free environment can sometimes be at odds with the demands of that society for goods and services. Levels of noise acceptable to society overall can be totally unacceptable to a small yet significant minority.

Individual responses to noise include annoyance and anger, frustration and a sense of helplessness that nothing is being done to remove the noise, and dissatisfaction with the amenity of the locale. Depression and anxiety are also common with a very real sense that the noise distracts the person from having a good relationship with the locale in which he or she is living. These emotional responses can lead to a fear that the noise will never go away. There can be distinct behavioural changes in the person and the individual can start waiting for the noise to begin. Sleep disturbance is common, with relaxation inside and outside the home becoming less satisfactory to the individual due to the disturbance caused by the noise. In a real sense the individual feels that his or her home environment has become contaminated. A sense of grievance is common, especially if the individual is unable to have the noise accepted by an independent authority due to difficulties in measurement or assessment. A common expression is "You should have been here half-an-hour ago, the noise was far noisier then." There can be significant financial costs with the individual obtaining advice and noise-proofing the home. In some extreme cases where the environment has become too adverse the individual leaves for a new, quieter, locale.

2.6 Sleep disturbance

Sleep disturbance is a major effect of environmental noise as described by, for example: Bullen, Hede and Williams (1996); Griefahn and Muzet (1978); Griefahn (1991, 1992); Griefahn et al. (1998); Griefahn, Basner and Marks (2006); Guski (1991); Horonjeff, Fidell, Teffeteller and Green (1982); Muir (1998); Pearsons, Barber, Tabachnick and Fidell (1994). Sleep disturbance is defined by Griefahn (1991, p. 256) as "measurable and/or experienced deviations from the usual or from the desired sleep behaviour and they are indicated by primary and after effects."

Primary effects of environmental noise that may occur during sleep-time include difficulty in falling asleep, awakenings and alterations of sleep stages or depth. Uninterrupted sleep is considered a prerequisite for good physiological and mental functioning. The World Health Organization (2000, Table 1) recommends an upper level of 30 dB(A) LAeq and a maximum level of 45 dB(A) for 8 hours sleep. Griefahn (1991, p. 256) has suggested tentative critical loads for both intermittent and continuous traffic noise. Intermittent noise causes larger reactions and is defined as a variation of more than 10 dB(A) between the LAeq level and the maximum levels. The critical load for continuous noise is suggested as 37 – 40 dB(A) Leq indoors. Sleep disturbance in the morning is found to cause more awakenings and changes in sleep stages, with more time needed to return to the preceding sleep stage.

Öhrström (1995) has shown that irregular traffic noise of a maximum level of 45 dB(A) affects subjective sleep quality, tiredness the next day, and work performance. The critical number of noise events exceeding a maximum 45 dB(A) is between 16 and 32 events. At higher maximum noise levels of 50-60 dB(A) the number of events should not exceed 16 events per night. To protect people who are ill, elderly or sensitive to noise effects Öhrström recommends that the maximum level should not exceed 45 dB(A) during the night.

An assessment methodology for sleep disturbance has been proposed by Bullen, Hede and Williams (1996) and Bullen (1998). The Sleep Disturbance Index depends on the number of individual noise events heard per night; the maximum noise levels of events; and the emergence of events above the ambient noise. Alternatively, Miedema, Passchier-Vermeer and Vos (2003) utilise noise (as sound exposure level and as maximum level), the number of noise events and the adverse effects on sleep disturbance.

The effect of low sound level, low frequency sound can have significant adverse effect on sleep, as discussed by Leventhall, Pelmear and Benton (2003, p. 5):

> It should be noted that low frequency noise, for example, from ventilation systems can disturb rest and sleep even at low sound levels.
> When prominent low frequency components are present, noise measures based on A-weighting are inappropriate.

Leventhall (2004, p. 59) discusses low frequency noise (10Hz – 200 Hz) as a special environmental noise problem and states that conventional methods of assessing annoyance with A-weighted Leq are inadequate for low frequency noise and lead to incorrect decisions by regulatory authorities. The noise levels are often low, in the region of an individual's hearing threshold. He considers that approximately 2.5% of the population may have a low frequency threshold which is at least 12 dB more sensitive than the average threshold. Onset of low frequency noise annoyance tends to occur in middle age, with complaints from persons in the 50-59 age group common in the UK. Leventhall notes (p. 65) the enhanced adverse effects on annoyance of low frequency amplitude- and frequency modulated sounds compared to their average sound levels. In quoting Vasudevan & Leventhall (1982), he notes (p. 66) that it is the quality of the sound (tonality as well as fluctuations) near threshold that is important. Sleep disturbance is, therefore, a primary consideration for low amplitude sound and noise assessment, especially if prominent low frequency components are present.

Night noise guidelines (2007) have been developed by a World Health Organization (WHO) working group as an extension of the World Health Organizations Guidelines for Community Noise (2000). The guidelines are linked to European Union Directive 2002/49/EC relating to the assessment and management of environmental noise. The Directive introduces a noise indicator for sleep disturbance called the night-time noise indicator (L_{night}). The indicator is the A-weighted long-term average sound level (equivalent continuous sound pressure level) determined over all the night periods of a year. The measured level is adjusted for time of day, character and source of the sound. A level of $L_{night.outside}$ above 55 dB is considered increasingly dangerous for public health as adverse health effects occur frequently and a high percentage of the population is highly annoyed. A level of 30 dB $L_{night.outside}$ is the ultimate target of the Night Noise Guideline to protect the public, including the most vulnerable groups such as children, the chronically ill and the elderly, from the adverse health effects of night-time noise. Sleep disturbance due to a discrete event may be measured by maximum level per event (L_{Amax}) and the A-weighted equivalent sound pressure level (L_{Aeq}) to predict short-term or instantaneous health effects. The guidelines indicate that the maximum level threshold inside may be considerably lower than the previous guideline of 45 dB(A), with indoor L_{night} threshold levels of L_{Amax} 35 - L_{Amax} 42 dB(A) necessary to protect quality of sleep.

2.7 Individual amenity, noise and annoyance

The relationship between individual amenity and the adverse effects of noise is fundamental in the description of intrusive noise. For a sound to become noise, it must be unwanted by the recipient. Noise intrudes upon the amenity of a person and due to its unpleasantness causes annoyance and distress. The mechanism for this transformation of sound to noise varies widely from person to person. Because our hearing is functioning all the time we are continuously monitoring, analysing and responding to what we hear. Our environment is a complex of competing sounds (Tixier, 2000; Truax, 1999), many are benign, and the sounds we hear are normally what we expect to hear. That is, they are the common, everyday sounds that we are used to and generally accept and ignore. However, sometimes a sound or event occurs that triggers a warning or alert response within us.

If the sound evokes a negative personal response the sound is unwanted and is noise. When an individual responds to intrusive sound or noise, the person is responding to a stimulus that is noticeable within the individual's environment. An individual may react differently to noise from a combination of sources than to noise from a single source at the same level. Significantly, other persons in the vicinity may not hear or be disturbed by the noise. There is, however, a stable personality trait for noise sensitivity that provides a foundation for the assessment of individual acceptability of a particular sound under general and specific conditions. Individual amenity is a complex mix of personal noise sensitivity, personal and cultural attitudes to noise in the environment, and habituation effects.

The physical characteristics of the sound in combination with all other sound sources are a smaller component of the response. There is no defined model for assessing intrusion or annoyance due to a combination of environmental noise sources as discussed in, for example, Berglund and Nilsson (1998a, 1998b); Job et al. (1999a), and Miedema (1987). Noise intrusion is not well documented with works primarily from Fidell et al. (1979); Fidell and Horonjeff (1982), and Fidell, Green and Pearsons (1987a).

Noise assessment for individuals is often confused with global noise exposure measures applied to communities. Individuals, however, respond differently to noise depending on the "level" of the noise, its character, and the meaning or effect of the noise on the person. Many noise measures do not apply until the sound is quite loud whereas individuals can be considerably disturbed by noise that is only just audible to them. To individuals, annoyance is personal.

Annoyance has been defined by the World Health Organization (Berglund, Lindvall & Schwela, eds, 2000, p. 50) as 'a feeling of displeasure associated with any agent or condition, known or believed by an individual or group to adversely affect them'. Used as a general term to cover negative reactions to noise, it may include anger, dissatisfaction, helplessness, depression, anxiety, distraction, agitation or exhaustion. Individual amenity, therefore, is described in relation to the adverse effects of intrusive noise, including noise sensitivity and annoyance, onto a person's sense of amenity or peace and tranquillity. Preis (1986) presented a new approach to the estimation of annoyance from intrusive and non-intrusive sounds by the application of measures of sensory consonance. Intrusion was related to "dissonanceless" or timbre, and pitch, including sharpness, roughness and tonality. In a further paper Preis (1997, p. 191) stated that:

> Annoyance cannot be defined with standard attributes of sound sensation such as loudness, pitch and timbre. Therefore it is defined with attributes that apply to noise: annoying loudness, intrusiveness, distortion of information content.

The "Genlyd" Noise Annoyance Model (Pedersen, 2007) is one of the results of the "Genlyd" project which had the purpose of quantifying and modelling noise annoyance. The model presents dose-response curves for different sound sources, as well as the reliability, effect and magnitude of modifying factors. The effects and parameters of the model are comprehensive. One perceived acoustic attribute, sound modulation, identified in this work as being of importance in consideration of annoyance response is not identified within the Model although roughness and fluctuation strength are identified. Noise annoyance and the effect of modifiers are defined within the Model (p. 2) as:

> Noise annoyance is an emotional and attitudinal reaction from a person exposed to noise in a given context. From this definition it is obvious that other factors, modifiers, than the noise level are highly relevant if one wants to quantify the annoyance.

Annoyance is one of the main effects of noise, whether on an individual or community basis. Annoyance is closely related to nuisance, unpleasantness and disturbance. The thesis presented by Verkeyn (2004) links to the soundscape concept referring to the interaction of people with sound, for the modelling of annoyance. Verkeyn (p. 89) states:

> In the field of annoyance modelling, authors have defined the sound concept as the acoustical as well as other sensory. Aesthetic, geographic, social, psychological and cultural stimuli in the context of human activity across space, time and society. Soundscape assessment is essential for a more complete, holistic modelling of annoyance.

The research investigating noise annoyance is well documented with works from, for example: Ahrlin and Rylander (1979); Angerer, McCurdy and Erickson (1991), Baird, Harder and Preis (1997); Berglund B, Berglund U and Lindvall (1976); Berglund et al. (1981); Berglund U (1981); Fastl and Yamada (1986); Fidell et al. (1987b); Fidell, Schultz and Green (1988, c1988); Fidell, Barber and Schultz (1991a); Fidell (2002); Fidell (2003a); Fields and Walker (1982); Fields (1984); Fields (1992a, 1992b); Finegold, Harris and von Gierke (1994); Green (1993); Guski (1997, 1998); Hellman (1982, 1985, 1986); Hellman and Broner (1999); Kryter (1970, 1882a, 1982b, 1983); Miedema (1998a); Miedema and Vos (1998b, 1999); Namba, Kuwano and Fastl (1987); Pederson and Waye (2004, 2006); Preis (1996); Preis, Hafke and Kaczmarek (2006); Schulte-Fortkamp (1998a, 1998b); Schomer (2001a, 2001b, 2002b, 2005); Schultz (1978, 1982a); Sutherland and Burke (1979); Tamura (1997); Taylor (1982); Zwicker (1991). The World Health Organization (Niemann & Maschke 2004) has published a report concerning noise effects and morbidity that investigates the effect of noise annoyance and noise induced disturbed sleep and health.

While individuals have their own reality, this reality may not be the same as the community average. This conflict is recognised by the Queensland, Australia, *Environmental Protection (Noise) Policy 1997* (EPP) that seeks to protect the environmental values of people. The environmental values under Section 10 of the EPP[1] are:

> The environmental values to be enhanced or protected under this policy are the qualities of the acoustic environment that are conducive to-
> (a) the wellbeing of the community or a part of the community, including its social and economic amenity; or (b) the wellbeing of an individual, including the individual's opportunity to have sleep, relaxation and conversation without unreasonable interference from intrusive noise.

This balance can be described in terms of audible sound or noise or intrusive noise, and is the fundamental approach to noise management decision making, including appropriate risk assessment and cost-benefit protocols.

[1] I had responsibility for the development of the Environmental Protection (Noise) Policy 1997 while employed by the Queensland Department of Environment and Heritage (now the Queensland EPA).

2.8 Annoyance and wind turbines

The sound from wind turbines is almost unique as an ideal reference source for this work on low-amplitude sound and intrusive noise. The issue with turbine noise is that it is not consistently audible and the nature of the sound is variable depending on wind directions and strength. Wind turbine or wind farm noise adversely affects an individual due to amenity interference (exterior to a dwelling) and disturbance (inside a dwelling). In both instances an individual can become annoyed and sleep disturbance is a potential issue for some individuals.

The mechanisms of annoyance are due to sound modulation (‘rumble – thump’) and the cessation - commencement of sound (‘when will that noise start again?’). In “The measurement of low frequency noise at three UK wind farms” (Hayes McKenzie Partnership Ltd, 2006) the issue of modulation from wind turbines is discussed as ‘blade swish’ (p. 53), aerodynamic modulation (p. 63) and risk of modulation (p. 65). The report comments on sleep disturbance at one residence with recorded interior sound levels of 22-25 dB LAeq with windows closed (p. 64) and states:

> This indicates that internal noise associated with the wind farms is below the sleep disturbance threshold proposed within the WHO guidelines.

Further, at p. 63 the Report states:

> However, wind turbine noise may result in internal noise levels which are just above the threshold of audibility, as defined within ISO 226. For a low frequency sensitive person, this may mean that low frequency noise is audible within a dwelling.

Van den Berg (2006, p. 81) notes that the relatively high annoyance level and characterization of wind turbine sound such as swishing or beating may be explained by the increased fluctuation of the sound. In a stable atmosphere van den Berg measured fluctuation levels of 4 to 6 dB for a single turbine. Individuals are highly sensitive to these forms of sound fluctuations. He found that the typical modulation frequency for wind turbines is 1 Hz, modulating the trailing edge sound that is itself at frequencies of 500 Hz to 1000 Hz and concludes that human sensitivity for wind turbine sound fluctuation is relatively high. Fluctuations in wind turbine sound can be readily perceived in a stable atmosphere (night-time) but during daytime the fluctuations are not as noticeable due to the unstable nature of the atmosphere.

Pedersen (2007, p. 24) states that amplitude modulated sound is more annoying than sound without modulations. The typical “swish” sound is seen as being related to aerodynamic sounds with a time-varying modulated sound with high frequency content. The comment from Pedersen about “high-frequency” content is part of the problem of description with respect to wind turbine sound. Low frequency sound is often cited as being in the range of 20 Hz to 200 Hz, or possibly 300 Hz.

This leaves a gap in definition – how is the mid-range and high-range to be described? ANSI S3.20 is silent on this. For the purposes of this work, ‘high frequency’ is defined as sound of 2000 Hz and above, and ‘mid-range’ are the frequencies in the range 200 – 2000 Hz. However, my interviews with respondents show that there is considerable difference in opinion as to what constitutes the upper-end of the ‘low-frequency’ range. This highlights the perceived difference in opinion between people who know what they hear and describe it in the best way they can, compared to people who work with professional knowledge or established guidelines of some sort.

Individuals are highly sensitive to changes in amplitude modulation and such variations can be expected in densely packed (compared to linear) wind farm designs on steep, broken hill country where turbines operating in-phase or slightly out of phase are highly probable due to the complex topography and variable wind patterns within the catchment. There has been only relatively limited research into noise annoyance from turbines, with significant results reported by Pedersen & Persson-Waye (2004) and Pedersen (2007). The relationship derived by Pedersen & Persson-Waye (2004, p. 3468) shows the effect of “percent people highly annoyed” by noise from transportation and from wind turbines. Annoyance from wind turbine noise occurs at noise levels far lower than for traffic noise. Their research indicates that, for example, 10 percent of the exposed population is highly annoyed with traffic noise at 60 dBA DNL whereas this same degree of annoyance occurs at 36 dBA Leq for a population exposed to wind turbine noise. Twenty percent of the population is highly annoyed with traffic noise at 68 dBA DNL whereas this same degree of annoyance occurs at 39 dBA Leq. The characteristics of wind turbine noise are explored by

Persson Waye & Öhrström (2002) who concluded that psychoacoustic parameters could not explain the differences in annoyance responses.

There is a wide gap in perception between inaudibility and severe annoyance and it is concluded, for this work, that the application of 'special audible characteristics' in New Zealand Standard *Acoustics-The assessment and measurement of sound from wind turbine generators* (NZS 6808:1998) is appropriate. The following conclusions relevant to this work have been drawn from the research necessary to investigate the effects of low amplitude sound from wind farms on individuals:

- Wind farms have significant potential for annoyance due to sound modulation effects even though these effects are of a low amplitude
- The potential adverse effects of low-amplitude sound and vibration that can induce adverse levels of low frequency sound are not well documented
- The interactions between background levels, ambient levels, modulation and tonal character of a wind farm overlaid within a soundscape are complex and difficult to measure and assess in terms of individual amenity
- Sound level predictions for complex noise sources of this nature are only partially relevant to this type of environmental risk assessment

2.9 Community response to noise

Community noise exposure is commonly measured in terms of a noise exposure measure. Noise exposure is the varying pattern of sound levels at a location over a defined time period. The time period is most often one day (short-term) or over weeks, months or a year (long-term). The practical difficulty in locale measurements is that many of them are needed to describe a neighbourhood. It is customary, therefore, to use a suitable single-number evaluation for community neighbourhood noise exposure. The most widely used general exposure measure is LAeq, in its various forms. With a night-time weighting the exposure index is called the 'day-night' average level, DNL. The choice of LAeq or DNL as a measure of the impact of noise on a community is sometimes questioned, because an average noise level measured over a 24 hour period may not be sufficiently sensitive to the effect of noisy events of short duration or infrequent occurrence. The European Community, for example, have promulgated a 'day-evening-night' assessment methodology. Noise criteria derived for community noise assessment are predicted from large-area noise surveys, incorporating a large number of noise sources and exposed individuals. A full description of noise impact combines at least one of both criteria; that is, an exposure measure and an impact measure. This is known as a *'dose/response'* or 'exposure/response' relationship. Typically this relationship is given in a response curve that shows the variability in human response to different types of noise. Impact analysis measures are also needed. These provide a direct estimate of the effect of an environmental factor; for example, 'percent of people highly annoyed by noise'. A generally accepted relationship between exposure and annoyance due to noise from transportation (road, rail and air) is illustrated in figure 2.9.1. The figure illustrates the "1991 Schultz curve" (solid line) as well as other relevant curves as more research became known. The figure illustrates that while there are differences between indicators there is general agreement that annoyance increases as level increases. Based on the information in figure 2.9.1, approximately 5% to 10% of an exposed urban population will be highly annoyed by long-term (e.g., yearly average) general road traffic noise at a level of 55dBA DNL.

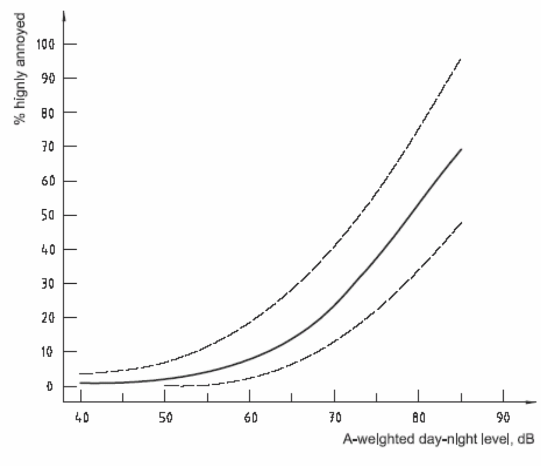

Figure D.1 — Percentage of respondents highly annoyed by road traffic sounds, as a function of the A-weighted day/night level

Figure 2.9.1: Percent respondents highly annoyed by road traffic sound.
Source: Figure D.1, Draft ISO/FDIS 1996-1:2003(E).

Figure 2.9.1 would suggest that no person exposed to noise levels below 42 DNL would be highly annoyed by road traffic noise. This is not true, as work by Miedema and Vos (1998, p. 3441) and Pedersen and Persson Waye (2004) demonstrates. Miedema and Vos suggest the percent 'highly annoyed' tends to zero at approximately 42 dB DNL. The community *per se* may not be highly annoyed by the noise from transportation but, as described, this does not apply to individuals. The value of the process presented in figure 2.9.1 is in identifying global noise and trends in noise levels and noise exposure over time.

Miedema (1987, 1998a); Miedema & Vos (1998b, 1999); Miedema & Oudshoorn (2001, p. 410) have shown that community response to transportation noise exposure depends upon the category of noise. The distribution of annoyance scores at a given noise exposure can be presented in different ways depending on the number of effective categories and boundary qualifications. In an 11-point categorical scale from 0-10 according to ISO 15666, converted to a 0-100 scale, the percentage of "highly annoyed" persons (%HA) is the percentage of people giving an answer above 72. This is the top 27%-29% of the response scale and corresponds to the verbal categories very and extremely annoyed. A cutoff of 50% is the percentage "annoyed" (%A) and a cutoff at 28% is the percentage "at least a little annoyed" (%LA). They state that, in relation to the analyses made:

> Extreme exposure levels (DNL < 45 or > 75 dB) were excluded from the analyses because there is no practical need for information concerning the annoyance at these extreme levels, and risk of unreliable data is high at these extremes.

This view seems to be common in noise exposure – health effect studies. Low amplitude noise annoyance does not appear within transportation studies and general industrial studies, apart from a relatively few for wind turbines, are not common. Miedema & Vos (2003) extended their work on noise exposure to explore the relationships between noise exposure, noise sensitivity and noise annoyance. The work by Pedersen (2007, p. 54) extends noise exposure – percentage annoyed studies to wind turbines, with identifiable effects to 30 dB day-evening-night level (DENL).

United States, Australian and European authorities have defined their environmental noise management decision making processes in terms of the perceived need of the community for a simple, uniform, and relatively easily understood noise assessment metric. This is evidenced in the 1974 USEPA publication *Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety*, where a population exposed to an outdoor day/night level of 55 dB is assessed as having a potential annoyance effect of 17% while the average community reaction is "none evident". The publication is referred to in this chapter as "the Levels Document". Further, at page D17, the Levels Document states:

> The "no reaction" response in figure D-7 corresponds to a normalized day-night sound level which ranges between 50 and 61 dB with a mean 55 dB. This mean value is 5 dB below the value that was utilized for categorizing the day-night sound level for a "residential urban community," which is the baseline category for the data in the figure. Consequently, from these results, it appears that no community reaction to an intruding noise is expected, on average, when the normalized day-night sound level of an identifiable intruding noise is approximately 5 dB less than the day-night sound level that exists in the absence of the identifiable intruding noise. This conclusion is not surprising; it simply suggests that people tend to judge the magnitude of an intrusion with reference to the noise environment that exists without the presence of the intruding noise source.

The stance taken by the Queensland Environmental Protection Agency (QEPA) to protect and enhance the environment of individuals, with respect to sleep disturbance, is to require any industrial activity to design their processes and transportation to achieve a sound level of no more than 3 dB(A) above the measured night-time background level. The limit is measured as the average maximum level of any noise, adjusted for tonality and impulsiveness. The background level is the sound level exceeded for 90% of a specified time interval (usually 10 minutes) in the absence of the noise under investigation. The QEPA, therefore, does not utilise internationally researched "community" noise guidelines and focuses solely on the perceived amenity of the individual and 'background' ambient sound levels.

The European Union has taken a major initiative requiring member states to comprehensively measure, assess and mitigate noise. The European Union Directive on Environmental Noise (2002/49/EC) is aimed at requiring Member States to produce strategic noise maps on the basis of harmonised indicators, to inform the public about noise exposure and its effects, and to draw up action plans to address noise issues. Noise Mapping is defined under Article 3 as:

> The presentation of data on an existing or predicted noise situation in terms of a noise indicator, indicating breaches of any relevant limit value in force, the number of people affected in a certain area, or the number of dwellings exposed to certain values of a noise indicator in a certain area.

Noise mapping does not recognize the effects of noise on individuals, as such. The Directive at Article 11(3) dealing with the review and reporting of the acoustic environment quality states that the reduction of harmful effects and the cost-effectiveness ratio shall be the main criteria for the selection of the strategies and measures proposed for the reduction of the number of persons harmfully affected by environmental noise. The Directive makes a clear distinction between ‘harmful effect’, ‘annoyance’ and ‘sleep disturbance’. Harmful effect and sleep disturbance could be associated with groups of individuals, whereas annoyance is defined in terms of field surveys and noise indicators referenced to one year.

2.10 Soundscapes

Our environment is a complex of competing sounds (Tixier, 2000; Truax, 1999), many are benign, and the sounds we hear are normally what we expect to hear. Transportation sound has dominated the design of attitudinal and acoustical surveys even though many measurement standards deal with industrial sound emission. Acoustical surveys have tended to concentrate on measuring a relatively few acoustical variables or predicting the effects of a given noise exposure. Acoustical survey measurements tend to measure average exposure or statistical ratings (Schultz, 1982). The more complex ratings tend to be used in aircraft noise surveys. The gradual acceptance of a single rating gathered strength in the US with the use of the Day-Night Level (USEPA, 1974). Berry (1998), however, has warned against this over simplified methodology. The USEPA approach to noise exposure measurement (USEPA, 1981b) incorporates longer-term monitoring ('extensive method') with short-term monitoring ('intensive method'). The extensive method seeks to derive general laws from quantitative statistical analysis of the information collected on limited factors from a large number of monitoring locations determined from the locations of the random survey interviewees. The survey makes detailed descriptions of a small number of cases and more closely identifies a person's responses to the acoustic environment in which they live and work. It is largely independent of the researcher's preconceptions and is designed to describe the reality of the residents' environment. Acoustical data from an area (extensive) survey can be significantly at variance with community response at a local (intensive) survey level and the socio-acoustical survey must be designed to investigate reactions to measured sound levels within the local environment.

The complex interaction of the soundscape and individual reaction was investigated within 'The World Soundscape Project', an innovative approach to raising awareness of the "global" effects of sound on people established by R. Murray Schafer. The Project was started in the late 60's and early 70's with 'The Vancouver Project' and Schafer was then a musician, composer, and Professor at Simon Fraser University in Vancouver. Soundscape analysis has a practical association with noise mapping and acoustical surveys. The Vancouver Project developed into the World Soundscape Project and is reported in, for example, the 'Handbook for Acoustic Ecology' (2nd edition, Truax editor, 1999). The project led to defining 'acoustic ecology' or 'soundscape ecology' describing the relationship between living beings and their environment and the analysis of how we interpret, and are affected by, natural and artificial sounds around us. Soundscape assessment is a significant tool for environmental amenity analysis. Subsequent to the Project the work of others such as Abe, Ozawa, Suzuki and Sone (1999); Brooks and Schulte-Fortkamp (2006); Kihlman, Öhrström and Skånberg (2002); Maffiolo, Castellengo and Dubois (1999); Schulte-Fortkamp (1999a); Schulte-Fortkamp and Nitsch (1999b); Schulte-Fortkamp (2000); Schulte-Fortkamp and Lercher (2003); Tixier (2000); Tamura (1997); Tamura (1998); Truax (1999) clearly show the effect of soundscapes as a factor in noise annoyance. The concept of psychoacoustic mapping is explored by Genuit, Schulte-Fortkamp & Fiebig (2008) to describe outdoor living areas with respect to acoustical conditions and their relevance for life.

People can become used to or habituated to varying levels of noise but this does not mean that unique or distinctive sounds quieter than the accepted level of overall sound will be acceptable. Individuals are different in their tolerance to specific sounds: there is a distinct duration – intensity relationship that varies depending on the character of the sound. Personal attitudes (Job et al. 1998; Job et al. 1999a, 1999b; Job et al. 2000) are, therefore, significant in defining an individual’s response to intrusive noise.

2.11 Amenity and economic values

Amenity values are based upon how people feel about an area, its pleasantness or some other value that makes it a desirable place to live. The valuation of quiet or noise as commodities is not an unusual concept. They are commodities that can be bought and sold like any other commodity. As there is not an accepted system for the definition of cost, mechanisms need to be defined for the distribution of value. Conceptually, peace, tranquillity and quiet have value while noise has cost. Noise affects individuals and the community by modifying the extrinsic and intrinsic nature of the environment that attracts and holds people to the locality (Altena, 1987). The noise may have a positive value or, more likely given its nature, a negative value. Unregulated noise emissions – immissions, for example, impose a cost on to the receiver of that noise, without compensation or redistribution of cost back to its creator. There is a cost in producing the noise, a cost in receiving the noise and a cost in reducing or mitigating such noise. Typically, noise can be quantified by sound exposure levels or audibility and qualified in terms of unwantedness, annoyance and loss of amenity. Different models have been proposed to value noise and changing values in environmental quality, with the most common being Hedonic Pricing. Hedonic Pricing has been primarily applied to transportation noise (Renew, 1998; Bateman, Day & Lake, 2004; Nellthorp, Bristow & Mackie, 2005; New South Wales EPA[2]) because of the relative ease in defining the noise source, the affected parties, and the use of property valuations as an assessment tool. Hedonic Pricing is not the only valuation methodology that can be applied (e.g., Kristensen (2004); USEPA 1976, 1981a). As caution is needed to assess clearly defined noise sources, the concepts are highly problematical for rural sources due to the extrinsic and intrinsic

[2] The New South Wales Environmental Protection Agency Australia has noise valuation data available on the Envalue website: < http://www.epa.nsw.gov.au/envalue/ >

nature of the receiving environment. Transportation noise annoyance and economics are specifically addressed by, for example: Lambert, Kail and Quinet (1998), Lambert and Aboki (2003), Moringa et al. (2006). The concept of tranquillity and tranquillity mapping is introduced by the Centre for Environmental and Spatial Analysis (CESA) UK (MacFarlane et al., 2004). There are practical difficulties in developing urban noise maps and associated cost-benefit analysis and an environmental value such as tranquillity requires refined attitudinal and noise sensitivity analysis. Noise annoyance and the implicit and explicit nature of an environment requires refined analysis in order to assess diminution of value compared to, for example, road traffic noise analysis referenced to house valuation. McIntyre, in the Queensland *Environmental Protection (Noise) Policy Regulatory Impact Statement 1997* (RIS SL1997 No342, p. 39), is quoted as identifying the notional costs of increased noise for a residential area as follows:

> The report considers the impact of increased noise on the following subgroups in the community:
>
> • natural emigrants — who would move away regardless of the noise
>
> • forced emigrants — who move away because of the noise
>
> • stayers — who stay and bear the noise
>
> • informed immigrants — who come into the area aware of its noisiness
>
> • uninformed immigrants — who move into the area without being aware of the noise.
>
> … From this analysis there are clear inequities suffered by elements of the community if excessive noise is allowed to continue.

Economic transfer considerations are a normal part of environmental noise impact assessments and the principles must be weighted in the consideration of acceptable sound and noise mitigation, especially building alterations to reduce noise. The most common situation is interior and exterior amenity consequent to the development of residential premises adjacent to main roads. Immediate and long-term effect of noise can affect amenity and impacts upon the responses of a “reasonable person” about a specific activity. With low amplitude sound this assessment is complex and is considered in the later case study concerning wind farms.

2.12 Acoustical amenity within a building

An acceptable standard of acoustical amenity is required inside a dwelling or other building. The definition of acceptable is open to debate (character of the sound vs overall sound level) and for New Zealand and Australia some guidance to overall sound level is given in Australian / New Zealand Standard AS/NZS 2107:2000 *Acoustics-Recommended design sound levels and reverberation times for building interiors*. The degree of acceptability will depend on the occupancy of the room (bedroom, living area, recreation area, meeting room, classroom and so on). This section deals only with a dwelling. Noise levels measured outside a dwelling are not the same as those measured inside a dwelling. The variation in sound levels depends on the construction of the building and the furnishings - materials within the receiving room. Acoustic measurements outside a dwelling cannot be interpreted as being the same or similar to a similar style of building in another location. The source levels and sound propagation paths will be different. Sound can be "filtered" as it passes through external walls or ceilings, or between rooms. Such sound is most often of lower frequencies and does not contain useful information to the recipient. It can, therefore, become highly intrusive.

Depending on the design of the room, standing waves can be excited within the room and sound levels at a particular frequency can increase. That is, specific frequencies measured outside a dwelling can be lower than those measured inside, in terms of amplitude. This is due to the creation of a standing wave that is clearly audible within the room and can result in significant complaint. Analysis of low frequency sound is most critical for assessment of disturbance and potential adverse effect within a bedroom or living area.

Leventhall, Pelmear and Benton (2003) have considered 'inside the home' acceptability criteria (pp. 64-66), audibility criteria (pp. 67-73), annoyance (pp. 30-32), unpleasantness (p. 32-33), spectrum balance (p. 33), level variation (p. 35) and inherent fluctuations or rumble (p. 37) effects for low frequency noise. Low frequency sound is considered to be in the range from about 10Hz to 200Hz. Their findings present analysis of two groups of people exposed to various types and levels of low frequency sound. A group sensitive to noise were very annoyed by indoor levels of low frequency sound of 27.5dB and above at night (p 75, Table 14). A group not sensitive to noise was only just annoyed by the same level of sound (p 75, Table 13). The findings illustrate the difficulty of linking building design to exterior-interior low frequency sound levels and individual response.

2.13 Issues with noise assessment and intrusion

It is concluded from the observations and research of others as presented in this section and from field work presented further in this work, that the measurement of sound and its interpretation as noise is a task fraught with difficulty. Simple measurement is of little use as sound level measurements tell only part of the story and tell us very little of the character of sound as perceived by an individual. Issues such as the duration to be measured and the type of measurement interfere with clear understanding of the potential or actual adverse effect of a sound on a person. Significantly, measurements as such can only be a guide to potential noise intrusion.

The following Chapter summarises hearing and personal response mechanisms that have been taken into account in this work. Chapter 4 summarises potential measures and assessment methods that have been taken into account in this work.

CHAPTER 3: HEARING AND PERSONAL RESPONSES TO SOUND

3.1 Introduction

This Chapter has two objectives. The first objective is to illustrate the processes involved in personal hearing and the importance that these processes have in the measurement, characterisation and assessment of sound. The second objective is to identify the essential processes needed to transform the "sound" from air movement to personal information and reaction in order to bring forward the information needed to develop an assessment methodology for perceived sound and noise.

The auditory system takes the mixture of sound that it derives from our complex natural environment in a process termed *auditory scene analysis* (Alain et al. 2001; Bregman, 1990; Ellis, 1996). In reviewing the text on auditory scene analysis by Bregman, Huron (2006) states that auditory streams are the mental streams an individual forms as "lines of sound" and our perceptual facilities evolved as a means of constructing a useful representation of reality from these streams. Stream determining factors include timbres (spectral shapes or envelopes), pitch proximity, temporal proximity, dissonances (harmonicity), intensity (amplitudes), spatial locations and changes of these variables.

It can be postulated, therefore, that noise perception depends on the same process of streaming and assignment, which argues for music and noise perception sharing similar auditory properties but defined by stream fusion for music and stream segregation for noise. Under stream segregation the character of a noise is retained independently of the overall sound.

Alain et al. (2001, p. 12301) describe auditory scene analysis methodologies identifying the content ("what") and the location ("where") of sounds in the environment. Ellis (1996) describes prediction driven computational auditory scene analysis in which there is reconciliation between observed acoustic features and the predictions of an internal model of the sound producing entities in the environment. An example of auditory scene analysis is the ability to hear, identify, locate and track different sounds in an environment at the same time and over time. This form of analysis is critical to our sense of hearing and informational responses.

3.2 Personal hearing response

This section is a brief presentation of human hearing response and is intended as a foundation for the sound analysis methodologies later in this work.

3.2.1 Sound reception – the head and ears

For a given acoustic source in the free-field there is a difference in sound pressure level (above 500 Hz) and phase (or time of arrival) between each ear. The maximum time difference (interaural time difference) between the ears is 760 microseconds for a sound source placed directly opposite one ear. However, we are able to pin-point a sound in front of the head within 1 to 2 degrees, corresponding to a time difference of 13 microseconds. Yost (2000, p. 70) states that the interaural time difference remains relatively constant across frequency.

3.2.2 The external ear

The external ear consists of the pinna (the fleshy "ear"), the concha (opening to the ear canal), the ear canal and the ear drum. The pinna, with the head and torso, collects and diffracts sound (or *acoustic*) waves into the ear canal. At this stage of "hearing" sound is the variation in sound pressure at the ear and within the ear canal. Both the sound pressure levels and the phase of the sound waves change while being propagated within the ear canal to the ear-drum. The changes vary with the frequency of the sound and for each direction of the sound waves. The ear canal is approximately 20 to 30 mm in length and the concha has a diameter of 5 to 7 mm. The outer ear causes an increase of level of about 10 to 15 dB between the free-field level and the level at the eardrum, in a frequency range of approximately 1500 Hz to 7000 Hz. This increase is due to complementary effects of resonant frequencies within the concha (approximately 5000 Hz) and the ear canal (approximately 3000 Hz) for an open ear canal length of 27 mm. An ear canal occluded with a close-fitting “in-ear” style earphone, has a resonant frequency of approximately 6000 Hz. It is the external ear and middle ear together which allow the transmission of acoustic energy at each frequency from the free-field to the inner ear. The energy at the eardrum is now a modified image of the free-field sound level at the ear that is, itself, a modified image of the characteristics of the sound source. That is, the sound in the ear being transferred to the brain is not the same as at the sound source.

3.2.3 The middle ear

Once the acoustic stimulus reaches the eardrum, sound can be transmitted through the middle ear to the inner ear in three ways:

- By bone conduction, with the stimulus bypassing the middle ear and travelling via the bones in the skull to the inner ear
- Via the air in the middle ear
- Across the middle ear to the inner ear by way of the ossicular chain. This is the most effective means of transmitting sound to the inner ear

The middle ear transfers the acoustic energy from the eardrum (“tympanic membrane”) to the inner ear. The process involves adjusting the difference in impedance between the air environment in the ear canal to the fluid environment in the inner ear. The middle ear forms the mechanical ossicular chain between the eardrum and the oval window of the inner ear. The sound waves move the eardrum and attached ossicular chain. The eardrum attaches to the malleus; the malleus attaches to the incus; the incus attaches to the stapes and the footplate of the staples attaches to the oval window of the scala vestibuli. The middle ear is open to the nasopharynx via the Eustachian Tube and air pressures inside and outside the ear equalise allowing the round window of the scala tympani to freely vibrate in an air environment. The maximum pressure gain is 30 dB in the region of 2500 Hz, but this varies with frequency. The acoustic reflex provides a partial “defence mechanism” against loud noise above 80 dB. The acoustic reflex works to around 2000 Hz, but is ineffective against impulsive noise such as from fireworks or gunfire as the minimum time for the reflex action to occur is a minimum of 10 ms for high intensity sounds (Yost 2000, p. 74). The acoustic reflex has approximately 10 dB attenuation and protects against gradual onset of low-frequency sounds, rather than being effective against high-energy fast-onset sounds.

3.2.4 The inner ear

The vibratory motion of the stapes moves the fluid and other structures of the inner ear. The motion causes the haircells of the inner ear to be stimulated and cause neural discharges in the auditory nerve. This is the transfer of mechanical energy into neural information. The inner ear provides the nervous system with information about the frequency, intensity and temporal content of the acoustical stimulation. The inner ear consists of the semicircular canals (primarily concerned with balance) and the cochlea, figure 3.2.4.1. The cochlea is the primary auditory organ of the inner ear.

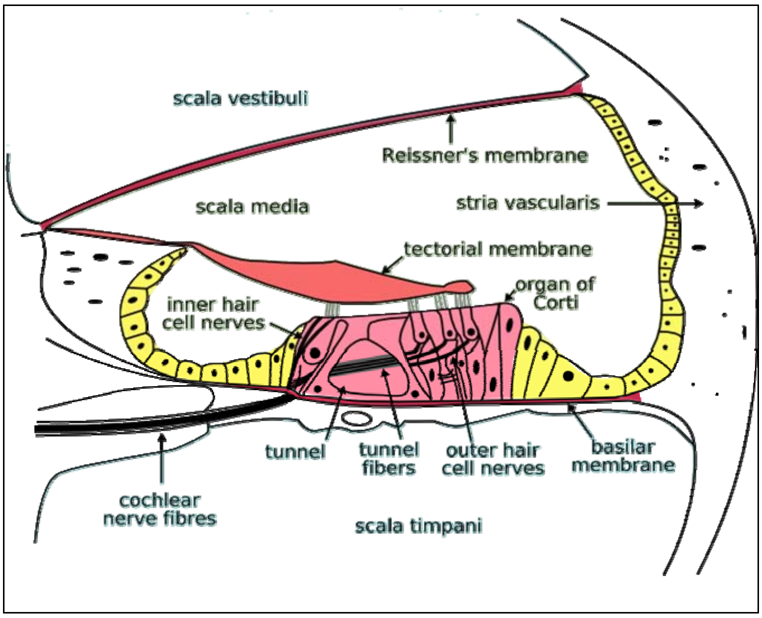

Figure 3.2.4.1: Cochlea cross-section

Source: http://en.wikipedia.org/wiki/Organ_of_Corti, Image: Cochlea cross section, viewed 5/3/2007

The scala vestibuli is filled with fluid (perilymph) and extends from the oval window to the helicotrema at the apex of the canal. The helicotrema is a small opening allowing fluid movement between the scala vestibuli and the scala tympani. The scala tympani is parallel to the scala vestibuli and extends from the helicotrema to the round window. There is a completely sealed duct or scala media within the middle of the cochlea and is separated from the scala vestibuli by Reissner’s membrane and from the scala tympani by the basilar membrane. The scala media contains endolymph.

The response mechanisms of the ear are contained within the basilar membrane and the organ of Corti. Depending on the frequency, the movements within the cochlea has a maximum effect or resonance at different points along the basilar membrane. The basilar membrane responds to the vibrations by initiating a travelling wave containing the signal. The amplitude and phase of the input signal varies for waves of different frequencies as they move along the basilar membrane from the oval window. The high frequencies (20,000 Hz) are sampled at the commencement (base) of the cochlea canal and the low frequencies (20 Hz) are sampled at the end (apex) of the canal. The whole of the basilar membrane is vibrated for the low frequency sounds, compared to high frequency sound that has maximum displacement near the oval window. When the oval window vibrates a pressure is applied to all the fluids and along the whole length of the basilar membrane. The pattern that develops is not dependent on which end of the cochlea is stimulated. Sounds can reach the cochlea via the bones in the head as well as through the middle ear. Pure tones produce patterns with single maxima and frequency-to-place conversion on the basilar membrane. This is the critical or centre frequency. The basilar membrane reacts in a similar way when responding to two distinct tones widely apart in frequency. When two tones are relatively close together in frequency, however, there is a single broad maximum produced, rather than two individual maximums.

The organ of Corti sits on the scala media surface of the basilar membrane, below the tectorial membrane. The organ of Corti forms a duct filled with cortilymph that runs for the full length of the cochlea. Within the duct are the rods of Corti. On the inner rods are the inner hair cells and the outer rods containing the outer hair cells. The haircells are the transducers for the auditory system. Both sets of haircells contain cilia and the tips of the tallest row of cilia in each outer haircell are in contact with the tectorial membrane. As the basilar membrane moves or flexes the cilia are bent and the cells are depolarised. This action energises the inner hair cells and the inner hair cell auditory nerve synapse is activated and a neural signal is sent to the auditory brainstem. The inner haircells perform the role of biological transducers for sound and the outer haircells assist in high sensitivity and high frequency resolution. The outer haircells are central to the function as a cochlea amplifier transducing small vibrations into neural impulses. The vibratory patterns are generally nonlinear in response and are crucial for the proper operation of the inner ear.

Not all cells in the auditory cortex respond to simple tones. Complex signals like clicks, voices, whistles, which contain many frequencies, excite many different regions of the basilar membrane simultaneously and there are specific cells in the auditory cortex that respond to these stimuli.

3.2.5 Auditory messages

Auditory messages are carried to the brain by two types of pathway:

- The primary auditory pathway which exclusively carries messages to (the afferent fibres) and from (the efferent fibres) the cochlea
- The non-primary pathway or reticular sensory pathway which carries all types of sensory messages

The primary auditory pathway contains the cochlea nuclei in the brain stem that receive stimuli from the auditory nerves. At this stage decoding of the basic signal occurs with duration, intensity and frequency. In the afferent pathway the majority of the auditory fibres from both ears synapse in the superior olivary complex. The auditory message is carried to the inferior colliculus which has an essential role in the localisation of sound. The neural impulse then travels via the medial geniculate body to the auditory cortex where the message, already largely decoded during its passage through the various neurons in the pathway is recognised, memorised and perhaps integrated into a voluntary response. The efferent pathways are capable of optimising the detection of acoustic signals of interest in the presence of competing background noises. One of the functions of the non-auditory pathways is to link the auditory pathway with the other sensory pathways[3]. The pathways are connected to the wake and motivation centres, as well as the vegetative and hormonal system. The main function of the pathways is to select the type of message to be treated first. Conscious perception requires the integrity and integration of both pathways. During sleep, for instance, the primary auditory pathway functions normally but no conscious perception is possible because the link between the reticular pathways and the wake and motivation centres are inactive.

[3] A graphical presentation of the processes is available at: <(http://www.iurc.montp.inserm.fr/cric/audition/english/ptw/fptw.htm)>.)

3.2.6 Pitch perception

Pitch perception is a vital function of the auditory system. Pitch is a perceptual attribute and plays a key role in the organisation, segregation and identification of sound sources. There are two distinct theories concerning pitch perception: the place theory and the temporal theory described in, for example: Shamma (2004, p. 1114); Moore (1988, p. 115 & p. 127); Oxenham, Bernstein and Penagos (2004, p. 1421); Wever and Lawrence (1952, p. 132). The place theory has the ascendancy. The variations in theory are important because they both help in understanding the mechanisms involved in pitch perception and timbre. As explained by Shamma (2004, p. 1114, Figure 1) when comparing the signatures of a violin and a piano:

> Both spectra have the same fundamental frequency (440Hz) and hence are perceived as the same pitch. The amplitudes of harmonic components are quite different between the two instruments, giving rise to their distinctive timbres.

Oxenham, Bernstein and Penagos (2004, p. 1421) conclude that the correct tonotopic frequency-to-place mapping in the inner ear is necessary for complex pitch perception. They identify the importance of the temporal coding theory to a diverse range of pitch phenomena and binaural coding but conclude that the "place" theory is more able to explain the relationship to pitch perception. The importance of pitch in sound analysis is stated as[4]:

> Pitch is one of the primary attributes of auditory sensation, playing a crucial role in music and speech perception, and in analysing complex auditory scenes. For most sounds, pitch is an emergent perceptual property, formed by the integration of many harmonically related components into a single pitch, usually corresponding to the sound's fundamental frequency (F0). The ability to extract F0 from a complex tone, even in the absence of energy at the F0 itself, is shared by a wide variety of species and is present from an early developmental stage in humans.

F0 described above is sometimes known as 'the missing fundamental'. The auditory system is nonlinear in nature and can produce aural harmonics and difference tones.

[4] The references included in the passage by the authors are not identified in this quotation.

The perception of these tones (pitches) is not due to the presence of these frequencies in the stimulus. The pitches are created as a result of the nonlinear distortion caused by the peripheral auditory system. Yost (2000, p. 167 & also p. 199) states that the 2nd and 3rd aural harmonics, difference tone and cubic difference tone are most often perceived. The cubic difference tone is the most significant as this tone can be heard at less than 40 dB. The primary difference tone is not detected at this level.

3.3 Auditory sensitivity

The auditory system is sensitive to frequency, amplitude, and phase of the signal. There are very high and very low frequencies that the auditory system is insensitive to and these establish the range of hearing, which varies from person to person and within a person as that person ages. The auditory system is also sensitive to the intensity of a sound, with the smallest level of detection called the threshold of audibility. The threshold of audibility also varies from person to person and within a person as that person ages or is exposed to sounds that cause hearing damage. A person who has a low threshold of hearing is described as being very sensitive to sound. This is not quite the same as being “noise sensitive”, as discussed previously. The audibility threshold levels for pure tones are measured as Minimum Audible Field (MAF) thresholds. Free-field MAF thresholds are measured using loudspeakers with the listener at 1 metre from the source, facing the source, listening with both ears. Minimum Audible Pressure (MAP) thresholds are determined using headphones.

The design of the sound analysis instrumentation for this thesis considered that headphones are calibrated using a coupler that simulates the volume between the tip of the earphone / headphone and the eardrum. A 2cc volume coupler for an insert earphone and 6cc volume coupler for a supra-aural headphone (i.e., a headphone that fits over the pinna) are referenced. Circumaural headphones fit completely over and around the pinna and are calibrated using an artificial ear. The threshold vs. frequency values (Yost 2000, p. 151) for the different types of headphones are not the same and are an important variable in the design of audiometric testing systems. The respective threshold of hearing values for a coupler combination and the MAF values are the Reference Equivalent Threshold Sound Pressure Levels (Yost 2000, p. 151).

The minimum audible field threshold (or absolute threshold of hearing (ATH) are the sound pressure levels for pure tones at absolute threshold, measured in the free-field, in a noiseless environment. The absolute threshold relates to the sound that can just be heard for a specified percentage of the time. Hearing response is nominally in the range 20 Hz to 20,000 Hz for a person aged 18 to 25 years with no hearing impairment. The upper end of the range decreases with age with the most pronounced decreases in sensitivity above 12,000 Hz. An individual's hearing thresholds have an important bearing on whether that person hears sounds clearly or whether the sound is distorted and this, in turn, has an effect on that person's sensitivity to sound and perceived noise. Observations during this work indicated that individuals who are nominally deaf (their words) have good sensitivity to some sounds and not to others. It was concluded that the practice of determining hearing thresholds at certain discrete octave bands does not present an accurate picture of an individual's hearing response.

The duration of a sinusoid affects the tonal threshold. The longer a sound lasts, the easier it is to hear. The duration of a tone influences the measurement of intensity, with significant difference between power and energy. At durations greater than approximately 250 to 500 ms the threshold in units of power for various tones does not change very much nor become easier to detect. If the tone duration is less than 200 ms to 250 ms the power of the tone must increase for the observer to detect the tone. A doubling in duration means that signal power must drop by 3 dB to keep energy constant. As reported by Yost (2000, p. 153) signal duration and threshold power vary considerably for various frequencies. In terms of temporal integration for detectability of a tone, the auditory system requires about 300 ms for maximum performance at a given intensity. If the signal is shorter than 300 ms then the intensity must be increased for maximal performance. The integration time, however, depends on the type of signal being processed. A short impulse sound (a 'click") requires considerably less time at a few milliseconds. If the duration of the sound is between about 10 ms and 300 ms, its energy must remain approximately constant for a constant level of detection by an observer. The just noticeable difference in frequency (jnd) or the threshold to discriminate a change in frequency from a given frequency is dependent on the frequency and sound level of the signal. For an intermediate range of frequencies (200 Hz to 2000 Hz) and sound levels (5 dB to 80 dB) the threshold frequency difference (Δf) is nearly constant at 0.2%. Yost (2000, p. 157) states that, for example, at 800 Hz frequency discrimination for a 40 dB signal is 1.6Hz and the auditory system is sensitive to approximately 0.5 dB to 1.0 dB change in level across a broad range of frequencies (200 Hz to 8000 Hz) and levels (5 dB to 80 dB).

A model of the auditory-brain system has been proposed by Ando and Pompoli (2002). The model takes into account the factors to be measured in the identification of environmental sound and noise and subjective responses to such noise. Annoyance as an overall response to temporary noise is considered to be described by all the factors extracted from the autocorrelation function (ACF) and the interaural cross correlation function (IACF). Equations for the calculation of loudness, pitch, timbre and duration sensation are presented. They conclude that: ‘we can describe any subjective attribute of noise and noise fields in term of processes of the auditory pathways and the brain.’ This approach is not pursued within this work

3.4 Critical bands

The concept of critical bands describes the auditory filtering processes of the human hearing system. Fletcher (1940) as reported by Lapsley Miller (1999, p. 14) described the critical band as a filter with a fixed bandwidth for a specific frequency. The masked threshold of tone was described as the level where its intensity just equalled the intensity of the noise within the critical band. The width of the critical bands at low frequencies show a constant width of about 100 Hz, while at frequencies above 500 Hz critical bands show a bandwidth that is about 20% of the centre frequency (Zwicker and Fastl 1999, p. 151). The critical bandwidth (CB) can be described in Bark or ERB-rate. Traunmüller (1997, p. 3) states that:

> Critical bandwidth B_c is a measure of tonotopic resolution in audition. Critical band rate z can be considered a measure of tonotopic position that is useful in models of hearing and for showing excitation patterns and auditory spectrograms of sounds (level by place by time). However, since the hearing system also performs a temporal analysis that contributes to frequency resolution for low frequencies, auditory frequency resolution cannot be represented on the basis of z alone.

Referencing Patterson, Lapsley Miller (1999, p. 15) notes it is considered that the shape and bandwidth of the auditory filter is important because it can have a significant effect on estimates of the critical band. While it is generally accepted that the critical bandwidth changes with the centre frequency, it is not certain whether it is fixed or adjustable at individual frequencies. Individual variability also has a significant influence. In order to mask tonal transients with durations of between 100-400 ms a critical bandwidth of about 145 Hz is required. Lapsley Miller (1999, p. 16) illustrates the variation in calculation of critical bandwidth:

- Zwicker and Terhardt (1980)

$$CB = 25 + 75[1 + 1.4(f/1000)^2]^{0.69} \qquad \text{eqn 3.4.1}$$

- Moore and Glasberg (1983)

$$CB = 6.23f^2 + 93.39f + 28.52 \qquad \text{eqn 3.4.2}$$

- Moore and Glasberg (1987) based on Greenwood (1961)

$$CB = 19.5(6.046f + 1) \qquad \text{eqn 3.4.3}$$

- Moore, Peters and Glasberg (1990)

$$CB = 24.7(4.37f + 1) \qquad \text{eqn 3.4.4}$$

The practical effects of the different expressions (3.4.1 to 3.4.4) are given for critical bandwidths of a noise signal centred at 500 Hz of 117 Hz, 76.77 Hz, 78.5 Hz and 78.7 Hz respectively. The Erb-rate scale is used in calculating the specific loudness pattern. Specific loudness is the loudness that a sound stimulates within each auditory filter, and is measured in sones per Erb. Auditory filters have tunings between 2 Erbs (50 Hz) and 39 Erbs (15,000 Hz).

The Zwicker and Terhardt (1999, p. 164) expression of critical-band rate (z) in Bark is related to frequency in the following way:

$$z = 13\arctan(0.76\, f/kHz) + 3.5\arctan(f/7.5\text{kHz})^2 \qquad \text{eqn 3.4.5}$$

Equation 3.4.1 is stated in Zwicker and Fastl (1999, p. 164) in kHz. Zwicker and

Terhardt (and Zwicker and Fastl) state the critical-band rate is in ‘Barks’. The Bark scale ranges from 1 to 24 and assumes broader auditory filters or critical-bands than for the Erb-rate.

3.5 Masking

A complex sound is split into different frequency components and these components cause a peak in the pattern of vibration on the basilar membrane. The components are coded by auditory filters with a sharply tuned filter having good frequency resolution. Damage to the cochlea causes reduced sharpness of tuning and difficulty, for example, in distinguishing between different consonants in speech. High frequency maskers are effective over a narrow band of frequencies while low frequency maskers are effective over a wide frequency range. Masking, therefore, establishes the limits of frequency selectivity or bandwidth of the auditory filters within the auditory system.

Auditory masking is the decreased audibility of one sound due to the presence of another. Masking consists of frequency masking and temporal masking, with a weaker sound inaudible in the presence of a louder sound. This has application in perceptual coding of digital audio using lossy compression which discards components that are inaudible to listeners. The effect of frequency masking is heard when a signal tone is presented simultaneously with another tone, the masking tone. The masking tone usually has a frequency and amplitude different from the signal tone. Frequencies different from the signal frequency are not as effective as masking those near the signal frequency. When two frequencies are close together the phenomenon of beats can occur with an audible tone equal to the difference between the two frequencies. The “best-beat” sensation is heard when there is a difference between the two frequencies of 3 Hz to 5 Hz. The beats are strongest when the amplitudes of the two tones are equal. The audibility of the beat is dependent on signal duration; that is, if the signal is less than one period of the beat the observer will not hear any loudness change or beating. The sensation of beats gives way to flutter and then to roughness as the frequency difference between the two tones is increased.

Temporal masking is the condition when the masker and the signal are different in time. If the signal is before the masker the condition is called backward masking. If the signal is after the masker the condition is called forward masking. Yost (2000, p. 174) states that:

> Forward masking of a stimulus can take place when a temporal difference between the two stimuli is between 75 and 100 ms, and backward masking occurs up to 50 ms.

Quoting Dai and Green (1993), Lapsley Miller (1999, p. 18) presents a somewhat different aspect of temporal effects on the critical band:

> It is very difficult to avoid confounding time and frequency when measuring the temporal nature of the auditory filter. For instance, comparing long and short transients, with the same bandwidth, is not enough, because potential interactions with the temporal integrator are ignored. In general, the evidence to date is not reliable enough to distinguish between a critical band that is constant over the duration of a particular stimulus, but may vary for different stimuli, and a critical band that varies over the duration of a stimulus.

3.6 Integration of sound signal

Our hearing system integrates temporal waveform information. Yost (2000, p. 154) states that further increases beyond 300 ms do not change the detectability of a tone. This property of detection is known as temporal integration and the time of integration depends on the type of signal being processed, with estimates from 1-2 ms to 500 ms (Yost, p. 155). For durations less than 200 ms the sound level necessary for detection increases as duration decreases (Moore 1988, p. 50).

Lapsley Miller (1999, p. 19) states that the two forms of rectification commonly used in modelling human hearing are the energy (square-law) or envelope (linear, full or half-wave) detectors. Quoting research by others, Lapsley Miller notes evidence that suggests the auditory nerve performs half-wave rectification but many researchers tend to not use linear detectors. The term “detector” is used to refer to the entire system of filters, rectifiers, integrators and samplers. An energy detector outputs the energy of the waveform and can be implemented, computationally and electronically, with a square-law rectifier, and a true integrator. An envelope detector outputs a function that is tangential to the peaks of a waveform. For practical purposes for this research the variation in detectors is about 0.2 dB. A true integrator is usually modelled as occurring over the duration of the signal, resulting in a single number at the end. Quoting Green Lapsley Millar (p. 21) notes:

> After considering the evidence, Green (1973, 1985) estimated the maximum integration time to be about 200 ms (±100 ms) and the minimum integration time to be in the order of 1-2 ms or 10-20 ms depending on which experimental paradigm was used.

Shepherd (2005, p. 124), however, presents the argument put forward by Jeffress for amplitude, rather than power, as the proximal stimulus for hearing:

> Jeffress argued that the primary auditory stimulus is the displacement of the basilar membrane, with maximal displacement correlated to the amplitude of the incoming acoustic wave. The amplitude of displacement is transformed into a neural count, a process that Jeffress (1979) deemed more "natural" than integrating squared voltages, and then accumulating with a leaky integrator.

3.7 Speech

There are differences between male and female voice fundamentals and in the bandwidth of individual hearing responses. Traunmüller and Eriksson (1995) report that typical values of the adult voice fundamental (F_0) are 120 Hz for men and 210 Hz for women. For an average speaker of European languages the value of F_0 for a male is 119 Hz and a standard deviation of 2.8 semitones. Similarly a female has a F_0 value of 207 Hz and a standard deviation of 2.7 semitones. Linguistic and cultural variations, as well as liveliness in speech, extend the range of F_0, known as F_0-excursions. Rodman (2006) emphasises the critical role of consonants in speech whereby most of the average energy in English speech is in the vowels (which lie below 3 kHz) while the most critical elements of speech lie above. He identifies how the high energy sound that distinguishes the "s" in "sailing" from the "f" in "failing" occurs between 4 kHz and 14 kHz. If these frequencies are removed no cue remains as to what has been said. Schwartz, Howe and Purves (2003, p. 7165) in their work on the statistical structure of human speech sounds and musical universals conclude that:

> The evidence presented here is consistent with the hypothesis that musical scale structure and consonance ordering derive from the necessarily statistical relationship between sensory stimuli and their physical sources. Generating perceptual responses to ambiguous periodic stimuli on this statistical basis takes the full complement of the stimulus characteristics into account, thus facilitating a listener's ability to glean biologically significant information about the sources of periodic sound energy, human speakers in particular.

3.8 Sound to sound analysis

Physical measures and instrumentation can only approximate our hearing response and the essential differences between our hearing and measurement instrumentation (e.g., a sound level meter) are:

- Individual sources can be clearly identified by people but not by a sound level meter
- Individuals can differentiate between source characteristics whereas a sound level meter cannot
- Individuals can respond to and identify different conditions that can modify response (such as high wind) whereas a sound level meter cannot

In terms of design, sound level meters cannot match our highly individualized hearing:

- The physical shape of the external ear modifies the signal (signal gain in the range 2000 Hz – 7000 Hz) entering the ear canal compared to the grid design changing the signal pressure variations on the microphone diaphragm
- The response characteristics within the middle ear (signal gain at 1000 Hz) and inner ear compared to the 'flat' microphone response
- The variation and amplification of sound within the ear canal and middle ear compared to the amplification within the microphone preamplifier
- A highly variable response system within the human response that is completely unique to the individual compared to a fixed response system within the sound level meter that is the same for all meters of a similar type

Individuals hear sound; sound level meters measure:

- Individuals can perceive changes in sound pressure or intensity but are not able to consistently describe the sound in terms of amplitude unless the sounds are significantly different and the variations are close together in time. Sound level meters are designed to display sound pressure variations in some form and will do this consistently over a long time period with a known degree of accuracy to sounds that have even very small variations in pressure
- Individuals can describe subtle variations in sound but cannot consistently identify the overall “loudness” of a sound. Sound level meters cannot describe subtle variations in sound but are designed to consistently identify the “loudness” of a sound using a variety of different measures
- Individuals respond to sounds. Individuals do so in different and unique ways, with variation possible to similar sounds. A sound level meter simply measures variations in atmospheric pressure

The complexity of our hearing processes outlined in the previous sections illustrates the reason why there can be significant variation in interpretation of sound from one person to another. Not only can a sound be interpreted differently between people but one person may not be able to hear a sound while a second person is seriously affected by the ‘noise’. This is a significant problem if some form of standardized physical measure is needed to describe ‘sound’. The following Chapters present the physical measures (Chapter 4) based on the hearing responses described in this Chapter and measurement instrumentation (Chapter 5) that are taken into account in this work.

CHAPTER 4: AN ASSOCIATION OF NOISE AND MUSIC

4.1 Musical noise

Luigi Russolo (1885 - 1947), Italian futurist painter and musician expounded his musical theories in 1913 in his manifesto entitled "L'arte dei rumori" (The Art of Noises) in which he presented his ideas about the use of noises in music:

> At first the art of music sought and achieved purity, limpidity and sweetness of sound. Then different sounds were amalgamated, care being taken, however, to caress the ear with gentle harmonies. Today music, as it becomes continually more complicated, strives to amalgamate the most dissonant, strange and harsh sounds. In this way we come ever closer to noise-sound. …
>
> To excite and exalt our sensibilities, music developed towards the most complex polyphony and the maximum variety, seeking the most complicated successions of dissonant chords and vaguely preparing the creation of MUSICAL NOISE. This evolution towards "noise sound" was not possible before now. The ear of an eighteenth-century man could never have endured the discordant intensity of certain chords produced by our orchestras (whose members have trebled in number since then). To our ears, on the other hand, they sound pleasant, since our hearing has already been educated by modern life, so teeming with variegated noises. But our ears are not satisfied merely with this, and demand an abundance of acoustic emotions.

4.2 Music, sound and noise

Since Russolo wrote to Pratella, music and noise or noise and music have become further entwined as a distinct art form. If music is sound and noise is a form of sound, then the expressions, attributes and descriptions applying to the art, form and description of music can be applied equally to the art, form and description of noise. Cobussen (2001), in chapter 3, ‘The Gift of Silence’, section [2] soliloquizes:

> [2] Music. Privileged over noise and silence. Opposed to noise and silence. Noise and silence seem to be on its outside, excluded in and by music. … Indeed, one part is always already part of (the definition of) the other as well. As applied to music, noise and silence have always already been part of music; noise and silence have always already been part of each other. …

If sound, music and noise can be considered as one, then the sounds of the environment can also be called music. R. Murray Schafer, composer, musician and convenor of the Vancouver Soundscape Project and the World Soundscape Project, is quoted by Wrightson (2000, p. 10) as suggesting '… we try to hear the acoustic environment as a musical composition and further, that we own responsibility for its composition….' Music is the linkage mechanism or "Rosetta Stone"[5] for the translation process needed to "describe" sound and noise in terms other than the relatively limited language of acoustics.

This work is concerned with a very limited range of musical descriptors and they are presented in a summary form. It is not intended that the work present an analysis of musical theory or practice. Musical theory underlies acoustical theory (as evidenced in Helmholtz, 1954) yet is rarely referenced, if at all, in the noise analysis methodologies described in standard works, for example in: Beranek (1960 & 1988), Kryter (1985), Schultz (1982b), Zwicker & Fastl (1999). Music provides a means to describe the perceptions of sound and intrusive noise, such as pitch, timbre and a lush variety of tonal descriptors. Music provides the palette on which mix the 'colours of sound' with acoustical and psycho-acoustical measures for visual and aural representations to illustrate sounds and intrusive noise.

The acceptability of a sound and its potential to be considered as noise is completely variable from person to person. Objective acoustical methods are not complete in themselves as the acoustical measures do not fully measure intrusive sound and whether a person considers the sound is noise. The subjective measures help identify an individual's response to sound and noise and his or her sense of amenity. Measures

5 The Rosetta Stone is a stele written with the same passage of writing in two Egyptian language scripts and in classical Greek. It was created in 196 BC and discovered in 1799 at Rosetta. The term Rosetta Stone has become idiomatic as something that is the critical key to a process of deciphering or translation of a difficult problem.

from acoustics, musical and sound quality disciplines are necessary to provide a template for the meaningful analysis of sound. The languages used in the fields of acoustics, sound quality and music are not readily amenable to a quick understanding, and there is considerable variation in the interpretation of the fine nuances of many of the terms shared by the different specialities. Music, however, has the richer language base for describing sound as sounds can be defined in objective mathematical terms, as well as subjective perceptual terms.

Music and noise are facets of the same entity, different only by degree, rather than completely separate entities co-existing. This is not the generally recognised case, however. On the face of it, music has only a passing relationship to noise – but, as illustrated in figure 4.2.1, describing sound and noise in terms of musical analysis provides the key to perception. Four relationship columns are presented: sound quality (psychoacoustic) measures, acoustical measures, musical attributes and personal sensitivity. The columns are graded with a subjective relationship given to each column on the basis of the number of people in the population who might have a reasonable understanding of the relationship or topic. The relationship is tentatively presented and is based on responses gained from interviews and from persons who have completed noise sensitivity and sound perception surveys for this work.

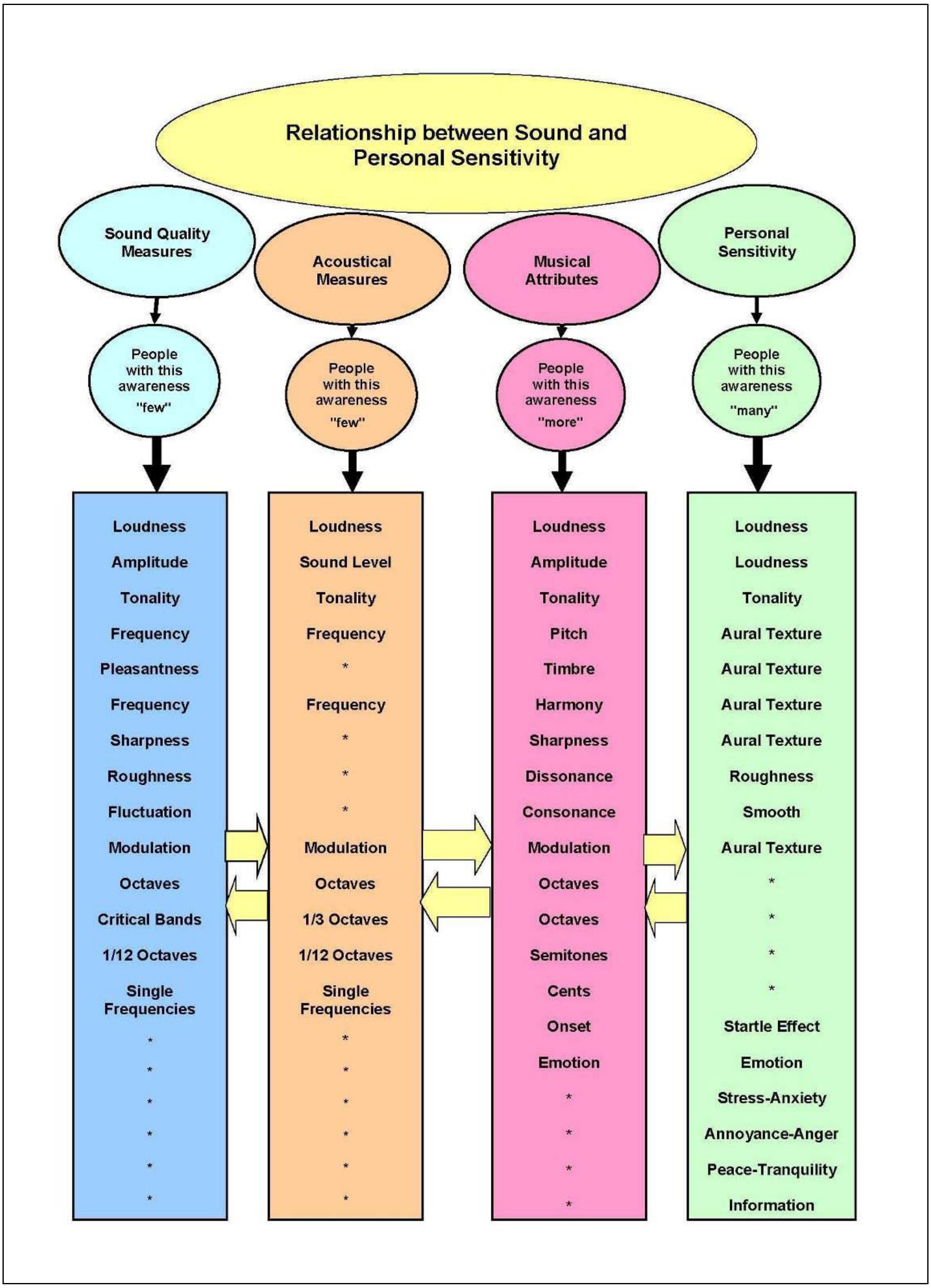

Figure 4.2.1: Relationships between music, sound quality, acoustics and personal sensitivity to sound

Environmental sound surrounds us all the time, awake and asleep. It is the music of the world in which we live. As music has discordant notes, so does our environment. When noise intrudes upon the well-being of an individual it can disturb and cause irritation, anxiety and anger.

Sethares (2005, p. 11) when considering 'what is sound' asks: *If a tree falls in the forest and no one is near, does it make any sound?* His answer (p. 37) encapsulates the correspondence between environmental sound and musical analysis:

> When a tree falls in the forest and no one is near, it has no pitch, loudness, timbre or dissonance, because these are perceptions that occur inside a mind. The tree does, however, emit sound waves with measurable amplitude, frequency and spectral content. The perception of the tone quality, or timbre, is correlated with the spectrum of the physical signal, as well as with temporal properties of the signal such as envelope and attack. Pitch is primarily determined by frequency, and loudness by amplitude. Sounds must fuse into a single perceptual entity for holistic listening to occur.

The statement of a concept for holistic listening appears to be unique to Sethares, yet it is fundamental to the perception of sound and noise. Sethares makes a distinction between analytical listening – where individual notes or tones are actively perceived by a person, and holistic listening, where the act of listening fuses all elements into one perceptual entity. Analytical listening, or sensory analysis as it is also known, is an example of actively listening for or perceiving a sound or noise. Holistic listening can be considered as our individual perceptual response to the ebb and flow of acoustic information with all sounds being listened to and actively analysed against memory but without any particular triggering of sensation.

This degree of perception, of analytic listening and holistic listening, correspond to a person's intrinsic and extrinsic value of a sound environment. Thus a person may enjoy a very noisy (bustling city) environment because the essential nature of the environment has value for that person, just as a very quiet (national park) environment can have a similar value for the same person. The sounds that catch our attention, and to which we are drawn analytically, are outside or extrinsic to the harmony of the overall or local soundscape. These values separate sound from noise.

4.3 Acoustical, sound quality and musical descriptors

“Rock ‘n’ roll ain’t noise pollution
Rock ‘n’ roll ain’t gonna die…”
From AC/DC’s ‘Back in Black’ Album

While Rock ‘n’ Roll isn’t going to die, nor is noise. The problem, to date, has been in describing what “we” mean by noise. Noise is not just “loudness”, nor just “unwanted sound”, whatever they may be. Noise has character, and as such can be described in terms appropriate to its prominence in an individual’s perception. The methods of measurement in acoustics ‘describe’ sound pressure and energy but, as is canvassed in this work, these descriptions are inadequate for the task of characterizing the nature of human perception. Acoustical measures are limited in their application to noise with various measures of magnitude and energy being of assistance to the task. Sound quality measures provide a link or shift to human perception and to acoustical measures. Sound quality incorporates both qualitative and quantitative measures. Music, however, has a rich set of descriptors that are ideally suited to describing noise in qualitative and quantitative measures. It does not, however, have the same measures available that are well documented for acoustical analysis of a sound.

Intrusive sound can be objectively characterised as being quiet or loud (having amplitude or loudness), it usually has some form of irritating tone (tonality) and possibly a beat of some sort (modulation in frequency and amplitude). It may be persistent (long duration) or intermittent (short duration) or it could be impulsive. The sound may startle (having a short attack time) or suddenly stop (fast decay). It can be repetitious or infrequent. The important distinguishing feature, however, is that it ‘stands-out’ in its environment; that is, it can be regarded as being atypical of the ‘normal’ environment. Intrusive sound must, therefore, be measured and assessed with respect to its environment. This is usually inside the home. Standard ‘noise’ investigations do not readily fit into this measurement and assessment scenario – primarily because there are few measurement and assessment methodologies to accommodate the scenario. Noise is a subset of intrusive sound; that is, noise must have some additional characteristic that makes it irritating or annoying. The psychophysical relationship to noise is to ‘establish firm relations between the physical magnitudes of sounds and the correlated perceptual magnitudes' (Fastl, 2002). This relationship has been explored by Fastl (2000); Green (1970); Stevens (1970); Torgerson (1970); Zeitler & Hellbrueck (1999). These works describe the analysis loudness, sound quality and pleasantness of sounds, and directly link to the perception of sounds.

The measurement and assessment of low amplitude intrusive sound requires a selection from all three groups of acoustical, sound quality and musical descriptors. Sound, apart from individual perception, can be described in terms of its aural texture, as shown in Table 4.3.1:

Table 4.3.1: Measures of aural texture

Acoustical measures	**Musical measures**
sound level	loudness
spectrum complexity	pitch
presence of pure tones or narrow frequency bands within a broad-band spectrum (tonality)	tonalness
fluctuation or modulation effects in either, or both, amplitude and frequency, sharpness and roughness	Timbre, described in terms of dissonance
impulsive characteristics	attack and decay
duration	duration

The difference between the two formats is that the first, the acoustical measures, have no 'humanness', they are simply measures, like a ruler or a measuring flask. The second set of descriptors has human feeling as well as definable measure (Genuit, 2002). A combination of both provides a toolbox of measures and methods that can describe any sound, and most importantly, measure low amplitude sound. The acoustical terms dealing with sound level, tonality and duration are well defined in International Standards such as ISO 1996-1 and ISO 1996-2. Spectrum complexity is not well defined, but it is reasonable to bring loudness in at this stage. Modulation is another effect that is not well described in acoustics, although the effects are well known (van den Berg, 2006). In the second set only loudness has some definition, and this is for stationary signals. Tonality is a vital issue and guidance is still open to debate (Bienvenue, 1986; Hastings and Davies, 2002; Hoare Lea Acoustics, 2004). Impulsiveness is described in the various measures reported by Hoare Lea Acoustics (2004).

The second set of descriptors is far better represented. Loudness has a large support-base from, for example: Chalupper (2000) and dynamic loudness; Chouard (1998) loudness and pleasantness; Florentine, Namba and Kuwano (1986) loudness, noisiness and annoyance; Fridrich (2002) Zwicker stationary loudness; Hellbrück (1991) loudness scaling; Hellman and Zwicker (1987a, 1987b, 1989) loudness measures; Hiramatsu, Takagi and Yamamoto (1988) rating loudness, noisiness and annoyance; Kuwano and Namba (1985) overall and instantaneous loudness; Kuwano, Fastl and Namba (1999) loudness, annoyance and unpleasantness; Moore, Glasberg and Baer (1997) loudness; Persson, Bjorkman and Rylander (1990) loudness in low frequency sounds; Pollack (1970) loudness and transportation; Suzuki and Stone (1993) frequency characteristics of loudness.

Noise can be described as ‘ugly acoustics’ (Höge, 1986) or sound that is ‘aesthetically unpleasant’. Pleasantness is a classic definition for ambience in, for example: Bengtsson, Waye and Kjellberg (2003); Zeitler and Hellbrueck (1999). If one takes unpleasantness as an attribute for noise then the effects of changes of pitch and tonality become significant, with dissonance, consonance, roughness and timbre all valid descriptors. Bolger and Griffith (2003); Daniel and Weber (1993); Helmholtz (1954), Parncutt (1989); Sethares (2005); Terhardt (2000); Terhardt, Stoll and Seewann (1982a, 1982b) all present different but similar approaches to the complex issue of ‘tonalness’ in all its forms. Parncutt (1989) describes sounds variously in terms of, for example, chroma, chroma salience, complex sound, complex tonalness, equivalent frequency, harmony, melody, pitch, pitch difference thresholds, pitch prominence, threshold of pitch, tones and tone sensations. Terhardt (2000) describes pitch perception with spectral and virtual pitch, sensory consonance and auditory roughness. Helmholtz (1954) describes cents, semitones, sensory consonance and sensory dissonance. This is a very small sample of a rich language compared to the paucity of description in ISO 1996-1 where only 6 major categories for sound levels are described. Admittedly the Standard does have other assessment methods but they are variations on the ‘sound level’ or amplitude theme.

4.4 Audibility of sound

A sound audible to one person may be inaudible to another and, therefore, a method is needed to define, measure and assess “audible sound”. A sound is said to be audible if it can be heard within the ambient sound (soundscape) of the locality. That is, the sound is not masked by the soundscape. This is a signal-to-noise phenomenon and can be defined in terms of sound detectability. Audibility can be considered as a psychophysical quantitative relationship between physical and psychological events:

- the physical relationship is considered as being the role of signal detection
- the psychological or behavioural and perceptive reactions of an individual are considered as psychoacoustical or sound quality relationships

A method for the prediction of the audibility of noise sources is detailed in the report “Graphic Method for Predicting Audibility of Noise Sources” (1982) by Bolt, Beranek and Newman for the US Flight Dynamics Laboratory Air Force Systems Command, publication AFWAL – TR – 82 – 3086. The report provides technical rationale and relationships between signal-to-noise ratio and frequency that govern detectability of acoustic signals by human observers and provides methods to:

- Predict the frequency region of a spectrum that is most detectable in any given sound environment
- Quantify the degree of detectability of the signal in question
- Estimate reduction in signal-to-noise ratio necessary to render the signal undetectable

The report states (p. 15) that detectability is the product of three terms:

1. the observer’s efficiency relative to an ideal energy detector
2. masking bandwidth
3. signal-to-noise ratio at the output of a hypothetical auditory filter

In the Report the sound in question is called the ‘signal’ and the masking noise spectrum against which it is measured is called the ‘ambient’, ‘background’ or ‘noise’ spectrum. The application in this work is slightly different than that envisaged in the Report by the addition of the 20 phon equal loudness level contour.

The audibility of a sound is applied in this work by plotting an analysed soundfile in unweighted one-third octave bands onto the ‘ambient’ curves containing the frequency weighted masking noise spectrum. The ambient curves have been derived from the intersection points in figure 6 of the Report. Figure 6 is appended in the Glossary. The sound can be compared against the hearing threshold level (‘Hearing TL’) and the 20 phon loudness level (LL20) contours to ISO 226:2003 *Acoustics-Normal equal-loudness-level-contours*. Depending on the frequencies chosen, the 20 phon contour reflects a sound level equivalent to 35 dB(A). A second sound, such as a defined broadband noise or ‘signal’, can then be analysed and compared against the masking noise spectrum. The sound is entered as unweighted third-octave band levels.

Signal detectability for the Report and this work is referenced to the ‘threshold of audibility’ for a human observer (p. 24) described as:

> … If the plotted signal spectrum exceeds the plotted noise spectrum in any one-third octave band, then the signal would be correctly detected more than 50% of the time, or with a false alarm rate of less than 1%. Conversely, if the plotted noise spectrum exceeds the plotted signal spectrum in all one-third bands, then the signal then the signal would be correctly detected less than 50% of the time, or with a false alarm rate greater than 1%.

Other levels of detection performance can be identified when the signal is below the background level or if there is a strong tonal component present in the signal itself. Any sound level, whether ‘signal’ or ‘noise’, below the hearing threshold level is considered to be inaudible. If only the masking noise spectrum is recorded then the detectability distance between the ‘noise’ curve and the two loudness level curves indicates the degree of audibility, in dB per third octave, of the sound contained within the soundfile.

Audibility is a significant measurement in the analysis methodologies for this work. The application of the audibility analysis method is presented later in this work.

4.5 Consonance and dissonance

Sensory consonance is defined by Terhardt (2000) as meaning to account for the auditory phenomenon that sounds of any kind in general differ with respect to how "pleasant" or "un-annoying" they are to a listener. Sensory dissonance has the opposite meaning. Sensory consonance may also be defined by saying it denotes the extent to which annoying factors are missing in a sound. Terhardt states that sensory consonance is basically dependent on three fundamental auditory attributes: roughness, sharpness and tonalness. Both Terhardt and Helmholtz identify auditory roughness as governing sensory consonance. Sethares (2005, pp. 349-359) describes the properties of dissonance curves and timbre, pitch extraction and amplitude-modulation models. Spectrum dissonance considers every element in the spectrum whereas tone dissonance considers tone elements in the spectrum.

Dissonance is a type of roughness. Unlike 'dissonance' models, these are sensitive to amplitude and frequency modulation effects, and model the effect of loudness on roughness. The analysis program PsySound2[6] incorporated as part of the analysis program for this work utilises the algorithms of Hutchinson & Knopoff, and Sethares for spectrum and tone dissonance. When applied to the compact spectrum in PsySound2 these algorithms measure the noisiness of the sound; when applied to the tonal components they come closer to measuring musical dissonance. The Hutchinson & Knopoff algorithm normalises the results, and uses linear intensity. Sethare's algorithm does not normalise the results, and uses scaled decibels. Cabrera (1999a, p. 18) notes that:

> Spectrum dissonance should be interpreted with caution, as it uses dissonance algorithms in a manner that the authors did not envisage. Spectrum dissonance might be interpreted as the 'noisiness' (flatness) of the spectrum. Tone dissonance is much closer to the implementation envisaged by Hutchinson & Knopoff and Sethares, and can be interpreted with greater confidence.

Vassilakis (2001, p. 271) takes a similar view to Terhardt and Sethares and describes consonance and dissonance as follows:

[6] The analysis programs of Aures and Daniel & Weber are implemented in PsySound3.

Consonance and dissonance are multidimensional concepts describing the degree of pleasantness / annoyance of a sound, or the degree to which a sound fits to others in a musical context. The primary acoustical cue determining consonance / dissonance is the absence / presence of roughness respectively (although the opposite relationship may also hold depending on musical tradition). Within the Western musical tradition, the presence of roughness is equivalent to acoustic or sensory dissonance.

Dissonance measures are applied in this work as measures of fluctuation or roughness for assessment of sound quality, sensory pleasantness, potential noise intrusion and annoyance. The spectrum and tonal dissonance measures to Sethares as implemented by Cabrera (1999a, 1999b) are adopted in the measurement methodologies of this work.

4.6 Fluctuation strength

Fluctuation is related to the temporal variations of sounds and is an indicator of sound quality, sensory pleasantness, potential noise intrusion and annoyance. Fluctuation strength measured as a function of modulation frequency shows a maximum near 4 Hz. Very slow variations of less than 0.5 Hz hardly affect dynamic hearing sensations. By definition a 1000Hz signal modulated in amplitude by a signal frequency $f_{mod} = 4$ Hz with a modulation rate m = 1 and a level of 60 dB yields a fluctuation strength F = 1 vacil. The calculation methodologies to be considered are presented in Zwicker and Fastl (pp. 247 – 256). Van den Berg (p. 83) states that fluctuations with peak levels of 3-9dB above a constant level may have effects on sleep quality. Zwicker and Fastl (p. 255) present a “relatively simple formula” for the fluctuation strength of sinusoidally amplitude-modulated broad-band noise where *m* is the modulation factor, L_{BBN} the level of the broad-band noise and f_{mod} the frequency of modulation:

$$F_{BBN} = \frac{5.8(1.25m - 0.25)\left[0.05\left(L_{BBN}/dB\right) - 1\right]}{\left(f_{mod}/5Hz\right)^2 + \left(4Hz/f_{mod}\right) + 1.5}\,vacil \qquad \text{eqn 4.6.1}$$

For amplitude or frequency modulated tones the fluctuation strength may be approximated by eqn 4.6.2 where ΔL is the temporal masking depth:

$$F = \frac{0.008 \int_{0}^{24Bark} \left(\Delta L / dB\,Bark \right) dz}{\left(f_{\text{mod}} / 4Hz \right) + \left(4Hz / f_{\text{mod}} \right)} vacil \qquad \text{eqn 4.6.2}$$

A different approach is taken by Van den Berg (2006, p. 81) with respect to fluctuation strength (F_{bb}) from broad-band noise from wind turbines with typical values of $f_{\text{mod}} = 1$, broad-band noise = 40 dB(A), level difference $\Delta L < 9$ dB and modulation factor $mf = 0.055\,\Delta L$:

$$F_{bb} = 0.072\,(\Delta L - 3.6) \quad \text{vacil} \qquad \text{eqn 4.6.3}$$

When ΔL rises from 3 dB, a maximum value for daytime (unstable or neutral) atmosphere, to 6 dB, *mf* rises from 17% to 33%. For a maximum value of $\Delta L = 9$ dB, *mf* is 50%. Values of fluctuation strength range from negligible (at $\Delta L = 3$ dB) to around 0.4 at $\Delta L = 9$ dB.

The calculation methods as described in this section are not readily amenable to implementation in this work and measures of dissonance are introduced instead.

4.7 Frequency centroid

The frequency centroid is often described as the ‘centre of gravity’ of a frequency spectrum and has been used as a measure of the ‘brightness’ of sound. In the following equation *C* is centroid, *I* is the intensity of a spectrum component (*I=10^(L/10)*), and *f* is its frequency in Hz:

$$c = \frac{\sum If}{\sum I} \qquad \text{eqn 4.7}$$

The frequency centroid is adopted as a measure of sound quality and sensory pleasantness of environmental sound for this work.

4.8 Impulsiveness (acoustical)

Impulse sounds are characterised by having a sudden beginning, which makes them more noticeable than continuous noise. Impulse sound can be extremely annoying, even at very low sound levels (dripping tap, for example) and is a measure of potential noise intrusion and annoyance. The reporting of measurement and assessment methods for impulsive noise has been a major research project by Hoare Lea Acoustics (2004). A significant result of the project is that a definition of impulse sound now exists. No specific measure was found to be “the best”. Two methods, the NPL Increment Method and the Delta Prominence Method have been identified as contenders for practical application as both can be implemented by post-processing. Pedersen (2000) has defined an impulsive sound as:

> The sudden onset of a sound is an impulse. The penalty for impulse depends on how prominent this characteristic is perceived through the continuous part of the noise including the background sound.

The various reports of Hoare Lea Acoustics identify the listening tests and methods of measurement used in assessing impulsive sound for intrusiveness and annoyance. Various A-weighted sound pressure levels were tested as well as loudness, sharpness, roughness and fluctuation. The Delta Method, as presented in Nordtest NT ACOU 112 (2002) *Acoustics-Prominence of Impulsive Sound and for Adjustment of* L_{Aeq} is referenced in the Reports. The method is extended to include the use of F time-weighting to provide a better psychoacoustic element than $L_{Aeq\ 10ms.}$ The application of impulsiveness is not considered further in the analysis methodologies for this work.

4.9 Just-noticeable differences

Just-noticeable differences (jnd) are the smallest difference in a sensory input that is perceivable by a person. Just-noticeable changes in amplitude, frequency and phase (Mannell; Zwicker and Fastl, pp 175-201) are an important feature for the assessment of low amplitude sound in a quiet background, where slight changes in frequency or amplitude can be readily noticed as a change in ambience. The characteristic of the sound is its absence; that is, the sound is not noticed until it has gone. It is the absence of the sound that defines its degree of intrusion and potential annoyance. Zwicker and Fastl (p 199) present a model for just-noticeable differences. Just-noticeable changes can be as a change in amplitude over time; typically modulations, as just-noticeable variations. The other kind of change is a just-noticeable difference where the one sound is compared to another sound; that is, increment detection vs. difference discrimination. The just-noticeable degree of modulation threshold factor is approximately 1 dB, with smaller sensitivity at high sound levels. Our hearing is most sensitive for sinusoidal frequency modulations at frequencies of modulation of approximately 4 Hz. At 50 Hz the just noticeable change corresponds to a semi-tone in music. Above 500 Hz a change in frequency of about 0.7% is noticeable.

The application of just-noticeable differences is not considered further in the analysis methodologies for this work as proven calculation methods are not implemented. This work introduces instead the concept of pitch salience where the prominence of adjacent semitones is presented to indicate degrees of difference for ‘just-noticeable differences’.

4.10 Loudness

Loudness is sound volume measured in sones. Zwicker and Fastl (1999, p. 203) state that loudness belongs to a category of intensity sensations. They also state that the loudness level measure was created to characterize the loudness sensation of any sound. Kryter (1985, p. 112) defines loudness as: “... the subjective intensity of a sound, independent of any meaning the sound may have.” The sone unit is proportional to loudness; a doubling in sones corresponds to a doubling of loudness. Silence approaches 0 sones. A 1 kHz tone at 40 dB(SPL) presented as a frontal plane wave in a free field has a loudness of 1 sone.

Loudness is calculated as the area under the specific loudness curve. When read directly, the specific loudness function shows the parts of the frequency spectrum that make the strongest contribution to loudness. Loudness to Zwicker is the integral of specific loudness over critical-band rate. The symbol N represents loudness (in sones), and N´ specific loudness in sone/Bark (Zwicker & Fastl 1999, p. 220):

$$N = \int_0^{24Bark} N'dz \qquad \text{eqn 4.10.1}$$

This work references a slightly different calculation of loudness (Cabrera 1999a, p. 15) with the integral of specific loudness on the Erb-rate (or *z*) scale (similar to a frequency scale). Various measures of loudness are presented. The symbol *N* represents loudness (in sones), and *N'(z)* specific loudness (in sones per Erb)

$$N = \int N'(z)dz \qquad \text{eqn 4.10.2}$$

The perception of loudness is often quoted as: "there is a doubling of loudness with an increase of 10 dB." Nave (2008) states that this comparison is approximate:

> …it is applicable only to adding loudness for identical sounds. If a second sound is outside the critical band of the first then this rule does not apply at all.
>
> When two sounds of equal loudness when sounded separately are close together in pitch, their combined loudness when sounded together will be only slightly louder than one of them alone.

The Stevens' (Method A) and Zwicker (Method B) methods for calculating loudness or loudness level are defined in International Standard ISO 532:1975 *Acoustics-Method for calculating loudness level*. Method A uses octave bands and Method B uses one-third octave bands for spectrum analysis to approximate critical bands. The Zwicker method makes allowance for masking and weights the different one-third octave bands depending on frequency and level. The measures of loudness described are designed for what is termed "stationary" signals. In broad terms, this is a measure over a relatively long time period, in seconds rather than milliseconds. Loudness, however, is also a short-term feature, with times of 2 ms (for example) for highly impulsive sound, 8-10 ms for less impulsive sound, and rates in the order of 50 ms to 300 ms for other sounds. These short-term loudness events are calculated as "dynamic" loudness. The loudness of a sound can therefore be described in both terms: stationary loudness for the overall sound event and dynamic loudness for short-term sound events. The dynamic process described by Chalupper (2000) provides a significant advance in noise assessment for short duration sound and also for elements of intrusiveness. The method is not implemented in this work. Loudness and loudness level measures are implemented in the analysis methodologies for this work. Loudness is calculated as both an overall level and as ‘short-term’ level every 50 ms to provide an assessment of loudness verses time.

4.11 Equal loudness level contours

The unit for loudness level is the phon. The phon is used to describe sounds that research has indicated are equally loud. It does not measure relationships between sounds of differing loudness. An equal loudness contour is a measure of sound pressure, over the frequency spectrum with pure continuous tones, for which a listener perceives an equal loudness. Loudness level contours are defined in International Standard ISO 226:2003 *Acoustics-Normal equal loudness contours*, as illustrated in figure 4.11.1. The revised ISO 2003 contours are in red, the 1961 contours are in blue. The 40 phon equal loudness contour is used to calculate the decibel A-weighted scale (dBA). The levels referenced for this work are the levels between 50 phon and just below the Minimum Audible Field (minimum level or approximately 4 phon).

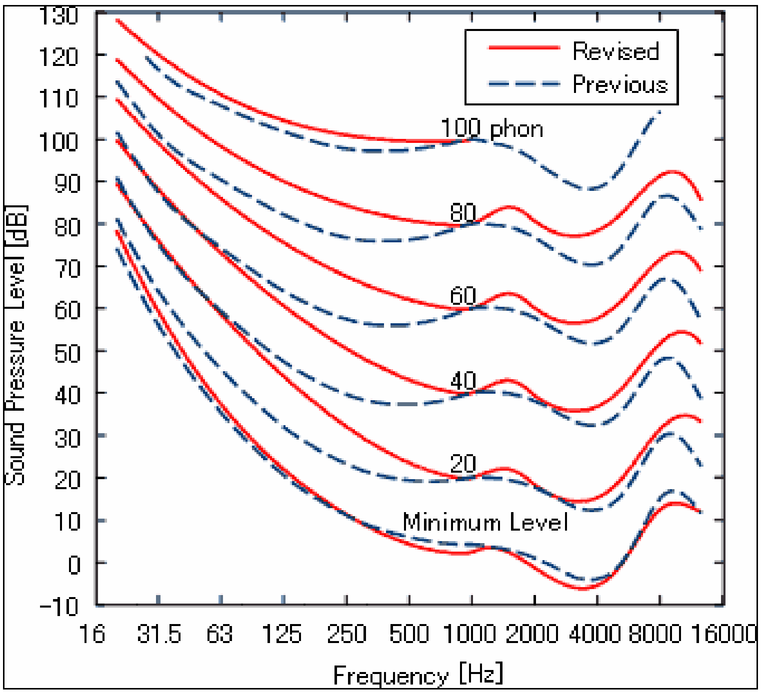

Figure 4.11.1: Equal loudness level contours vs sound pressure levels
(reference source: http://www.aist.go.jp/aist_e/latest_research/2003/20031114/20031114.html)

In relation to the use of the equal loudness-level contours Schomer (2001a, 2002b) suggests the use of the contours as a dynamic filter that changes with both sound and frequency. After comparing his proposal between the 'old' contours and the 'new 2003' contours he found that the method failed to work because the new contours shifted the levels (contours) in the low frequencies. The outcome is that the result shows the importance that low frequency noise plays in assessing noise annoyance. Schomer tested his method with both loudness-level-weighted sound exposure (LLSEL) and loudness-level-weighted equivalent level (LL-LEQ). After adding an "windows-closed house filter" Schomer (2002b) found a useful correlation between outdoor measured sound and indoor assessed noise annoyance and in relation to A-weighted measurements he states:

> It offers a clear picture why other methods do not work very well when measured indoors at the listener and why the A-weighting is inadequate to assess environmental noise across varying sources.

Loudness level is referenced in the audibility measurement methodology of this work.

4.12 Modulation

Modulation is perhaps the most 'difficult' of the sound quality measures in that it has wide definition and can be interchanged colloquially with almost similar physical processes, such as beating or pulsing. Modulation, as defined in American National Standard ANSI S3.20-1973 Pyschoacoustical Terminology, is:

> The variation in the value of some parameter characterizing a periodic oscillation. Thus, amplitude modulation of a sinusoidal oscillation is a variation in the amplitude of the sinusoidal oscillation.

Essentially, under this definition, modulation is the variation of amplitude or frequency of a carrier frequency. In music it can be described as a change in stress, pitch or loudness or the changing from one key or tonal centre to another. Modulation depth is the amplitude level at which the signal is varied and is expressed in percent or decibels. Modulation is similar to the roughness of a tonality. An explanation of roughness by Cox and Moorhouse (2008) provides a starting point for a modulation metric, referenced to a calibration factor, the frequency of modulation and the perceived masking depth. Atlas and Shamma (2003) present a summary of amplitude and frequency modulation-based analysis or synthesis techniques. Conversely, Randall (1987, p. 72) states the relationships for amplitude and frequency modulation and the ‘modulation index’.

Vassilakis (2001, p. 261-266) states his definitions of various aspects of modulation. In describing ‘modulation’ he states that the term was introduced into acoustics and psychoacoustics literature from radio engineering to describe distortions of any arbitrary wave profile. ‘Amplitude’ is defined in terms of relative rather than absolute reference points. ‘Amplitude fluctuation’ is described perceptually as beating, roughness combination tones (depending on fluctuation rate per second). ‘Amplitude modulation’ is a spectral modification process that produces discrete upper and lower sidebands determined by the modulation frequency and the modulation depth *m*. ‘Amplitude modulation depth’ is a measure of the spectral energy spread of an amplitude modulated signal. ‘Beating’ is the most familiar perceptual manifestation of amplitude fluctuation and describes loudness fluctuations perceived when sound signals with an amplitude fluctuation rate of ~≤ 20 per second reach the ear.

For this work modulation, by amplitude, is defined as a peak to trough variation that exceeds 3dB on a regular basis (3dB is taken as negligible, 6dB as unreasonable and 9dB taken as excessive); by frequency, modulation is defined as a variation that exceeds one semi-tone on a regular basis.

4.13 Perceived noisiness

Perceived noisiness (PN) is a scale developed by Kryter (1985, p. 120-169). Noisiness is synonymous with annoyance and ‘perceived’ emphasizes the quantity is a physiological-psychological entity. The concept excludes from consideration the meaning conveyed by a sound or noise (p. 122). Perceived noisiness is a subjective quantity and not to be confused with a physical measurement, such as dB(A). Perceived noise level, however, is given in PNdB (p. 126). Kryter reports the separation between loudness, noisiness and annoyance as: loudness is a perceptual aspect of volume of sound; noisiness is the quality of the noise; and annoyance is the nuisance aspect of a noise. Kryter (p. 168) states that phons and PNdB are ‘yet more accurate predictors of perceived loudness or noisiness of broad-band and, especially, narrow-band noise.’ For reasons of practicality and simplicity Kryter proposes that all measurements of noise level, impulsive or non-impulsive, be made with a basic integration time of 1 second.

$$PNdB = 40.0 + 33.3 Log N \qquad \text{eqn 4.13.1}$$

From the following expression 4.13.2 where *N* is the perceived noisiness in noys; n is the number of noys in a 1/3 octave band and *n(k)* is the largest of the 24*n* values

$$N = n(k) + 0.15\left[\left(\sum_{1}^{24}\ \right) - n(k)\right] \qquad \text{eqn 4.13.2}$$

Perceived noisiness is applicable in the description of environmental sound as measures of sound quality and potential intrusion. The application of perceived noisiness is not considered further in the analysis methodologies for this work.

4.14 Pitch

Pitch can be defined by reference to Terhardt (2000) as: “An auditory attribute in terms of which sine waves can be ordered on the low-high dimension”. Terhardt also introduced the concepts of spectral pitch: “An elementary auditory object that immediately represents a spectral singularity, e.g., a sine tone” and virtual pitch: “An attribute of auditory sensation with the fundamental pitch ‘extracted’ by the auditory system from a range of the Fourier spectrum that extends above the fundamental”. There are two different pitch assessments: harmonic sound and inharmonic sound. Pitch is multidimensional, involving the components of pitch height and pitch strength or salience. Pitch is often measured by frequency (e.g., 440 Hz) and its musical notation and label (e.g., A). “Pitch class” is all the octaves of a frequency; for example, A4 and A5 are one octave apart. Pitches are named with integers, from 0 to 8. This work is presented referencing the twelve-tone equal temperament scale (12-

tet) with 1200 cents to an octave (Helmholtz 1954, pp. 41d & 446c). The pitch ratio between any two successive notes is the twelfth root of two (about 1.05946) or approximately 6%.

The pitch of a pure tone depends not only on frequency, but on its amplitude as well as other parameters. The relationship between pitch and sound level is not ordered on a low-high ratio: a 200 Hz tone at 80 dB produces a softer pitch than the same tone at 40 dB, whereas a 6000 Hz tone at 80 dB produces a higher pitch than the same tone at 40 dB. The pitch of complex tones can be assessed by pitch matches with pure tones. The pitch of harmonic pure tones depends on level. The pitch of a complex tone is based on the spectral pitch of its lower components. A pure tone has a frequency lower than the fundamental frequency of a complex tone of the same pitch. Pitch is, therefore, a multiplicity of sine tones and complex tones (Zwicker and Fastl, p. 113). There is a difference between the pitch of notes compared to the pitch of pure tones. Furthermore, a slight change in frequency need not lead to a perceived change in pitch, but a change in pitch implies a change in frequency. The pitch of a tone sensation is measured in 'pitch units', pu. The sensation "pitch of pure tones" can be described by that frequency of a pure tone at 40 dB SPL which produces the same pitch as the pure tone in question. The 'just noticeable difference' or threshold at which a change in pitch is perceived is about five cents, but varies over the range of hearing.

The concept of pitch has been explored in detail by Terhardt, who introduces the alternative concepts of spectral pitch and virtual pitch. Spectral pitch presents 'the harmonic complex tones of real life.' Terhardt (2000) states that:

> When, and if, any real-life sound (e.g., foot step, knock at the door, splashing water, sound of a car's engine, fricative phoneme of speech) can be identified by ear, one can be sure that – besides temporal structure – spectral pitch is involved.

Virtual pitch, however, is a fascinating phenomenon and is deduced from a set of spectral pitches occurring on another stage of auditory processing. The auditory system is nonlinear in nature and can produce aural harmonics and difference tones. The perception of these tones (pitches) is not due to the presence of these frequencies in the stimulus. The pitches are created as a result of the nonlinear distortion caused by the peripheral auditory system. The 2nd and 3rd aural harmonics, difference tone and cubic difference tone are the most often perceived. (Yost 2000, p.167 & p.199). The cubic difference tone is the most significant as this tone can be heard at less than 40 dB. The primary difference tone is not detected at this level. The ear has the ability to recreate a "missing" fundamental and generate a sound that does not exist physically, although virtual pitch is dependent on spectral pitch. Sethares (2005, p. 34) explains virtual pitch as:

> When there is no discernible fundamental, the ear will often create one. Such virtual pitch, when the pitch of the sound is not the same as the pitch of any of its partials, is an aspect of holistic listening.

This raises the very real possibility that a person may be able to hear a sound that does not physically exist outside the hearing of that person. In the example given by Sethares, three partials at 780 Hz, 1040 Hz and 1300 Hz recreate a single sound at 260 Hz. This sound could not, therefore, be measured "in real-time" exterior to the person but it is real none-the-less. The practical import of the effects of virtual pitch is that a low amplitude noise problem may need to take into account "missing" fundamentals, as well as measured partials[7].

Pitch salience is the perceptual importance of prominence of tone sensations. The salience of a pure tone component is its probability of being noticed, or the degree to which it contributes to the perception of complex tones. It depends on audibility and frequency to a lesser extent. The differences between a pure tone sensation and a complex tone sensation are measures of audibility, not of salience.

Pitch salience, or more correctly *tone salience*, is calculated following Parncutt (1989) and is implemented in PsySound2. Cabrera (1999b, p. 52) states that the pitch salience patterns, as the mean pitch salience, are presented linearly over the pitch height range. This provides a visual analysis of the semitone values or 1/12 octave band values.

[7] The converse is that, if designed to generate real partials, a sound amplifier may be able to "fill-in" fundamentals "missing" within a sound to create a more harmonic or smooth sound, or possible cancellation or masking of a nuisance noise.

Parncutt (p. 93) states that:

> The salience *(S)* of an individual tone component is defined as its probability of being noticed. Assuming independent probabilities, and given that the tone simultaneity itself has been noticed, it follows that the sum of all the tone saliences *S(P)* in a sound equals the number of simultaneously noticed tones *M.* In addition, tone salience is assumed to be proportional to tone audibility *A*. The expression satisfies these criteria:

$$S(P) = A(P).M / A_{max}.M' \qquad \text{eqn 4.14.1}$$

> where M is the multiplicity and is the number of tones simultaneously noticed in a sound and A_{max} is the maximum audibility of the most audible pure or complex tone component in the sound.

Independent of the pitch, the sensation can be labelled as faint pitch or strong (distinct) pitch, leading to a scale of pitch strength. The pitch strength of sounds can be assessed quantitatively using magnitude estimation. Line spectra generally elicit relatively large pitch strength, whereas sounds with continuous spectra produce only small values of pitch strength (Zwicker and Fastl 1999, p. 134). *Pitch shift* is calculated as the difference in frequency of a pure tone at 40 dB SPL and that of another pure tone under the condition in which the pure tones of different levels produce the same pitch. Pitch shift is measured in percent.

The pitch measures are presented as measures of environmental sound for audibility, smoothness of the sound (overall pitch salience) and potential noise intrusion. Pitch measures are implemented in the analysis methodologies of this work.

4.15 Roughness

Roughness is a basic sensational entity that has a negative effect on sound quality and reduces the sensory pleasantness of a noise. The sensation of roughness is created when modulations faster than that causing fluctuation strength are experienced. Maximum roughness appears for sounds with a modulation frequency of about 70 Hz. The perception of roughness can be evoked by fast envelope fluctuations between 15 and 300 Hz. The roughness quantity R = 1 asper is defined as a 1000Hz tone at 60 dB that is 100% amplitude-modulated at a modulation frequency of 70 Hz.

Daniel and Weber present a model for calculating psychoacoustical roughness. The excitation pattern for each frequency component is analysed in a filterbank of 47 filters each 1 Bark wide and with an overlap of 0.5 Bark between filters. The dependence of roughness on modulation frequency is modelled by an appropriate bandpass weighting of the modulation spectrum in each critical band i. A measure for the degree of modulation of the envelope is given by m_i. Specific roughness is estimated by the square of the weighted m_i with $g(z_i)$ between 0.6 and 1.1 applied according to the dependence of roughness on the carrier frequency of amplitude-modulated tones; k_{i-2} and k_i are cross-correlation coefficients and 0.3 is a calibration factor:

$$R = 0.3\sum_{i=1}^{47}\left(k_{i-2} \cdot k_i \cdot g(z_i) \cdot m_i^*\right)^2 asper. \qquad \text{eqn 4.15.1}$$

Zwicker and Fastl (1999, p. 257-264) present a somewhat different explanation of the sensation as well as a calculation method. The two main factors that influence roughness are frequency resolution and temporal resolution within our hearing system. Frequency resolution is modelled by the excitation pattern or by specific-loudness verses critical band pattern. Masking level can be used to estimate the excitation-level differences produced by amplitude modulation. The temporal masking depth, ΔL, becomes larger for lower modulation frequency. A very slow temporal change does not produce roughness whereas a quick periodic change does. Roughness, therefore, is proportional to the frequency of modulation. Equation 4.15.2 is from Zwicker and Fastl (1999, eqn. 11.3) but they note that there are limitations due to paucity of data for ΔL as a function of critical-band rate. The calculation method (eqn 4.15.2) is not implemented in this work.

$$R = 0.3\frac{f_{\mathrm{mod}}}{kHz}\int_0^{24Bark}\frac{\Delta L_E(z)dz}{dB/Bark} asper \qquad \text{eqn 4.15.2}$$

Vassilakis (2001, 2007 pp. 319-325) has a different approach to signal amplitude fluctuations and perceptual categories in a musical context. He has proposed a roughness calculation model, R, that is dependent on intensity (X), amplitude fluctuation degree (Y) and amplitude fluctuation rate (Z):

$$R = X^{0.1} * 0.5\left(Y^{3.11}\right) * Z \qquad \text{eqn 4.15.3}$$

In his definitions (2001, p. 288) Vassilakis defines roughness as a harshness perceived when sound signals with amplitude fluctuation rate between about 20 and about 75 to 150 fluctuations per second reach the ear. A rate of 50 beats per second is said to be of intermediate character. Roughness is the principal measure of sensory dissonance and is a perceptual measure and can be considered as one of the main auditory attributes along with pitch, loudness and timbre.

Roughness is applicable in the description of environmental sound as a measure of sound quality, sensory pleasantness, potential intrusion and annoyance. The calculation methods as described in this section are not readily amenable to implementation in this work and measures of dissonance are introduced instead.

4.16 Sensory pleasantness

Sensory pleasantness, in relation to environmental sound, is an indicator of individual amenity perception. Terhardt (2000), in his paper on musical consonance, states that "the concept of consonance obviously implies the aspect of pleasantness". It is apparent to him that there are basic sensory factors that affect the pleasantness of both musical and non-musical sounds. The collection of such factors is one aspect of musical consonance and he termed this component *sensory consonance.* Sensory consonance is dependent on the basic auditory attributes of roughness, sharpness and tonalness.

Zwicker and Fastl (1999, p. 243-245) in assessing the factors contributing to the annoyance or pleasantness of sounds present a relationship between psychoacoustic annoyance and loudness, sharpness, fluctuation strength and roughness:

..sensory pleasantness depends mostly on sharpness. Loudness, however, influences sensory pleasantness only for values that are larger than the normal loudness of communication between two people in quiet.

Zwicker and Fastl state that sensory pleasantness increases with tonality. Tonality in this instance is stated as being subjective and related to critical band rate spread. For this work a default value for tonality of 0.2 for a critical-band-rate spread of 0.57 Bark. Sensory pleasantness is related to relative values of sharpness S, roughness R, tonality T and loudness N:

$$\frac{P}{P_0} = e^{-0.7R/R_0} e^{-1.08S/S_0} \left(1.24 - e^{-2.43T/T_0}\right) e^{-\left(0.023N/N_0\right)^2} \qquad \text{eqn 4.16}$$

The measure is applied in the research investigations but sensory pleasantness is not applied further as a primary measure in the analysis methodologies of this work.

4.17 Sharpness

Sharpness, in relation to environmental sound, is an indicator of individual amenity perception. Sharpness is a measure of the high frequency content of a sound, the greater the proportion of high frequencies the ‘sharper’ the sound. Sharpness is a subjective measure of sound on a scale extending from dull to sharp and is an indication of the spectral envelope of a sound affected by spectral content and the centre frequency of narrow-band signal. Sometimes it is thought of as a pitch-like (low-high) aspect of timbre. ‘Brightness’ and ‘density’ are two other terms that have been used to denote equivalent or closely related attributes. The unit of sharpness is the acum. One acum is defined as the sharpness of a narrow band of noise one critical-bandwidth wide at a centre frequency of 1kHz having a level of 60 dB(SPL). A 1000 Hz pure tone at 60 dB(SPL) will have a similar sharpness. Critical band rate is the Bark. Sharpness is not standardised.

Zwicker & Fastl’s sharpness is calculated in the following manner - where N is loudness, $N'(z)$ is specific loudness, z is the critical-band rate, and $g(z)$ is a weighting function that emphasises high frequencies (Zwicker and Fastl 1999, p. 242):

$$S_{Z\&F} = 0.11\frac{\int_{z=0}^{24Bark} N'(z)\cdot z\cdot g(z)dz}{N} \qquad \text{eqn 4.17.1}$$

Aures' sharpness is a revision of Zwicker and Fastl's calculation and is more sensitive to loudness:

$$S_{Aures} = 0.585\frac{\int_{z=0}^{24Bark} N'(z)\cdot g(z)dz}{\ln\left(\frac{N+20}{20}\right)} \qquad \text{eqn 4.17.2}$$

The Aures method of analysis for sharpness as implemented by Cabrera (1999a, 1999b) is adopted in the measurement methodologies of this work.

4.18 Sound pressure and sound levels

The rating methods for special audible characteristics described in New Zealand Standard NZS 6808:1998 are adopted in this work. New Zealand Standards NZS 6801:1999 *Acoustics-Measurement of Environmental Sound* and NZS 6802:1999 *Acoustics-Assessment of Environmental Noise* provide methods of measurement and methods for rating noise. New Zealand Standards tend to follow the definitions given in International Standards such as *International Standard ISO 1996-1 Acoustics – Description, assessment and measurement of environmental noise – Part 1: Basic quantities and assessment procedures* and ISO 1996-2:2003 *Determination of environmental noise levels*. The standards define the basic quantities and rating methods to be used for the description of noise in community environments. Definitions required for this work are:

Sound pressure level

ten times the logarithm to the base 10 of the square of the ratio of a given root-mean-square sound pressure to the reference pressure. The reference sound pressure is 20 μPa. Sound pressure is expressed in pascals (Pa). Sound pressure level is expressed in decibels (dB).

Time-weighted and frequency-weighted sound pressure level

ten times the logarithm to the base 10 of the square of the ratio of a given root-mean-square sound pressure to the reference sound pressure, being obtained with a standard frequency weighting and standard time weighting. The standard frequency weightings are A-weighting and C-weighting as specified in IEC 61672-1, and the standard time weightings are F-weighting and S-weighting as specified in IEC 61672-1. Time-weighted and frequency-weighted sound pressure level is expressed in decibels (dB).

Maximum time-weighted and frequency-weighted sound pressure level

The greatest time-weighted and frequency-weighted sound pressure level within a stated time period, expressed in decibels (dB).

***N* percent exceedance level**

The time-weighted and frequency-weighted sound pressure level that is exceeded for N% of the time interval considered, expressed in decibels (dB).

Equivalent continuous sound pressure level

ten times the logarithm to the base 10 of the ratio of the square of the root-mean-square sound pressure over a stated time interval to the square of the reference sound pressure, the sound pressure being obtained with a standard frequency weighting. The A-weighted equivalent continuous sound pressure level (also termed the time-averaged sound pressure level) is given in the standard as

$$L_{\mathrm{Aeq}T} = 10\,\mathrm{lg}\left[\int_T p_\mathrm{A}{}^2(t)/p_0{}^2\mathrm{d}t\right]\mathrm{dB}$$

The equation is implemented in this work as

$$L_{\mathrm{Aeq,t}} = 10\ \mathrm{lg}\ (1/\mathrm{T}) \int_0^{\mathrm{T}} (p_\mathrm{A}(\mathrm{t})/p_0)^2\ \mathrm{dt} \qquad \mathrm{dB} \qquad \text{eqn 4.18.1}$$

Where T is the time interval in seconds
p_A(t) is the time varying sound pressure in pascals
p_0 is the reference value 20μPa

Octave and fractional octave bands can be calculated with either equivalent continuous sound pressure levels or frequency-weighted sound pressure levels. Sound pressure level measures are implemented in the analysis methodologies of this work.

4.19 Specific loudness

Specific loudness is calculated as a measure of audibility and relative ‘smoothness’ of the sound and is the loudness attributable to an auditory filter. The specific loudness pattern can be used to find the loudest part of the sound spectrum (Cabrera, 1999a, p. 14). The scale used is the critical-band rate or Erb-rate and the measure is sones / erb. Loudness is calculated as the area under the specific loudness curve. When read directly, the specific loudness function shows the parts of the frequency spectrum that make the strongest contribution to loudness. In assessing environmental sound the measure is implemented in a time-history format (to observe changes over time) or as an overall summation in either graphic or numeric format. The specific loudness pattern can be used to find the loudest part of the sound spectrum. Specific loudness is implemented in the analysis methodologies of this work.

4.20 Timbre

The character of the environment is defined by its soundscape; that is, the nature of all the sounds within that environment. There is, however, no single methodology in environmental acoustics that can provide a description of the soundscape. The descriptors for sound quality, as presented in this work, do not provide suitable definition in themselves. The musical concept of timbre, however, uniquely presents an over-arching concept to describe the soundscape. A summary definition for this work is that:

> Timbre or tone quality or tone colour is a function in time of the frequency content or spectrum of a sound, including its transients and pitch, loudness, duration and manner of articulation. Timbre allows a person to distinguish between different sounds, instruments and voices.

The timbre of a sound has been defined by Parncutt (1989) as being “the attribute of a tone sensation by which different tone sensations of the same pitch and loudness may be differentiated”.

Sethares (2005, p. 29) reports that timbre is a multidimensional attribute of sound. The envelope of the sound describes how the amplitude of the sound evolves over time and the attributes of timbre includes (in part) the amount of fluctuation being the change in spectrum over time.

Moore (1988, p. 83) links timbre with critical bands but also introduces the effect of prominent frequency components:

> The perception of timbre seems to depend, at least in part, on the distribution of activity across different critical bands. However, in order to predict whether a complex sound will be detected in a given background noise, it is usually sufficient to calculate the detectability of the most prominent frequency components.

Acoustic features and timbral adjectives based on listening tests have been described by Howard, Disley and Hunt (2007). Timbre is presented as: "... two sounds that are perceived as being different but which have the same perceived loudness, pitch and duration are said to differ by virtue of their timbre." The acoustic features and adjectives presented in Table 4.20.1 provide a practical relationship for correlating measures with perception.

Acoustic feature	**Dim. 1**	**Dim. 2**		**Adjective**	**Dim. 1**	**Dim. 2**
Spectral centroid	**0.67**	0.43		Bright	-0.21	**0.68**
Spectral slope	**0.77**	-0.11		Clear	-0.38	0.34
Spectral smoothness	**0.77**	0.28		Warm	0.07	**-0.89**
Attack time	**0.63**	0.05		Thin	-0.19	**0.65**
Decay time	-0.47	0.40		Harsh	0.39	**0.82**
Ratio of attack to decay	**0.59**	-0.20		Dull	-0.04	**-0.57**
Ratio f0:harmoic 2-4	-0.12	0.02		Percussive	**-0.97**	0.18
Ratio f0:harmoic 5-8	**0.61**	0.53		Gentle	-0.14	**-0.83**

Table 4.20.1: Acoustic features and timbral adjectives (contributions to each of the two dimensions established from multidimensional scaling analysis of the comparison listening test). *(Reproduced with permission)*

Sandell (2006) presents a compilation of descriptions of the word “Timbre”. The consensus appears to be that timbre is a perception, *relating* loudness, sharpness, pitch, tones, spectral envelope, duration and sound quality.

Ando and Pompoli (2002) however, take a different stance, *including* pitch, loudness and duration within their equation for timbre. Their basic premise (p. 3) is that: “Thus, we can describe any subjective attribute of noise and noise fields in terms of processes of the auditory pathways and the brain.” The challenge of this premise is not tested in this work.

4.21 Timbral width

The width of the peak of the specific loudness spectrum is called the timbral width. *Zmax* is the Erb-rate at which the specific loudness spectrum reaches its maximum. Theoretical values range between 0 and 1: a single pure tone is likely to have a smaller width than broad-band noise.

$$TW = \left[\frac{\left(N - \int_{z_{\max}-0.5}^{z_{\max}+0.5} N'(z)\,dz \right)}{N} \right]^2 \qquad \text{eqn 4.21.1}$$

Timbral width and specific loudness measures are implemented in the analysis methodologies of this work.

4.22 Tonality (acoustical)

The tonality measures are calculated as measures for audibility, amenity and pleasantness. Measures can be broadly grouped as: tone-to-noise ratio (TNR method outlined in ANSI S1.13 1995[8]); rating the prominence of tonal character (PR method outlined in ANSI S1.13); perceived tonality (to Aures); audibility of tones in noise (Joint Nordic Method). All methods have shortcomings in relation to non-stationary

[8] ANSI is the American National Standards Institute

time varying signals. The tonality (TNR, PR) procedures in ANSI S1.13 are based on the equivalent continuous (Leq) unweighted FFT power spectrum. The tone-to-noise ratio (TNR) is the ratio of the power contained in the tone under investigation to the power contained in the critical band centred on that tone, but not including the tone. A discrete tone is classified as being prominent if the sound pressure level of the tone exceeds the sound pressure level of the masking noise in the critical band by 6 dB. This corresponds to a tone being prominent when it is more than 10 dB above the threshold of audibility. The prominence ratio (PR) is the ratio of power contained in the critical band centred on the tone under investigation to the average power contained in the two adjacent critical bands. A discrete tone is classified as being prominent if the sound pressure level of the critical band containing the tone exceeds the average sound pressure level of the adjacent critical bands by 7 dB.

The tonality method as presented in *International Standard ISO 1996-2 Acoustics – Description, assessment and measurement of environmental noise – Part 2: Determination of environmental noise levels; Annex C: Objective method for assessing the audibility of tones in noise – Engineering method* is identified as the practical tonal analysis method for this work. The method is similar to Joint Nordic Method 2. The method includes procedures for steady and varying tones, narrow-band noise, low-frequency tones, and the result is a graduated 0 dB to 6 dB adjustment. The issue of identifying a real tone in a critical band appears to be the most difficult problem with the tonal analysis methods. The tonal audibility, ΔL_{ta}, is expressed in decibels above the masking threshold. With an effective analysis bandwidth of 5% of a critical band, just audible tones normally appear as local maxima of at least 8 dB above the masking noise in the averaged spectra.

$$\Delta L_{ta} = Lt_{pt} - L_{pn} + 2dB + \lg\left[1 + \left(\frac{f_c}{502}\right)^{2.5}\right] dB \qquad \text{eqn 4.22.1}$$

where L_{pt} is the total sound pressure level of the tones in the critical band; L_{pn} is the total sound pressure level of the masking noise in the critical band; and f_c is the centre frequency of the critical band, expressed in hertz. Brüel & Kjær Application Note BO 0499-11 *Tone Assessment using the 2260H Sound Level Analyser* is of considerable assistance in understanding the ISO standard. The application of ISO tonality is implemented in the analysis methodologies for this work but is a ‘work in progress’.

4.23 Tone sensations: pure, complex and multiplicity

The measures of pure and complex tone sensations are included in this work as part of the physical assessment of sounds. Pure tone sensation (Parncutt p. 34) depends on the number and audibility’s of pure tone components and reflects the audibility of spectral pitches. The salience of a pure tone component is defined as its probability of being noticed, or the degree to which it contributes to the perception of complex tones. Complex tone sensation (Parncutt, p. 35) is the perception of tone sources and the audibility of a sound’s most audible complex tone component. Most tone sensations in music and in everyday sounds are complex. Complex tone sensation reflects the audibility of harmonic patterns among spectral pitches of pure tone sensations. The harmonic template resembles the pitch pattern of audible harmonics of a typical harmonic complex tone. The formation of complex tone sensations is simulated by shifting the harmonic template through the musical pitch range in steps of one semitone. The overall audibility *A(P)* of a pure or complex tone component is given (p. 91) by the maximum of the pure and complex tone audibility’s in that pitch category:

$$A(P) = \max\{Ap(P), Ac(P)\} \qquad \text{eqn 4.23}$$

The pure tonalness of a sound or group of tones depends on the number and audibility’s of pure tone components. The complex tonalness of a sound is proportional to the audibility of a sound’s most audible complex tone component.

Multiplicity is the name given by Parncutt (1989, p. 92) to the number of tones simultaneously noticed in a sound. Multiplicity is assumed to depend partly on a sound’s pitch configuration (tone audibility as a function of pitch category) and partly on how analytically the sound is perceived. The calculation assumes that the sound’s most audible pure or complex tone component is noticed with a probability of 100%, while other less audible tone components are noticed with probabilities proportional to their calculated audibility. Tone sensation, tonalness and multiplicity are applicable in the description of environmental sound as measures of sound quality. Tone sensation, tonalness and multiplicity are implemented in the analysis methodologies of this work.

4.24 Unbiased annoyance and psychoacoustic annoyance

4.24.1 Unbiased annoyance (UBA)

Unbiased annoyance is defined by Zwicker (1991) as “the response of subjects annoyed exclusively by sound under describable acoustical circumstances in laboratory conditions without relation to the nature of the source”. The definition is important as it has been drafted to separate the attribute of individual human perception out of the sound. Thus, unbiased annoyance is a quantitative measure where the measurement conditions of ambient sound, time function and sound spectrum are describable and reproducible.

Zwicker states that loudness is the most important factor for annoyance apart from the fact that a given sound produces more annoyance during the night than during the day. The effects of fluctuation strength and modulation are related to loudness and unbiased annoyance is influenced by low levels of fluctuation strength. Zwicker found that roughness seems to play a secondary role in unbiased annoyance. The measure is an effective method to assess the peak value of standing waves where an individual can vary position within the room. Tonal components are accounted for in the influence of loudness.

Unbiased annoyance increases for large sharpness. Sharpness is taken into account in equation 4.24.1 by multiplying the weighted loudness by a factor ‘s’ that depends on both sharpness (*S*) and loudness (N_{10}):

$$s = 1 + 0.25\left(\frac{s}{[acum]} - 1\right) \cdot \lg\left(\frac{N_{10}}{[sone]} + 10\right) \qquad \text{eqn 4.24.1}$$

Unbiased annoyance (UBA) is calculated by the procedure of equation 4.24.2 which includes the effect of fluctuation (*F*). Loudness (N_{10}) is the loudness in sone which is exceeded for 10% of the time. (The exponent in the first expression is 1.3). The stated calculation and values are in annoyance units, au:

$$UBA = d(N_{10})^{1.3} \cdot \left\{1 + 0.25(S-1)\cdot \lg(N_{10}+10) + 0.3F \cdot \frac{1+N_{10}}{0.3+N_{10}}\right\} \quad \text{au}$$

eqn 4.24.2

Unbiased annoyance is modified for night-time. The value of '*d*' in Equation 4.24.2 for the day is 1, for night-time the value of $d = 1 + (N_{10}/5)^{0.5}$. The expression 'lg' in Equations 4.24.1 and 4.24.2 means '$\log_{10}$'.

The measure for unbiased annoyance is analysed in the research for this work. Different implementations of the measure are tested by substituting Sethare's spectrum dissonance and tonal dissonance for the fluctuation measure.

4.24.2 Psychoacoustic annoyance (PA)

The psychoacoustic annoyance calculation (Zwicker & Fastl, pp. 324-327) is slightly different to the measure of unbiased annoyance but still includes loudness, sharpness, fluctuation strength and roughness.

Psychoacoustical annoyance, like unbiased annoyance, has a primary dependence on loudness, the tone colour and the temporal structure of the sounds. Zwicker and Fastl (1999, p. 8) use the expression tone colour to illustrate the difference between loudness and character of a sound when that sound is presented in different ways; in a living room through speakers or through headphones, for example. The measure is designed for sound quality and has been applied to noise from air conditioners, cars and power tools:

$$PA = N_5\left(1 + \sqrt{w_S^2 + w_{FR}^2}\right)$$

eqn 4.24.3

with N_5 percentile Loudness in sone and Sharpness in acum as

$$w_S = \left(\frac{S}{acum} - 1.75 \right) \cdot 0.25 \lg \left(\frac{N_5}{sone} + 10 \right) \; for \; S > 1.75 acum \qquad \text{eqn 4.24.4}$$

and the influence of Fluctuation strength F in vacil and Roughness R in asper as

$$w_{FR} = \frac{2.18}{(N_5)^{0.4}} \left(0.4 \cdot \frac{F}{vacil} + 0.6 \cdot \frac{R}{asper} \right) \qquad \text{eqn 4.24.5}$$

The expression ‘lg’ in Equation 4.24.4 means ‘$\log_{10}$’.

The measure is applied in the research investigations but psychoacoustic annoyance is not applied further as a primary measure in the analysis methodologies of this work.

CHAPTER 5: MEASUREMENT OF LOW AMPLITUDE SOUND

5.1 Is there a problem?

The answer is yes to the question “Is there a problem in measuring environmental sound in order to assess nuisance?” Sound is able to be measured with any degree of confidence only under very specific conditions. These conditions are usually when the sound is loud enough, or when there are specific special audible characteristics that are clearly distinctive and annoying.

Very broadly, sounds above about 40 to 50 dB are addressed in combined socio-acoustic surveys but nuisance caused by low amplitude sound is not well addressed. In part, the reason for this lies in the instrumentation that was available in the 60s to 90’s when many of the published acoustical surveys were undertaken. The bottom of range of many instruments of that era was 30 dB and the measurement range was often limited to 15 dB to 30 dB. Only after the early 1980’s has computer-based instrumentation become readily available that can measure, record and analyse low amplitude sound. Noise however, cannot be measured; it can only be assessed. This Chapter presents the thoughts and design concepts for instrumentation to measure and record low amplitude sound.

5.2 Sound measurement instrumentation

A simple enough question from a person with a noise problem: “I can hear the noise, why can’t you measure it?”

A likely response is that the person’s hearing is so much better than the meter; or that the meter is “only measuring loudness in dBA”. Both responses are valid, but the underlying message is that the person is a better noise meter than the sound level meter. This is to be expected. A person responds to the qualities in a sound, not just it's "loudness". A sound level meter, however, has one significant advantage in that it is able to quantify the sound against a reference level, whereas a person tends to say the sound is "too loud". Individuals, unknowingly and automatically, use many different filters to measure and assess sound. Methodologies for measuring sound to International Standards Organization: ISO1996-1 (2003); ISO 1996-2 (2005) however, tend to concentrate on a relatively narrow range of measurement parameters, but this is gradually changing. The changes are occurring partly in the sound level meters and partly in the analysis software. A sound level meter is an instrument designed to respond to sound in approximately the same way as human hearing and to give objective, reproducible measurements of sound pressure level. There are many different systems available for measuring sounds. Although different in detail, every system consists of a microphone, a sound processing unit and a display. Initially, sound level meters consisted of a microphone and electronic circuit to provide a visual display of the instantaneous signal. The meters often had a narrow range, in the order of 30 dB, and the sound level was presented using a moving coil display. Sound levels had to be written down individually or recorded on a paper chart recorder. While it was possible to get reasonably accurate readings over a 15 minute time interval, 24-hour surveys were difficult and simplified measurement protocols were common.

Komorn (1979) identified a new general method for the objective measurement of noise environments that ultimately changed the way instrumentation was to be designed and used. The concept introduced a short time-average level or "short-LAeq", calculated in the range of 1 to 10 seconds, and stored over a longer-term of, for example, 24-hours. The methodology was quickly adopted by instrumentation manufacturers, notably Cirrus Research in the UK (Wallis, 1987) and 01dB in France (Luquet, 1987). The issues of what to measure, why and how led to the promotion by Wallis and Luquet (1987) of the concepts of 'Short LAeq' and 'outbox processing', now taken as standard by most instrumentation manufacturers. There is no universal agreement between countries as to suitable universal sound measurement metrics. Schultz (1982b) suggested that any acoustical survey undertaken to assess human response to noise must measure a wide range of acoustic features and this has not changed to the present time.

Up until the early 1980's instrumentation was relatively simple, with exponential devices being the most common. A very few instruments were capable of measuring 'time-average' levels. By the end of the 1980's computer based time-averaging systems were available that could provide exposure data over a long period of time (Luquet 1981; Luquet and Wallis 1987; Wallis 1987). Sound measurement instrumentation has changed dramatically over the years (Silverman, 1993) with the advent of powerful, low-power, digital signal processing systems to provide the processing power within the sound level meter. Analysis programs to simplify data presentation are now available within the meter and separately as computer-based programs.

The expression “measuring sound”, in its broad sense, encompasses all the designs and techniques needed to measure the change in sound pressure at the ear. A sound level meter, by comparison, ordinarily measures sound levels at distances well away from any ear and the data must then be converted into meaningful information in the range of human hearing “at the ear”. Unfortunately, as examined previously, sound level meters cannot do this. Sound level meters, however, can do two things that humans find extremely difficult to do, and that is:

- measure variations in amplitude; and
- measure variations in frequency.

A sound level meter is usually built to national and international standards (IEC 61672-1, 2000) for exponential or integrating-averaging characteristics and for the microphone (IEC 1094-4, 1995). The general design considerations are examined in this Chapter. The standards provide different specifications and tolerances for class 1 and class 2 sound level meters and class 1 and class 2 microphones.

5.3 Consideration of sound measurement instrumentation for this work

The consideration of the design of sound measurement instrumentation by definition, is fundamental to this work. Two essential items are required: instrumentation to record and measure sound and an assessment methodology or methodologies for intrusive sound and noise.

Sound measurement instrumentation includes the physical instruments needed to quantify sound and the assessment protocols needed to qualify the sound in terms of human response. The choice of suitable sound measurement instrumentation was based on the earlier design considerations as outlined, plus future needs for meaningful analysis of the measurements and assessments made. Although this may seem to be a plain and common-sense approach, the choice becomes complex when the question is asked: why is the sound being measured? If it is to gain an indication of how ‘loud’ the sound is, then for most practical applications sound measurement instrumentation consists of a simple sound level meter. A more detailed measurement may be supported by the use of a recording system of some type. The measurement becomes more complex when a specific form of assessment is required, or if the sound level meter must conform to some national or international design specification. The most difficult form of measurement occurs when the sound is of low amplitude and has some audible characteristic that needs to be defined, qualified and quantified. It is the latter form of measurement and assessment that is the subject of this work.

Historically, environmental noise research has been oriented to quantifying the noise and correlating it to community reaction, usually with the aim of establishing "acceptable" or "recommended" levels, or in some cases, in order to predict the impact of higher noise levels. This work deals with the measurement and assessment of environmental noise that can only just be heard (hums, etc) but are intrusive and annoying. The sound levels to be analysed are just above a person’s nominal threshold of hearing to around 50 dB. Instrumentation and methodologies for assessment of this type of sound are not readily available, except in complex hardware and software used by people in the field of acoustic research or similar work such as industrial sound quality or audiometry.

'State of the art' instrumentation for this work needed to provide the acoustical information for socio-acoustic analysis, such as that discussed in or by: ANSI S1.13-1995; Couvreur and Bresler (1988); Berry (1998c); Darlington and Tyler (1996); Dickinson (1996); Shelton (1996a, 1996b); Schomer (2006); USEPA (1974, 1982) as well as being a class 1 integrating-averaging sound level meter. The instrument needed to include FFT and digital filter signal processing (Randall 1987), a wide range of automatic templates for ratings or procedures (loudness, noisiness, tone, impulsiveness and so on) and audio files. Ideally the instrument would be 'intelligent' and have adaptive recognition systems incorporating annoyance templates. No standard instrument currently available does this. All existing systems require extensive and intensive post data capture analysis and none have comprehensive remote video and audio-data capture features that will allow identification of noise sources in real-time or in short-term delay.

Significant data analysis can be achieved through purpose-designed software or through programs available off the internet. The intelligent approach to data analysis is discussed by Sakurai, Sakai and Ando (2001). Research into noise and its effects, and associated statutory regulations and guidelines, have significantly changed the use and design of instrumentation to the stage where there is now a distinct difference between 'sound level meters' compared to 'noise data logging systems'. Berry (1998, p. 628) states:

> A modern field portable data logging sound level meter system should be capable of recording a wide range of noise indicators. Unfortunately, all of these conventional indicators…are mostly measuring much the same thing…The root of the problem here is that no sound level meter system yet developed can identify acoustic features separately without intelligent human intervention…In addition, what human listeners are most interested in is the type of source and what it means to them, and they are not directly interested in tonal or impulsive content, per se.

The works of Fidell, Schultz and Green (1988, pp. 2109-2113), Fields (1998a, pp. 2245-2260), Job (1988), Kryter (1970, pp. 69-84; 1985), Schultz (1978, 1982), Stevens (1970, pp. 114-128), Young (1970, pp. 45-58; 1970, pp. 129-150) and Zwicker (1987) suggest that any acoustical survey undertaken to assess human response to noise must measure a wide range of acoustic features. Simultaneous ambient and personal noise exposure measurements are required for exposure-response relationships to be established. A secondary task is the possible identification of primary sources (for example, aircraft, road traffic, distinctive noise events). Instrumentation to assess the meaning of the measured levels and to link with human reaction to an identified noise source does not exist.

Schultz (1982), Kryter (1885), WHO (Berglund, Lindvall & Schwela, eds, 2000) and the criticism of Berry (1998, p. 628) show that 'simple' noise measurements, while adequate for community sound assessments, are not sufficient for individual noise assessments. Clearly missing are sensitivity assessments or how acceptable a sound might be. Previously, instrumentation and acceptability criteria have concentrated on moderate to high levels of sound; that is, levels above 50 dB. The measures of acceptability for low amplitude sound below 50 dB were rarely investigated.

5.4 Measurement design – practical issues

The measurement of low amplitude sound presents practical problems with respect to the choice and application of sound measurement instrumentation. In most instances of noise measurement the sound is measured outside the dwelling, whereas the sound being complained about is heard inside the dwelling. Most importantly, a sound level meter is a single channel (mono) electronically defined non-interpretative recorder compared to humans who are dual channel (stereo-ears) variable complex interpretative sound analysers. Dual channel recording is useful, therefore, in providing signal to or simulating head response. For the environmental analysis purposes of this work both single-channel and dual-channel recording is used to compare interior against exterior sound levels and sound character. Single channel recording requires the use of two sound measurement systems for comparative measurements. The design of the sound analyser, therefore, requires dual channel sound recording facilities but only a single channel needs to analysed at a time.

The aim of this research component was to provide a design for high-quality inexpensive instrumentation that would allow, as far as possible, recording of the sound that a person would hear. This means that the sound recorder must be dual channel (or a designed combination) to simulate hearing response with both the left and right ears. The importance of this is illustrated in the wind turbine noise simulation soundfile (appended to this work). This is a constructed dual channel sound file with a distinctive tonal characteristic. If listened to as individual left and right channels only the tone and characteristic noise source are audible. When the soundfile is listened to in stereo, however, a modulation tone is clearly audible. The tone is a function of personal hearing response and clearly marks the difference between sound recording/measurement and human response.

The system design is for a simple, high-quality inexpensive measurement system that can referenced to standard designs for sound level meters[9], microphones[10] and calibrators[11]. The system is verified against the research reference system, figure 5.4.1, consisting of a Larson Davis LxT1L Class 1 low-noise sound level meter fitted with one-third octave band analyser, a Quest CA22 dual level - dual frequency calibrator, Sony DAT recorder, Emagic 6-2 soundcard, NoiseLAB 3.0 analysis software[12], SpectraPLUS v5.5 analysis software[13] and Audacity recording software[14].

A prototype measurement system module was constructed with a Class 1 microphone and preamplifier combination working through a purpose-designed low noise preamplifier and power supply. The prototype sound recording system for measuring and assessing low amplitude intrusive sound consists of:

- Hardware consisting of a microphone; preamplifier modules; a balanced cable to connect the preamplifier to a soundcard; a computer sound card; a power supply for the preamplifier; a calibration system
- Recoding and analysis software programs to record the sound into digital format; calibrate the soundcard and analysis program; simulate a Class 2 sound level meter; analyse the recorded sound; and display the results of the analyses made
- A Class 1 sound level meter to provide the reference – verification module

The overall uncertainties for use with a sound level meter are described by Payne, 2004. As a practical approach for this work instrumentation was measured by comparative verification to the reference instrumentation. The overall design concept was for the research instrumentation LAeq sound levels (under free-field or random

[9] IEC61672-1:2002, Electroacoustics – sound level meters – Part 1 Specifications. Class 1 and Class 2 instruments are described.
[10] IEC1094-4:1995 Specifications for working standard microphones. Working Standard units 1 to 3 are described.
[11] IEC60942:2003 Electroacoustics – Sound calibrators. Class 1 and Class 2 instruments are described
[12] NoiseLAB v3.0 software available from DELTA, Denmark (contact CTH@delta.dk)
[13] Spectraplus 5 software available from http://www.spectraplus.com
[14] Audacity software available from http://audacity.sourceforge.net

incidence conditions) to be within 1 dB (± 0.5dB) of LAeq sound levels of the Class 1 LxT1L reference system, over 90% of simultaneous side-by-side measurements.

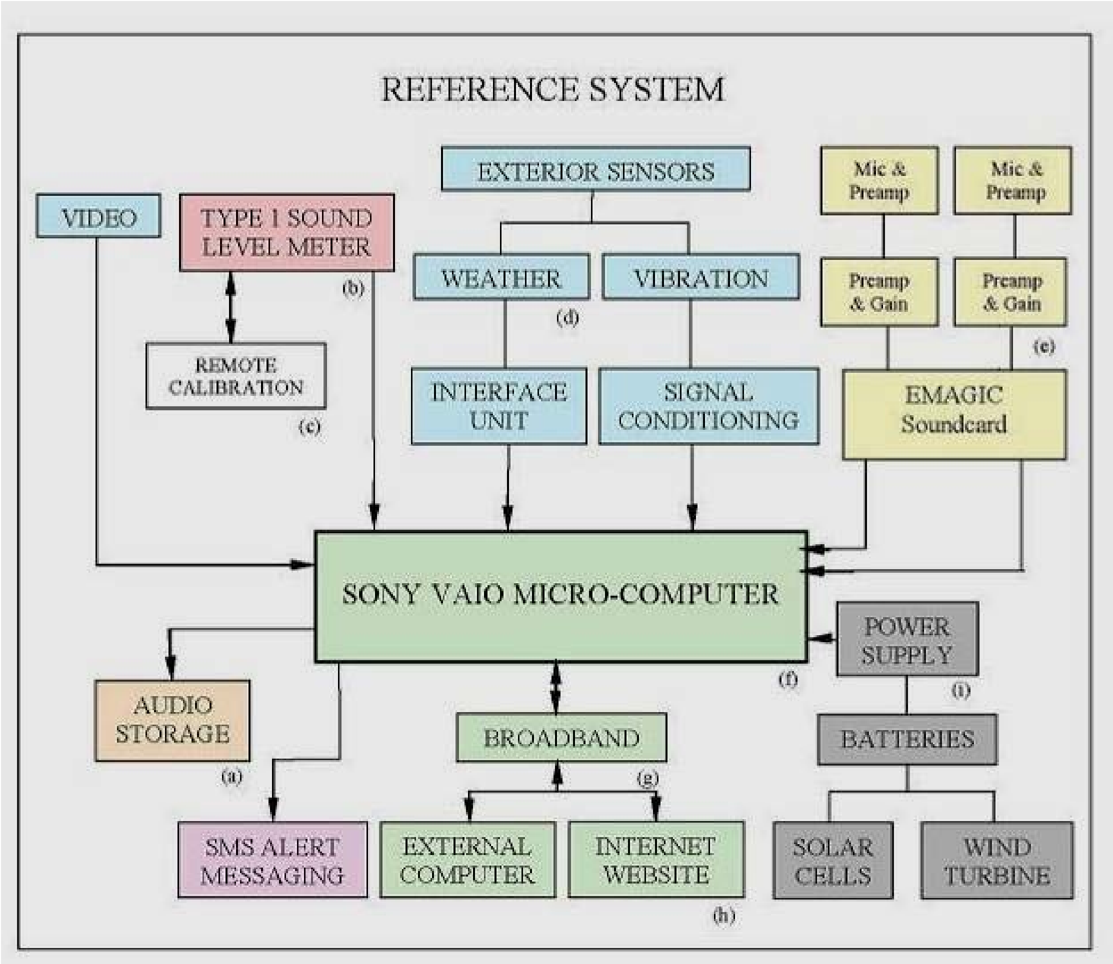

Figure 5.4.1: Reference sound recording system

Notes to figure:

(a) Audio storage – a critical memory problem is the large size of soundfiles that require the use of the Sony Vaio computer

(b) Class1 sound level meter to record actual sound levels and for recording output

(c) Remote calibration unit (used with a Larson Davis 870B sound level meter system)

(d) External sensors for weather (wind speed and direction, rain), vibration and video – functions supplied by standard commercial modules

(e) Microphone and preamplifier system under test

(f) Sony Vaio computer for remote access and control of complete system

(g) Broad-band access is essential to upload soundfiles

(h) Data download to website for interested parties to access summary data

(i) Un-interruptible power supply, including sealed lead-acid batteries, solar panels or small 'hobbyist' wind turbine power generator

5.5 Design of microphone, preamplifier, balanced cable and calibrator

Sound levels (and noise) that affect people must be recorded so the sounds can be analysed and assessed. The critical problem with measuring low amplitude sound is to have a measurement system that can faithfully record low levels of sound. An instrument system with a low noise floor to the nominal threshold of hearing or below is essential. Ordinary microphone and preamplifier systems used with soundcards are of unknown quality but testing for this work indicates the quality is not good enough as noise floors are high and the modules introduce significant levels of electronic noise from the computer or the microphone – preamplifier design. High quality low-noise, low amplitude microphone units are expensive and cannot be used with instruments other than their specific systems.

The design presented is for a low-noise, broad-band, high quality microphone / preamplifier / cable system to meet the requirements of IEC 61672 for Class 2 ‘z’ weighting. The design is primarily for interior use within a limited temperature range (nominally 10°C to 35°C) and does not require the electronic robustness of an exterior design. The design[15] considerations are:

- A maximum tolerance for the microphone / preamplifier / cable combination to IEC61672 Table 2, Class 2 or better within the audio range of 63 Hz to 8000 Hz in one-third octaves
- A design noise floor to 5 dB lower in one-third-octave bands than ISO 226:2003 nominal threshold of hearing
- An overall system signal-to-noise ratio of not less than 70 dB
- Low power consumption and capable of battery operation while maintaining fidelity including amplitude and phase
- The overall system including cable and connections to be audibly “noise-free” and free of distortion or audible effects potentially induced by the system
- Must be able to use a variety of inexpensive condenser microphones
- The preamp must have adjustable gain on the output

[15] The working preamplifier, balanced cable and calibrator prototypes numbers 1 & 2 were developed in 2005 in association with me by Mr Jean-Marie (John) Ntahonkiriye, Auckland, New Zealand, who designed, built and tested the units. The calibrator attenuator unit was designed, built and tested by Mr Brian Crook, Rotorua, New Zealand.

- Must be able to connect directly to computer / PDA soundcards and mobile phone microphone inputs.

5.6 Microphones

The microphone choice is relatively straight-forward compared to the preamp / cable design. There are 2 practical options based on price and quality-

- A Digitor, Panasonic WM61 or similar microphone – inexpensive (in the order of $5 one-off), good quality, unclassed for use with sound level meters
- Measurement microphones – relatively expensive (in the order of $60 to $1200) microphones for use with Class 1 or Class 2 sound level meters

The Digitor or Panasonic microphones can achieve the specifications for a Class 2 sound level meter under "on-axis" response. BSWA microphones, however, are good examples of a range of inexpensive Class 1 and Class 2 measurement free-field microphones available. The system requires a response of a Class 2 system and very low noise characteristics. In addition, by improving the response from Class 2 to Class 1, the free-field / random incidence characteristics can be adjusted with a secondary amplifier and filter set after the preamplifier. The design specifications Class 1 and Class 2 systems are found in the international standards IEC 61672 for sound level meters. The microphone specification is found in IEC1094-4, 1995, *Specifications for working standard microphones*. Measurement condenser microphones are described as being free-field, random incidence (diffuse), or pressure response, depending on their application (Brüel 1983; Wong & Templeton 1995). They are omni-directional. Other condenser microphones that can be used in this research, depending on their directivity frequency characteristics, are termed as omni-directional, unidirectional or noise-cancelling. Although not tested in this work, a noise-cancelling design may be ideal for measuring low amplitude sound as the directivity characteristic could be "tuned" to simulate the response at or within the ear. Small microphones, however, have low sensitivity and this inhibits their ability to measure low amplitude sound. A half-inch microphone, for example, does not have the sensitivity to measure low levels unless additional amplification is provided to the signal and measurements are made in (for example) one-third octave bands in order to exclude frequencies affected by electronic noise. Measurement microphones can therefore be used as reference microphones for the research-work microphones and provide a "known degree of inaccuracy". Brüel & Kjær technical literature, for example, states that the B&K 4176 reference microphone has a free-field response of 6.5Hz to 12.5kHz ±2dB, a noise floor of 13.5dB at 3% distortion and a sensitivity of nominally 50mV/Pa (-26dB re 1V/Pa).

Table 5.6.1 presents a summary of the microphones used as reference units to test the soundcard and calibration systems. These units are different from the initial prototype units. The preamplifiers used are Cirrus MV 200 units with a 26 dB gain switch. The voltage values in the Table[16] are for reference purposes only and were obtained using a Quest CA22 dual level calibrator. The test results indicate that different microphone / preamplifier combinations have a significant effect on the recording ability of the whole system. The following photo presents the test system. The unit has variable outputs so the effect of different microphones/preamps systems can be tested. It is clear from the test results that gain matched microphones and preamplifiers are essential for this research work. Low amplitude sound must be amplified prior to analysis. Photo 5.6.1 presents the gain responses of the microphone and preamplifier systems under test.

Table 5.6.1: Microphone and preamplifier gain responses

CARTRIDGE			**B&K 4176** (CC)	**MK215** (AC)	**MK215** (BC)
Serial No			1008526	112446	112571
Class			1	2	2
TEST VALUES	**Cal**	**Gain**			
Test values, mV, RMS, MV200 preamp unit CA sn 1590 at 1000Hz	94dB	Hi	11	25	155
	110dB	Hi	75	256	965
	94dB	Lo	1	1	5
	110dB	Lo	2.7	5	30

[16] The Cirrus preamplifier junction unit and power supply was designed, built and tested by Mr Brian Clancy, Technical Services, Roma. Additional circuitry (amplifier, power supply module) was designed, built and tested by Mr Joji Quidim, Vanguard Instruments, Brisbane.

Photo 5.6.1: Illustrating the microphone and preamplifier modules

5.7 Preamplifier designs

Ordinary measurement microphone and preamplifier combinations are expensive and generally not designed to interface with soundcards. Initial preamplifier, amplifier and octave band-pass equalizer designs were sourced from the information presented in the National Semiconductor Audio Handbook (Bohn, 1976, pp. 2-1 to 2-62). Three preamplifier designs were finally considered to provide a range of options. The first is a concept design using Maxim surface mounted components. The two other preamplifiers are implementations of commercial designs. The concept design uses Maxim amplifier and USB power-supply components, figure 5.7.1.

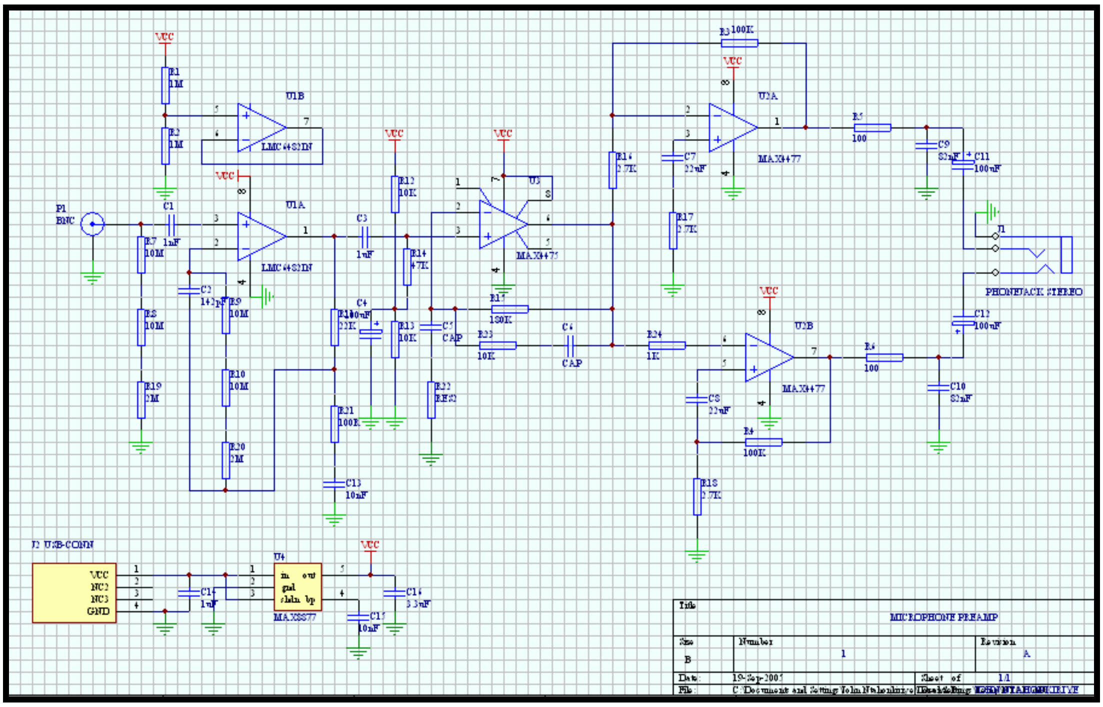

Figure 5.7.1: “Maxim” preamplifier design

Notes to the Maxim Design:

- Input stage consists of an LMC6482IN amplifying the signal from the microphone.
- Intermediate stage consists of a single MAXIM IC MAX4475 to further amplify the signal from the input stage while keeping the noise at its minimum.
- The output stage consists of a dual MAXIM IC MAX4477, which is configured to drive the sound card.
- The power supply is taken from the +5V of the USB computer port through a Maxim IC (MAX 8877) to be regulated to + 3.3V.
- The design does not have an anti-aliasing filter incorporated.

A second preamplifier implemented a commercial design, *Project 93*, sold by Elliot Sound Products (ESP), <http://sound.westhost.com/project93.htm>. The project preamp design was modified from the balanced line (2 signal lines) version to an unbalanced (1 signal line) version. An anti-aliasing filter is not incorporated in the design. Two preamplifiers are enclosed in the plastic box in photo 5.7.1. The enclosure accommodates two separate inputs (Left and Right) and their corresponding outputs (one input/output per unit). A plastic case was used for ease of assembly; a metal case is needed for good noise rejection. With an input signal of 32 mV RMS taken from the signal generator, the output signal taken between the hot and audio return (“cold”) points is 136 mV RMS which corresponds to a gain of 12.6 dB. The ESP design indicates that the requirements for an inexpensive, high-quality microphone and preamplifier unit for use with a soundcard can be achieved.

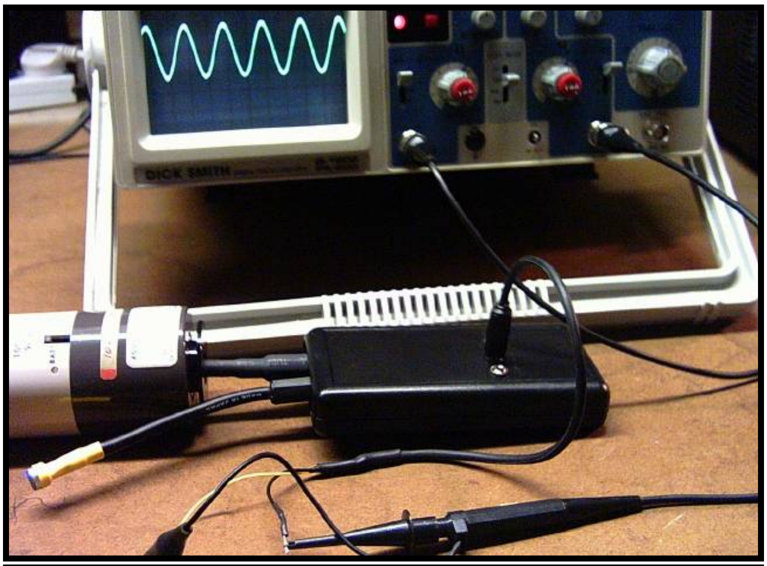

Photo 5.7.1: Signal from calibrator using mobile phone microphone

The third preamplifier design, based on a Cirrus Research Plc CRL 704 sound level meter preamplifier, consists of a microphone and dual-gain (0-26dB) preamplifier; screened microphone cable; secondary adjustable gain amplifier (30dB) and associated power supplies. The module is illustrated in photo 5.7.1 and connects to the balanced cable for signal input to a soundcard. A dummy microphone (18 pF capacitor) is required across the second channel of a “stereo” input when only one channel is used. This is to reduce noise in the second channel and is useful in determining the noise floor / character of the soundcard and microphone system.

A summary of the results of ‘side-by-side’ testing of two of the microphone preamplifier combinations is given in Table 5.7.1. The test results are the arithmetic average of 60 by 1-minute LAeq side-by-side surveys of the ambient soundscape characterised by distant road traffic noise as heard inside a dwelling with windows closed. Each microphone was 1.2 metres above floor level, 1.5 metres from the window and 50 mm distant from the adjacent microphone. Each microphone was directed to the window and in-line with its neighbour. Each system was field calibrated and adjusted to read 94.0 dB using the same commercial 94.0 dB calibrator. The design system was tested using the various modules in combination, the standard soundcard in the Vaio computer and Jade 2.65[17]. The Jade analysis program is one of the few commercial programs that present sound levels in an 'acoustical' format rather than an 'engineering' format. The acoustical format has ascending decibel values while the engineering format has descending decibel values from a nominal zero. The secondary amplifier unit was connected to the soundcard by means of the balanced cable designed for this work. The reference system is the Larson Davis LxT1L class 1 sound level meter.

Table 5.7.1: Results for 'side-by-side' microphone-preamplifier system tests

Digitor mic + ESP Preamp + secondary amplifier, LAeq	LxT1L Sound Level Meter LAeq
57.2, sd ± 4.3 dB	57.6, sd ± 4.8 dB
51.6, sd ± 4.2 dB	52.2, sd ± 4.5 dB
38.0, sd ± 3.1 dB	38.7, sd ± 3.9 dB
25.3, sd ± 1.8 dB	24.8, sd ± 2.1 dB
B&K 4176 mic + Cirrus Preamp + secondary amplifier, LAeq	LxT1L Sound Level Meter LAeq
57.5, sd ± 4.6 dB	57.6, sd ± 4.8 dB
52.6, sd ± 4.7 dB	52.2, sd ± 4.5 dB
37.9, sd ± 3.7 dB	38.7, sd ± 3.9 dB
25.0, sd ± 2.2 dB	24.8, sd ± 2.1 dB

Note: 'sd' is one standard deviation

The test results indicate each of the systems designed for this work are within design specification for differing levels of sound as heard in the home.

5.8 Balanced cable design

Significant problems with microphone cabling are the risk of signal degradation over distance, signal pickup from external sources such as mobile phone systems, induced

[17] Jade 2.65 (or subsequent versions) is a sound analysis program available from ptolserv.com

noise, fragile cable leading to breakage, and so on. Balanced inputs and outputs have been used for many years in professional audio, but are not common in sound measurement instrumentation. The issues with unbalanced signal lines are-

- The output from the AC signal on various sound level meters present a lot of hum and pick-up noise, as well as sounding “hollow”. While the signal may be suitable for signal analysis (and this is doubtful) it is totally unacceptable for recording purposes and for subsequent signal analysis.
- Most “domestic” computer soundcards have only one unbalanced signal line and these systems are most commonly available to people to use.

The design of the balanced cable presented in this work overcomes these issues. The cable consists of three blocks:

- The left and right inputs sending blocks
- The left and right receiving block
- The cable used between the sending and the receiving blocks consists of 4 twisted pairs (although 5e cable has been used).

The left and right sending / receiving blocks (only the left channel is shown as they are both similar) are illustrated in figures 5.8.1 and 5.8.2:

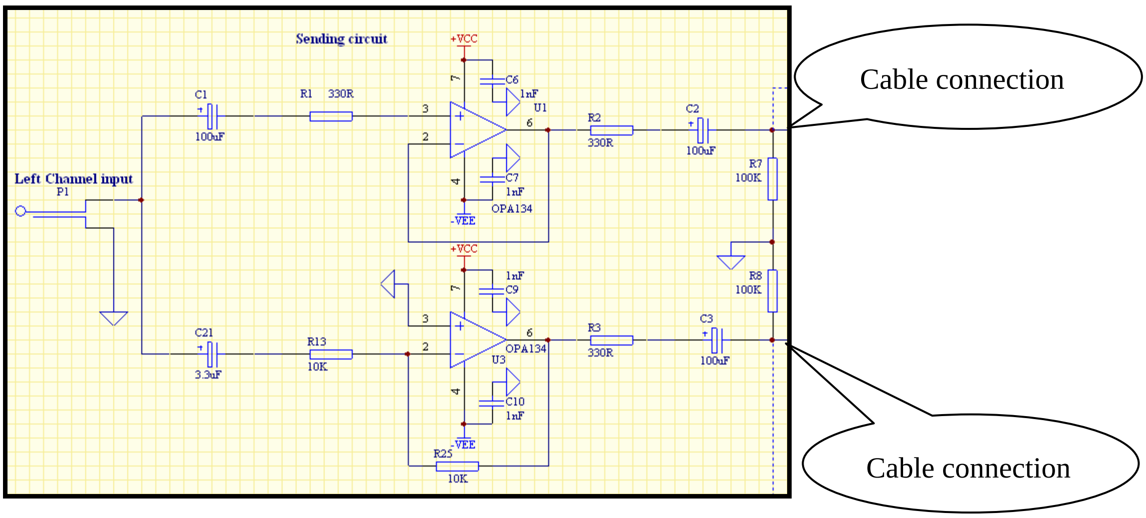

Figure 5.8.1: Balanced cable sending block circuit diagram

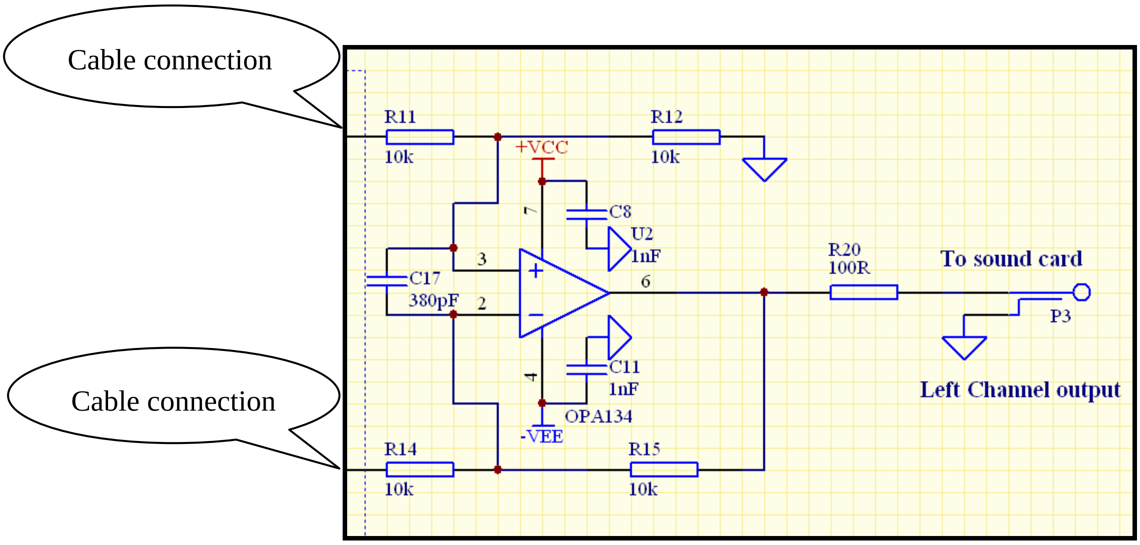

Figure 5.8.2: Balanced cable receiving block circuit diagram

The values of the capacitances and resistors are chosen so that the inverting and non inverting inputs have the same high frequency roll off. The network, made off R11, C17 and R14 at the input, assure the “anti-aliasing” frequency is ≈ 21kHz. A 0.1nF capacitor is required across resistors R12 and R15 in figure 5.8.2. The operational balanced cable is illustrated in photo 5.8.1.

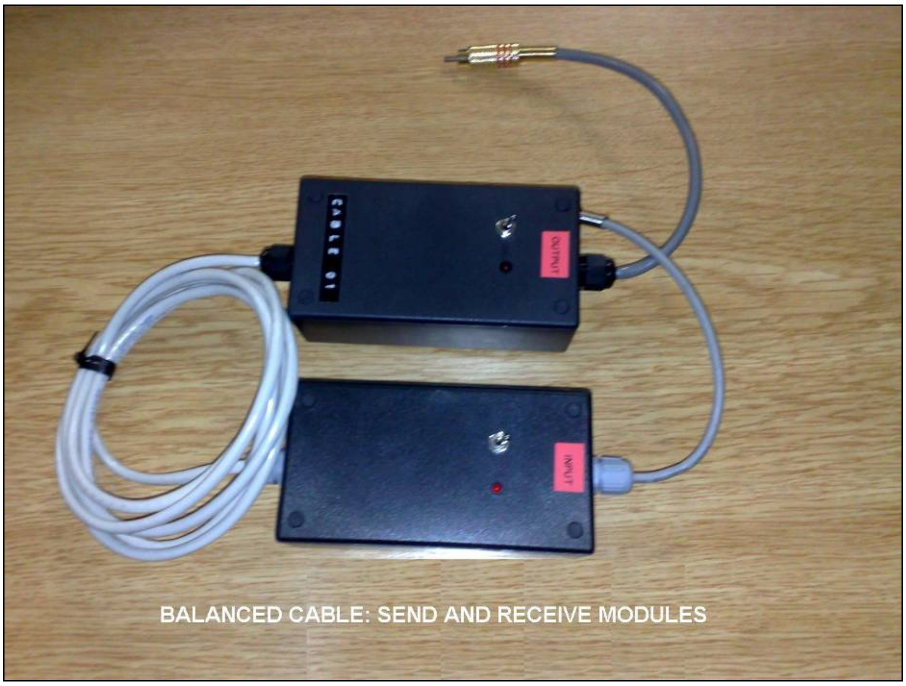

Photo 5.8.1: Balanced cable modules

5.9 Calibration system

A purpose-design calibration is essential to provide the test signals (pure tones, tonal sequences, bands of noise) needed for instrumentation verification and to ensure that sound levels being recorded onto a computer are set to a known sound level. The tolerance limits for class 1 and class 2 sound calibrators designed to IEC 60942:2003 are based on the use of a working standard microphone, as specified in IEC 61094-4. As the calibrator is needed only for the purposes of the research the design requirements of the standard are applied for a class 2 system; a sound pressure level tolerance of ± 0.75 dB and an output frequency tolerance of ± 2%. The calibration system consists of a microphone interface unit and a sound source. The sound source is a series of sound levels / frequencies / compilations recorded and stored on disk (CD) for transfer to portable music player or mobile phone. The sound sources are linked to the player or phone menu system so a wide range of signals can be readily replayed. The microphone system is fitted into the interface unit and the sound sources played to calibrate the sound system. The calibration soundfile *"12M_440_1000Hzdual level441k16mono.mp3"*, for example, has two frequencies (1000Hz and 440Hz) at 2 different amplitudes (10dB variation). The soundfile is in mp3© format for use in an mp3 music player, or it can be ported into other formats.

Output from any player is variable, both in volume (voltage) and in tonal quality. To overcome this problem the headphone output is taken to an instrumentation amplifier and an external 'calibration' adjustment potentiometer. A LED lights when a specific calibration sound (94 dB, 1000 Hz) is replayed at a known level (94.0 ± 0.3 dB). The tonal issue is addressed by using the player in "flat" mode. The calibrator design is presented following, figures 5.9.1 and 5.9.2. The design is that a series of test tones can be taken from any music player and adjusted to provide defined dB levels at the transducer coupler and headphone outputs.

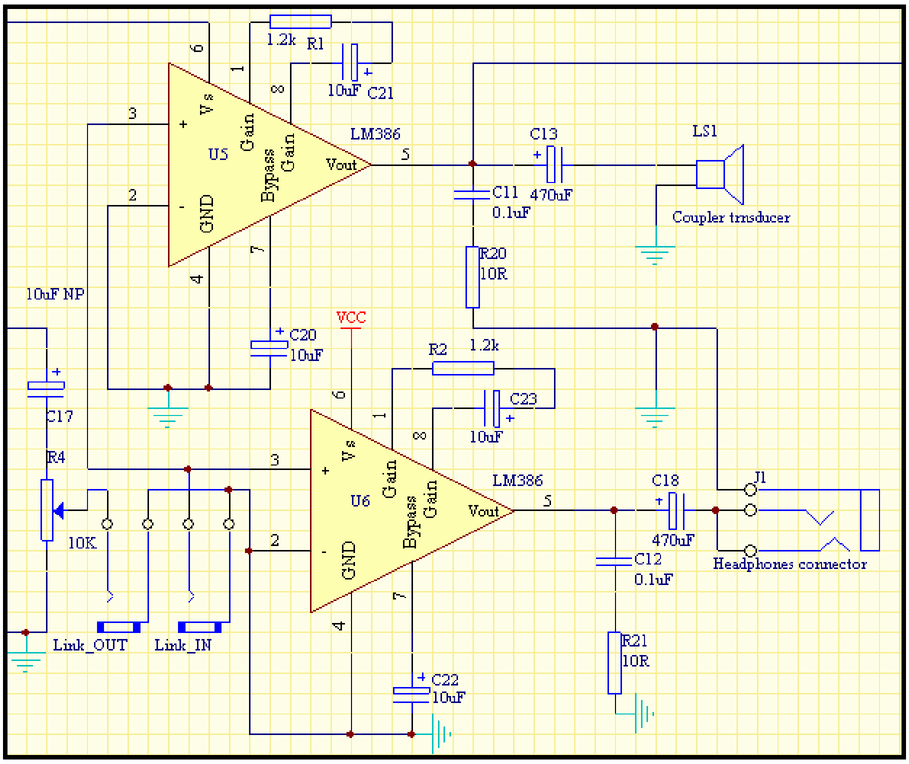

Figure 5.9.1: Sound coupler-calibrator output with links to attenuator module

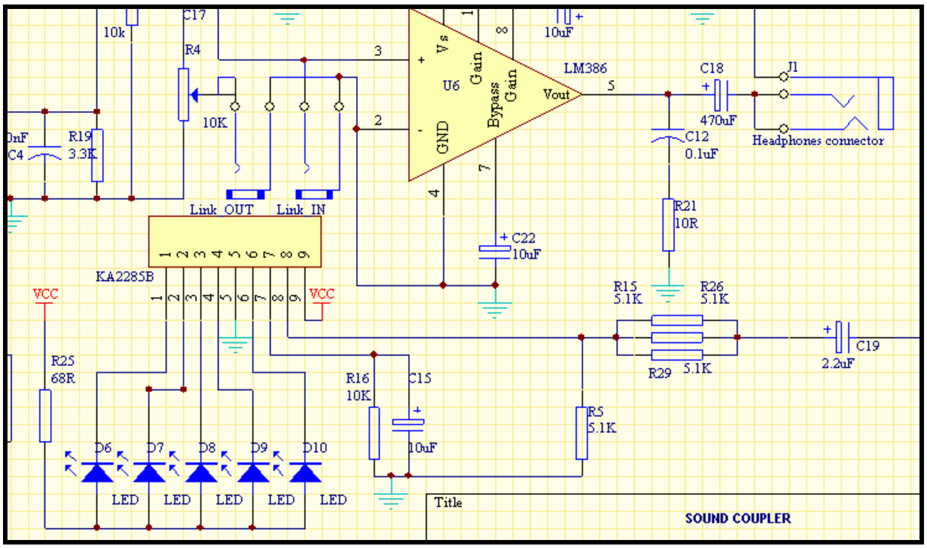

Figure 5.9.2: Calibrator indicator driving circuit

The design and construction of the external attenuator box is based on switching a series of "symmetric pi" reciprocal two port-circuits, interconnected in a cascade mode connection with an input / output impedance of 6000 Ω. The attenuations range from 1 dB to 64 dB. The link between the calibrator and attenuator can be shorted with a good audio cable if the attenuation is not needed, alternatively the signal can be fed through the attenuator while set to 0 dB gain (flat). The signal to the external attenuator box is taken from the output of the signal conditioning stage (Link_OUT on the circuit diagram) then the returning signal from the attenuator is driven through the output stage to the coupler (Link_IN on the circuit diagram). The test point on the calibrator can be used to monitor the signal entering the attenuator or the output stage when the attenuator is not used or is set to 0dB gain. The KA2285B circuit has been modified so that the green LED starts turning on just at 94.0 dB with a tolerance of –0 to + 0.3 dB. The method is to use the first two LEDs with the first LED (orange) serving as a reference to help visualize when the green LED (which is the second LED) just turns on. The complete system is presented in photo 5.9.1.

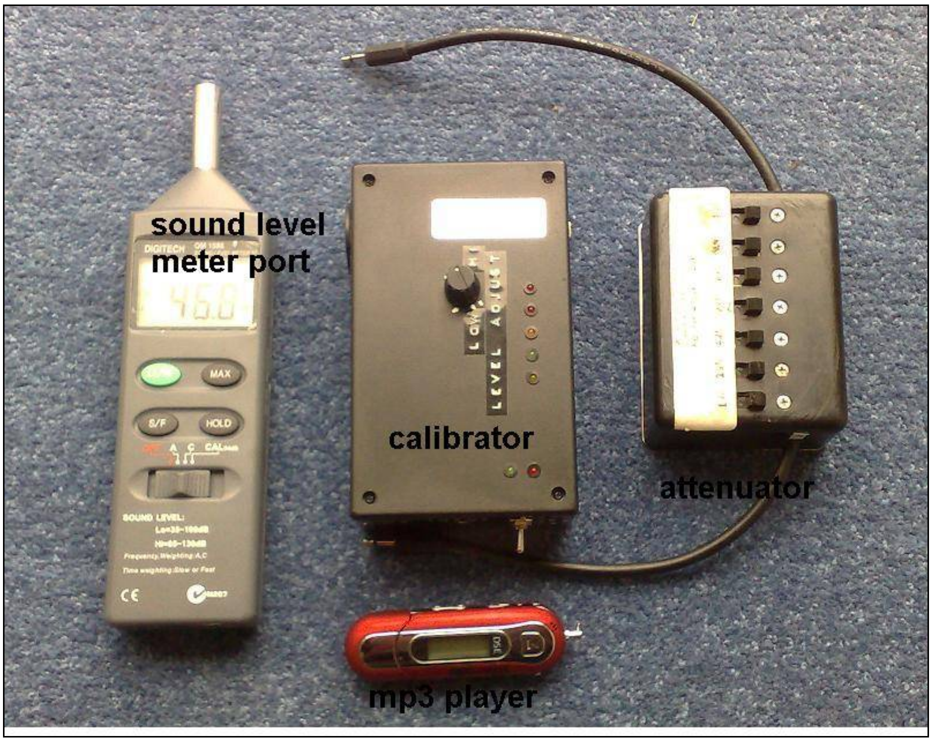

Photo 5.9.1: Complete microphone-preamplifier-calibrator system

Note to photo 5.9.1: The calibrator is the large black box at centre of the photo; the MP3 player is to the bottom of the calibrator; the attenuator box is to the right of the calibrator unit. The sound level meter port is used with the sound level meter to check the amplitude of the signal. A signal test port and a headphone outlet are fitted to the unit.

Table 5.9.1: Results for attenuator tests

Attenuator settings (dB)	Sound Level meter reading (dB)
0	94.1 – 94.2
-10	84.0
-20	74.3
-40	55.2 – 55.3

The calibrator module incorporates a sound level meter or transducer port. This permits signal level verification by a sound level meter. The port also allows the testing of signal level to a transducer, such as the Koss ear-bud earphones. This feature is important to verify the response of the earphone against that of test signals presented at a known level at the earphone. The adjustments for 'in-ear' signal modification discussed in a previous chapter are allowed for in the verification process. The signal at the signal test output port and at the headphone output is the same amplitude as that supplied to the sound level meter transducer port.

5.10 Sound analysis software

This work incorporates three distinctly different approaches to analysis methodologies. The methodologies have been implemented with different commercial software programs or specifically designed spreadsheet implementations.

The primary analysis program is the psychoacoustical, acoustical and music soundfile analysis program PsySound2[18]. This extremely comprehensive program provides a wide range of outputs including critical band values (Erbs), loudness measures, pitch measures, tonalness, dissonance and measures of sound pressure level. PsySound2 is a Macintosh computer implementation. In its native format PsySound2 has a 4096 line spectrum, which is double sided so only 2048 lines are taken as valid. Each line is equivalent to approximately 10.7 Hz.

[18] PsySound2 is implemented by permission of the author Dr Densil Cabrera. A revised implementation, PsySound 3, is being developed by the PsySound team for Windows and Linux and is based on MatLab routines. A release version is not yet available.

The second analysis approach incorporates a suite of commercial acoustical and sound quality analysis programs. Analysis for one-third and one-twelfth octave band analysis, tones and ISO 1996 / Joint Nordic tonality is provided in NoiseLab3 by DELTA. Analysis for unbiased annoyance, loudness, roughness, sharpness and fluctuation is provided in dBFA32 by 01dB[19]. Different values of loudness, roughness, sharpness and fluctuation are provided in dBSONIC available from 01dB. Graphical analysis is provided by Adobe Audition 1.5[20], SpectraPlus v5 and YMEC Realtime Analyser v5[21]. Sound recording and analysis tools are provided in the very comprehensive ‘freeware’ program, Audacity 1.2.4[22]. The programs in this suite are needed for basic analysis in this work as well as verification and testing purposes.

The third analysis suite incorporates spreadsheets for unbiased annoyance and sensory pleasantness. A commercial program (SPSS16) is referenced for statistical analysis of research investigations and to test suitable programs for this work.

Table 5.10.1 illustrates the relationships between FFT size, line - temporal resolution, and spectral lower limit as identified in SpectraPLUS. Narrow band analysis is able to extend the low frequency analysis below that available to octave band analysis. Choosing an appropriate FFT processing time is vital to suit the sound being investigated; that is, neither too long nor too short. The process is evident, for example, in PsySound2 which analyses soundfiles using a 93 ms window because (a) the temporal acuity of the auditory system is of a similar order and (b) the models implemented by PsySound2 were mainly developed for steady or near-steady sound. For noise, however, we are able to detect gaps as short as 5 ms. The Hanning window is chosen for this work. Variable window overlaps are available with 50% as the default.

[19] dBFA32 and dBSONIC available from 01dB-Metravib, France <http://www.01db-metravib.com>
[20] Adobe Audition available from stockists of Adobe products
[21] YMEC Realtime Analyser available from <http://www.ymec.com>
[22] Audacity v1.2.4 (or later) is available from <http://sourceforge.net/>

Table 5.10.1 FFT size and resolution

FFT size (samples)	Sample rate (Hz)	Spectral line resolution (Hz)	Time Resolution (ms)	Lower Limit 1/12 octave (Hz)
1024	44100	43.07	5.80	972
2048	44100	21.53	11.61	487
4096	44100	10.77	23.22	244
8192	44100	5.38	46.44	122
16384	44100	2.69	92.88	58
32768	44100	1.35	185.76	29

Verification of the analysis routines (Payne, 2004) is achieved through comparison to appropriate "reference" analysis programs from respected sources. The reference programs are SpectraPLUS5, 01dB in France (products dVFA32 and dBSONIC) and DELTA in Denmark (product NoiseLAB3). To assist in the validation process the program methodology has been designed to allow input data as text files and the outputs of all arrays are placed into comma delimited files. This allows constructed data to be introduced into the program and all the outputs verified to orders of uncertainty referenced to independent validation routines or sourced results for identical inputs.

5.11 Hearing assist device

During the progress of this research it became obvious that instrumentation to selectively amplify sound to assist hearing could be designed and produced inexpensively. The design described in this Section[23] is an outcome from the instrumentation in the previous Sections for measuring low amplitude sound and calibration of instruments. The device is not a hearing aid, as such, but an inexpensive, high-quality audio microphone - amplifier combination that can be very finely tuned. An observed concern by people who would like to be able to hear clearly within domestic, social, business, educational or travel situations is the lack of inexpensive high-fidelity hearing assistance. The concern is of considerable importance to persons who are hard of hearing. The features of the device are:

[23] Provisional New Zealand patents 553736 (iHearAudio Assistive Hearing Accessory) and 553737 (iCalAudio calibrator) were issued in March 2007.

- Personalised sound enhancement of reduction to manage sound within different domestic social, business, educational or travel situations.
- Settings can be stored in the host / control unit for ease of recall; for example, while watching TV, to listen to conversations, to reduce background noise in a car, to listen to a speaker or teacher.
- Audio levels are individually set for each ear.
- Noise cancellation features are designed using hearing response templates.

5.11.1 Design

The design of the system is based on the inexpensive high-quality systems developed for the research work. Interfacing software has been developed as a simple iterative process, taking a person through "octave band" audibility steps (similar to existing standard audiometric tests), then "third-octave" band audibility steps (to refine critical-band responses) and finally to semitone audibility steps in order to refine vowel and sibilance responses for persons who need this level of response. The templates can be designed on any computer for transfer to device. The templates can, therefore, be varied at any time and place. The design concept is to evoke and enhance auditory perception through selective stimulation of the auditory system and by application of pitch response techniques to invoke auditory memory. The basis of the response process is the selective amplification of a person's hearing to a nominal "normal" auditory response.

The individual hearing response templates requires a personal hearing response assessment using a series of test tones (from 'loud' to quiet') for a wide range of frequencies. The assessments can be made at home using ear-bud headphones and industrial earmuffs to provide good fidelity at the ear and to reduce external noise. Depending on the quietness of the "test" room, a person will be able to easily identify their hearing thresholds within a range of 3 dB. The threshold information is automatically recorded for each ear. The personal audibility responses (referenced to individual ears) are confirmed as hearing threshold templates and refined levels of amplification provided in one-third octaves. Further refinement is available using 1/12 octave (semitone) adjustment to provide an overall response of ±30 dB in 1 dB steps from the individual's nominal "normal" auditory response. These personal loudness level templates are transferred into the digital signal processor firmware and are used as the baseline templates for the individual ears.

Situational response templates, similar to equalizers used in music players, provide different sound levels for different activities. Activities that have been identified during the course of the research include decreasing low frequency sound in a vehicle, reducing audible background “clutter” when in a party or when on a busy street, reducing high and low frequencies when watching television or a movie. The different “activity” settings are varied as simple graphic interface choices, similar to that used in most music players. Templates can be adjusted to provide a variety of personal responses over the audible range of 50 Hz to 16,000 Hz. Response within the octave to $1/12^{th}$ octave bands is adjusted by equalizers to defined templates to manage sound within different domestic social, business, educational or travel situations. The concept design is illustrated in figures 5.11.1 to 5.11.3.

The prototype ‘proof-of-concept’ design was implemented using standard analog components developed for this work; that is, the microphones, preamplifiers, octave filter sets, amplifiers and calibration modules. Design of the octave equalizers was informed by the paper by Bohn (1986) and Elliot Sound Products (<http://sound.westhost.com/>). The headphone earpiece and ‘at-ear’ microphone is a standard commercial product. The working prototype design is based on analog filter circuitry rather than digital filters. The prototype is dual-channel with both channels incorporating octave band adjustment. One channel is set with a variable adjustment arrangement. The adjustment incorporates switchable one-third octave and one-twelfth octave filters. Physical adjustment of the filter sets allows template design for different environmental conditions. Each octave band has a nominal cut or gain of 12 dB. Additional amplification is presented at the ear through individual amplifiers built into the filter set. Interfacing is designed for music players, mobile phones, and radio / TV audio. There are two microphone modules; one module with 2 microphones at the ‘front’ of the unit and the microphones external at the ear in the headphone units. Microphone switching allows the ‘at-ear’ microphones to be used in conjunction with the ‘front’ microphones or with the front microphones switched off. The microphone preamplifier gain is 26 dB across all audible frequencies.

A concept digital design is being implemented in a Sony Vaio UX17GP computer and Analog Devices ADAV400 sigma DSP processor with associated hardware and software. Signal processing for this digital design provides a nominal flat response from 50Hz to 16,000Hz generated by 96 by 1/12th octave bands. Signal refinement is available by graphic equalizer within the 1/12th octave bands to accommodate personal listening preferences through personal response templates. The amplifier module (gain of ±30 dB per one-third octave and ±6 dB per 1/12th octave) is designed for the incorporation of audio modules to enhance ease of listening to radio-TV audio and mobile phone audio output.

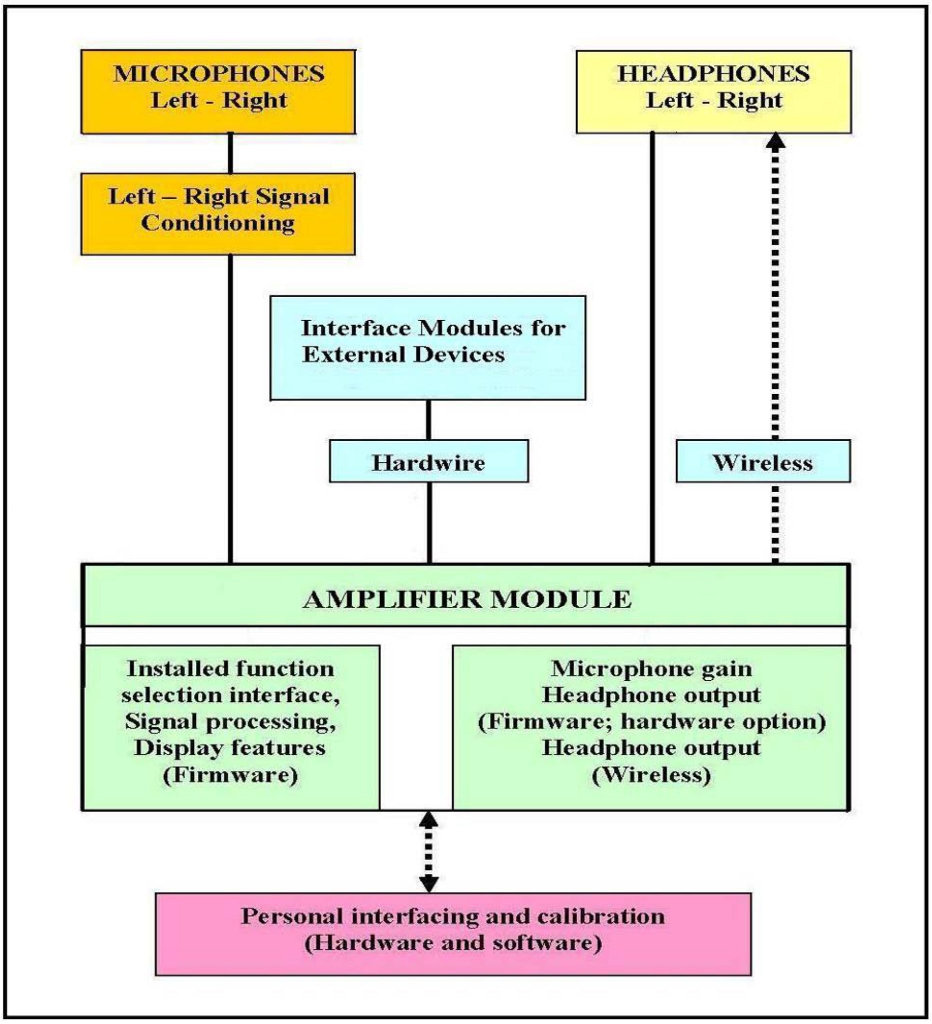

Figure 5.11.1: Overall Design for Hearing Assistance Device

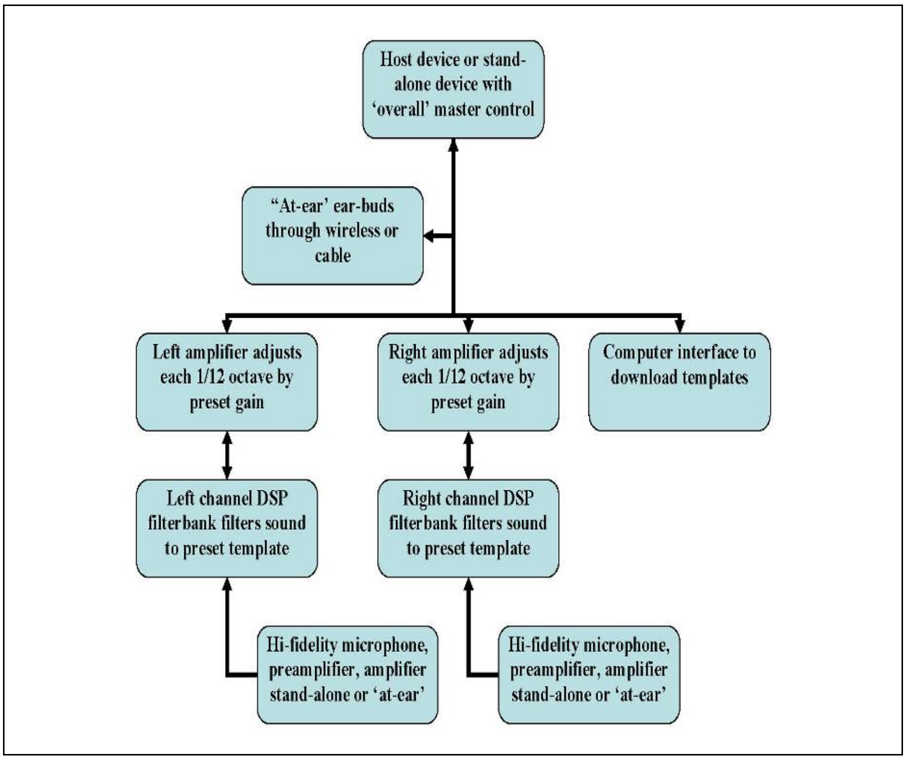

Figure 5.11.2: Simplified prototype design for Hearing Assistance Device

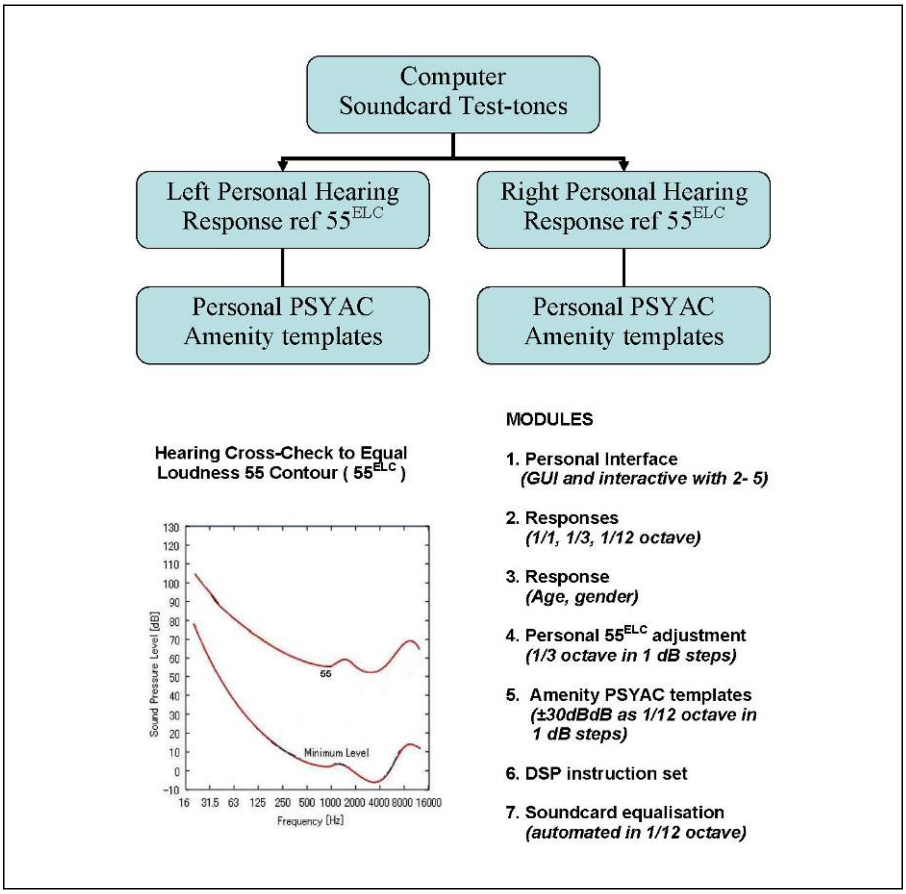

Figure 5.11.3: Computer-based template modules for Hearing Assistance Device

5.12 Benefit-cost summary for instrumentation

The purpose of this component of the research work was to investigate the practicality of designing and building instrumentation to undertake extensive research into low amplitude sound. Cost[24] is a significant factor. A class 2 sound level meter is approximately $1,000 - $7,000 depending on features and the microphone is easily damaged. It is not, therefore, suitable as an instrument to be sent to potential respondents around the world. In addition a class 2 sound level meter has an operational sound floor of around 20 dB(A) and is no real use in measuring low amplitude sound. Calibrators are around $1400 and generally only have one tone and one sound level at 94 dB (or higher). Class 1 instrumentation is even more expensive and the instrumentation noise floor not necessarily better than a Class 2 instrument. Analysis software is available but is in the range of $18,000 for a full psychoacoustical analysis package. In comparison, the component cost of the designed Class 2 analysis system, including Class 2 measurement microphone, calibrator, balanced cable and analysis software is under $340.

The analysis methodologies presented in this work for sound analysis have implemented the sound recording and analysis abilities of the instrumentation systems described in this Chapter. The instrumentation (microphone systems, preamplifiers, amplifiers, multi-function calibrator, filters and balanced cable) and analysis software described in a further Chapter are designed specifically to support inexpensive practical research into noise analysis and low amplitude sound. A defined standard of measurement precision is achieved by the instrumentation and calibration of complete systems is readily achieved.

[24] Prices are quoted in New Zealand dollars and were for specific units in 2004-2005.

CHAPTER 6: WIND FARM NOISE PREDICTION

6.1 The sound from wind farms is unique

The sound from wind farms is a unique source for low amplitude sound and intrusive noise analysis, presenting complex human responses requiring noise sensitivity and health-risk assessment in order to establish practical decision support systems. Research into wind farm sound assessment has been informed through investigations for two Environment Court (New Zealand) wind farm hearings: West Wind Wind Farm at Makara, Wellington, and Motorimu Wind Farm at Palmerston North. Both Hearings required detailed investigation that in total extended over 2½ years'. The results of the investigations have been discussed in part in Chapter 2 and technical issues as well as a further investigation are presented in this Chapter.

In summary, the conclusions reached after the investigations are:

- there is clear evidence that individuals can hear wind farm sound at distances of 2500 metres or more
- wind farm sound can cause severe sleep disturbance to some individuals
- sound modulation by amplitude and frequency appears to be the problem
- sound levels at and within a residence are very hard to measure and to separate from ambient sounds
- the physical layout design of the wind farm is important in reducing the adverse effects of wind turbine sound and vibration within a residence

A significant finding, however, is that standard sound prediction methods do not provide accurate modeling of effects and as a consequence, whether intended or not, create considerable confusion within the decision-making process. This work provides, in part, a response to that critique by describing methods of analysis and characterisation of noise from low amplitude modulating sources of sound and outlining essential components of a risk analysis for noise assessment decisions.

6.2 Wind farm sound emission

The sound from wind turbines is almost unique as an ideal reference source for this work on low-amplitude sound and intrusive noise. Adverse effects from wind turbines are in two parts: amenity (exterior to a dwelling) and disturbance (inside a dwelling). In both instances an individual can become annoyed and sleep disturbance is a potential issue for some individuals. The issue or problem with assessment of noise from a wind farm is that turbine noise is not consistently audible and the nature of the sound is variable depending on wind directions and strength.

Audible noise from modern wind turbines is primarily due to the effects of turbulent flow and trailing edge sound as illustrated in figure 6.2.1. The effects of infrasound and low frequency sound have been described by van den Berg (2006) and Leventhall (2003, 2004):

- Infrasound (below 20Hz) is noted by van den Berg as "… infrasound from (upwind) wind turbines does not appear to be so loud that it is directly perceptible. Leventhall has a 20Hz threshold for infrasound. He notes that that "Although audibility remains below 20Hz, tonality is lost below 16-18Hz, thus losing a key element of perception."
- Low frequencies in the range 20 Hz to 200Hz. Van den Berg notes that because of atmospheric turbulence there is a random movement of air superimposed on the average wind velocity.
- Mid Range Frequency 500-1000Hz.

Van den Berg states trailing edge sound is the dominant audible sound source in a modern turbine. The level increases steeply with blade speed and is highest at the high velocity blade tips. Most sound is produced at the high velocity, outer parts of the blades. It is broad-band noise with no tonal components and only a little variation, known as blade swish. This identified source of noise emission is borne out by other researchers, as presented in this section. The observations are important because of the potential noise effects that the sound generating processes may have in combination with other turbines.

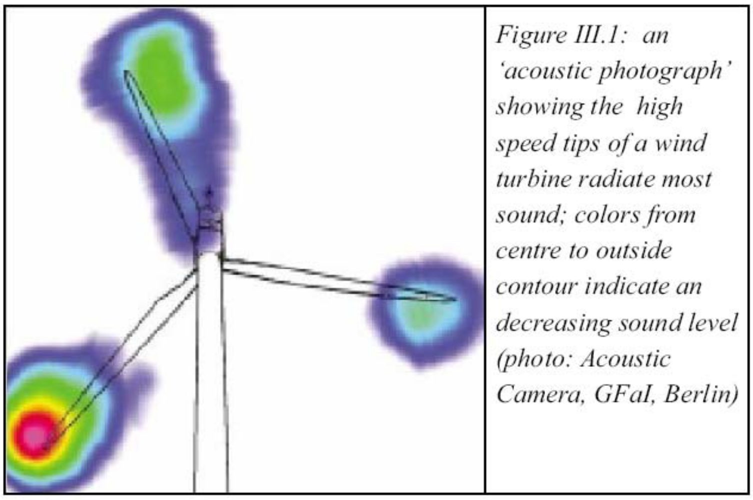

Figure 6.2.1: High speed turbine tips and noise generation

Source: The Sounds of High Winds, by permission

Wind turbines are designed with optimal tip speed ratios to extract as much energy from the wind as possible. Ideally the tip speed ratio is chosen so the blades do not pass through turbulent air from the previous blade. A 3-blade design has an optimum tip speed ratio of around 5 to 7. If the tip speed ratio is too low the turbine can slow or stall. The Danish Wind Industry Association (www.windpower.org) states that most wind turbines have constant rotational speed with the blade tip moving typically at 8-10 times the wind speed. Hubbard and Lassiter (1952, p. 459), in their report on propeller noise at subsonic and supersonic tip speeds, state that:

> The rotational noise is that component due to the steady aerodynamic forces on the blades and the frequencies are multiples of the rotational speed. …The vortex noise is due to the oscillatory forces on the blades associated with vortices in the wake. It consists of a random spectrum distributed over a wide band of frequencies.

A turbine has different sound power levels at different wind speeds and, as an example, the sound power levels for a Vestas V80 – 2MW turbine are presented in figure 6.2.2. The figure illustrates theoretical verses measured sound levels. In order to assess the potential effects of wind farm sound, noise prediction modeling must take into account the variation in sound power for different wind speeds as these can be significant.

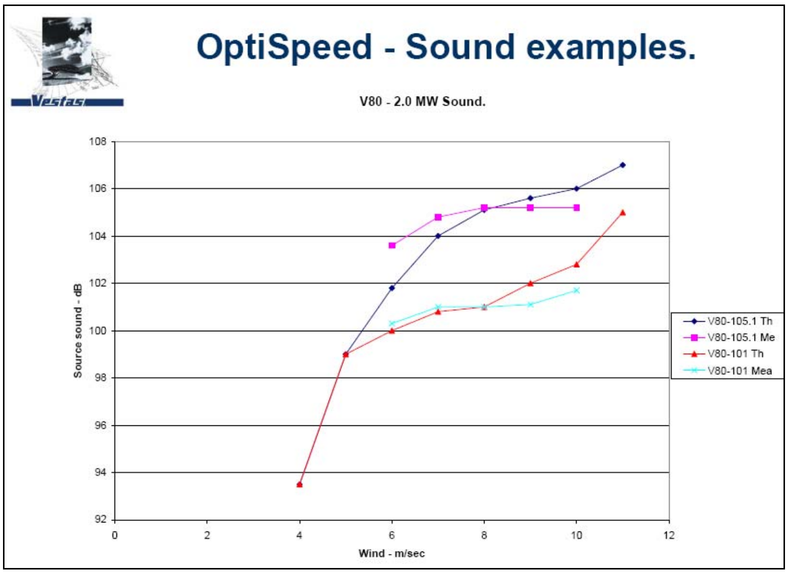

Figure 6.2.2: Vestas V80 sound power vs wind speed

Source: H Jorgensen, Vestas Presentation 'Power curve and Sound – Some Vestas Experience' (p. 37) provided in the information bundle for the 'West Wind' Wind Farm Hearing[25]

The maintenance of a machine's rated power to prevent the generator from being overloaded can be done by changing the angle of attack of the rotor blades (stall control) and the slowing to stop processes can generate noise. In addition there is noise from the turbine machinery. The dominant audible characteristics of the turbines are amplitude and frequency modulated sounds from the blades passing the tower plus broad-band and tonal sounds from the hub or centre of the blades, the turbine itself and the rotation machinery turning the turbine unit into the wind.

Observations at various wind farms in the Manawatu region, New Zealand, indicate the sound characteristics of a wind turbine vary considerably depending on the position of the turbine blades. As a blade passes the tower there is a distinct scissor-cut or swish sound. Just past the tower the character changes as the sound is shed off the blade. The shed air can be heard as a 'warble' suggesting the shedding is in the form of a helix or spiral. Observations also indicate a distinctive "thump" that appears to be as the blade is altering position within the disturbed wind-flow around the tower.

In "The measurement of low frequency noise at three UK wind farms" (Hayes McKenzie Partnership Ltd, 2006) the issue of modulation from wind turbines is

[25] The provision of extensive wind turbine product information by Vestas Wind Systems A/S (Australian office) for the 'West Wind' wind farm hearing is acknowledged with appreciation.

discussed as ‘blade swish’ (p. 53), aerodynamic modulation (p. 63) and risk of modulation (p. 65). The report comments on sleep disturbance at one residence with recorded interior sound levels of 22-25 dB LAeq with windows closed (p. 64) and states:

> This indicates that internal noise associated with the wind farms is below the sleep disturbance threshold proposed within the WHO guidelines.

Further, at p. 63 the Report states:

> However, wind turbine noise may result in internal noise levels which are just above the threshold of audibility, as defined within ISO 226. For a low frequency sensitive person, this may mean that low frequency noise is audible within a dwelling.

Bowdler (2007) reports amplitude modulation in the frequency ranges 500 Hz to 2000 Hz, with blade swish centred around 800 Hz to 1000 Hz. Bowdler (p. 9) concludes that there are two distinct mechanisms that create amplitude modulation. The first is ‘swish’ which is a function of the observer’s position relative to one turbine. The second which is ‘thump’ which is due to turbine blades passing through uneven velocities as they rotate. In the second case the uneven air may be due to interaction of other turbines, excessive wind shear, or topography.

Oerlemans, Sijtsma and Méndez López (2007, p. 869) state that aerodynamic noise from the blades is generally considered to be the dominant source of wind turbine noise. Low-frequency noise is caused by the aerodynamic interaction between the tower and the blades, but such noise is relatively unimportant for modern turbines with the rotor upwind. Inflow turbulence noise is caused by the interaction between upstream atmospheric turbulence with the leading edge of the blade and depends on atmospheric conditions. Test results (pp. 874-876) show that practically all noise emitted to ground is produced during the downward movement of the blades. The noise transmitted to the ground on the upward movement of the blade was found to be in the order of 10 dB to 15 dB less than during the downward movement. Blade noise is higher than noise from the hub. The hub noise had a peak at 630 Hz probably due to the gearbox. Broadband trailing edge noise was shown to be the dominant noise source with the highest A-weighted sound levels occurring around 800 Hz and a secondary peak at around 2000 Hz. A 'tripped' blade that is affected by insects and dirt was found to be significantly noisier than a clean blade. The sound level differences are practically independent of the wind speed.

Moriarty and Migliore (2003) identify different sources of noise, including turbulent boundary trailing edge (TBL-TE); laminar boundary layer vortex shedding (LBL-VS); trailing-edge bluntness vortex shedding (TEB-VS); tip-vortex formation (Tip); turbulent inflow (inflow) and tower-wake interaction. TEB-VS noise can dominate the total radiated noise. The authors comment (p. 4) concerning tip vortex formation that '…typically, the sound pressure levels from tip noise are less than those from trailing edge noise, but tip noise can add significant amounts of noise at higher frequencies'.

Wind turbines may give rise to infrasonic and / or ground-borne vibration effects. In terms of an environmental risk-analysis decision process, infrasound can be considered as 'sound' or 'vibration' or, in a more practical sense, a combination of the two. This work does not investigate the potential for adverse effect due to infrasound or vibration effects on individuals but is informed by the work of Mosley and a broad statement of the issues (B Rapley, 2008, in discussion with me, pers. comm., September) summarised as:

> The point of geophysical vibration is that it sets other structures into resonance in the range of frequencies at which that they are able to resonate. With a three-tipped turbine rotating at 28 rpm this equates to a fundamental frequency of 1.4 Hz so the interaction of dozens of oscillators all out of phase producing 1.4 Hz is extremely complex. The 1.4 Hz results from a pressure wave created as the turbine blade passes the tower. The resulting energy pattern cannot be accurately calculated due to the stochastic nature of the phenomenon as there are an infinite number of possible solutions. The only practical method is to actually measure what actually happens. If such complex Rayleigh waves radiate outwards from the wind farms and set into resonance certain structures, such as dwellings, then it is necessary to accept that is what is happening. The amplitude of the Rayleigh waves are in the order of nanometers; however, as the effect is a resonance phenomenon each wave crest effectively adds to the last so creating significant amplitude. The stochastic nature of the phenomenon and the relative infrequency at which the actual serious geo-acoustics generate a problem for

the inhabitants of a dwelling fits well into a risk-analysis of the causative phenomenon described.

Wind turbines, however, have variable rotational speeds depending on design and the turbine literature suggests speeds of more than 30 rpm are not uncommon, depending upon the turbine. The interaction, therefore, is even more complex that outlined previously as a wind farm could have significant variation between different turbines within the farm.

6.3 Wind turbine noise at a distance

It is concluded from the previous section that the physical processes involved in noise emissions from a wind farm are highly complex and do not readily give themselves to simple noise assessment based on noise prediction modeling. This conclusion is addressed in this section.

Figures 6.3.1 to 6.3.3 illustrate the difficulty in identifying intrusive noise elements within wind turbine emissions at a distance. The soundfiles in figures 6.3.1 and 6.3.2 were analysed with dBSONIC for an auditory spectrogram with a time interval of 1 ms, frequency range of 20 Hz to 22050 Hz, an analysis bandwidth of 0.5 Bark. Each soundfile was 120 seconds in length, corresponding to the standard analysis time for a wind turbine survey. The turbines are approximately 2000-2500 metres distant from the recording location. Figure 6.3.1 presents an auditory spectrogram of ambient sound plus wind farm noise. The sound appears to fluctuate in the mid-frequencies but the auditory spectrogram does not indicate any distinctive feature apart from bird song at around 3500 Hz. Figure 6.3.2 is an auditory spectrogram very close to the previous location but without audible wind farm noise. In both surveys bird song was clearly audible and there was no breeze stirring vegetation. Figure 6.3.3 presents the two soundfiles re-analysed in Audacity v1.2.4 using the FFT filter to identify any audible difference. The soundfile analysis is displayed in Adobe Audition v1.5. An audible feature in the ‘wind farm’ soundfile is identified as a 7,700 Hz pulse at a repetition rate of 0.4 to 0.5 seconds. The pulse does not appear to be a modulation or beat effect. The soundfile that is not affected by wind farm noise does not show the pulse effect.

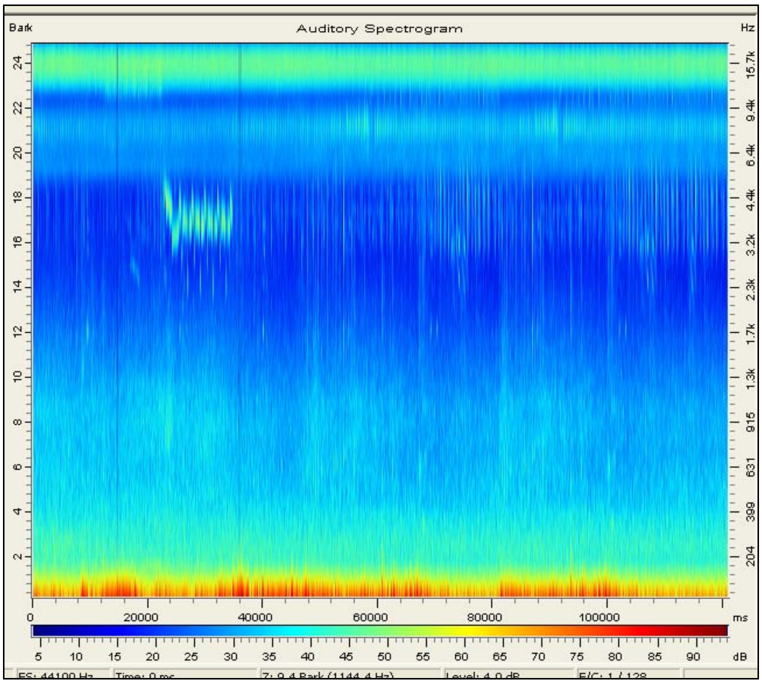

Figure 6.3.1: Auditory spectrogram of wind turbine noise and bird song

The spectrogram in figure 6.3.1 indicates considerable noise in the low frequencies and this is similar to the spectrogram in figure 6.3.2. Both figures also show a distinctive sound band at approximately 7000 Hz. Measurements were taken under calm conditions and it is concluded that wind noise is not the primary source of noise.

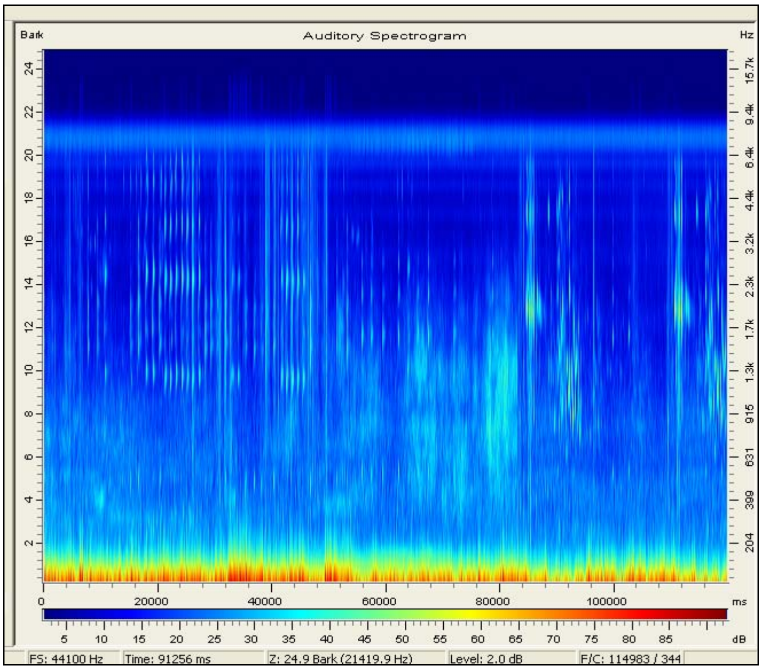

Figure 6.3.2: Auditory spectrogram of ambient and bird song in the absence of audible wind farm sound

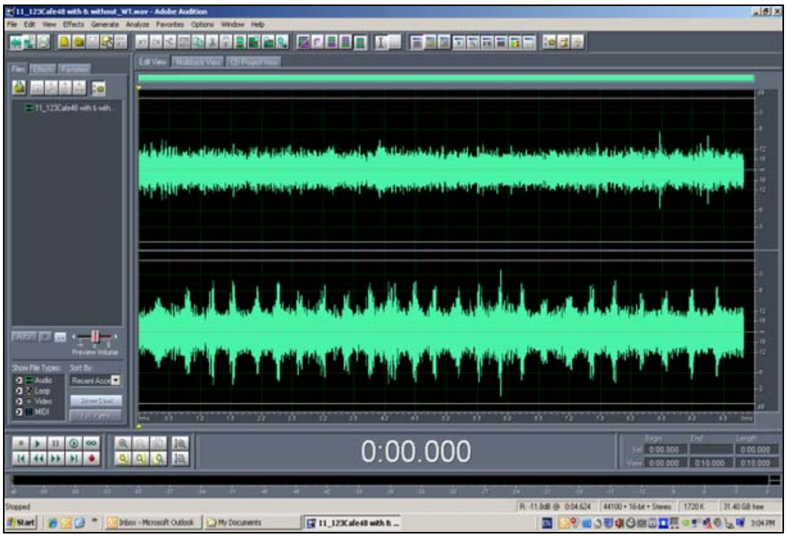

Figure 6.3.3: Left channel (top) with no wind turbine and the right channel (lower) with a wind turbine at approximately 2000 – 2500 metres. Recordings are on different days in same locale.

The sound is not due to insect noise as insect noise is evident in both soundfiles. Application of different methods of analysis indicates that the fundamental is in the 31.5 Hz octave band and the dominant harmonics appear in the 63 Hz to 500 Hz octave bands. The physical effect may be due to enhanced propagation due to some form of ducting effect with no high frequency attenuation. Such an effect can occur, for example, when high wind speeds at a relatively low height (in the order of a few hundred metres above ground) refracts sound from the wind farm downwards with little or no sound reduction due to ground characteristics. It is therefore concluded audible wind farm sound can be measured at a distance utilizing real-time filtering and analysis for 'modulation' in one or more of its methodologies[26].

6.4 Annoyance in New Zealand due to wind farm noise

The issues relating to annoyance due to wind turbines are presented in Section 2.8 of this work. This section presents New Zealand specific research.

Attitudinal studies by Mosley (2007), Phipps (2007), and Phipps et al. (2007) present significant evidence as to the perception of noise affecting people who live in the

[26] Further investigation of appropriate methodologies to analyse sound character from distant wind turbines is desirable. This work, however, is not part of this research.

vicinity of extensive wind farms in New Zealand. The work by Mosley presents brief case studies of residences affected and unaffected by wind farm noise and/or vibration. The work by Phipps et al. presents a comprehensive attitudinal study of residents affected and unaffected by wind farm noise. My observations run parallel with the research of both Mosley and Phipps et al.

In July 2006 as an expert witness to the Environment Court (New Zealand) I presented the outcomes of my investigations on behalf of the Makara Guardians Incorporated (MGI) into potential adverse effects of wind farm noise. The case involved the 'West Wind' wind farm Wellington New Zealand. Professional technical advice on behalf of MGI was tendered to the Environment Court by Dr Fritz (GP) van den Berg who supported his evidence by reference to his published work (van den Berg, 2006). In accordance with standard practice the acoustics experts were called to an Experts' Caucus meeting to discuss the technical issues and to arrive at conclusions that would help the Court make a decision. The applicants' advisors relied on the provisions of NZS 6808:1998 - *Acoustics – The Assessment and Measurement of Sound from Wind Turbine Generators.* The standard provides a nominal guideline as to acceptable sound from a wind farm:

> As a guide to the limits of acceptability, the sound level from the WTG (or wind farm) should not exceed, at any residential site, and at any of the nominated wind speeds, the background sound level (L_{95}) by more than 5dB(A), or a level of 40 dB(A) L_{95}, whichever is the greater.

Under NZS 6808 the limits of acceptability are subject to an assessment for special audible characteristics. The Experts' Caucus process is normally of one day. In this case, the caucus continued for nearly 4 days and the issues concerning wind turbine noise, measurement and assessment were vigorously debated. The Conditions (detailed in Decision W59/2007) developed during the Caucus relevant to this research relating to 'acceptable' levels and special audible characteristics are:

> 17. Wind turbine sound levels, when measured at the notional boundary of dwellings existing or holding all resource consents necessary for construction at the date of this consent, or able to be constructed as a permitted activity shall not exceed the appropriate regression curve of the A-weighted background sound level (L_{95}) by more than 5dBA, or a level of 40dBA L_{95}, whichever is greater, and

When the background sound conditions are at or below 25dBA L_{95} determined from the appropriate regression curve, without the interference of the wind farm, and when the mean wind speed at a representative location for the dwelling is less than 1.5m/s measured at a height of 10m AGL, then noise from the wind farm shall not exceed 35dBA L_{95} at the dwelling.

33. When wind farm sound within the notional boundary of a dwelling has a special audible characteristic, i.e. impulsiveness, tonality and/or an audible modulation, the measured sound level of the source shall have a maximum 5dB penalty applied by adjustment of the measured sound level by the arithmetic addition of the penalty. The total penalty for all special audible characteristics shall be no more than 5dB.

34. Sound with a special audible characteristic includes clearly audible tones. A test for the presence of tonality shall be made by comparing the levels of neighbouring one-third octave bands in the sound spectrum. An adjustment of +5dB for tonality shall be applied if the level (L_{eq}) in any one third octave band exceeds the arithmetic mean of the L_{eq} levels in the two adjacent bands by more than the values given in Table 1.

Table 1: One-Third Octave Band Level Differences

One-third octave band	Level difference
25 - 125Hz	12dB
160 - 400Hz	8dB
500 - 10,000Hz	5dB

There might be cases where this analysis does not result in a tonal component being defined although the sound is in fact tonal. For these cases it will be necessary to undertake a narrow band analysis in order to determine if a sound is tonal using Joint Nordic Method Version 2 with the penalties in that document applied.

35. A test for modulation is if the measured peak to trough levels exceed 5dBA on a regularly varying basis or if the spectral characteristics, third octave band level, exhibit a peak to trough variation that exceeds 6dB on a regular basis in respect of the blade pass frequency.

A significant outcome of the Caucus was the acknowledgement that there needed to be specific tests for tonality and modulation. Neither Dr van den Berg nor I agreed with the acceptable criteria of Condition 6 and approval was given for a dissenting statement to the agreed matters:

> We believe that the conditions here agreed upon will protect residents from severe annoyance and sleep disturbance, but not from annoyance and loss of amenity. We believe annoyance and loss of amenity will be protected when the wind turbine noise limit would be 30 dBA L_{95} in conditions of low wind speed at the dwellings and modulation restricted to 3 dB.

In an affidavit to the Environment Court (Hayes, 2007, clause 34) states that:

> …In contrast, in Project Westwind the selected turbines are to be warranted as free of tonal noise. On this basis, one would expect the wind turbine to be audible even if the turbine noise was 10 – 15 dB below the background noise level, something which is confirmed by the analysis undertaken by Nelson. It should also be noted that the intent of NZS6808 is not inaudibility but the prevention of severe annoyance. …

The issues of low frequency sound and modulation was addressed by Hayes in his affidavit, clauses 15-18, and confirms that modulation of the aerodynamic noise of the blade passage frequency can be audible within a dwelling and can cause complaint. The Environment Court decision requires continuous noise monitoring (Condition 30A) to measure background levels in order to ensure compliance with the conditions. Continuous monitoring of the characteristics of the sound in order to assess special audible characteristics is not required. In hindsight, this is a significant failure within the monitoring program as 'noise levels' are not the sole determinant of noise intrusion. The measurement and assessment of special audible characteristics is more important for noise intrusion within the home.

Subsequently, at another wind farm (Mill Creek) hearing near to the West Wind proposal, evidence was presented by James (2008) and Trevathan (2008). The prevention of health risks, Mill Creek evidence submitted by Hayes, measurement artefacts due to windscreen limitations, amplitude modulation, computer model accuracy and flaws in the New Zealand wind turbine standard are critiqued.

The decision and submissions are significant in the development of this work as they are taken into account for the low amplitude sound and intrusive noise analysis assessment methods.

6.5 Prediction model verification

Sound prediction for adverse effects (and not just from a source such as a wind farm) is considered in this work as a function of propagation effects, and hence the character of received sound levels, referenced to a known sound source. Sound has an obvious characteristic of decreasing with distance but this decrease depends on the type of source (for example, point or line source) and meteorological and ground conditions between source and receiver. Sound characteristics vary considerably between the source of the sound and the receiver, as discussed for example, in Daigle (2006). Propagation prediction becomes important at longer distances; ISO 9613-2 (1996) *Acoustics – Attenuation of sound propagation outdoors Part 2: General Method of Calculation* (Table 5) advises a prediction accuracy of ± 3 dB at 100 metres to 1000 metres because of attenuation effects due to ground cover, reflection from surfaces, barrier effects and negative/positive effects from wind and meteorological conditions. The research investigations confirm that the properties of sound propagation that must be considered include:

- the character of the acoustic environment in which the sound is being heard
- background sound levels at the receptor location
- the characteristics and unique nature of the sound; for example, a wind turbine has unique features that include phasing between turbines, amplitude and or frequency modulation (blade swish and / or beating) and low frequency effects
- the variation in wind speed and strength at the source of sound and at the receptors
- any ground or barrier effects between the sound source and receptors
- the amount of time a receptor is exposed to the sound levels
- non-acoustic factors, such as the sensitivity of the listener and attitude to the source

The factors listed indicate that a sound that may be predicted as “inaudible” may in fact be readily heard. This is particularly true on cold clear evenings when sound travels well and noise events can be heard over distances of thousands of meters. One-third octave band source sound power levels are preferred for prediction purposes but octave bands will suffice for a broad assessment. Single level source data is not preferred as it has no information concerning the source characteristics. Increases or variations of sound from a densely designed wind farm (that is, a wind farm with multiple rows and columns of turbines) may be due to sound aggregation from the vortices of two or more turbines appearing in-phase or slightly out-of-phase. The effects are temporary in time with the vortices dissipating relatively quickly as wind speed and direction changes. Such changes in source energy and sound character cannot be readily modeled.

Tonal elements can be predicted by substitution of the required band within the calculation procedure. Sound prediction models can predict, with a degree of uncertainty, anticipated sound levels from specified sources under highly defined conditions. Known and/or unknown meteorological conditions can cause significant problems with prediction accuracy. All environmental sound prediction models must be verified to known conditions before being used in the prediction of an unverified scenario. Propagation predictions are subject to uncertainty and so the assumptions used in the preparation of the model must be stated. The output from the model is always subject variation and the use of sound level contours as "objective measures" is not supported by this work as such contours are highly variable in nature depending upon the interpolation calculation process employed. Sound levels predicted at a defined location are preferred as the calculations are specific to that point.

The following conclusions have been drawn from the research into the effects of low amplitude sound from wind farms on individuals:

- Wind farms have significant potential for annoyance due to sound modulation effects even though these effects are of a low amplitude;
- The potential adverse effects of low-amplitude sound and vibration that can induce adverse levels of low frequency sound are not well documented;
- The interactions between background levels, ambient levels, modulation and tonal character of a wind farm overlaid within a soundscape are complex and difficult to measure and assess in terms of individual amenity;

Sound level predictions for complex noise sources of this nature are only partially relevant to this type of environmental risk assessment.

From the observations it is determined that a wind turbine cannot be considered as a single point source but as a complex line source. Figure 6.2.1 indicates that a point of maximum sound is not at the hub. However *IEC61400-11, 2002 Wind Turbine Generators Part 11, Acoustic noise measurement techniques* and NZS 6808:1998 - *Acoustics – The Assessment and Measurement of Sound from Wind Turbine Generators* treats the turbine as a whole as being a point source referenced to the hub height.

In order to test the predictive results calculated from various assumptions, two different sound propagation models were referenced to PEN3D, a sound prediction model implementing a variation of ISO 9613 and CONCAWE. The base-case referenced is the final noise predictions' report (Report 1610-R3 Draft) for the Project West Wind Makara wind farm, Wellington, prepared by the Hayes McKenzie Partnership. The Hayes McKenzie report sets out the assumptions used in their predictions. Hayes McKenzie did not use hub height as the source height for the sound power levels but a height above the actual tip height of the wind turbine. The Report states:

> The increase in height is to allow for the potential bending of sound waves by the flow of air over the hill sides. This has the effect of increasing the apparent height of the source.

New Zealand standard NZS 6808:1998, however, adopts the hub height as being the source height. The verification testing assumed the Hayes McKenzie predictions as the nominal benchmark. Hayes McKenzie prepared their predictions under ISO 9613 implemented by CadnaA. The first verification check implemented ISO 9613 under SoundPLAN using the Hayes McKenzie assumptions and a further series of verification tests were implemented under PEN3D.

The verification tests under PEN3D implemented the two different source heights (at hub height of 68 metres and 135 metres. The 'apparent' source height at 135 metres is 1.24 times maximum blade tip height. Alternative models with an acoustic centre at height of two-thirds the blade, or the blade 'split in half' and have a lower component at one-quarter height and an upper component at three-quarters height and predicted as a line source rather than a point source have been advanced as being appropriate. The variations illustrate the wide range of approaches to prediction modeling and why statements of assumptions are so important.

The predictions indicate that, overall, PEN3D is predicting levels slightly above CadnaA and SoundPLAN is predicting slightly lower than CadnaA for the same daytime assumptions. Both PEN3D and SoundPLAN are within margins of error in relation to “baseline” CadnaA. There is a slight (taken as ± 2 dB across all predictions) difference between PEN3D predictions for night-time (moderate inversion) conditions and daytime levels as PEN3D implements attenuation due to atmospheric absorption using Pasquill Stability Categories.

The variation between PEN3D hub height and blade tip predictions, however, is significant, with an increase in predicted levels of around 7 dB. The modeling verification and source height variations indicate that sound sources at hub height will under-predict noise levels at receivers. It is concluded from the verification analysis that it is not appropriate to adopt the ‘hub’ as the acoustic centre of the wind turbine, assuming half the noise is produced above the hub and half below. The modeling indicates a significant “reduction” in the sound levels by lowering the prediction height to hub level. This means that the ISO 9613 model, using hub height as the source, will *under-predict* the downwind sound levels at receivers.

The verification analysis also illustrates the importance of meteorological and topographic conditions on sound propagation and potential for increased sound levels under night-time conditions or conditions where moderate temperature inversions occur. PEN3D allows for bending of sound waves within the model and is based on meteorology and terrain inputs. In the West Wind case, the topography of the locality is very rugged, with the wind turbines on the ridges and the residents within the valley to the immediate right of the wind farm, figure 6.5.1.

The predicted noise contours for the West Wind wind farm and the Siemens turbine are presented in figure 6.5.1. The figure presents two different approaches to establish a visual representation of the potential noise impact from a noise source onto residences. The first approach is a single 35 dB(A) contour to represent the ‘average’ noise levels for 24 hours per day, 365 days a year. This approach has finely stated contours that interplay with the terrain and imply a high degree of acoustical precision. As the expected variation at 1000 metres is in the order of ±3 dB the approach is not supported by this work. A second approach is taken by defining broad lines for the contours, rather than fine lines. The day and night contours are drawn through the points where the noise level is predicted at a specific residential location. The day and night contours are directly related to specific locations and do not infer that noise levels will be an exact value at a specific contour point. This second approach can be defended as it is responsive to time of day and variable weather conditions and is the approach supported by this work.

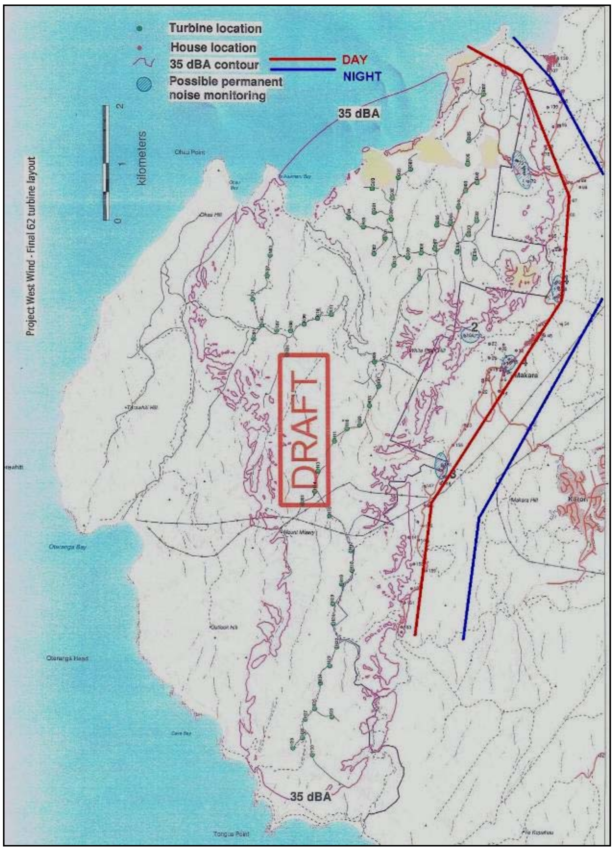

Figure 6.5.1: West Wind ‘35dB(A)’ contours
Hayes McKenzie Partnership draft contours and ‘day-night’ 35 dB(A) contour lines from this investigation

The sound level predictions in Table 6.5.1 have referenced 9m/s wind speed and the calculated levels are at 135 metres and hub height. The Table presents day and night calculations. The night calculations present a stable atmosphere with a moderate inversion as would be expected at night and early morning. The Table is part of the evidence dataset to illustrate the variation in prediction calculations at defined locations due to different models and scenarios. The referenced wind turbine is the Siemens SWT-2.3-82 VS and sound power levels from the Hayes McKenzie report.

Table 6.5.1: Prediction implementations by different models

Project	Makara selected residences								
Project	Receiver at 1.5m above ground level								
	Siemens SWT-2.3-82 VS turbine at 135m and 68m above ground level								
Leq	Day AND Night								
	Only PEN3D has the day/night option; CadnaA and SoundPLAN predict day and night levels as the same								
Conditions	day temperature 15 degrees, relative humidity 70%								
	PEN3D night temperature 10 degrees, relative humidity 50%, moderate inversion with temperature gradient of 4.5 (C/100m)								
	day temperature gradient -1.4 (C/100m)								
	wind speed 9 m/s								
	wind speed at 10m AGL								
	surface roughness 0.5 (grass and trees)								
L95 calculation	Leq -2		(note: assessed to NZS6808 c4.4.2)						
Model	SoundPLAN	*SoundPLAN*	PEN3d2000	*PEN3D2000*	PEN3d2000	*PEN3D2000*	PEN3d2000	PEN3d2000	**Cadna A**
Predictions	Noise Level	*dBA margin*	Noise Level	*dBA margin*	Noise Level	*dBA margin*	Noise Level	*135m night*	**Noise Level**
Residence	Leq dB(A)	*above*	Leq dB(A)	*above*	Leq dB(A)	*above*	Leq dB(A)	*above*	**Leq dB(A)**
	day 135m	*CadnaA*	day at 135m	*CadnaA*	night at 135m	*CadnaA*	night at 68m	*68m night*	**Hayes at 135m**
R26	31.6	-2.4	35.6	1.6	37.6	3.6	30.2	7.4	**34**
R32	28.3	-3.8	33	0.9	36.6	4.5	28.1	8.5	**32.1**
R3	28.2	-2.2	31.9	1.5	33.3	2.9	24.7	8.6	**30.4**
R22	29.7	-3.4	34.8	1.7	36.8	3.7	29.1	7.7	**33.1**
R66			34.9	1	36.9	3	30.1	6.8	**33.9**
R161	34.3	-1.1	36.2	0.8	37.9	2.5	31.6	6.3	**35.4**
R163	33.9	-1.4	36.3	1	37.9	2.6	31.6	6.3	**35.3**
R160	32.9	-1.9	35.3	0.5	37.5	2.7	30.9	6.6	**34.8**
R159	32.5	-1.3	34.7	0.9	36.5	2.7	29.5	7	**33.8**
R158	33.4	-1.3	35.1	0.4	36.7	2	30	6.7	**34.7**
R142	32.9	-1.5	35.4	1	36.9	2.5	29.9	7	**34.4**
R141	34	-1.1	35.9	0.8	37.4	2.3	30.7	6.7	**35.1**
R143	33.1	-1	35.2	1.1	36.7	2.6	29.4	7.3	**34.1**
R145	32.9	-1.1	35.3	1.3	36.8	2.8	29.4	7.4	**34**
R147	33.2	-1	35.6	1.4	37.2	3	29.8	7.4	**34.2**
R148	32.3	-1.1	34.9	1.5	36.4	3	28.7	7.7	**33.4**
R149	32.2	-1.1	34.9	1.6	36.3	3	28.7	7.6	**33.3**
R151	32.5	-1.2	35.3	1.6	36.8	3.1	29.3	7.5	**33.7**
R156	32.1	-1.4	35.1	1.6	36.7	3.2	29.1	7.6	**33.5**
R23	31.1	-2.1	34.3	1.1	36.7	3.5	29	7.7	**33.2**
R2	27.3	-2.9	31.8	1.6	33.3	3.1	24.6	8.7	**30.2**
R4	30.4	-1.9	34.1	1.8	35.9	3.6	27.8	8.1	**32.3**
R5	29.6	-2.8	34.1	1.7	36	3.6	28.1	7.9	**32.4**
R6	29.6	-3.5	34.6	1.5	36.4	3.3	28.6	7.8	**33.1**
R9	30.7	-2.2	34.9	2	36.6	3.7	28.8	7.8	**32.9**

It is concluded that noise predictions and noise contours presented as part of a decision making process can only be regarded as indicative of a particular situation defined by specific assumptions and confidence levels of the calculations referenced to well defined measured source sound characteristics and propagation variables.

6.6 Meteorological conditions

Observations at various locations within the Manawatu region indicate that wind turbines in a stable (night-time) atmosphere generate more sound than in a neutral or unstable (daytime) atmosphere. At the same time the wind velocity near the ground is low and the natural ambient sound due to rustling vegetation is weaker. As a result the contrast between wind turbine sound and natural ambient sound is more pronounced in stable than neutral conditions. The wind profile after sunset changes and the atmosphere becomes more stable. This causes a change in the trailing edge sound. The differences in wind speed lead to variations in the sound radiated by blade tips that reach their highest values when the tip passes the mast. Under downwind conditions the sound generated by the turbines is affected by downwind refraction. There can be considerable variation in sound levels due to atmospheric conditions and the presence of stable conditions are critical for noise prediction and analysis because, as established by van den Berg (2005, pp. 79-81):

- a turbine operating at high speed into a stable atmosphere can give rise to fluctuation increases in turbine sound power level of approximately 5 dB
- fluctuations from 2 or more turbines may arrive simultaneously for a period of time and increase the sound power level by approximately 9 dB
- In-phase beats caused by the interaction of several turbines increases the pulse height by 3 to 5dB
- The enhanced levels are not consistent and will change as the wind changes

The purpose of this section is to illustrate the effects of topography and wind profiles onto resident's down-wind of turbines and the difficulty in predicting sound levels under complex wind patterns. The effects of topography (previous section) mean that digital terrain mapping is essential in order to define a locality in terms of noise sources, receivers and potential attenuation effects. The effect is marked when there is a valley between two ridges. The flow on the initial ridge (on the prevailing side) is mostly upward. At the bottom of the valley there may exist a region of relatively calm air depending on the width of the valley and the airflow along the valley. The airflow lifts over the crest of the next ridge and the flow pattern is repeated. Airflow patterns are distinctive showing the variations in wind speed with height and distance. Atmospheric stability influences the wind profile over complex terrain. The wind profile affects the received noise levels at residents and this profile can vary frequently over a 24-hour period, so requiring long-term (12-months or more) accurate meteorological data that is specific to a locality. The complexity of wind profiles over complex terrain and resultant noise production has been well documented by van den Berg (2006). The difficulty for noise prediction is that prediction models are not sufficiently advanced to be able to calculate the potential effects of variable wind patterns. Prediction models relate to average conditions and do not take into account variations of known probability that will present enhanced sound levels.

6.7 Sound prediction for sound character

It is concluded from the investigations for this work that the “standard” sound prediction methodology of either ISO 9613-2 or CONCAWE must be modified when considering the potential audibility of intrusive sound at an affected building by adding factors for:

- building fabric attenuation, in one-third octave bands (Abf_3)
- the increase in received sound, as a tonality, due to standing waves or narrow-band noise at the receiver within the room, in one-third octave bands (Tk_3)

As part of this work a review was undertaken to confirm a simple model for analysis of a complex wind farm. The ideal model requires third-octave analysis and contouring ability for multiple turbines. No one commercial model meets all these requirements but a combination of models and calculation by way of spreadsheet can achieve most of the requirements. The models implement point source rather than line source propagation but are flexible enough to be modified to allow different calculation techniques. The basic equation for a prediction model implementing point source, spherical spreading and attenuation is:

$$SPL = SWL - 10\lg(4\pi\, r^2) - Ae + Tk_3 \qquad \text{eqn. 6.7.1}$$

Where
SPL is the sound pressure level at an observer
SWL is the sound power level of the source
(r) is the distance in metres
Ae is the excess attenuation factors and is determined as the sum of the contributions comprising $Aa + Ag + Am + Ab + Af + Abf_3$

And where

A_a = Excess attenuation due to atmospheric absorption to ISO9613-1 or (preferably) Pasquill Stability Categories using CONCAWE

A_g = Excess attenuation due to ground reflection

A_m = Excess attenuation due to meteorological effects

A_b = Excess attenuation due to barriers

A_f = Excess attenuation due to forests

A_{bf_3} = Excess attenuation due to the relevant building fabric, in one-third octave bands

T_{k_3} = increase in sound level due to standing waves or directivity within the room, in one-third octave bands

Note that excess attenuation reduces the sound level whereas room interior effects present a potential increase in sound level. Equation 6.7.1 does not take into account source directivity factors.

A "contouring" prediction method is implemented in part in PEN3D[27]. As an aid for wind farm design downwind conditions can be modeled in detail using exSOUND2000+, a noise prediction model that has been developed from the wind turbine noise prediction model WiTuProp.[28] The program is useful for a small number of turbines compared to the contouring ability of the programs (CadnaA, PEN3D, SoundPLAN) previously described.

[27] PEN3D is available from Noise Mapping Australia <www.noisemapping.com.au>

[28] exSOUND2000+ is available from DELTA (www.delta.dk). The program WiTuProp is no longer available.

CHAPTER 7: ATTITUDINAL AND ACOUSTICAL SURVEYS

7.1 Introduction

The investigations and outcomes of this Chapter summarise work undertaken into community and individual attitudes to noise and noise levels within the environment and within dwellings in New Zealand and Brisbane Australia. The studies are taken into account in the development of intrusive noise analysis and assessment of low amplitude sound methodologies of this work.

7.2 Southern Scene attitudinal and acoustical surveys

Over the period October-November 1992 and February-March 1993 in New Zealand I completed a series of attitudinal and acoustical surveys in Gore District (1992), and Southland District, Invercargill City Council, Clutha District and Waitaki District (1993) in order to obtain a better understanding of noise in the community and the community's response to noise. The broad locality is the southern third of the South Island of New Zealand. The survey locations are based on Oamaru (Waitaki District) and south of a line drawn from north of Milton, across to just south of Roxburgh, to Lumsden and across to Milford Sound. Stewart Island and Dunedin City were not included in the surveys. Apart from a summary paper (Thorne, 1993) the outcomes of the attitudinal and acoustical surveys have not been reported, nor has any interpretation been given previously to the information recorded.

The attitudinal surveys were designed on the basis of the questionnaires, Annex A. In order to assess the communities' attitude towards noise, random postal surveys were sent to households in the various Districts. Potential respondents were chosen at random using telephone listings of the households in the various Districts and the questionnaires hand delivered to the chosen address. Four survey papers were sent to each address for members of the household to respond to the questions. The Clutha and Southland District responses and acoustical surveys inform the development of a rural attitudinal template. The surveys for Invercargill City inform the development of an urban attitudinal template. The Gore and Waitaki District surveys are taken into account in the development of a rural-urban attitudinal template.

7.2.1 Southern Scene attitudinal surveys

The primary objective of the surveys was to assist the various communities in deciding what a "reasonable level of noise" in the community will be. Twenty-seven percent of the households polled responded, Table 7.2.1.

Table 7.2.1: Attitudinal surveys sent and responses received

District	Households Polled	Households Responded	
		Households	Responses
Clutha	500	162	223
Gore	300	104	175
Invercargill	800	170	298
Southland	500	111	183
Waitaki	600	187	342
Total	2700	734	1221

The responses to the initial question "Do you think noise is a problem to you?" (Q.1) are presented in Table 7.2.2. Of the overall responses 47.7% think noise is a personal problem. For the rural areas the 'Yes' response is 39.4%, for the urban area 53.7% and for the rural-urban area 50.7%.

Table 7.2.2: Noise as a personal problem

District	Yes	No	Sometimes	No Reply	Total
Clutha	85	107	6	24	223
Gore	98	54	3	19	175
Invercargill	160	112	5	21	298
Southland	75	95	6	6	183
Waitaki	164	159	1	21	342
Total	582	527	21	91	1221

The responses to the question “Are you ever annoyed by noise?” (Q.3) are presented in Table 7.2.3. Of the overall responses 62.4% have some experience of being annoyed by noise at some time. For the rural areas the ‘Yes’ response is 57.1%, for the urban area 70.1% and for the rural-urban area 62.3%.

Table 7.2.3: Persons annoyed by noise

District	Yes	No	No Reply	Total
Clutha	119	87	17	223
Gore	131	32	12	175
Invercargill	209	73	16	298
Southland	113	65	5	183
Waitaki	191	138	13	342
Total	763	395	63	1221

The question “does noise affect you while..?” (Q.16 - 22) provided a range of responses, Table 7.2.4.

Table 7.2.4: Responses to ‘Does noise affect you while…’

District	Reading		Watching TV		Listening Talking		Relaxing		At work		At school		Sleeping	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Clutha	43	180	36	187	52	171	61	162	23	200	11	212	75	148
Gore	58	117	56	119	63	112	102	73	18	157	6	129	9	166
Invercargill	68	229	75	223	97	201	153	145	30	268	9	289	-	-
Southland	55	128	46	137	58	125	71	112	28	155	35	148	70	113
Waitaki	64	278	81	261	83	259	97	245	37	305	21	321	116	226
Total	289	932	294	927	353	868	484	737	136	1085	82	1139	270	653

The overall responses indicate that of the persons that had an opinion, 24% were affected while reading, 24% while watching TV, 29% while in conversation, 40% while relaxing, and 29% while sleeping (or attempting to get to sleep). The figures for sleep disturbance in Clutha, Southland and Waitaki are high for rural or rural-urban localities. Invercargill City did not produce figures for sleep disturbance.

The main responses to the question "is there any particular type of noise that can really annoy you?" (Q.23) provided a wide range of responses, Table 7.2.5. Respondents could respond to more than one "really annoying noise".

Table 7.2.5: Responses to 'Really annoying noise…'

District	A	B	C	D	E	F	G	H	S	N	O	Total
Clutha	31	47	12	-	-	11	7	3	25	9	35	134
Gore	31	67	36	6	17	23	14	3	-	3	1	126
Invercargill	56	53	46	27	22	13	13	10	-	18	12	179
Southland	35	34	17	12	-	10	8	6	10	12	8	94
Waitaki	66	92	33	8	22	21	19	6	45	25	52	217
Total	219	293	144	53	61	78	61	28	80	67	108	750

Key:
A: Loud music from stereos and parties; B: Motor cars and motorbikes; C: Dogs barking and yelping; D: Aircraft (especially early in the morning); E: People (voices, domestics); F: Lawnmowers, Chainsaws; G: Industrial Noise; H: Persistent intrusive noise; S: Special noise noted in the district (e.g., truck noise); N: "nothing annoys them"; O: Other

The responses to the locality, gender and age questions (Q.26 - 30) tested against "are you ever annoyed by noise" (Q.3) are summarised in Table 7.2.6.

Table 7.2.6: Responses by locality, gender and age tested against annoyance

By Age Group	Living locality			female	male	Total
	near road	rural area	urban area			
<20	50	39	41	48	33	81
20-29	57	20	57	47	35	82
30-39	99	45	84	79	57	136
40-49	84	58	78	81	62	143
50-59	92	51	71	60	72	132
60-69	81	35	75	54	68	122
70+	45	10	44	33	34	67
Responses	508	258	450	402	361	763
% of Total	66.6%	33.8%	36.9%	52.7%	47.3%	100%

The interview responses and written responses from respondents identified issues that people were concerned with. The responses did not, however, give any substantial indication as to why people were disturbed or annoyed by noises in their environment to the extent presented in Table 7.2.6. The comments were, in the main, concerned with some traffic noise and some industrial or commercial activity in the various townships. It is concluded that level of annoyance in Table 7.2.6 can be considered as an indication of 'moderate' annoyance compared to 'high' annoyance in Table 7.2.5.

7.2.2 Southern Scene acoustical surveys

Acoustical surveys, Tables 7.2.7 and 7.2.8, were conducted at the same time as the attitudinal surveys to assess the general sound levels in the environment. The monitoring locations were chosen to be representative of the general localities identified through the attitudinal survey selection process. Weather conditions and existing and potential noise sources were identified at each monitoring location.

Table 7.2.7: Southern Scene acoustical surveys

District	Full Survey	Random
Clutha	20	18
Gore	15	20
Invercargill	17	69
Southland	17	23
Waitaki	40	52
Total	109	182

The 'full' surveys were taken over at least 24 hours (usually 72 hours) using Cirrus 702 type 1 sound level meters, or Quest M28 type 2 dataloggers. The Cirrus units recorded sound levels every 15 minutes and had the function to record levels at the rate of 1 sample per second. The Quest units were normally set to record on the basis of 60 second-averaged-levels. Analysis software for both units used Acoustic Editor by Cirrus. The 'random' surveys used were for at least 15 minutes at each site. The loggers could record noise levels from 30 dBA to 110 dBA. Table 7.2.8 notes these variations for daytime (7am to 10pm) and night-time (10pm to 7am). The levels are the levels for the whole of the ‘day’ or ‘night’ period. The Table shows the variations across the four Districts and Invercargill City. Although there is wide variation in sound levels meaningful analysis for individual or community noise assessment can be made on the basis of the lower levels recorded. Individual site data, however, are more detailed and useful in characterising a locality.

Table 7.2.8: Average daily sound levels – all districts

Land Use	Daytime L10		Nighttime L10	
	Districts	City	Districts	City
Residential	33-63	48-63	26-63	35-58
Residential (near main roads)	46-70	59-67	28-61	51-61
Commercial	44-70	62-70	28-57	44-56
Industrial	44-75	48-68	30-59	38-59
Rural	36-64	48-56	32-57	34-51

The detailed summary results are presented to illustrate the variability in ambient sound levels between different locales and between times of day. For the purposes of this work the detailed information informs the design of the decision support system and is reported accordingly.

Tables 7.2.9 to 7.2.11 present the sound levels for “full” surveys in the various Districts. Table 7.2.9 presents the combined ‘rural-urban’ Districts of Gore (G) and Waitaki (W). Table 7.2.10 presents the predominantly urban Invercargill City data. Table 7.2.11 and figures 7.2.1 and 7.2.2 present the data for the rural localities in Clutha (C) and Southland (S) Districts. The site numbers refer to the location of the measurements. The dataset is presented as day (7am to 10pm) and night (10pm to 7am) sound levels. The sound levels at each site were continuously measured over either 15 minute or 1-hour intervals and the day / night levels calculated as the arithmetic average of the statistical levels (L10, L90) or the energy average of the equivalent continuous (LAeq) levels. These day/night levels were recalculated to provide an overall average level and standard deviation of the average. All sound levels are A-weighted and have been rounded to the nearest whole decibel.

Table 7.2.9: Average daily sound levels, Gore (G) and Waitaki (W) Districts

Site	Locale	Day			Night		
		Leq	L10	L95	Leq	L10	L95
G2	Ind	55	60	35	51	52	36
G3	Rural	47	48	34	34	35	34
G4	Res	66	70	44	55	58	33
G5	Rural	57	53	38	45	47	33
G6	Res	66	70	56	60	63	53
G7	Ind	66	68	57	62	63	41
G8	Rural	48	49	34	36	38	34
G9	Rural	57	59	41	47	47	32
G10	Rural	50	53	38	55	52	33
G11	Res	52	54	34	47	47	29
G12	Ind	65	69	56	60	64	32
G13	Res	45	43	36	37	37	36
G14	School	60	59	38	54	60	32
G15	Rural	46	44	34	36	37	33
G16	Res	59	54	39	39	40	30
W1	Rural	51	48	35	34	34	33
W2	Rural	51	56	34	48	51	35
W3	Res	59	54	39	44	40	35
W4	Com	58	62	41	47	44	39
W5	Res	66	63	49	50	51	49
W6	Res	50	48	31	34	35	29
W7	Rural	51	51	36	42	45	33
W8	Res	57	59	45	47	51	31
W9	Res	63	54	39	65	39	32
W10	Res	56	47	36	36	39	33
W11	Rural	53	54	41	47	46	35
W12	Res	60	63	46	54	58	37
W13	Ind	61	61	45	45	43	29
W14	Res	58	60	36	56	57	34
W15	Res	65	67	57	57	61	35
AVERAGE		56.6	56.7	40.9	47.5	47.9	34.6
Std Deviation		6.4	7.6	7.4	8.9	9.3	5.1

Key to localities: Ind (industrial), Res (residential), Com (commercial)

Table 7.2.10: Average daily sound levels, Invercargill City

Site	Locale	Day			Night		
		Leq	L10	L95	Leq	L10	L95
1	Res	54	50	42	51	50	41
2	Ind	58	55	43	47	48	40
4	Res/Com	58	53	30	47	31	26
5	Res	57	46	29	46	28	28
6	Res	58	55	33	50	51	28
7	Com	62	57	39	48	48	40
8	Com	52	44	33	38	40	33
9	Res	54	47	28	30	29	28
10	Res	54	51	33	45	45	28
11	Res	52	46	26	39	36	26
12	Res	53	44	35	42	45	34
13	Res	51	44	28	36	39	26
14	Hospital	58	54	33	57	56	31
15	Res	48	43	30	36	34	26
16	Ind	70	75	43	49	45	37
17	Res	55	54	43	51	52	37
18	Res	46	43	33	45	43	31
19	Res	65	66	45	59	57	33
20	Com	43	44	27	31	28	26
21	Res	35	33	26	26	26	26
22	Ind	55	48	29	33	34	27
23	Ind	63	63	29	64	38	26
24	Res	54	48	32	43	36	30
25	Res	57	55	39	51	55	34
26	Rural	49	44	31	46	43	25
27	Rural	57	54	34	48	33	29
28	Res	58	61	30	48	37	26
29	Res	64	69	32	55	45	25
30	Res	55	50	30	40	35	28
31	Res	61	59	29	54	43	26
AVERAGE		55.5	52.3	33.5	45.5	41.3	29.9
Std Deviation		6.9	9.1	5.7	8.9	8.8	4.9

Key to localities: Ind (industrial), Res (residential), Com (commercial)

Table 7.2.11: Average daily sound levels, Clutha (C) and Southland (S) Districts, all rural

Site	Locale	Day			Night		
		LAeq	L10	L95	LAeq	L10	L95
C1	Rural	50	46	36	43	46	36
C2	Rural	54	46	34	38	41	33
C4	Rural	48	49	45	48	48	46
C9	Rural	50	46	36	43	44	37
C11	Rural	43	43	30	44	48	29
C12	Rural	43	46	31	38	37	25
C13	Rural	45	46	34	38	39	26
C15	Rural	56	60	41	45	48	41
C16	Rural	46	41	32	34	34	32
C17	Rural	51	55	36	44	41	36
C18	Rural	58	58	33	39	41	29
C19	Rural	59	64	32	44	46	31
C20	Rural	43	44	29	34	32	29
S1	Rural	46	50	36	37	38	35
S6	Rural	48	51	38	43	45	35
S7	Rural	52	42	34	35	35	33
S8	Rural	70	62	37	47	52	36
S11	Rural	46	48	36	38	39	36
S13	Rural	36	36	32	34	35	31
S14	Rural	47	51	29	38	37	29
S15	Rural	50	52	36	42	45	36
S16	Rural	52	57	36	43	34	32
AVERAGE		49.6	49.7	34.6	40.4	41.1	33.3
Std Deviation		7.0	7.2	3.8	4.3	5.6	4.7

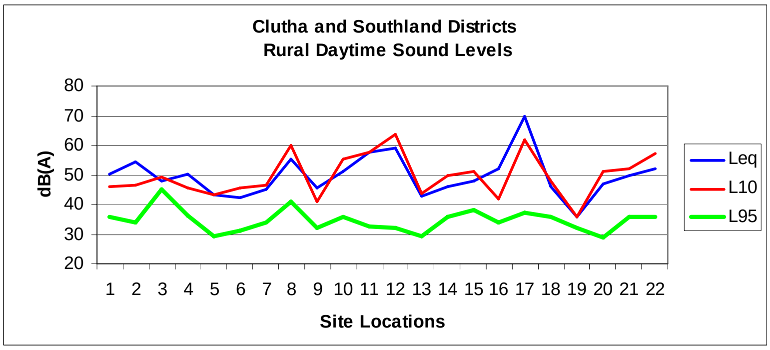

Figure 7.2.1: Average rural daytime sound levels, dB(A), Clutha and Southland Districts

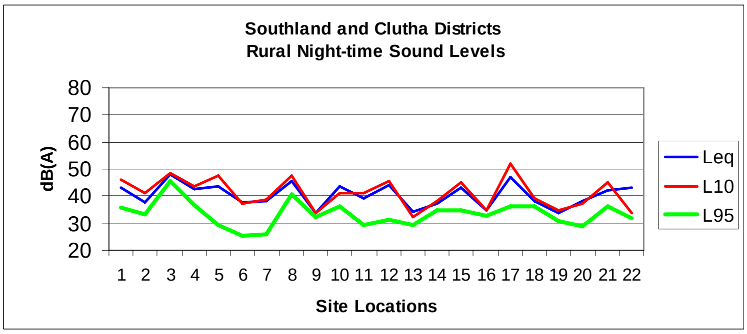

Figure 7.2.2: Average rural night-time sound levels, dB(A), Clutha and Southland Districts

7.2.3 Conclusions from investigations

The surveys had the express purpose of providing information that would assist local authorities in setting noise management controls into District Plans. Noise identified during the surveys was almost always due to transportation. In the rural areas animal noise is distinctive but not noted as being a nuisance. High ambient sound levels were almost invariably due to the wind and tree or vegetation noise. Analysis of the surveys suggests no extremes in levels; rather they show that levels vary during the day and vary according to weather and traffic conditions. Daytime levels exhibit quite wide variations between localities and this is expected as wind and vegetation noise provide the fundamental soundscape modified by sounds in the locality from vehicles and human activity. The night-time sound levels are not as varied indicating less modification by vehicles or activity. At no time were ‘intrusive’ sounds heard and general ambient character could be described as being ‘smooth’ or regular wind over vegetation or regular traffic noise. The average daytime and night-time background levels at one standard deviation show good correlation indicating assessments of potential adverse effect can be predicted from the datasets.

It was concluded from the investigations that there is no evidence that an external level of 45 dBA L10 is an acceptable or desirable night-time upper limit at a dwelling. Similarly, there is no evidence from the surveys that 55 dBA L10 is an acceptable or desirable daytime upper limit. These limits are those recommended in many New Zealand District Plans and various New Zealand standards for environmental noise.

7.3 Auckland City attitudinal pilot study

An environmental health needs analysis into environmental noise by way of attitudinal and acoustical studies was proposed in 1999 by the Public Health Protection division of Auckland Healthcare Services Ltd[29]. A series of pilot attitudinal surveys based on previous New Zealand surveys (Annex A) and draft International Commission on the Biological Effects of Noise 1997 guidelines for reporting the results of combined socio-acoustic surveys of noise annoyance were developed. Census meshblocks were selected using random numbers to ensure that every household in a meshblock in the greater Auckland region had the same chance of being selected. A mail-drop pilot survey was implemented in August 1999 with 4000 questionnaires distributed to 1000 randomly selected households. The response rate was 435 responses from 416 urban households. The design of the questionnaire is presented in Annex B.

Of 424 respondents with an opinion, 38.6% found noise in the environment a problem; 10.8% did not have a problem and 48% sometimes had a problem. Only 30% of the respondents recorded their locality as being quiet or very quiet, 36.7% as moderately noisy, while 33.3% found their locality noisy or very noisy.

In response to the question “Does noise from your neighbourhood (not including from those living in your household) affect you?”, 41.4% said “yes” while reading, 55.2% while watching TV, 52.4% while in conversation, 56.1% while relaxing and 56.1% while asleep or attempting to get to sleep.

[29] Dr V. Hope (Manager) and Ms M. Owen (Project Coordinator) managed the project. Ms Owen developed the attitudinal surveys and instituted the work program and data analysis. My involvement was in an advisory role for the acoustical surveys.

The question “Are you ever disturbed or annoyed by noise at home (not including from those living in your household)?” was answered by 409 persons with 75.6% saying ‘Yes’ and only 18.4% saying ‘No’.

It is concluded from this attitudinal study that residents in Auckland are sensitive to noise in their environment, with a high number affected while trying to go to sleep or being disturbed from sleep.

7.4 Brisbane sound levels and attitudinal study

The Brisbane study considers whether soundscapes could be comparable between these two similar cities (Auckland and Brisbane). If there is similarity then a noise risk analysis decision process for one environment might be appropriate for the other environment.

7.4.1 Brisbane acoustical studies

Brisbane City has a population of approximately 1 million people and is a widely spread city with extensive road and rail networks. Large commercial centres are common-place and road traffic noise is a major issue. The widely spread nature and emphasis on lowest-highset residences and apartment building complexes is similar between the two cities, Brisbane and Auckland. In order to investigate the sound levels within a major city a set of 50 sound surveys were chosen at random from a database of approximately 1000 Brisbane urban surveys undertaken either by me or under my guidance since 2004. The surveys in Table 7.4.1.1 were chosen at random and extend across the whole of the Brisbane metropolitan area. The process for undertaking a site study starts with a request for a noise assessment. This follows a fairly standard format and involves setting up a sound monitoring station for 3 days’ on-site and recording sound levels every 15 minutes. The survey location is the part of the site most exposed to noise, whether from road, rail or commercial activity. Observations are made of the sound levels in the environment and the character assessed with octave or third-octave band analysis. The ambient sound character can be described as ‘smooth’ with ever present traffic noise hum. No modulating or beating noise sources were identified. Analysis is then made with respect to the occupancy of the building to be built (usually a residence or apartment building) and 10-year design period future sound levels modeled. The summarized data indicates the day-night (DNL or Ldn) levels in the city are in the order of 62.9 dB(A) ±5.7 dB(A). Between 5% and 20% (referenced to figure 2.9.1) of the exposed population will be highly annoyed by traffic noise at these levels. The issues, however, concern audibility of noise and amenity within the dwelling and outside in private open space.

A principal purpose of the review of the acoustical survey data was to investigate whether the use of the ‘day-night’ or ‘day-evening-night’ descriptors would be better for the decision making processes considered in this work. The day-night and day-evening-night descriptors have the advantage of methodologies for annoyance analysis. It is concluded that there is no significant difference between the day-night and day-evening-night descriptors in relation to Brisbane City. There is, however, a significant difference of 3.8 dB(A) between the sound levels of these two descriptors and the 24-hour LAeq sound levels, figure 7.4.1.1. On balance, the day-night descriptor is preferred because of the extensive research by others into its application.

Average maximum (L10) levels have been by shown by observation for this work to under-estimate potential annoyance from ‘peak’ levels of sound. In order to identify potentially annoying levels of sound a new definition was developed for the statistical measure ‘L01’:

> The L01 level is calculated as the noise level equalled and exceeded for 1% of the measurement time, for example 9 seconds in any 15 minute interval. L01 is an appropriate level to characterise single events, such as from heavy vehicle bypass. The measured L01 levels for day/evening/night are *not* averaged but are arranged from low to high in the relevant day/evening/night interval and the value that is found at the 90^{th} percentile (L10 of L01 sample) in the interval is recorded as its “L01” level.

The detailed summary results are presented to illustrate the variability in ambient sound levels between different locales and between times of day. For the purposes of this work the detailed information informs the design of the decision support system and is reported accordingly.

Table 7.4.1.1: Brisbane City ambient sound surveys, dB(A)

Record	Project		Day			Evening			Night		Ldn	Lden	24hr
		L10	L90	Leq	L10	L90	Leq	L10	L90	Leq			Leq
1	**807**	68.7	59.1	66.0	67.9	51.7	64.4	60.6	50.9	61.0	68.5	68.6	64.4
2	**835**	53.3	42.0	53.0	51.7	47.0	52.4	46.0	39.5	46.8	54.8	53.5	51.0
3	**836**	48.5	38.4	50.4	44.9	38.2	44.5	42.5	38.1	42.3	50.7	50.7	47.8
4	**843**	51.9	45.4	51.7	48.7	43.5	47.5	44.6	37.1	45.3	53.1	53.3	49.6
5	**844**	61.3	50.1	58.8	59.2	46.9	56.5	56.1	42.1	53.2	60.8	60.7	56.9
6	**869**	61.9	45.7	59.7	61.0	41.8	57.7	46.8	35.7	52.1	60.6	60.8	57.7
7	**875**	54.2	40.0	55.2	53.3	37.8	56.7	47.0	35.0	54.4	61.0	61.2	55.2
8	**891**	59.7	48.4	58.1	57.0	44.2	55.6	55.0	45.9	55.3	62.1	62.0	56.8
9	**894**	60.0	53.1	58.1	57.1	50.8	55.1	51.5	40.1	51.2	59.2	59.5	56.0
10	**896**	60.3	50.2	58.4	56.2	48.8	55.0	52.6	44.4	52.4	60.1	60.2	56.4
11	**885**	64.1	48.6	60.7	64.0	44.4	61.1	49.5	38.9	55.8	63.4	63.8	59.6
12	**919**	74.8	62.0	72.1	72.2	59.0	70.7	65.6	45.3	65.8	73.8	74.2	70.4
13	**924**	58.0	46.1	56.9	56.9	42.3	58.5	48.5	35.5	52.4	60.0	59.4	55.9
14	**932**	68.6	54.8	65.4	66.6	50.5	64.0	59.7	38.3	62.1	69.1	69.3	64.2
15	**939**	63.2	47.5	62.3	60.8	43.4	60.1	53.4	39.7	54.5	63.1	63.4	60.3
16	**941**	59.3	55.8	59.8	60.4	55.7	60.3	56.8	53.2	55.7	63.0	63.4	58.8
17	**951**	64.3	45.6	61.4	56.8	40.6	56.2	53.6	37.2	55.3	62.9	63.1	59.2
18	**957**	67.9	47.5	64.5	65.5	45.2	62.1	49.0	38.3	57.1	65.4	65.8	62.5
19	**966**	75.1	61.1	72.1	75.3	56.8	71.4	71.7	48.1	69.6	76.4	76.6	71.2
20	**967**	63.9	50.8	64.0	55.6	45.0	55.0	57.3	49.9	57.4	65.1	65.1	61.4
21	**969**	61.7	49.4	60.0	55.5	47.0	61.6	46.5	40.7	50.4	60.5	61.1	58.7
22	**976**	47.8	37.7	48.2	42.4	35.2	50.9	41.1	36.2	49.8	56.2	56.2	49.4
23	**980**	63.2	54.2	61.0	58.9	51.8	60.5	57.7	50.9	57.5	64.6	64.9	59.9
24	**981**	58.9	44.7	56.2	53.4	40.4	54.1	45.0	35.8	45.7	55.7	55.9	54.0
25	**982**	62.9	52.8	60.1	59.0	46.6	56.1	58.3	40.9	56.7	63.6	63.7	58.5
26	**985**	69.0	56.2	67.4	58.3	49.6	65.3	49.5	40.3	52.4	65.7	65.8	65.0
27	**990**	55.6	48.2	53.1	52.3	43.5	49.8	45.0	35.4	46.2	54.2	54.4	51.0
28	**992**	53.6	46.9	52.4	53.4	46.5	54.1	48.5	41.6	48.8	56.1	56.1	51.7
29	**1015**	53.4	47.0	54.4	53.4	48.4	52.7	46.7	42.4	50.2	57.4	57.5	52.9
30	**1027**	66.4	52.0	67.1	64.1	50.1	60.5	55.3	38.1	56.9	66.4	66.7	64.4
31	**1037**	54.7	48.3	52.7	48.8	43.5	47.3	44.0	38.4	45.6	53.6	53.7	50.3
32	**1072**	69.0	58.5	66.6	70.0	61.7	68.3	64.0	49.3	61.9	69.6	70.1	66.1
33	**1133**	66.9	54.3	65.6	64.3	50.2	64.1	53.8	41.4	59.1	67.1	67.5	63.9
34	**1178**	56.6	46.3	54.2	57.5	51.7	56.1	46.0	36.2	49.8	57.4	58.3	53.9
35	**673**	68.6	55.6	65.6	67.1	52.1	65.1	59.1	40.1	59.1	67.2	67.6	64.1
36	**1235**	66.3	52.4	64.0	64.2	49.5	60.5	60.6	43.3	58.0	65.7	65.7	62.0
37	**112**	74.0	66.7	71.7	72.7	63.1	70.4	68.6	52.7	65.9	73.6	73.8	70.0
38	**1251**	61.8	52.1	59.6	58.7	49.8	56.3	56.3	47.9	55.2	62.4	62.6	58.0
39	**203**	71.0	56.2	67.8	69.8	52.2	66.2	62.2	40.4	63.5	70.7	70.9	66.4
40	**664**	67.8	62.6	66.0	64.8	59.1	63.0	61.7	51.9	61.1	68.4	68.5	64.2
41	**799**	68.7	56.3	66.0	66.2	52.5	64.7	58.6	44.3	59.2	67.4	67.7	64.2
42	**887**	59.2	50.3	61.2	55.2	49.3	53.2	52.0	47.5	56.4	63.6	63.6	59.0
43	**910**	55.8	49.8	56.8	53.0	48.8	51.5	50.7	45.6	49.6	57.7	57.7	54.4
44	**952**	62.4	47.3	58.8	56.5	42.0	55.4	48.8	39.4	51.8	59.9	59.9	56.6
45	**971**	62.1	51.2	59.3	60.8	48.9	57.9	56.1	46.0	56.3	63.2	63.4	58.2
46	**977**	62.3	47.0	58.3	55.4	38.4	54.9	47.3	36.5	52.7	60.3	60.5	56.4
47	**1133**	66.9	54.3	65.6	64.3	50.2	64.1	53.8	41.4	59.1	67.1	67.5	63.9
48	**638**	70.3	55.3	67.2	69.4	47.6	65.5	60.2	35.1	62.3	69.7	69.8	65.6
49	**782**	54.7	45.5	54.1	54.4	44.1	59.5	51.1	43.3	49.6	57.8	59.4	54.8
50	**705**	61.9	56.0	60.7	60.6	53.0	58.9	62.0	51.2	60.5	66.9	66.8	60.4
Average		**62.2**	**50.9**	**60.6**	**59.5**	**48.0**	**58.7**	**53.6**	**42.2**	**55.0**	**62.9**	**63.0**	**59.1**
Std Deviation		**6.6**	**6.1**	**5.8**	**7.1**	**6.0**	**6.1**	**7.1**	**5.3**	**5.9**	**5.7**	**5.8**	**5.7**

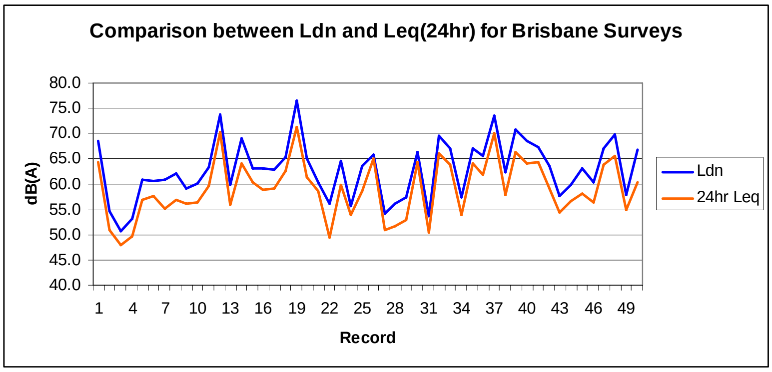

Figure 7.4.1.1: Brisbane City Ambient Sound Surveys, Ldn vs Leq(24hr), dB(A)

Figure 7.4.1.2 illustrates ambient sound levels within the city from representative residential and open-space locales. Observations and reference to the daytime equivalent continuous (LAeq) levels in Table 7.4.1.1 indicate that the levels as presented in the figure are at the upper range for noise levels expected at residential locations. 'Res1' is a residential location adjacent to a busy main road; 'Res2' is a residential location adjacent to a minor road; 'Central city park' is a park surrounded by roads, commercial and residential premises; 'Train and traffic' is a residential location near to an overhead train line and busy inner city streets; 'Train' is the same location as previously but with only train pass-by sound. The surveys indicate high levels of ambient sound, with equivalent continuous (LAeq) levels over 5 minutes as 72.0 dB(A) for 'Res1', 65.8 dB(A) for 'Res2', 53.4 dB(A) for the park, 65.6 dB(A) for train and traffic noise, and 72.0 dB(A) for the train pass-by. The levels are indicative of a 'noisy' city yet the attitudinal survey following indicates considerable satisfaction with the overall city environment.

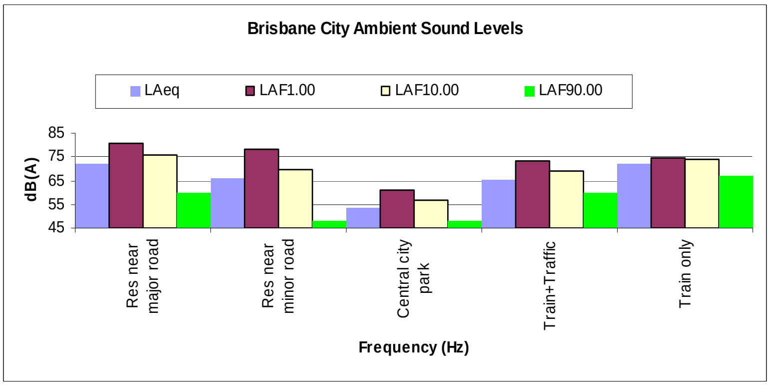

Figure 7.4.1.2: Brisbane City Ambient Sound Surveys, representative ambient sound levels at different locations

The levels in figure 7.4.1.3 illustrate the ambient sound levels in third-octave bands (Z-weighted) within the locales. The levels are presented in Z-weighting as these are the values referenced for audibility analysis.

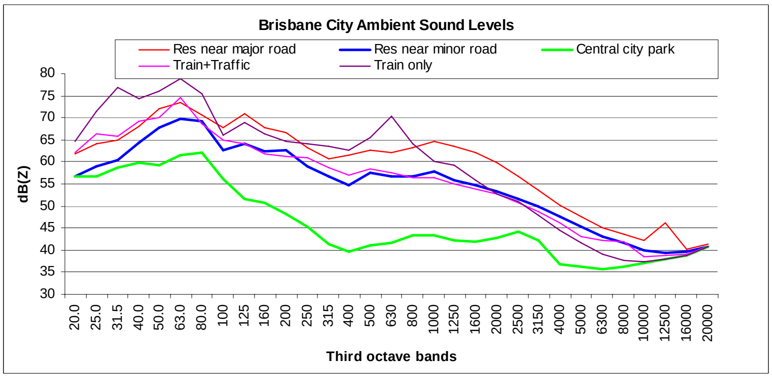

Figure 7.4.1.3: Brisbane City Ambient Sound Surveys, representative third-octave band sound levels (Z-weighting) at different locations

Further assessment was made with sound quality measures on the ambient levels and these are reported later in this work.

7.4.2 Brisbane City attitudinal study

In 1998 Brisbane City Council initiated a city-wide attitudinal study (unpublished[30]) into noise. Of the 450 responses 81% felt their neighbourhood was quiet, 13% thought noisy, and 5% were undecided.

In response to the question "In the past 12 months or so have you ever been bothered or annoyed by noise in your neighbourhood?" 47% said 'yes' and 53% said 'no'. In response to a question about whether the person was bothered more by noise from outside the dwelling, 20% said 'yes' to outside, 53% were more bothered by noise coming into the dwelling, and 23% felt there was no difference. Sensitivity to noise was answered by 37% who felt they were less sensitive to noise, 45% were neither more nor less sensitive, while 18% felt they were more sensitive.

In an earlier state-wide self-selected attitudinal response[31], of the 605 responses received, 62% of the respondents found that noise disturbed their sleep. Of the responses from Brisbane city, 72% felt their sleep was disturbed by noise. The city responses were very low (58) and are not seen as being typical of the city population as a whole. Conversely, it could be said that while people may be disturbed at home by noise from their neighbourhood, their overall environmental satisfaction out-weighed any particular sensitivity to noise as such.

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[30] Approval from Brisbane City Council to access the dataset is acknowledged, with thanks.
[31] Public responses to the draft Environmental Protection (Noise) Policy 1997.

The results of both these studies, plus the observations made during noise surveys, indicate that predicted levels of annoyance based on overseas studies and measured ambient levels, may not be appropriate for Queensland and Brisbane in particular, nor can the Brisbane studies readily transfer to New Zealand (Auckland).

7.5 Sleep disturbance investigation

Environmental noise impact assessments are often based on measured or predicted external sound levels and then extrapolated to ‘standard’ interior noise criteria. The intent of the interior noise criteria is to achieve a good standard of amenity for occupants and protect against (for example) sleep disturbance. The results of a series of simultaneous outdoor-indoor measured levels recorded in Brisbane during May 2001 are presented.

A first floor apartment 30 metres to a main road was chosen as the test site. The test rooms were 2 bedrooms directly affected by traffic noise. Traffic noise is very audible from an adjacent road intersection (Stewart Rd / Elimatta Rd carrying 40,750 vehicles/24 hr) as well as from a major road intersection (Waterworks Rd / Stewart Rd, carrying 20,000 vehicles/24 hr) approximately 250 metres away. The building is of brick veneer construction and the internal walls and ceiling are lined with 13mm plasterboard. The floor under the carpet is concrete. The slider doors to the balconies are of 5 mm glass in solid aluminium frames. The bedrooms under test are carpeted and each room contains a bed. The slider doors are not fitted with acoustic seals.

Acoustic Research Laboratory Model 315 type 2 sound level loggers were used to capture sound levels. The loggers have a bottom of range of approximately 25 dB(A). The recording locations are presented in Table 7.5.1. Each logger was calibrated before and after each survey and the shift in calibration was 0.2 dB(A) or less. At the start of the measurement session each logger was reset, re-calibrated and the date and time set by the analysis computer. The loggers were set on Fast response, 'A' weighting and set to record over time periods from several days (at 15 minute intervals) to 4-5 hours (at 1 minute intervals). The data in Table 7.5.2 is the average value of the 271 by 1 minute samples recorded. The façade location is 1.0m outside the relevant wall ('glazed' is BR1 glass slider door, 'solid' is BR2 balcony wall). Free-field is 3.5 metres from the building.

Table 7.5.1: Building noise attenuation microphone locations

1	3.5m outside the building in 'free-field' condition and approximately 3m above ground level
2	1.00m in front of midpoint of closed glass slider door and 1.23m above balcony
3	1.00m in front of solid balcony wall and approximately 4m above ground
4	1.00m in front of open slider door; 0.9m from front of (solid) balcony; 1.23m above balcony floor and 1.3m from balcony interior walls (centre of balcony)
5	Midpoint of open slider door; 1.23m above floor; the slider door was fully open (640mm x 2010mm)
6	Mid-bed position; 225mm above mattress and 300mm from wall (to simulate head position) slider door open

Table 7.5.2: Average values of 1 minute samples (dB(A)) by location

Location	LAeq	Lmax	L90
1	56.2	62.9	52.0
2	57.2	64.4	52.6
3	59.0	66.2	54.3
4	55.5	63.1	51.3
5	53.6	61.3	49.3
6	46.4	55.3	41.9

Façade level vs interior level (BR1 slider door open 150mm)

To assess the sound levels outside and within the bedrooms over a longer period of time a further series of recordings were taken with the slider door to bedroom 1 open 150 mm. Microphone positions are noted in Table 7.5.3. Two loggers were set running over various periods recording traffic noise levels at 15 minute intervals. The data in Table 7.5.4 are the average values of the 203 samples recorded.

Table 7.5.3: Façade vs interior microphone locations

2 outside	1.00m in front of midpoint of open (150mm) glass slider door and 1.23m above balcony
8 inside	2.0m from open (150mm) slider door, 1.23m above carpeted floor and 1.2m from nearest wall

Table 7.5.4: Average values of samples (dB(A)) - Bedroom 1 slider door open 150mm

Location	LAeq	Lmax	L90
2 outside	54.1	70.6	47.8
8 inside	38.9	55.8	33.0
Sound reduction	15.2	14.8	14.8

Façade level vs interior level (BR1 slider door closed)

The interior microphone positions are the same as in Table 7.5.3. Two loggers were set running over various periods recording traffic noise levels at 15 minute intervals. The data in Table 7.5.5 are the average values of the 204 samples recorded.

Table 7.5.5: Average values of samples (dB(A)) – Bedroom 1 slider door closed

Location	LAeq	Lmax	L90
2 outside	52.9	70.0	45.3
8 inside	28.6	45.9	25.5
Sound reduction	24.3	24.1	29.8

The standard deviation of the averages for the inside levels of Table 7.5.5 are LAeq ± 3.4 dB(A); Lmax ± 6.9dB(A) and L90 ± 1.2 dB(A). Observations at this survey location over 15 months is that one person was consistently disturbed (sleep awakening, annoyance) by traffic noise, especially in the early morning hours around 4 am. Doors remain open (even partially) for ventilation. Observed reaction to sound immission levels indicate that 'acceptable' interior traffic noise levels of 30 dB(A) LAeq and 45 dB(A) Lmax do result in sleep disturbance. This is primarily due to single event maximum noise levels (vehicle accelerating from traffic lights, vehicle deliveries at nearby supermarket) rather than the ambient (LAeq) sound level. Of the between 2 and 4 people in the apartment, over 15 months, only one person was consistently woken by traffic noise. This is a clear indication that one person’s sensitivity cannot be said to apply to others in a similar situation; nor that persons undisturbed by noise can be said to represent the population.

It is concluded that the World Health Organization's recommended guideline values of 30 dB(A) LAeq and a maximum level of 45 dB(A) in a bedroom do not apply to the 'most exposed receiver' but could be valid for the general population. This issue is the actual design measurement procedure for the maximum level. If the building interior is to contain a maximum level of 45 dB(A) then the average maximum will be considerably less; at least 7 dB(A) as indicated by this investigation. This and similar investigations have been taken into account in the design of the personal perception analysis presented later in this work.

7.6 Just noticeable noise investigation

The audibility of a sound is the primary precursor to annoyance. This investigation involved a distinctive sound that could be heard in the bedroom and living room, with windows closed. The sound was just audible inside the home. The source of the sound was from a local concrete factory approximately 750 metres distant from the residence. The factory was screened from the dwelling by the local topography. The residence is on a hill and the industry is approximately 100 metres lower and at right angles to the residence. The sound being investigated was a well defined 'rising hum' with a distinctive start and end cycle.

Instrumentation to measure the sound consisted of a 01dB Symphonie Class 1 dual channel sound card and dBBATI32 building and sound capture software. The 01dB system has a lower dynamic range to around 15 dB but could not record the sound sufficiently clearly for it to be analysed at the time. Subsequent analysis of the soundfiles with sound quality software dBSONIC was not able to clearly retrieve the noise under investigation.

The following excerpt from the interview with the homeowner (a professional musician and teacher) clearly states the issues with personal sensitivity to different sounds:

> The timbre link to sound is quite substantial and being involved in music there are all kinds of emotional ways to respond to any given sound. Muso's for many years have

talked about 'colour' in music and how tones have colour. In pictorial art terms, comparing a Jackson Pollock painting to a Mondrian. A pure tone can trigger a response in some people, such as those who have true or perfect pitch hearing sensitivity, as apposed to myself with relative pitch.

So, as an example, a plane flying overhead and away from you creates a sound which also goes through a Doppler effect where pitch lowers over distance/time. It’s something everyone hears and accepts but to some one with perfect pitch it can be almost agonising as the pitch and tone change passes through areas of their sensitivity that can be like your reaction to someone scratching their fingers down a blackboard. Those with perfect pitch can hear that sliding doppler effect as a series of notes. Those with relative pitch hear it as a sliding noise.

I have a friend with perfect pitch who is currently employed as the 'mastering' sound mixer. He has been in pain listening to some music where the recording, say, for want of the need to extend its radio time, has to be slowed down. So the pitch changes. This is not such a problem with digitally recorded stuff, but analogue is a different kettle of mackerel. To the guy with perfect pitch, it’s 'playing in the gaps'. He can hear that 'gap' as being somewhere between 'C' and 'C#"....awful! For me with relative pitch, I know its wrong and I can't tell you what note it actually is, but its 'WRONG" and the sound is hideous.

For me, my tolerance to loud music is very high but specifically if I enjoy the type/style and texture of the music. But if you were to isolate, say, a tenor sax and play its solo part loud, it may very well get a very negative reaction from me regardless of what notes are being played or what style. So for me it’s a multiplicity of components within the sound that I like. Otherwise known as 'ear candy' to muso's. If you were to compare a rock concert to a lawnmower...that’s the picture. Any number of muso's might give you a different story each but most certainly the colour of the sound is the difference between 'ear candy' and whatever else.

The important outcome from this investigation was the need to establish the design for high quality easy to use sound recording instrumentation to measure, and software to analyse, a low amplitude soundfile in a set standard format to identify audibility and noise intrusion.

CHAPTER 8: WIND FARMS AND THE MANAWATU STUDY

8.1 Wind farms and the Manawatu study

The second Environment Court Hearing that has informed this work is the Motorimu Wind Farm, Palmerston North. Prior to the Environment Court Hearing a series of acoustical surveys and attitudinal studies were undertaken. The studies were supported by the local community group, Tararua Aokautere Guardians Inc. The attitudinal studies included interviews with people living near existing wind farms and others living well away from wind farms. Some people living near the wind farms find noise a problem whereas others did not. The persons living away from the wind farms are in areas termed as being ‘greenfields’; that is, unaffected by the sound of a proposed activity.

Evidence for the Hearing was collected over a 4-month period within the Manawatu region, with extensive sound monitoring and analysis to better understand the mechanisms involved in low-amplitude sound and intrusive noise measurement and analysis with respect to sound from a wind farm. The Motorimu locality was not affected by wind turbines but Ashhurst approximately 24 kilometres to the north is affected. The Hearing presented the opportunity to investigate the effects of low amplitude sound and intrusive noise in a real situation and to design the decision support system and analysis methodologies accordingly.

8.2 Acoustical surveys – stage one

Four acoustical surveys at key residential locations on both sides of the ranges were undertaken using Larson Davis LxT Class 1 sound level meters. Three locations were affected by wind farms and one location was greenfields and unaffected by any wind farm. The purpose was to obtain background and ambient sound levels in third-octave bands and correlate the changes in levels attributable to a specific sound source, wind turbines. Statistical and third octave sound levels were recorded over 10-15 minute intervals (datasets) for approximately 4 to 8 weeks, depending on location. The summary data from the various surveys is presented in Table 8.2.1. The greenfield (RuralS) locale is rural environment with the residence unaffected by wind turbine noise. The Ashhurst (AshRes) locale is a residential location on the edge of a township. The locale is affected by wind farm noise. The RuralJN locale is a rural residence on the eastern side of the ranges. The RuralM locale is a rural residence on the western side of the ranges.

Table 8.2.1: Wind farm locale ambient sound level data, in dB(A)

Area	Time	Statistic	LAeq	L01	L10	L90	L95
RuralS	Day	Average	47.2	54.6	48.8	39.6	38.7
		sd ±	7.0	8.0	6.5	6.3	6.3
RuralS	Night	Average	40.0	46.3	40.8	34.0	33.5
		sd ±	11.4	12.4	11.4	9.8	9.6
AshRes	Day	Average	43.9	51.8	46.1	38.1	37.4
		sd ±	6.0	6.5	6.3	5.2	5.1
AshRes	Night	Average	35.8	42.7	37.7	31.5	31.0
		sd ±	6.4	7.8	6.9	5.3	5.2
RuralJN	Day	Average	47.1	54.6	48.8	40.0	39.2
		sd ±	6.5	7.7	6.4	6.4	6.4
RuralJN	Night	Average	38.3	45.1	40.3	33.0	32.5
		sd ±	8.0	8.9	8.2	7.7	7.6
RuralM	Day	Average	42.5	51.7	44.3	35.1	34.4
		sd ±	5.9	6.8	5.8	5.6	5.7
RuralM	Night	Average	36.3	44.1	38.1	31.2	30.6
		sd ±	8.5	9.5	8.2	8.0	8.0

Note: ‘sd’ is one standard deviation

The RuralS site recorded 3906 daytime and 2309 night-time datasets. The AshRes residence recorded 3347 daytime and 2064 night-time datasets. The RuralJN residence recorded 4993 daytime and 3026 night-time datasets and the Rural residence recorded 568 daytime and 370 night-time datasets. The data in figures 8.2.1 to 8.2.3 illustrates the character of the various environments, measured in third-octave bands, Z-weighted dB. The graphs illustrate the difficulty in determining potential audibility of ‘noise in sound’ with energy-average (Leq) levels, compared to using ‘minimum’ levels.

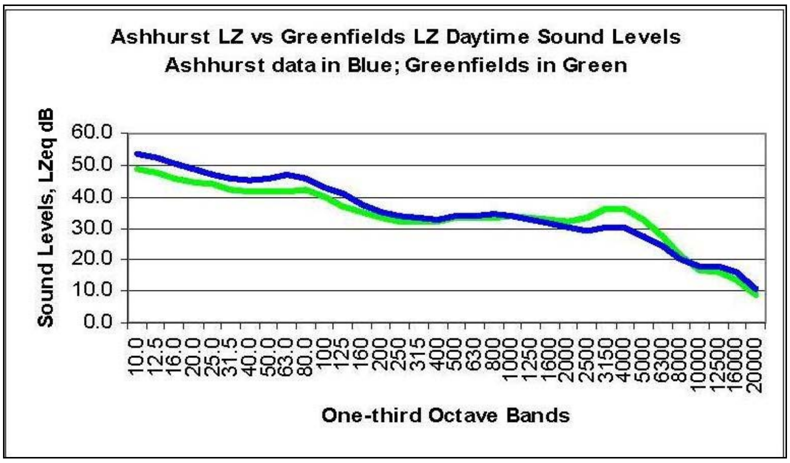

Figure 8.2.1: Ashhurst vs Greenfields Unweighted (Leq, Z-weighted dB) daytime sound levels (in third-octave bands, wind farm audible at Ashhurst)

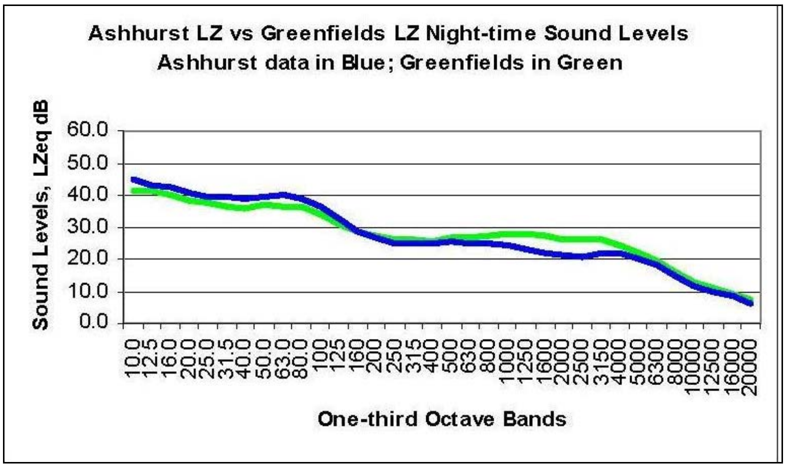

Figure 8.2.2: Ashhurst vs Greenfields Unweighted (Leq, Z-weighted dB) night-time sound levels (in third octave bands, wind farm audible at Ashhurst)

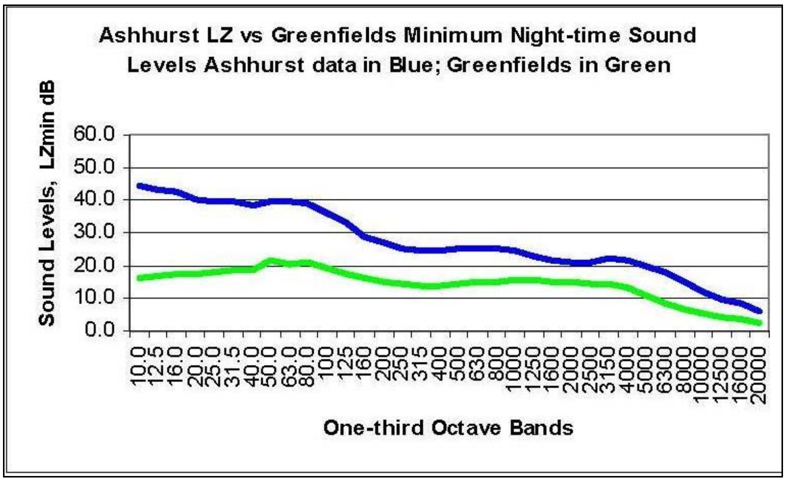

Figure 8.2.3: Ashhurst vs Greenfields minimum (Lmin, Z-weighted dB) night-time sound levels (in third octave bands, wind farm audible at Ashhurst)

The sound levels in any locale will vary through the day. This is due to increased activity within the environment and changes in wind conditions. The data in figures 8.2.4 – 8.2.5 is presented as the average and one standard deviation (sd) of the day (7am – 10pm) and night (10pm – 7am) time periods. It is not possible to separate out activity sound levels such as wind farm noise, from sound levels due to other sources.

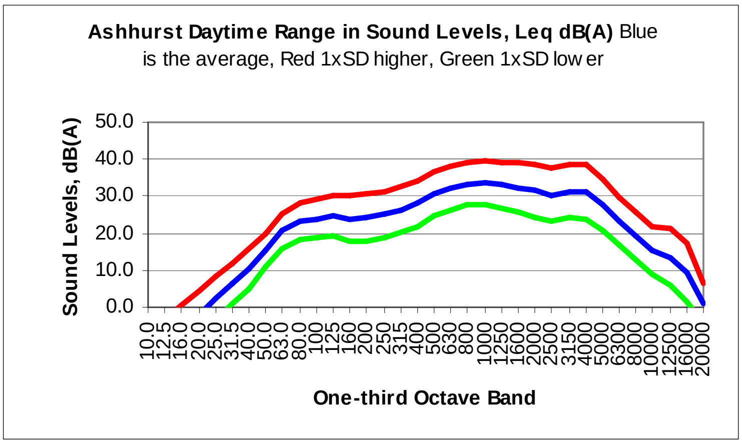

Figure 8.2.4: Ashhurst A-weighted (LAeq, dB) variation in daytime sound levels, in third-octave bands with upper and lower bands to one standard deviation, wind farm audible at Ashhurst

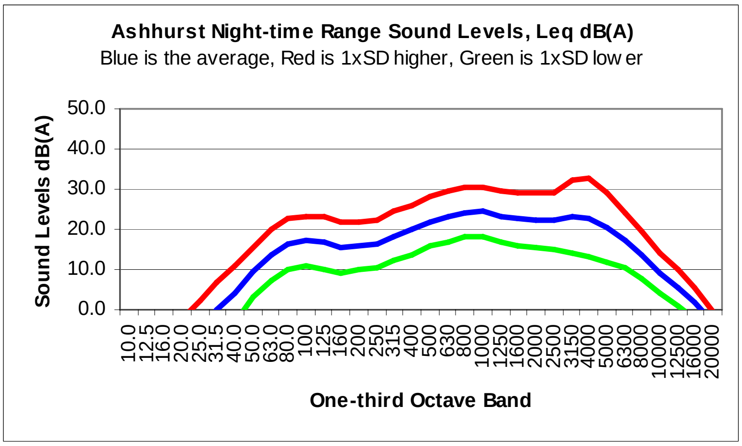

Figure 8.2.5: Ashhurst A-weighted (LAeq,dB) variation in night-time sound levels, in third-octave bands with upper and lower bands to one standard deviation, wind farm audible at Ashhurst

Figure 8.2.6 and Table 8.2.2 present a common approach to sound levels by illustrating the variability of sound levels over time. This locale illustrated is ‘AshRes’, the residential location at Ashhurst. The sound levels include ambient sounds as well as sound from the nearby wind farm.

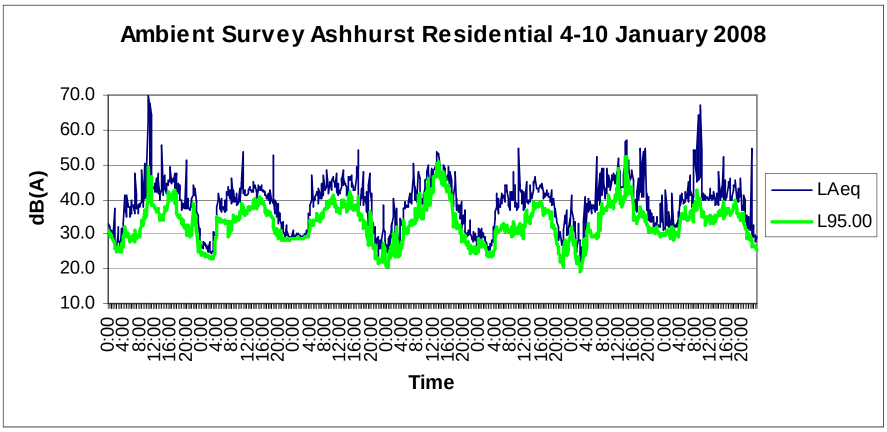

Figure 8.2.6: Ambient sound levels, Ashhurst residential, with quiet and 'noisy' nights

Table 8.2.2: Averaged ambient sound levels, Ashhurst residential

Date	Time	Leq dB(A)	L95 dB(A)
4 January	7 am – 6 pm	45.4	36.9
	6 pm – 10 pm	40.0	32.7
	10 pm – 7 am	32.9	28.6
5 January	7 am – 6 pm	42.0	36.3
	6 pm – 10 pm	36.2	30.8
	10 pm – 7 am	32.9	28.7
6 January	7 am – 6 pm	44.2	37.9
	6 pm – 10 pm	35.3	28.3
	10 pm – 7 am	33.4	30.4
7 January	7 am – 6 pm	45.6	41.0
	6 pm – 10 pm	34.1	29.2
	10 pm – 7 am	32.8	26.9
8 January	7 am – 6 pm	41.9	34.3
	6 pm – 10 pm	34.7	28.7
	10 pm – 7 am	32.1	27.3
9 January	7 am – 6 pm	45.7	39.2
	6 pm – 10 pm	39.5	32.7
	10 pm – 7 am	33.9	27.1
10 January	7 am – 6 pm	43.4	36.0
	6 pm – 10 pm	38.9	34.3
	10 pm – 7 am	36.3	31.8

Turbine noise at Ashhurst was recorded as being audible in the home on the nights of 4 and 9 January and audible outside the home on 10 January, all under strong easterly conditions. The background levels for these nights were in the range of 27-32 dB(A) with Leq levels in the range 33-36 dB(A). The Leq levels outside the home indicate interior Leq dB(A) levels in the order of 18-21 dB(A) for a timber framed home with light glazing and windows closed and 15dB attenuation through the fabric of the building. Sound levels vary depending on wind direction (easterly to south-easterly) and do not happen every night but cloud cover causes an increase in sound. The sound of the turbines at Ashhurst is a low-amplitude rumble with occasional “thumps” that are audible and attention-gaining. The figure and Table are not adequate to present the above information and it is concluded that, while the methods do have some validity for overall levels, they fail to identify the risk of noise annoyance due to special audible characteristics of sounds of interest.

In order to provide an analysis of the audibility of wind turbine sound some other form of measurement graphic is needed illustrate the character of the sound. Figures 8.2.7 and 8.2 8 illustrate what is termed a ‘waterfall’ plot of the sound levels in third octave bands over time (the chart on the left of each figure). A time-history chart is on lower right and a spectrum chart of the overall file is on the top right of the chart. Analysis is with SpectraPLUS. Additional information is given by the signal trace and the method presents the sound levels in a form that is visually more informative as to the character of the sound. The following two figures are from the same soundfile recorded at locale ‘RuralCafe’ on the eastern side of the ranges. (This locale will be discussed in more detail in the next section). The figures illustrate the loss of information in an A-weighted analysis compared to an unweighted analysis. The sound of the wind turbines was clearly audible at the locale over the existing ambient of bird song and very light breeze in trees.

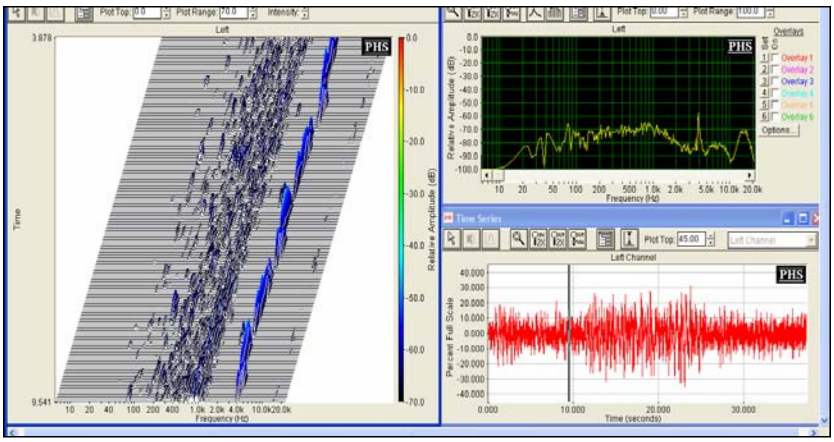

Figure 8.2.7: Locale RuralCafé spectrum analysis (A-weighted) of turbine noise in almost no breeze (near Woodville Ferry Reserve to east of range and screened by trees. Wind noise not evident. Levels at 4 kHz are due to bird song. Sound level Leq = 44.0 dB(A).

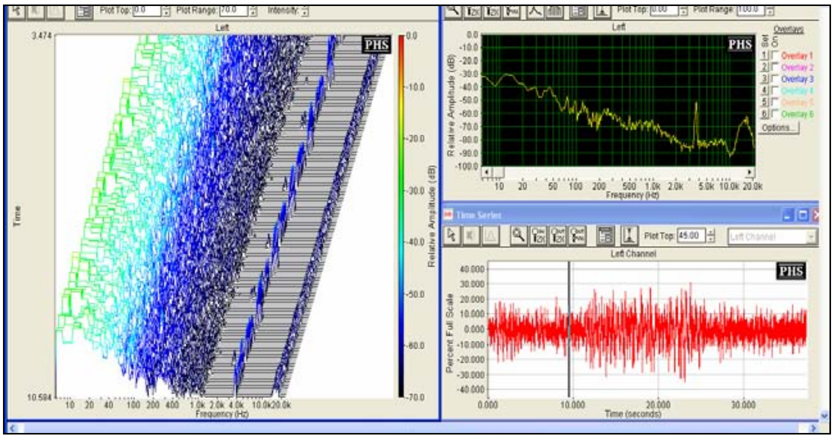

Figure 8.2.8: Locale RuralCafé spectrum analysis (unweighted) of turbine noise in almost no breeze (near Woodville Ferry Reserve to east of range and screened by trees, wind noise evident. Levels at 4 kHz are due to bird song. Sound level Leq = 44.0 dB(A).

Personal observations of the sound of the wind farms at Ashhurst and ‘RuralCafe’ is that the sound can be characterised variously as “ocean waves”, “rumble”, “boot in a dryer (rumble-thump)”, “chuffing”. The sounds appear to be in the low – medium frequency range of 200 to 800 Hz and the beating - modulation of the sound is clearly audible outside even with wind noise and noise of trees shaking in the wind. The difficulty in describing the sound, as well as being able to define frequencies of interest, is a significant issue with the analysis of wind farm noise in terms of low amplitude sound and intrusion characteristics.

Weather data was also recorded but correlation with the “noise events” was not possible as it was found that separate weather stations are needed at each locality. It is concluded from observations, interviews and measurements that:

- Wind farm noise can be intrusive in the home and is identified as low amplitude modulated sound (modulated in amplitude and frequency)
- The sound of wind turbines are clearly audible at distances of between 2000 metres and 3500 metres turbines-to-receiver to the extent that the sound can be recorded inside and outside a residence at these distances
- The sound of the turbines is not masked by wind or by wind through vegetation or leaf rustle in trees
- The ambient sound character in the absence of wind farm noise, and in the greenfield localities, is smooth wind in vegetation and animal (most often bird song) with no modulation effects

The overall conclusion from the investigations is that sound levels of wind turbines cannot be readily analysed from ambient levels using one-third-octave band analysis, with or in the absence of the turbines, at a residence 2500-3000 metres distant from the nearest wind turbine. The effect of this is that any decision support system relying solely on one-third-octave band analysis or time-history data will not be effective unless combined with other measures. It is concluded, however, that the 'waterfall' time-history form of graphical representation is helpful in describing the character of the overall soundfile and discrete parts of the sound.

8.3 Acoustical surveys – stage two

A second series of acoustical surveys were completed in a one-day period in June 2008 in association with a second series of attitudinal surveys. The purpose of the surveys was to obtain 'snapshots' of sound under near calm, clear weather conditions at representative sites in order to assess the character of the environment. The localities chosen represent previous survey locations RuralS (S), AshRes (A), RuralJN (JN), RuralM (M) with the RuralCafé (C) location approximately 1500 metres away from the original locale (previous section) to avoid people and traffic noise. Location (JA) represents a new greenfield location (RuralJA) at Turitea and (TA) is the Te Apiti turbine. At each of the rural and the one residential site a 120-second sound sample of the soundscape was recorded to be compared to the sound of the Te Apiti demonstration turbine. All surveys, except at Te Apiti, were taken with only natural sounds recorded; that is, breeze in vegetation and bird song. The soundfiles and concurrent sound level data were recorded into a Larson Davis 831 class 1 recording sound level meter. Each soundfile was recorded at a 16000 Hz sampling rate.

The wind farms were not audible at any of the locations (except Te Apiti); in the main the blades were either stationary or rotating slowly. The breeze at all sites was light with no leaf rustle. Vehicle and voice sounds were excluded as far as possible. The Te Apiti recording excluded all vehicle and people noise. The microphone was partly screened from the strong on-site wind and at a slight angle approximately 10 metres from the arc of the blade. Figure 8.3.1 illustrates the energy average (LZeq) sound levels and figure 8.3.2 illustrates the background levels. The wind turbine noise was predominantly a hum at 100 Hz and the swish of the blades.

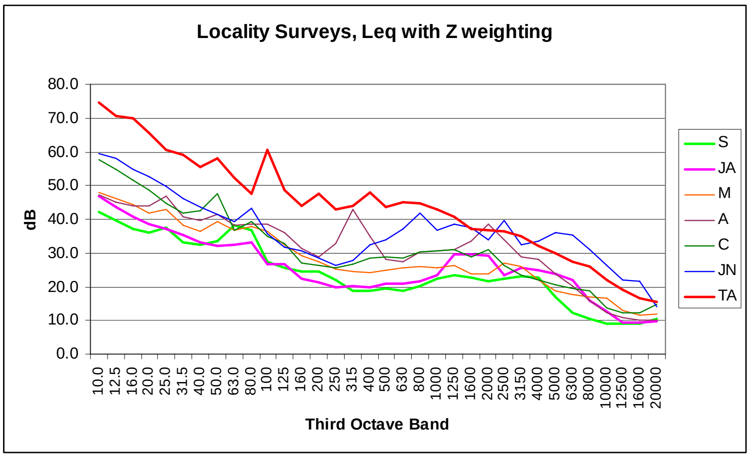

Figure 8.3.1: Manawatu locality surveys, Leq, Z-weighted dB

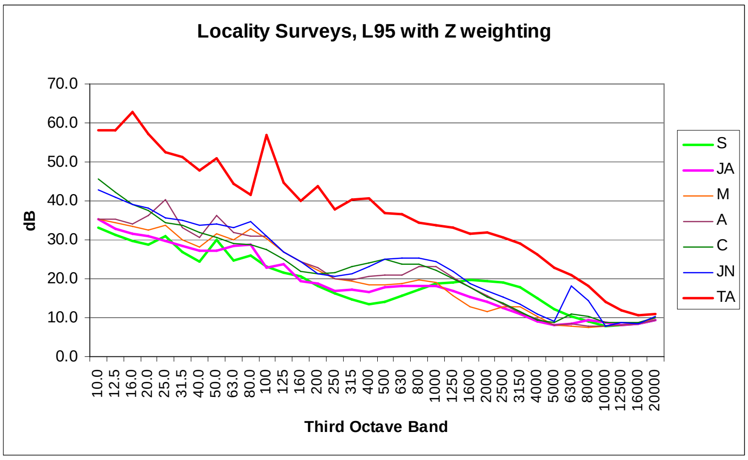

Figure 8.3.2: Manawatu locality surveys, L95, Z-weighed dB

The assumption was that all the locales would be very similar in character, with the possible exception of the residential locale and, of course, the Te Apiti site. The sound level curves are from the sound level meter's one-third octave band data storage. The analysis indicates quite significant variation between the locales, even though the general trend is the same. It is concluded, therefore, that analysis at one location cannot be inferred for another locale in the near vicinity under similar weather conditions. This is significant for a decision support system as it means that decisions made for one location based on that locations soundscape may not be transferable to a another location in the near locale. The soundfiles are further analysed in the next Chapter for their sound quality characteristics and potential for annoyance.

8.4 Cumulative noise effects of Manawatu wind farms

A noise impact assessment must consider the effects of the sources under investigation and of significant sources external to the application. The sound levels are compared to the soundscape of the existing environment. This is a fundamental requirement for the consideration of effects of potential and existing noise and to the acoustical risk-analysis process. As in the New Zealand Resource Management Act 1991, the approach explicitly requires consideration of:

- Any temporary, permanent or cumulative adverse effect
- Any potential adverse effect of high probability
- Any potential adverse effect of low probability and high potential impact

In the Manawatu the potential effect of all turbines within a locality must, therefore, be considered. Increases or variations of sound from a densely designed wind farm (that is, a wind farm with multiple rows and columns of turbines) may be due to sound aggregation from the vortices of two or more turbines appearing in-phase or slightly out-of-phase. The effects are temporary in time as wind speed and direction changes. This analysis is taken into account in the work into decision making processes with regard to potential adverse effect and the investigation into low amplitude intrusive sound analysis. The 'most-likely' cumulative effect in figure 8.4.1 is modeled with ground contours at 20 metres, sound levels calculated at receivers, overall noise contours interpolated within 1000 x 1300 metre grids and all predictions at 1.8 m above ground level. The 'most-likely' night-time scenario references turbine sound power levels (SWL Lin dB) modeled at "blade-tip" height as:

- Te Apiti: 55 Vestas NM72 turbines (113 dB), area A
- Tararua 1 and 2: 103 Vestas V47 (111 dB), area B/C
- Tararua 3: 31 Vestas V90 (118 dB), area B/C
- Te Rere Hau: 97 Wind Flow (111 dB), area D
- Turitea: 131 turbines modeled as the Vestas V90 (118 dB), area E
- Motorimu: 113 turbines (as applied for) Vestas V52 (113 dB), area F

The locale in figure 8.4.1 illustrates the locality in which the 'Manawatu' sound level and attitudinal studies were undertaken.

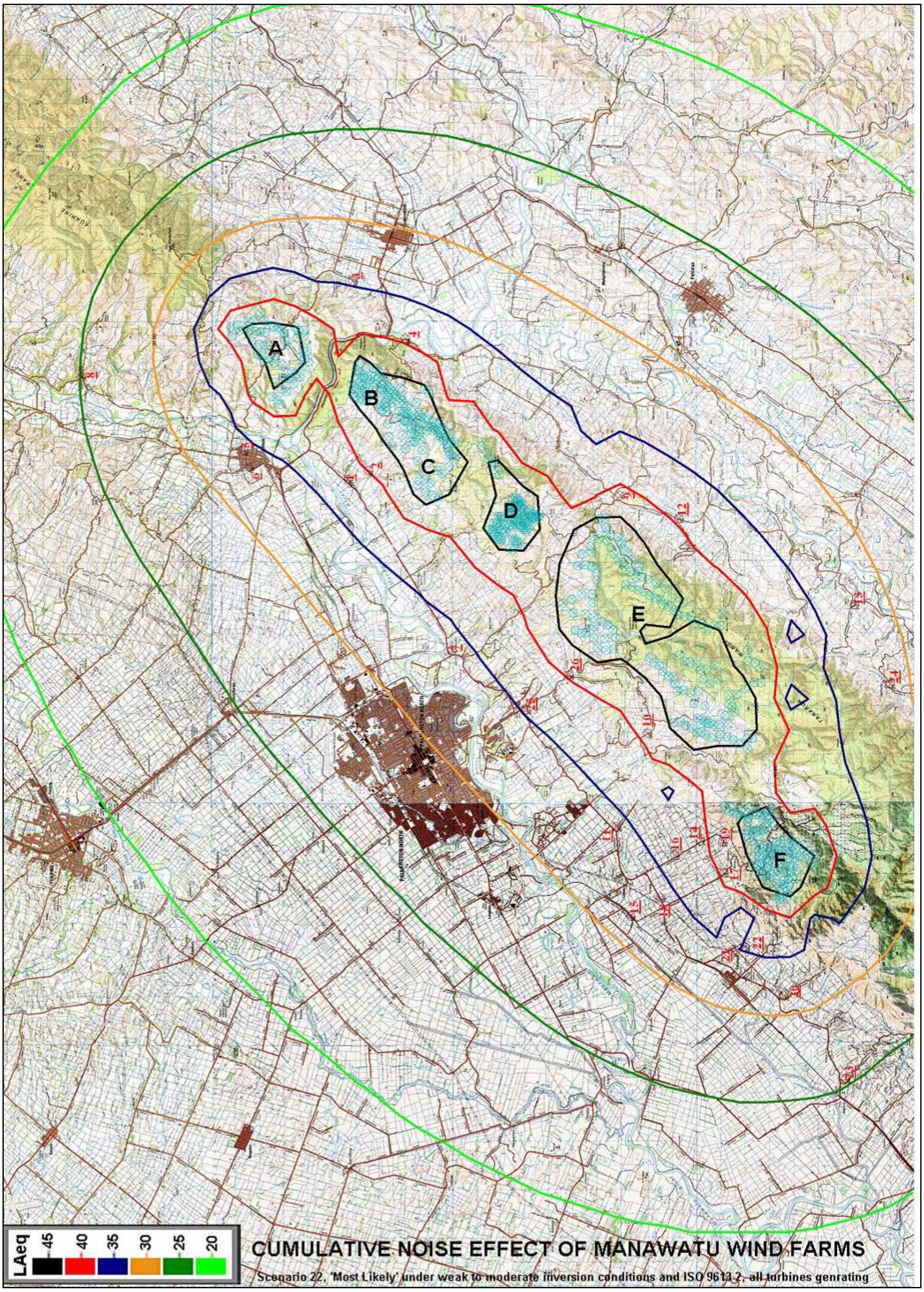

Figure 8.4.1: Cumulative noise effect of wind farms including Turitea within the Manawatu region

Note to figure: showing receiver locations (numbers), indicative sound level contours, turbines (blue crosses within the black contours) and farms (identified as A to F)). Turbine locations are taken from published data (except most of Te Rere Hau is not available)

The prediction model PEN3D implemented ISO 9613-2, temperature 10°C, relative humidity 50% and the specific atmospheric condition Pasquill Stability Category F for night with weak to moderate inversion conditions and a temperature gradient 2°C/100m. Table 8.4.1 presents the effect of the total network at representative receivers and sound levels in LAeq, 1hr. The predicted levels correspond well to the predicted contour locations in figure 8.4.1. Based on existing weather data, for the western side of the ranges (Tokomaru to Ashhurst), there were approximately 49 days of weather supporting adverse noise conditions. As a starting point for assessment, it is reasonable to assume that 13% of the weather experienced in the locality will support or promote adverse noise propagation from the wind farm network to any residence within 3000 metres of the nearest turbines. Under adverse conditions the predicted levels in Table 8.4.1 can increase. The potential increase is in the order of 3 dB(A) to 6 dB(A). Thus the level at ‘Receiver 1’, for example, may shift from 38 dB(A) to 41-44 dB(A). Similarly, the ‘40 dB(A)’ contour will extend further into the community to the position, approximately, of the ‘35 dB(A)’ contour. Not all receivers will be affected equally as not all levels will increase; some levels will decrease due to local topography and micro-climate conditions.

Table 8.4.1: Sound levels at receivers, all wind farms operational, weak to moderate inversion conditions

Receiver No	LAeq, 1hr	Receiver No	LAeq, 1hr
1	37.9	14	39.3
2	40.4	15	31.6
3	34.5	16	36.6
4	39.2	17	40.8
5	33.8	18	33.9
6	33.0	19	42.0
7	34.0	20	31.4
8	25.1	21	34.5
9	41.3	22	35.5
10	41.5	23	25.4
11	34.2	24	31.2
12	39.3	25	35.3
13	32.1	26	40.7

It is concluded that, referenced to the known background levels as reported in this work, the cumulative effect of all wind farms, proposed and existing, for the Manawatu will have a significant adverse acoustical effect that is more than minor on residents living within 2500 – 3000 metres of the wind turbines nearest to them.

8.5 Manawatu wind farm attitudinal studies

In addition to the investigations so far presented, two studies have been undertaken by others with respect to wind farm noise in the Manawatu. The studies were prepared as part of the evidence to the local authority consent hearings for the Motorimu wind farm in March 2007. The evidence presented by Mosley (2007) identified the effects of wind farm noise and vibration on houses at Ashhurst. The evidence of Phipps (2007) and Phipps et al. (2007) reported the results of a wind farm attitudinal survey conducted in the Manawatu – Tararua region.

The study by Mosley clearly presents the effects of wind turbines, under easterly wind conditions, on persons in the township of Ashhurst. Residences in Ashhurst are affected by noise and vibration from wind farm activity. Vibration is attributed to a typical turbine tower acting as tuning fork being ‘struck’ when the blade passes the tower and interacts aerodynamically with it. This effect is evident even when the blade is not turning and is due to wind effects on the tower. The vibration wave travels as a sub-surface wave with little attenuation. Persons who responded (22 in total) indicated their response to noise and vibration intrusion as different severity levels with 32% suffering sleep disturbance at the maximum severity level. Noise and vibration rated equally as the cause of sleep deprivation. Noise was not accompanied by vibration in 31% of the responses. In the course of his study and personal interviews Mosley found that not all residents were affected by, or even noticed, noise and vibration from the wind farms.

The study by Phipps presented the results of a random self-report wind farm attitudinal study in the greater Manawatu – Tararua district. A total of 1100 surveys were delivered and a response rate of 56% was achieved. All households responding to the survey were more than 2 km from operational turbines. The survey indicated that 52% of the respondents living 2 km-2.5 km from the nearest wind farm could hear wind farm noise. Responses were received from persons living at 3 km, 10 km and 15 km distant.

When asked about the frequency of hearing noise from turbines during the day, of 294 respondents 27% reported “never”, 64% “occasionally”, 8% “frequently”, and 2% “most of the time”. For the frequency of hearing noise from turbines at night, of 284 respondents 29% reported “never”, 58% “occasionally”, 10% “frequently”, and 3% “most of the time”.

As a measure of a reduction in quality of life, of 287 responses, 68% replied “never”, 18% replied “occasionally”, 13% replied “frequently’ and 2% replied “most of the time”. The response percentages are rounded up.

When asked to describe the sound of the wind farm of 592 replies responses included: “a train that never arrives” (128), “swish” (108), “hum” (90), “rumble’ (79), “low-frequency sound” (68), “storm in the ocean” (13), “noise makes my house vibrate” (12), “thumping” (12) and other descriptions such as “clothes in dryer”.

The studies illustrate the potential adverse effect from wind farms but also confirm considerable variability in responses. The responses required further investigation and the results are presented in the next Chapter.

8.6 Inter-relationship of the studies

The studies presented in the previous Chapter, this Chapter and the next Chapter present information essential to the development of a decision support system to integrate perceived noise with noise performance indicators, annoyance criteria and individual noise sensitivity. Analyses of the results of the attitudinal studies and noise sensitivity are presented in Chapter 10.

CHAPTER 9: NOISE SENSITIVITY AND SOUND PERCEPTION

9.1 Noise sensitivity studies

The investigations into attitudes and sound levels provide a basis for community assessment as well as some insight into individual responses, as evidenced by interviews and survey responses in the previous three Chapters. The investigations, however, needed to be informed about the attitudes and responses of individuals who were presently either exposed to low amplitude sound and intrusive noise or who were living in an environment where such distinctions are not wholly relevant. Noise sensitivity appeared to be a confounding factor. This is the presumption behind the purposive investigations in the Manawatu and Brisbane as presented in this Chapter. The investigations, combined with the previous research, led to question fundamental issues within existing decision support analysis methodologies. The investigations sought evidence to establish what measure of noise annoyance is appropriate for low amplitude sound and intrusive noise and the relationship, if any, of noise sensitivity to annoyance. In order to investigate the issues as outlined a set of attitudinal surveys were developed, Annexes C and D. Their purpose is to assist in the development of a psychometric questionnaire to measure an individual's attitudes and sensitivity to low amplitude sound, intrusive sound and noise. The first study (Annex C) investigated noise sensitivity using two standard questionnaires, a noise-annoyance questionnaire and an environmental questionnaire. The second study (Annex D) investigated noise sensitivity using the NoiSeQ questionnaire, a noise-annoyance questionnaire and a series of soundfiles to be critiqued. The second study was a development from the responses given in the first study.

9.2 Noise sensitivity vs. environment

The Manawatu – Brisbane Pilot Study was established as a focus survey with study offered to respondents to an earlier survey investigating wind farm issues. The Manawatu respondent's are determined as being an 'environmentally aware' population. This group was chosen on the basis that this segment of the research required responses from persons who had an interest in their environment and who would be willing to answer a lengthy questionnaire. The occupational status of the Manawatu group was not identified. It was anticipated that the Manawatu group would exhibit a wide range of noise sensitivities as the group was drawn from different ‘zones’ within the Manawatu: wind-farm affected urban and/or rural locales, and ‘greenfields’ unaffected by wind farms. A control group was selected in Brisbane. The Brisbane group was self-selected from invitations to musicians, teachers, lawyers and acoustical professionals. The Brisbane group was defined on the basis of previous investigations that indicated these occupations showed considerable attention to detail and focussed on issues more than ‘ordinary’ individuals. It was anticipated that this group would be significantly noise-sensitive.

The questionnaires and Zone map are presented in Annex C. The questionnaires are the LEF noise sensitivity questionnaire (Questionnaire 1); “Character of Sound” questionnaire (Questionnaire 2); a second character of sound questionnaire (Questionnaire 3, a variation on Questionnaire 2) and Weinstein’s noise sensitivity questionnaire (Questionnaire 4). Questionnaire 2 has only minor question variations to the Auckland study and is sufficiently similar to the Annex A study to provide a point of comparison to these earlier random surveys. A response of 69 replies was obtained to the Weinstein questionnaire; 57 in Manawatu and 12 in Brisbane. The other questionnaires were answered by 43 respondents; 31 in the Manawatu and 12 in Brisbane. The LEF noise sensitivity questionnaire (Zimmer & Ellermeier 1997, 1998, 1999) encompasses statements about a wide variety of environmental noises in a range of situations that affect the whole population. The authors state that for every item as score was assigned to each response item so that the higher its numerical value the more noise sensitive the respondent. The LEF ordinarily scores from 0 to 156 points (coding noted in the form) and four different factors (F1, Achievements and general attitudes; F2, Sleep; F3, Music and F4, Social and public context). On the basis of the questionnaire design information, the questionnaire has four questions marked as showing a higher degree of confidence for each of the factors. The LEF Questionnaire appears to have been superseded by a variant called the “Noise-Sensitivity-Questionnaire” (NoiSeQ). Unfortunately, the questionnaire was not available at the time the LEF and Weinstein questionnaires were distributed.

Weinstein Noise Sensitivity

Using the Kruskul Wallis H test there is a significant difference between the 4 zones in the Manawatu and the Brisbane control group. Table 9.2.1 tests for significance between the zones using Mann-Whitney U tests and a Bonferonni correction (p = 1-((0.95) ^ (1/9)) which scaled the alpha from 0.05 to 0.006. The null hypothesis is that there is no difference between the zones and the control.

Table 9.2.1: Weinstein Noise Sensitivity: significance by zone

Zones	*p*	Zones	*p*	Zones	*p*
1 vs 2	.45	2 vs 3	.401	3 vs 4	<0.001
1 vs 3	<0.001	2 vs 4	.329	3 vs control	<0.001
1 vs 4	.912	2 vs control	.383	4 vs control	.964
1 vs control	.894				

The analysis indicates that the null hypothesis is rejected for the respondents in Zone 3; that is, their responses are statistically different from the other zones and the control. The respondents in Zone 1, who were as salient as those in Zone 3, did not affect the outcome. The results, by zone, of the Weinstein Noise Sensitivity are presented in figure 9.2.1. All respondents to the survey are considered to be noise sensitive. This is an unexpected outcome from the study.

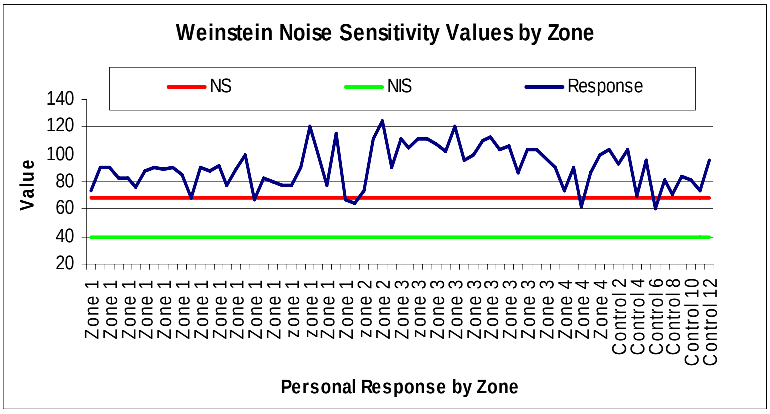

Figure 9.2.1: Weinstein Noise Sensitivity values by zone

Note: In his study Weinstein reported the group mean score for the noise sensitive (NS) group was 67.9, and the group mean score for the noise insensitive (NIS) group was 39.8

LEF Noise Sensitivity

In the LEF questionnaire, using the Mann-Whitney U test there is no significant difference between zone 1 and the control. This questionnaire is not adopted further.

Noise Annoyance

The responses to the noise annoyance questions indicate noise is sometimes a problem in both groups, with the local environment heard as being quiet / very quiet. The percentages in the responses have been rounded to the nearest whole number.

In response to the question "Do you find noise in your environment (including your home environment) a problem?" (Q.1) 65% within Manawatu have some experience of noise being a problem sometimes, 19% did not and 16% did find noise a problem. In the Brisbane group, 50% found noise a problem sometimes and 50% did not.

In response to (Q2) in the Manawatu 84% of the respondents recorded their locality as being quiet or very quiet, 13% as moderately noisy, while 3% found their locality noisy or very noisy. For the Brisbane group 67% of the respondents recorded their locality as being quiet or very quiet, 17% as moderately noisy and 17% found their locality noisy or very noisy.

In response to "Are you ever disturbed or annoyed by noise at home (not including from those living in your household?" (Q.5) 71% within Manawatu said 'Yes' while 29% said 'No'. In the Brisbane group, 83% said 'Yes' and 17% said 'No'.

The question "does noise affect you while..?" (Q.4) provided a range of responses, Table 9.2.2. Noise during relaxation and sleeping causes the most affect.

Table 9.2.2: Responses to 'Does noise affect you while…'

Locale	Reading		Watching TV		Listening Talking		Relaxing		Sleeping	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Manawatu	13%	87%	13%	87%	13%	87%	48%	52%	52%	48%
Brisbane	33%	67%	33%	67%	25%	75%	50%	50%	25%	75%

Questions concerning the character of the sounds within the local environment were answered mainly by the Zone 1 respondents (27 of the Manawatu total of 32). This zone is affected by wind turbines and is partly 'residential' urban and partly rural. The Brisbane group (12 of 12 responses) are from a completely urban environment. figures 9.2.2 – 9.2.4 present the responses of the survey. The Brisbane group responses are adjusted by *2.25 to allow direct comparison to the Manawatu responses.

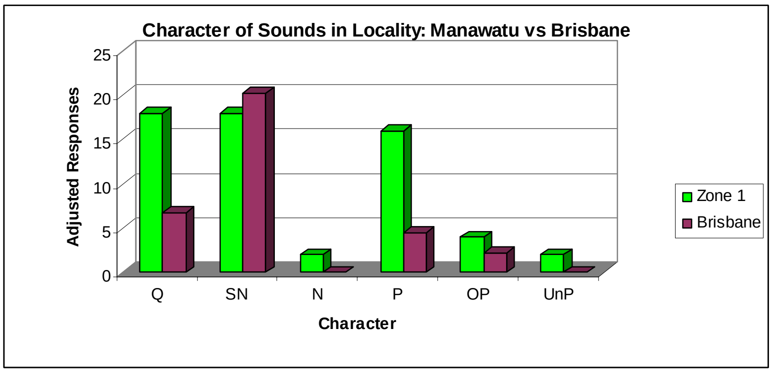

Figure 9.2.2: Character of the environment, Manawatu vs Brisbane

Key: (Q) quiet, (SN) sometimes noisy, (N) noisy, (P) pleasant, (OP) often pleasant, (UnP) unpleasant.

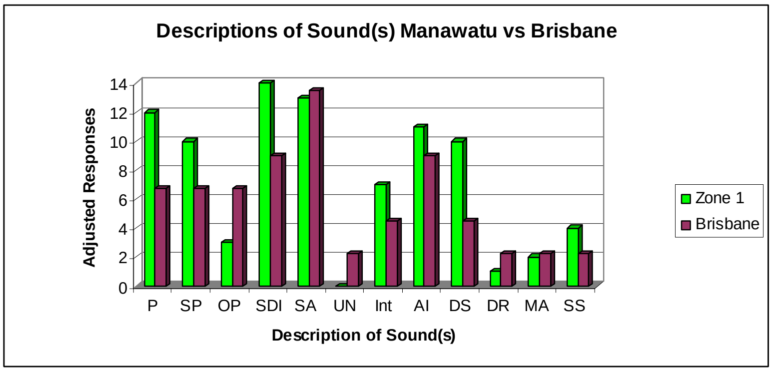

Figure 9.2.3: Description of sound(s) in the environment, Manawatu vs Brisbane

Key: (P) pleasant, (SP) sometimes pleasant, (OP) often pleasant, (SDI) sometimes disturbing/irritating, (SA) sometimes annoying, (UN) ugly/negative, (Int) intrusive, AI (able to be ignored), (DS) disturbs sleep, (DR) disturbs rest or conversation, (MA) makes the respondent anxious, (SS) the respondent is sensitised to a particular sound.

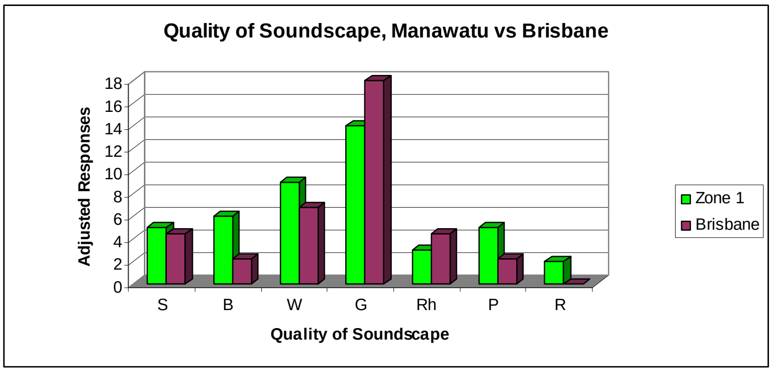

Figure 9.2.4: Qualities of Soundscape, Manawatu vs Brisbane

Key: (S) smooth, (B) bright, (W) warm, (G) gentle, (Rh) rich, (P) powerful, (R) rough

In describing a sound clearly noticeable when at home, 39% of the Zone 1 respondents replied with "repetitive hum". The source was not identified in all responses but the source mentioned most often was from wind turbines. The turbines were described, overall, as being heard within a pleasant, gentle soundscape; they were sometimes disturbing, irritating or annoying but able to be ignored except for occasions when the sound disturbed sleep.

It is concluded from the survey that there can be considerable difference between populations in perception to similar sounds. This is explored further in the next section.

9.3 Noise sensitivity vs. specific sounds

The responses from the previous study indicated further investigation into individual noise sensitivity, the quality of the environment and individual responses to specific sounds was desirable. A new noise sensitivity questionnaire (NoiSeQ), a slightly revised annoyance questionnaire and set of soundfiles were presented to individuals in Manawatu and Brisbane. The questionnaires and analysis are presented in Annex D. The Manawatu focus group of 13 persons were self-selected by invitation from the previous Manawatu study. Approximately 50% of the group was from Zone 1 and 50% from Zone 3. The Brisbane group of 14 persons were self-selected by invitation from a group of people interested either in music or in acoustics. Individuals in this group may or may not have an interest in environmental issues. It was concluded that this is an acceptable component within the study design. The “Annoyance” questionnaire is included for consistency in application of the surveys. The survey was circulated by means of meetings in Manawatu and Brisbane and copies of the soundfiles and questionnaires distributed to persons interested in participating.

9.3.1 NoiSeQ Noise Sensitivity

The NoiSeQ noise sensitivity questionnaire is divided into an overall scale and subscales. The subscales are communication, habitation, leisure, sleep and work. The sensitivity of the respondents can vary depending on the subscale being measured. Higher values indicate higher noise sensitivity. This study is referenced to the German version of the NoiSeQ and the survey was analysed[32] to categorize respondents into more than average, average and less than average noise sensitive persons, Table 9.3.1. Average, in the context of the questionnaire design, is the range expressed as the median value ± the confidence interval. The confidence interval has been determined from the German decision study.

Table 9.3.1: NoiSeQ Noise Sensitivity: median and confidence intervals

1st test	Comm’n	Habitation	Leisure	Sleep	Work	Overall
Median	1.14	1.43	1.36	1.29	1.64	1.37
CI (p=.05)	± 0.55	± 0.56	± 0.68	± 0.56	± 0.56	± 0.26
CI range	0.59-1.69	0.87-1.99	0.68-2.04	0.73-1.85	1.08-2.2	1.11-1.63

The results in Table 9.3.1 take into consideration the confidence interval for the different scales and the respondents are classified using the confidence interval range around the median. As there are two different groups (Manawatu and Brisbane) a test was required to check whether both groups are compatible or equivalent with respect to the noise sensitivity. The confidence interval is the tolerable difference. The equivalence test of the two groups with respect to global noise sensitivity shows the

[32] The survey was analysed by Dr Schütte referencing a decision study (D study) of 288 persons in Germany to establish the range of sensitivities. The calculation procedure for the confidence interval is found in Cardinet, J, Tourneur, Y & Allal, L 1976 *The symmetry of generalizability theory: Application to educational measurement*, Journal of Educational Measurement, 13, 119-135.

groups are not compatible with respect to this characteristic. Further testing was taken on the overall scales and subscales with Mann Whitney U with alpha = .05 to test if there is a significant difference between the two groups in respect to mean rank. Table 9.3.2 presents the test of significance difference between the Manawatu and Brisbane groups.

Table 9.3.2: NoiSeQ Noise Sensitivity: significant difference between groups

1st test	Comm'n	Habitation	Leisure	Sleep	Work	Overall
$p<0.05$	NS	*	*	*	NS	*

Key: (NS) not significant, * significant (the value of p for 'overall' is .019)

It is concluded that a statistically significant difference exists between the mean ranks of the Manawatu (M) and Brisbane (B) groups. The differences appear in the noise sensitivity rankings of the groups, Table 9.3.3 and figure 9.3.1 as more than average, average and less than average.

Table 9.3.3: NoiSeQ Noise Sensitivity: sensitivity by rank and group as percentage

Noise Sensitivity	Comm'n	Habit'n	Leisure	Sleep	Work	Overall
M: >average	92%	69%	54%	69%	31%	85%
M: average	8%	31%	46%	15%	69%	15%
M: <average	0	0	0	15%	0	0
B: >average	71%	50%	21%	21%	14%	64%
B: average	29%	43%	79%	57%	86%	28%
B: <average	0	7%	0	21%	0	7%

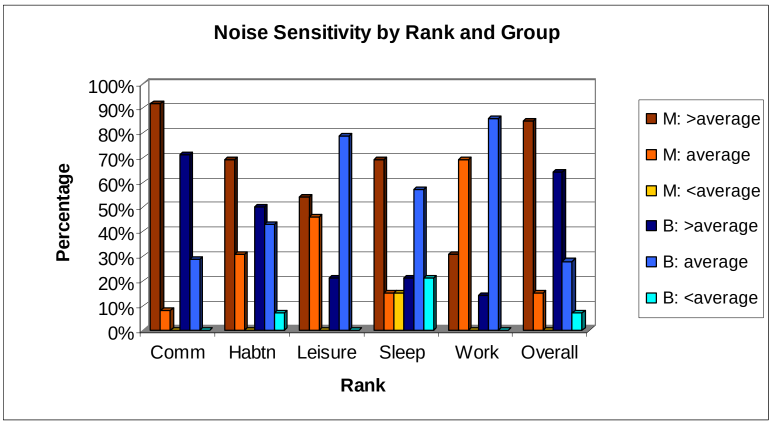

Figure 9.3.1: NoiSeQ Noise Sensitivity: sensitivity by rank and group as percentage

9.3.2 Noise Annoyance

The responses to the noise annoyance questions indicate noise is sometimes a problem in both groups, with the local environment heard as being quiet / very quiet. The percentages in the responses have been rounded to the nearest whole number.

In response to the question “Do you find noise in your environment (including your home environment) a problem?” (Q.1) 62% within Manawatu have some experience of noise being a problem sometimes, 15% did not and 23% did find noise a problem. In the Brisbane group, 43% found noise a problem sometimes, 43% did not and 14% did find noise a problem.

In response to (Q2) in the Manawatu 84% of the respondents recorded their locality as being quiet or very quiet, 15% as moderately noisy and nil found their locality noisy or very noisy. For the Brisbane group 86% of the respondents recorded their locality as being quiet or very quiet, 14% as moderately noisy and nil found their locality noisy or very noisy.

In response to “Are you ever disturbed or annoyed by noise at home (not including from those living in your household?” (Q.4) 85% within Manawatu said “Yes” while 15% said “No”. In the Brisbane group, 64% said “Yes” and 36% said “No”.

The question “does noise affect you while..?” (Q.3) provided a range of responses, Table 9.3.4. Noise during relaxing and sleeping causes the most affect.

Table 9.3.4: Responses to ‘Does noise affect you while…’

Locale	Reading		Watching TV		Listening Talking		Relaxing		Sleeping	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Manawatu	8%	92%	0	100	15%	85%	31%	69%	31%	69%
Brisbane	29%	71%	0	100	7%	93%	36%	64%	7%	93%

It is therefore concluded that there are significant differences between the two groups, not only in noise sensitivity (which is a personality trait) but also in perception and responses to similar situations. The responses to the characteristics of different sounds investigated as part of this study are presented in the next section.

9.4 Sound perception

Two studies were undertaken in order to establish how individuals perceived a selection of sounds. This analysis is utilised in determining methods of measurement or assessment for the specific characteristics of each sound. The sound is given character or characteristics and these are correlated to significant acoustical, musical and sound quality measures.

9.4.1 Soundfiles to identify characteristics

An outcome of the observations and interviews of the previous studies indicated a need to establish a baseline reference point with sounds of known characteristics that could be reviewed by any person at any time. The purpose was (and is) to identify the perceptions of the sound as experienced by the person listening to the sound. The study was expanded by presenting a series of environmental sounds or 'soundfiles' to be judged by the respondents. The detail of the soundfile questionnaire is presented in Annex D. Each soundfile was recorded at a sampling rate of 44100Hz, 16 bit, mono and saved in Microsoft PCM .wav format. The reference soundfiles are:

1: Amplitude modulated fluctuating noise (Salford)
2: Ashhurst2Febafternoon (includes ambient and wind farm sound)
3: Building component clicks
4: Café Wind Turbines1Feb
5: NoiseLab031asC3
6: NoiseLab032asC4
7: NoiseLab071asC6
8: Pink noise 5Hz to 20kHz
9: Rough noise (Salford)
10: Sharp noise (Salford)

11: Wind turbine noise simulation

12: A calibration tone sequence of 440Hz at -2.5dB and -12.5dB; then 1000Hz at -2.5dB and at -12.5dB. Each individual tone is 1.5 seconds in duration.

In the context of the research, ‘simulation’ means a soundfile that is recorded by using a sound recording program to layer-in one or more different sounds. This process allows the recorded soundfile to be strictly controlled as to spectrum content and amplitude. A large number of supplementary soundfiles were created in the process of the work; including pure tones, sweep tones, stepped tones, highly impulsive sounds, music examples, wind turbine, urban and rural soundscapes. The reference soundfiles do not include music due to potential copyright issues. The characteristics of the individual research soundfiles are:

- Soundfiles 2 and 4 are real ambient sounds recorded to present the character of wind turbine and ambient sounds. These two soundfiles are the most important in the library as they illustrate modulated sound that is close to threshold of hearing but is highly audible.
- Soundfiles 1 and 9 are from the Salford University Sound Quality library and present sounds with distinctive modulation that can be classed as dissonant.
- Soundfile 3 has distinctive sharp, impulsive sound due to ‘stick-release’ movement of a steel pin inside a steel housing. The fastest click has a rise time rest to maximum amplitude of 10 ms and the decay time to rest is 200 ms, with standard clicks around 30-50 ms rise and 300 ms decay.
- Soundfiles (SF) 5, 6 and 7 have been referenced from the NoiseLAB library and have tonal features. These soundfiles are identified within ISO1996 for tonality features; SF5 tones at 150, 990 and 4000Hz; SF6 tones at 330, 400 and 471 Hz; SF 7 contains frequency modulated tones at 690-760 Hz.
- Soundfiles 8 and 10 are from the Salford University Sound Quality library and present sounds that have hissy and sharp characteristics.
- Soundfile 11 has modulation and a distinctive tonal characteristic at 800 Hz. This soundfile is a simulation of wind turbine noise and in stereo format presents the effect of two sounds from a similar source arriving with a slight delay. The beat is highly noticeable.
- Soundfile 12 is the calibration soundfile at 440 Hz and 1000 Hz. The step in

level between similar tones is 10 dB (high-low). The tones therefore vary significantly both in amplitude and frequency modulation.

The calibration tones (e.g., 1000Hz or 440Hz) are classified as stationary signals; that is, sounds whose average properties do not vary with time. Stationary signals can be deterministic (such as the single frequency calibration tones) or random (such as the pink noise calibration signal). In the case of a random signal the output is determined as a statistical measure, such as the mean value. Speech and music, however, are classified as continuous non-stationary signals. Impulsive sound is classified as transient non-stationary signal(s). The soundfiles present or illustrate features that are important to this research: modulation or roughness, sharpness or smooth sound, impulsive sound, tonality and soundscapes of a highly complex nature. Testing of the soundfiles was undertaken with 01dB's dBSONIC and dNFA32, NoiseLAB3 and PsySound2. A test for roughness was made by the Vassilakis[33] method. Each soundfile was analysed to form data arrays and overall data values so the reference soundfiles could be independently analysed and cross-checked.

9.4.2 Manawatu vs Brisbane Perception of Soundfiles

The soundfiles were presented to the two groups in different ways. The Manawatu group heard the soundfiles together as a listening panel and the Brisbane group heard the soundfiles individually in their own home. The investigation tests the effectiveness of the two approaches as future perception studies would, of necessity, be undertaken by individuals in their own home. The soundfiles are recorded at a level where the sounds can be heard clearly at approximately Leq = 55 dB(A) at the ear. Some characteristics, such as the fluctuating sounds in soundfiles 2 and 4 need to be slightly louder but this does depend upon the hearing of the person. The Manawatu listening panel had the first set of soundfiles played at Leq = 55 dB(A) but this level within a room was found to be too low and the level in a second series was played at Leq = 65 dB(A). As the soundfiles are recorded at different levels the individual does need to adjust the volume. It was the character of the sound that was under review, not the 'loudness' of the sound. The character or characteristics of the sounds as

[33] Soundfiles for analysis uploaded to http://musicalgorithms.ewu.edu/algorithms/roughness.html

perceived by the respondent's are presented in figures 9.4.2.1 to 9.4.2.12. The responses are recorded as percentages.

The Manawatu focus group of 13 persons were self-selected by invitation from the previous Manawatu study. Approximately 50% of the group was from Zone 1 (residential township and rural affected to some degree by wind farm noise) and 50% from Zone 3 (a rural area unaffected by wind farm noise). The Brisbane focus group of 14 persons were self-selected by invitation from a group of people interested either in music or in acoustics and who lived in the urban environment of Brisbane City. Individuals in this group may or may not have an interest in environmental issues. For the purposes of the study "focus group" means that the group had an interest in environmental issues possibly greater than the population generally.

The Manawatu group had the benefit of discussion concerning the sounds but all responses were made independently. The Brisbane group was not made aware of the nature of any of the soundfiles apart from the soundfile title.

The perceptual responses help to characterise the groups of sounds investigated for individual response. A significant outcome is shown in the perception of wind farm noise between the Manawatu and Brisbane groups. The Manawatu group has a negative outlook to the sounds while the Brisbane group are not negatively inclined towards wind farm noise. This has two possible explanations: the Manawatu group has an unbiased negative response due to pre-knowledge and environmental awareness. Or, the group has a biased negative response due to pre-knowledge and environmental awareness. Either way it would suggest that any attitudinal study that asks questions concerning environmental modification (whether wind farm, waste dump or any other similar industrial activity) must be significantly biased if the respondents have no first-hand experience of the activity.

Further discussions with colleagues from different countries indicate a significant cultural influence into the acceptance or rejection of noise in the environment. The decision process findings with respect to the Manawatu and Brisbane studies recognise this 'enviro-cultural' influence. An integration mechanism is not defined within this work.

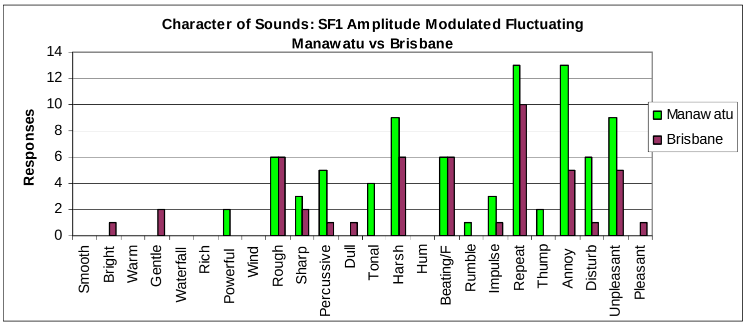

Figure 9.4.2.1: Responses to the character of soundfile 1

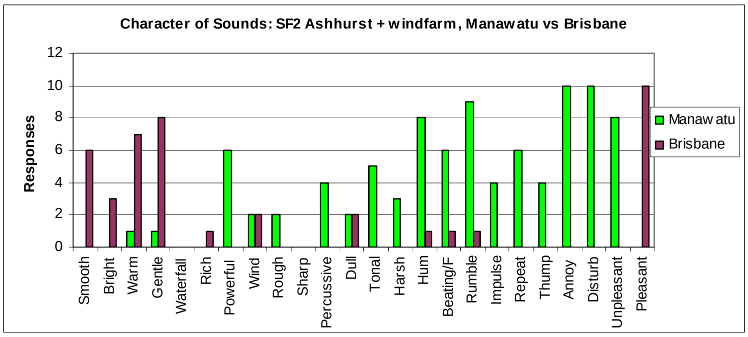

Figure 9.4.2.2: Responses to the character of soundfile 2

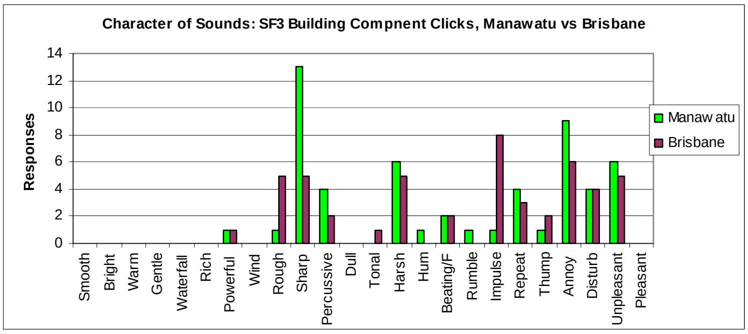

Figure 9.4.2.3: Responses to the character of soundfile 3

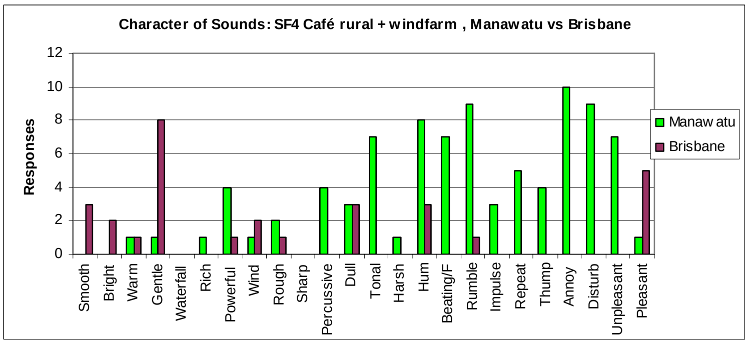

Figure 9.4.2.4: Responses to the character of soundfile 4

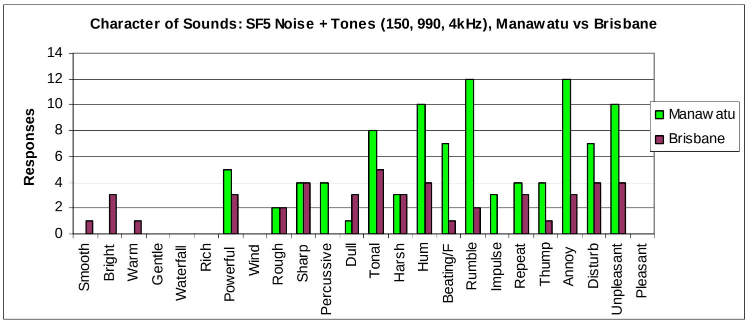

Figure 9.4.2.5: Responses to the character of soundfile 5

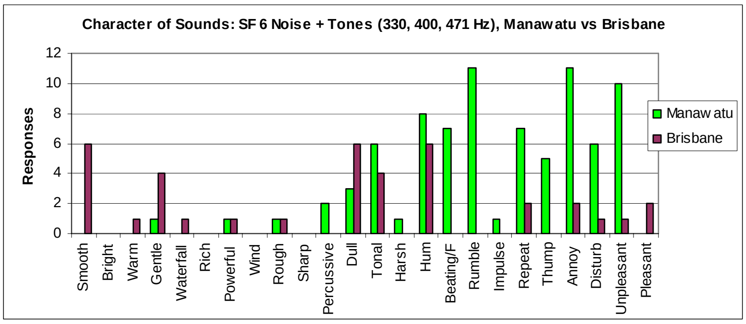

Figure 9.4.2.6: Responses to the character of soundfile 6

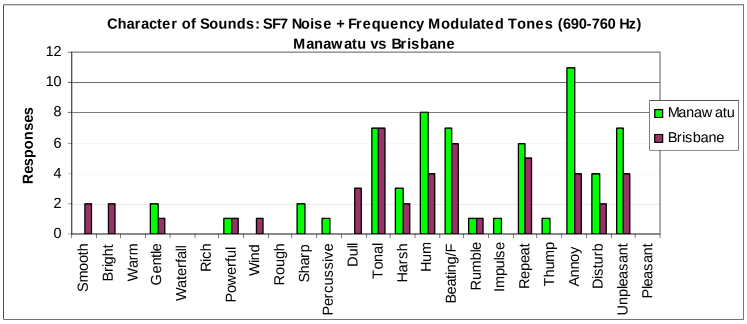

Figure 9.4.2.7: Responses to the character of soundfile 7

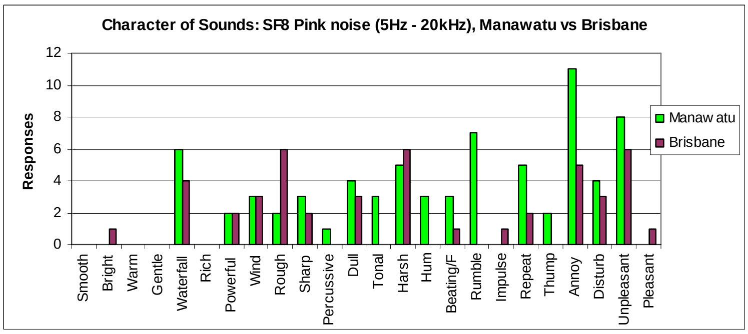

Figure 9.4.2.8: Responses to the character of soundfile 8

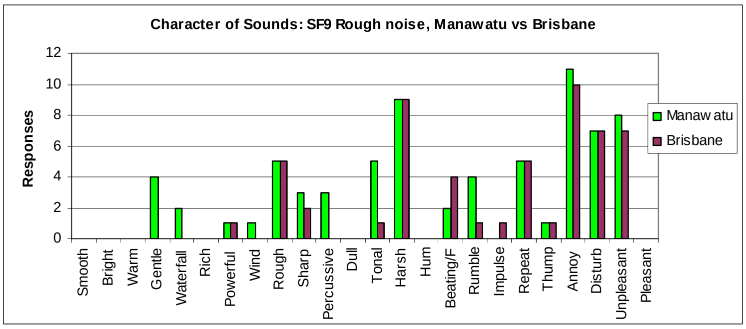

Figure 9.4.2.9: Responses to the character of soundfile 9

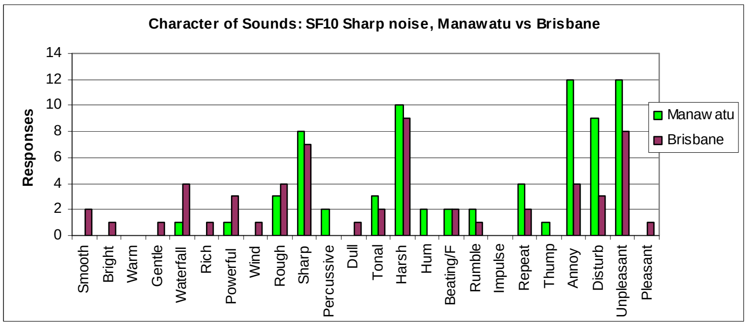

Figure 9.4.2.10: Responses to the character of soundfile 10

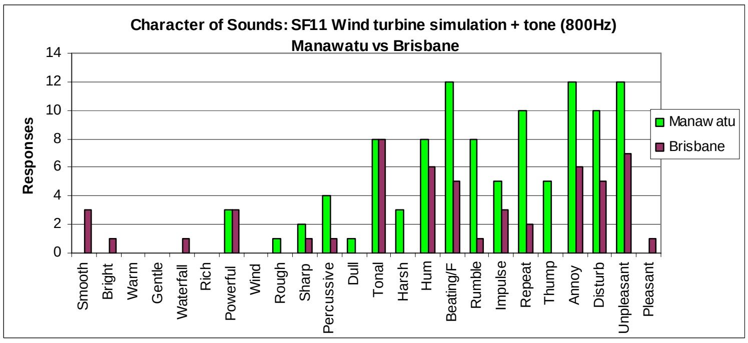

Figure 9.4.2.11: Responses to the character of soundfile 11

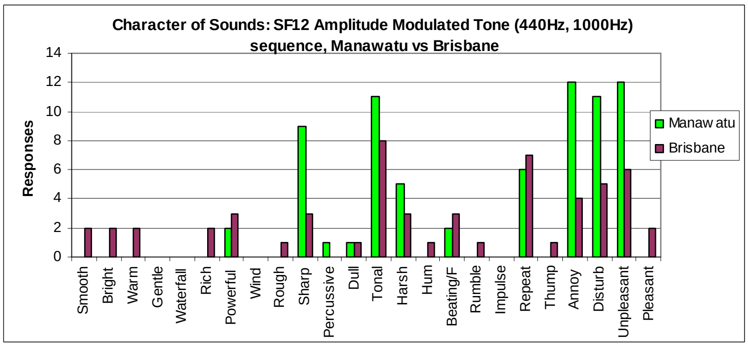

Figure 9.4.2.12: Responses to the character of soundfile 12

9.5 Analysis of the character of sounds

All sounds in the environment contain audible characteristics. These characteristics may be continuous for all the time-history (a continuous hum or modulating beat, for example) or may occur for only short periods of time (reversing alarms or bird song, for example). Such characteristics are defined, in part, by the duration, attack and decay rate of the sound. To define the sound by measurement requires either analysis of the overall soundfile or comparison between the soundscape in the absence of the sound and the sound of interest. Both processes require a standard methodology with defined measurement protocols in order to provide a consistent approach to analysis and, as closely as possible, individual perception of the sound(s).

9.5.1 Analysis programs

Each soundfile has its own unique character and was chosen to illustrate or typify a particular feature or features (e.g., modulation, roughness, tonality, pleasantness). The analysis programs for this work are 01dB dBSONIC, dBFA32 v4.530 and PsySound2 (Macintosh version). These programs implement various standard methods of analysis for sound levels as well as different approaches to musical, sound quality and psychoacoustical measures. The analysis programs were needed in combination to analyse the soundfiles for most of the measures described in Chapter 4. The dBSONIC and dBFA32 settings were:

- level vs time parameters - no frequency weighting, fast exponential time averaging and time interval of 2 ms
- FFT spectrogram parameters: window length (4096 sample at 93 ms), window overlap (75%), window type (Hanning), time interval (1024 sample at 23 ms), side lobe attenuation (31.5 dB), frequency resolution (5.4 Hz), analysis bandwidth (16.3 Hz)
- Psychoacoustics parameters: sound field (free-field), loudness time interval (2 ms), fluctuation/roughness time interval (2 ms), fluctuation /roughness block length (200 ms)
- Prominence parameters: tone-noise ratio / prominence ratio method (ANSI S1.13(1995), frequency resolution (1.3 Hz), FFT window overlap (50%), computed frames (1), Fourier spectrum (not weighted)

- Modulation spectrum was analysed with maximum analysed modulation frequency (99.3 Hz), modulation frequency resolution (1.6 Hz), averaged modulation spectra (374), FFT window overlap (50%), FFT window length (644 ms), analysed bands (24), band type (critical band), frequency range (0.5 – 23.5 Bark (47.4 – 13526.6 Hz), band overlap (0%). The modulation vs time parameters has a centre frequency of 1000 Hz and band width of 162.2 Hz
- The abbreviations in the summary data are: (PR) is the Prominence Ratio for a tone as described in ANSI S1.13(1995) and (TNR) is the Tone-to-Noise Ratio for a tone as described in ANSI S1.13(1995). (N) is loudness and the statistical level is stated (nominally 10%), (S) is sharpness to Aures, (F) is fluctuation strength to Zwicker-Fastl, (R) is roughness to Zwicker-Aures, (UBA) is unbiased annoyance to Zwicker, (SenPl) is sensory pleasantness to Zwicker

PsySound2 Analysis was implemented with the original Macintosh version. The following information has been drawn from the documentation for PsySound2. The analysis results are from the Macintosh version of the program. Frequency analysis is achieved initially by a 4096-point Fourier transform. In order to speed up processing, the frequency spectrum is reduced to a compact form: linear frequency distribution is retained at low frequencies, while twelfth-octave distribution applies to higher frequencies (reducing the spectrum from 2048 to 108 components). PsySound2 analyses soundfiles using a 93 ms window. This produces good frequency resolution, but poor temporal resolution. The relatively long window can be justified in the following ways:

- The temporal acuity of the auditory system is of a similar order. For example, loudness is almost independent of duration for sounds longer than 100 ms, but the loudness of shorter sounds is directly related to their duration. This phenomenon is modelled in the crudest terms by the 93 ms window, and it could be argued that a longer window would be better.
- The frequency resolution of the 93 ms window is similar to that used by Terhardt et al (1982) in their original pitch program.
- The models implemented by PsySound2 were mainly developed for steady or near-steady sound. Very rapidly changing sound would be poorly represented by these models, even if the temporal resolution were higher.

Key to Abbreviations for the features described in the Tables following:

N : Loudness, stated in sones (Moore)

Nmax : Maximum loudness during the time period represented by the row.

S(Z&F) : Sharpness, in acums (Zwicker & Fastl).

S(A) : Sharpness, in acums (Aures, 1985).

TW : Timbral Width, loosely based on Malloch

SDiss(H&K) : Spectral Dissonance (Hutchinson & Knopoff, 1978).

SDiss(S) : Spectral Dissonance (Sethares, 1993).

TDiss(H&K) : Tonal Dissonance (Hutchinson & Knopoff, 1978).

TDiss(S) : Tonal Dissonance (Sethares, 1993).

PTonal : Pure Tonalness (Parncutt, 1989).

CTonal : Complex Tonalness (Parncutt, 1989).

MTones : Multiplicity (Parncutt, 1989).

Analysis of the soundfiles is presented in section 9.5.3 and includes measures of unbiased annoyance, sensory pleasantness and psychoacoustic annoyance.

9.5.2 Analysis of Brisbane Locales

An application of dBFA32 calculating sound quality measures and sound levels is presented in figure 9.5.2.1 for representative areas within Brisbane City. The figure presents the relationships between loudness, unbiased annoyance and sound level.

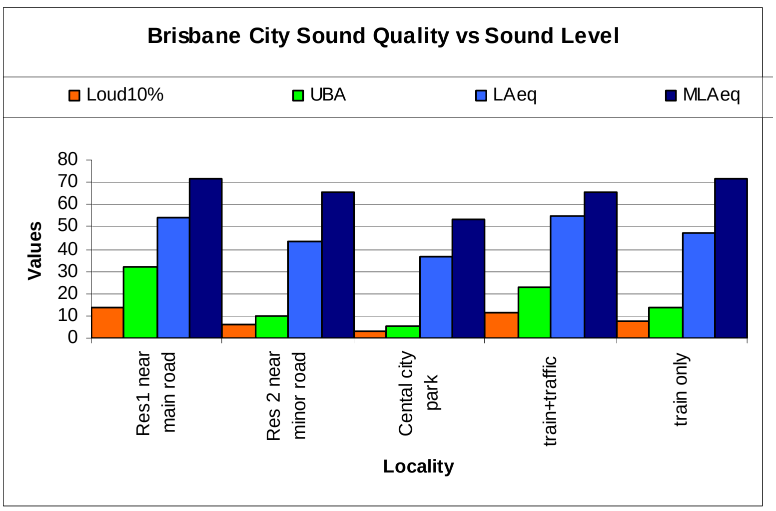

Figure 9.5.2.1: Brisbane city sound quality verses sound level.

The figure includes the actual measured sound levels as previously reported in this work and the levels are in the order of 11 dB(A) to 25 dB(A) higher than the levels recorded by dBFA32. The reason for this variation is not known but the calculated levels for loudness and unbiased annoyance are acceptable for comparison purposes. There are, for example, locales where the calculated LAeq sound levels are representative of their soundscapes.

The primary outcome of this signal issue, however, is that the analysed soundfile needs to be adjusted to the 'true' ambient level. This can be achieved either by modifying the soundfile through a sound analyser such as Adobe Audition, or by adjusted the level with some calibration factor. For practical reasons and to keep the research analysis protocols 'standard' and unvaried, this work adjusts the soundfile through Adobe Audition rather than through the analysis program.

9.5.3 Unbiased annoyance

Analysis of the soundfiles shows that roughness appears across all the soundfiles, even the soundfiles that were not perceived by the focus groups as being rough in nature. Roughness does not appear to identify soundfiles that are "rough", compared to soundfiles that are perceived as being pleasant. In the course of the testing process it was observed that fluctuation, as applied in the other models, did not appear to make a significant difference to the overall UBA value. The overall scale values do not necessarily reflect nil annoyance or extreme annoyance; the values describe the relationships between different sound complexes. The analyses indicate that tonal dissonance provides enhanced response to sounds that appear to be sharp in nature or contain significant higher frequencies that prominent salience. It is observed that roughness and fluctuation measures are not adequate to describe modulation effects in an environmental (wind farm) context. The modulating effects are clearly audible in the respective soundfiles (SF2, SF4) but only pre-knowledge calls the human perception of modulation.

Unbiased annoyance, sensory pleasantness and psychoacoustic annoyance are redefined in this work by applying Sethare's tonal and spectrum dissonance. Dissonance has application across the audible spectrum rather than the constraints for roughness and fluctuation as described previously in this work. Sethare's tonal dissonance is applied for fluctuation as the method takes into account tonal variation while spectrum dissonance takes partly into account amplitude fluctuations. A new measure for unbiased annoyance is derived: *modified unbiased annoyance (UBAm).*

The modified unbiased annoyance measure, equation 9.5.3.1, is referenced to Zwicker's unbiased annoyance, equation 4.24.1, of this work. The modified unbiased annoyance measure applies loudness (N10 in sones), Aures sharpness (in acums) and a new approach to fluctuation by implementing Sethare's Tonal Dissonance, *TD(S)* in *sets*, to account for frequency as well as amplitude fluctuation. The UBA*m* measure has an effect on soundfile measured values by emphasising the contribution of tonalness. The measure provides a partial objective analog for timbre. The tonal dissonance measure to Sethares as implemented by Cabrera (1999a, p. 18) is implemented in equation 9.5.3.1. The calculation is given in 'intrusion units, *iu*':

$$UBAm = d(N10)^{1.3} \cdot \left\{1 + 0.25(S-1) \cdot \lg(N10+10) + 0.3TD(S) \cdot \frac{1+N10}{0.3+N10}\right\} \quad \text{iu}$$

eqn 9.5.3.1

Loudness (N10) is the loudness in sone which is exceeded for 10% of the time. (The exponent in the first expression is 1.3). UBA*m* is modified for night-time. The value of '*d*' in equation 9.5.3.1 for the day is 1, for night-time the value of $d = 1 + (N10/5)^{0.5}$. The expression 'lg' is '$\log_{10}$'.

The decision process taken to adopt the modified unbiased annoyance calculation method (eqn 9.5.3.1) is given in section 9.6.

9.5.4 Soundfile analysis results

The summary test results that inform this work and methods of test are presented in this section. The soundfile analysis determines various measures, including loudness, roughness, fluctuation strength, sharpness and a measure for sound level. The analysis involved calculating measures of unbiased annoyance, psychoacoustic annoyance and sensory pleasantness, as well as spectrum and tonal dissonance and sound levels. The first set of data is the dBSONIC analysis, the second dBFA32 and the third PsySound2. The values are presented in Tables 9.5.4.1 to 9.5.4.4. For the purposes of this work, PsySound2 is defined as the standard measure; dBFA32 is the baseline method as it calculates unbiased annoyance and sensory pleasantness directly and dBSONIC provides comparative values.

Additional soundfiles not presented to the focus groups are included in the acoustical and sound quality analysis. The soundfiles are from five rural areas and one urban area, as well as a wind-turbine and two music soundfiles. The rural soundfiles are from the previous locations but, as far as possible, all sounds other than birdsong and wind over vegetation are excluded. The rural soundfiles are deemed to represent the highest standard of environmental amenity. The Ashhurst soundfile had voices (children) and a 'flick-flick' sound from a water sprinkler, both in the background. The Tararua wind turbine at the visitor's area was recorded and all sound other than blade swish and turbine noise was excluded as far as possible. The music soundfiles are: Music Classical (Pavarotti singing 'Nissan Domra') Music Rock (Black Sabbath presenting 'Paranoid'). A subset of the soundfiles was further analysed with dBFA32 by reducing the overall level in 10 dB steps to 20 dB(A) and recalculating all the measures. This process allowed assessment of the measures in terms of low amplitude sound.

An unexpected outcome of the analysis process was that the reporting of the overall sound level (LAeq) of each soundfile was different for each of the three sound analysis programs. There was close agreement of approximately ± 0.5 dB between dBSONIC ('Lmean') and dBFA32 ('LAeq') for each of the 120 second soundfiles. The range between the two commercial programs and PsySound2 is wider for some soundfiles but only a 60 second soundfile is analysed in PsySound2. Any variation was expected to be the least for the 'SF8 pink noise' soundfile but there was considerable variation between each analysis program and PsySound2. Comparatively, however, the application of PsySound2 is acceptable for this work.

The following Tables present the comparisons between soundfiles and different methods of calculation.

Table 9.5.4.1: Psychoacoustic measures to dBSONIC

Psychoacoustic Measures to dBSONIC					
	Te Apiti WT tower	**SF1 AmpMod**	**SF2 Ashhurst**	**SF3 BldgClick**	**SF4 Café WT**
N 5% soneGF	4.9	33.5	8.2	43	8.5
S 5% acum	1.1	2.2	1.5	1.6	1.7
F 5% vacil	0.16	0.67	0.19	1.76	0.18
R 5% asper	0.39	0.66	0.30	0.75	0.31
UBA day au	8.55	162.99	18.79	238.57	20.68
UBA night au	17.02	584.89	42.86	938.20	47.63
PsychoAnnoy	6.83	46.91	10.28	67.19	10.54
SenPleasantness pu	14.32	2.02	9.67	2.47	7.72
TNR mean dB	3.7	0	0	0	0
PR mean dB	4.5	0.3	10.2	6.4	5.2
Lmean dB(A)	42.1	74.9	49.1	73.3	51.3

Psychoacoustic Measures to dBSONIC				
	SF5 NL031C3	**SF6 NL032C4**	**SF7 NL071C6**	**SF8 Pink**
N 5% soneGF	21.7	7.4	7.5	18.2
S 5% acum	1.4	1	1	1.8
F 5% vacil	0.04	0.04	0.4	0.02
R 5% asper	0.31	0.19	0.21	0.38
UBA day au	63.50	13.67	15.52	56.34
UBA night au	195.79	30.29	34.53	163.82
PsychoAnnoy	25.69	9.36	10.22	21.15
SenPleasantness pu	8.64	18.05	17.78	5.75
TNR mean dB	7.10	5.4	8.9	0.2
PR mean dB	11.1	5.9	8.9	0.2
Lmean dB(A)	64.6	51	51.8	62.8

Psychoacoustic Measures to dBSONIC				
	SF9 Rough	**SF10 Sharp**	**SF11 WT sim**	**SF12 Dual tone**
N 5% soneGF	32	40	21.3	27.2
S 5% acum	2.2	2.2	1.7	1
F 5% vacil	0.03	0.02	0.03	1.233
R 5% asper	0.72	0.41	0.24	1.6
UBA day au	135.42	183.37	67.77	101.1
UBA night au	478.00	702.00	207.65	336.56
PsychoAnnoy	41.70	49.17	23.47	51.54
SenPleasantness pu	2.04	1.87	6.63	4.68
TNR mean dB	0	0	9.7	15
PR mean dB	0.2	1.7	12.8	35
Lmean dB(A)	74.8	80.2	66.5	83.3

Psychoacoustic Measures to dBSONIC				
	Rural S	Rural JA	Rural M	Ashhurst Res
N 5% soneGF	4.5	5.3	5.3	5.7
S 5% acum	1.8	1.9	1.7	1.6
F 5% vacil	0.11	0.43	0.13	0.2
R 5% asper	0.21	0.32	0.23	0.29
UBA day au	8.97	12.34	10.94	11.98
UBA night au	17.49	25.04	22.20	24.76
PsychoAnnoy	5.42	7.47	6.43	30.04
SenPleasantness pu	7.64	6.32	8.36	8.9
TNR mean dB	0	3.7	0	0
PR mean dB	10.8	8.7	10.8	9.6
Lmean dB(A)	41.8	48	42.4	44.3

Psychoacoustic Measures to dBSONIC				
	Rural Café	Rural JN	Music Classical	Music Rock
N 5% soneGF	4.5	5.4	43.8	29.6
S 5% acum	1.7	1.6	1.2	1.5
F 5% vacil	0.36	0.23	0.693	0.654
R 5% asper	0.63	0.29	0.384	0.557
UBA day au	9.38	11.25	176.52	114.54
UBA night au	18.27	22.93	698.98	393.23
PsychoAnnoy	7.31	7.01	58.73	39.95
SenPleasantness pu	6.34	8.92	4.74	5.27
TNR mean dB	0	1	0	0
PR mean dB	7.6	10.4	3.5	4.4
Lmean dB(A)	43.3	48	77.1	67.3

Table 9.5.4.2: Psychoacoustic measures to dBFA32

Psychoacoustic Measures to dBFA32					
	TeApiti WT tower	**SF1 AmpMod**	**SF2 Ashhurst**	**SF3 BldgClick**	**SF4 Café WT**
Loudness N sone	4.67	35.06	8.84	42.5	8.93
S 10% acum	1.01	2.38	1.43	1.61	1.71
F 10% vacil	0.03	2.11	0.13	2.12	0.14
Tonality tu	0.3	0	0.05	0	0.05
R 10% asper	9.54	5.77	10.43	5	10.3
UBA day au	8.82	275.25	21.80	285.70	22.79
UBA night au	17.90	1059.59	51.73	1162.12	53.68
PsychoAnnoy	39.28	127.91	62.31	131.67	60.64
SenPleasantness pu	0	0.00	0.00	0.00	0.00
N 10% sone	5.29	40.6	9.43	47.05	9.19
Leq dB(A)	43	75.7	49.9	74.1	52.6

Psychoacoustic Measures to dBFA32				
	SF5 NL031C3	**SF6 NL032C4**	**SF7 NL071C6**	**SF8 Pink**
Loudness N sone	24.21	8.67	8.43	19.99
S 10% acum	1.4	0.89	1.02	1.86
F 10% vacil	0.36	0.04	0.07	0.14
Tonality tu	0.21	0.48	0	0
R 10% asper	4.22	4.82	5.51	5.75
UBA day au	84.24	17.68	17.24	70.29
UBA night au	273.54	41.73	40.06	213.50
PsychoAnnoy	65.88	33.50	35.53	67.93
SenPleasantness pu	0.02	0.04	0.01	0
N 10% sone	25.25	9.26	8.75	20.76
Leq dB(A)	65.4	51.9	52.7	63.5

Psychoacoustic Measures to dBFA32				
	SF9 Rough	**SF10 Sharp**	**SF11 WT sim**	**SF12 Dual tone**
Loudness N sone	35.15	43.47	23.58	34.17
S 10% acum	2.38	2.39	1.8	0.77
F 10% vacil	0.19	0.41	0.02	1.89
Tonality tu	0	0	0.11	1.04
R 10% asper	5.37	5.35	4.94	0.62
UBA day au	176.20	243.74	82.84	116.15
UBA night au	652.92	974.78	265.16	393.5
PsychoAnnoy	99.68	118.24	68.08	49.95
SenPleasantness pu	0	0	0.01	0.67
N 10% sone	36.6	44.98	24.22	28.51
Leq dB(A)	75.6	80.6	67.3	84.2

Psychoacoustic Measures to dBFA32				
	Rural S	Rural JA	Rural M	Ashhurst Res
Loudness N sone	4.99	6.62	5.41	6.17
S 10% acum	1.69	1.73	1.56	1.51
F 10% vacil	0.07	0.4	0.1	0.05
Tonality tu	0.02	0.02	0.03	0.03
R 10% asper	9.54	8.94	9.52	9.49
UBA day au	10.51	12.29	11.47	13.36
UBA night au	21.25	25.12	23.68	28.58
PsychoAnnoy	41.42	38.80	41.19	44.80
SenPleasantness pu	0	0	0	0
N 10% sone	5.72	5.46	5.67	6.5
Leq dB(A)	42.5	48.8	43.2	45

Psychoacoustic Measures to dBFA32				
	Rural Café	Rural JN	Music Classical	Music Rock
Loudness N sone	4.97	7.26	39.71	29.55
S 10% acum	1.46	1.39	1.02	1.35
F 10% vacil	0.3	0.44	2	2.49
Tonality tu	0.03	0.05	0.04	0
R 10% asper	9.74	9.3	9.94	7.93
UBA day au	9.72	14.02	236.45	177.76
UBA night au	19.31	29.84	955.52	632.96
PsychoAnnoy	38.54	44.49	194.10	134.67
SenPleasantness pu	0	0	0	0
N 10% sone	4.88	6.37	46.24	32.76
Leq dB(A)	44.1	49.3	78	68.1

Table 9.5.4.3 Soundfiles recalculated to lower (quieter) sound levels using dBFA32

SoundFile	dBA Level	N10%	S10%	F10%	R	LAeq	UBA day	SenPl
TeApiti WT tower	45	5.73	1.03	0.03	8.84	44.2	9.86	0
TeApiti WT tower	40	3.9	0.98	0.02	8.58	39.2	5.86	0
TeApiti WT tower	30	1.54	0.86	0	8.34	29.2	1.69	0
TeApiti WT tower	20	0.37	0.63	0	8.28	19.2	0.25	0.01
TeApiti WT tower	10	0.02	0	0	8.19	9.4	0	0
SF1 Amplitude Modulated	76	40.69	2.38	2.52	10.17	75.7	291.23	0
SF1 Amplitude Modulated	50	7.76	2.47	2.21	9.18	49.7	31.24	0
SF1 Amplitude Modulated	40	3.66	2.56	1.23	8.86	39.7	10.13	0
SF1 Amplitude Modulated	30	1.43	2.72	0.07	8.55	29.7	2.36	0
SF1 Amplitude Modulated	20	0.34	2.89	0	8.28	19.7	0	0
SF2 Ashhurst with WT	50	9.15	1.43	0.22	9.43	49.4	21.5	0
SF2 Ashhurst with WT	40	4.11	1.41	0.02	9.02	39.4	7.06	0
SF2 Ashhurst with WT	30	1.55	1.29	0	8.68	29.4	1.91	0
SF2 Ashhurst with WT	20	0.31	1.03	0	8.43	19.4	0.22	0
SF3 Building Clicks	74	37.46	1.59	2.08	9.22	74	209.3	0
SF3 Building Clicks	57	12.76	1.6	2.37	8.61	57	53.48	0
SF4 Café with WT	53	9.69	1.67	0.11	9.45	52.9	23.97	0
SF4 Café with WT	40	3.57	1.67	0.02	8.93	39.9	6.27	0
SF4 Café with WT	30	1.3	1.61	0.01	8.6	29.9	1.63	0
SF4 Café with WT	20	0.25	1.56	0	8.35	19.9	0.19	0
SF7 NL071C6 FreqMod Tones	52	8.83	1.02	0.04	9.69	52.7	17.27	0
SF7 NL071C6 FreqMod Tones	50	7.69	1.01	0.03	9.63	50.7	14.35	0
SF7 NL071C6 FreqMod Tones	40	3.65	0.93	0.01	9.26	40.7	5.3	0
SF7 NL071C6 FreqMod Tones	30	1.47	0.8	0	8.88	30.7	1.56	0
SF7 NL071C6 FreqMod Tones	20	0.36	0.58	0	8.68	20.8	0.24	0
SF9 Rough	76	36.46	2.38	0.64	9.91	75.6	189.68	0
SF9 Rough	50	6.82	2.47	0.03	8.9	49.6	17.7	0
SF9 Rough	40	3.12	2.56	0.01	8.56	39.6	6.31	0
SF9 Rough	30	1.15	2.72	0	8.29	29.6	1.74	0
SF9 Rough	20	0.25	2.9	0	8.06	19.7	0	0

Table 9.5.4.3 (cont'd) Soundfiles recalculated to lower (quieter) sound levels using dBFA32

Name	dBA Level	N10%	S10%	F10%	R	LAeq	UBA day	SenPl
Rural M ambient	44	6.49	1.51	0.05	8.71	44.3	13.3	0
Rural M ambient	40	4.74	1.49	0.02	8.62	40.3	8.7	0
Rural M ambient	30	1.9	1.42	0	8.35	30.3	2.56	0
Rural M ambient	20	0.48	1.33	0	8.07	20.3	0.42	0
Ashhurst Res ambient	44	6.46	1.55	0.08	8.88	44.5	13.5	0
Ashhurst Res ambient	40	4.75	1.54	0.05	8.78	40.5	8.91	0
Ashhurst Res ambient	30	1.89	1.48	0.01	8.59	30.5	2.59	0
Ashhurst Res ambient	20	0.47	1.4	0	8.34	20.6	0.41	0
Café ambient	42	4.73	1.49	0.43	9.08	42	9.74	0
Café ambient	40	3.71	1.48	0.3	8.99	39	6.83	0
Café ambient	30	1.38	1.39	0.07	8.82	29	1.72	0
Café ambient	20	0.29	1.32	0	8.44	19	0.22	0
Music Classical	76	41.22	1.03	2.06	7.76	76.2	206.42	0
Music Classical	50	7.28	1.01	0.3	7.74	49.2	14.53	0
Music Classical	40	3.56	0.99	0.08	7.75	39.2	5.35	0
Music Classical	30	1.52	0.96	0.01	7.85	29.2	1.71	0
Music Classical	20	0.45	0.91	0	7.74	19.2	0.35	0
Music Rock	68	32.64	1.35	2.66	6.9	68	181.88	0
Music Rock	50	9.85	1.38	0.56	6.57	50	25.55	0
Music Rock	40	4.77	1.32	0.13	6.4	40	8.68	0
Music Rock	30	1.99	1.23	0.02	6.24	30	2.62	0
Music Rock	20	0.55	1.17	0	6.23	20	0.48	0

Table 9.5.4.4: Psychoacoustic measures to PsySound2

Psychoacoustic Measures to PsySound2					
	TeApiti WT tower	**SF1 AmpMod**	**SF2 Ashhurst**	**SF3 BldgClick**	**SF4 Café WT**
Loudness N sone	47.7	35.8	52.6	57.1	52.2
N 5% sone	33.1	35.4	28.3	49.6	31.5
N 10% sone	18.3	35.2	12.7	43.7	13
S (Z&F)	1.2	2.4	1.4	29.6	1.7
S (A)	2	6	2.6	1.8	3
SDiss(H&K)	0.692	0.3865	0.689	2.4	0.7818
SDiss(S)	0.0012	0.008	0.0024	0.4446	0.0031
TDiss(H&K)	0.0073	0.0197	0.0494	0.0111	0.0403
TDiss(S)	0.0041	0.0075	0.00	0.0881	0.0002
Centroid	52	10634	108.00	3367	180
UBA*m* day iu	59.71	314.64	41.99	186.31	47.17
UBA*m* night iu	173.95	1149.48	108.91	737.13	123.23
SenPleasantness pu	1.61	0.02	0.95	1.22	0.56
PsychoAnnoy	36.48	97.73	37.82	56.77	47.43
LA50	43.6	70.1	49.8	64.9	49.6
Leq dB(A)	54.5	68.3	49.7	71.8	50.2
PTonal	0.12	0	0.02	0.0373	0.01
CTonal	0.01	0	0	0.03	0
MTones	1.24	0.07	0.3	0	0.24

Psychoacoustic Measures to PsySound2				
	SF5 NL031C3	**SF6 NL032C4**	**SF7 NL071C6**	**SF8 Pink**
Loudness N sone	48.4	33	11.8	24
N 5% sone	33.1	12.5	11.4	23.2
N 10% sone	29.2	12.3	11.4	23
S (Z&F)	1.5	1	1.3	1.9
S (A)	3.6	1.7	2.2	4.2
SDiss(H&K)	0.516	0.8226	0.2776	0.475
SDiss(S)	0.0053	0	0	0.0013
TDiss(H&K)	0.0129	0.0225	0.0077	0.0934
TDiss(S)	0.0076	0.0002	0	0.0007
Centroid	425	77	542	2864
UBA*m* day iu	163.76	32.28	33.10	130.50
UBA*m* night iu	559.49	82.90	83.08	410.41
SenPleasantness pu	0.30	3.53	2.08	0.19
PsychoAnnoy	58.12	12.71	13.11	44.82
LA50	65.20	54.2	53.1	60.9
Leq dB(A)	63.1	52.1	50.6	58.4
PTonal	0.06	0.15	0.1	0.01
CTonal	0	0.01	0	0
MTones	0.98	1.64	1.07	0.17

Psychoacoustic Measures to PsySound2				
	SF9 Rough	**SF10 Sharp**	**SF11 WT sim**	**SF12 Dual tone**
Loudness N sone	33.7	40.5	27.1	51.2
N 5% sone	33.4	39.2	26.3	49.6
N 10% sone	33.2	38.8	26.2	49.6
S (Z&F)	2.3	2.6	1.9	1.9
S (A)	6	7	4.3	4.9
SDiss(H&K)	0.4029	0.3016	0.0637	0.1147
SDiss(S)	0.0115	0.0182	0.0025	0.0081
TDiss(H&K)	0.1084	0.1398	0.0041	0.0257
TDiss(S)	0.0498	0.1039	0.0048	1.4329
Centroid	10652	9774	2517	4670
UBA*m* day iu	290.50	414.44	159.64	506.69
UBA*m* night iu	1039.06	1568.94	525.07	2102.56
SenPleasantness pu	0.03	0.01	0.17	0.16
PsychoAnnoy	91.51	126.26	52.45	120.17
LA50	69.9	74.8	65.7	79.6
Leq dB(A)	67.1	72	63	78.7
PTonal	0.01	0.01	0.12	0.6
CTonal	0	0	0	0.07
MTones	0.13	0.18	1.05	2.26

Psychoacoustic Measures to PsySound2				
	Rural S	**Rural JA**	**Rural M**	**Ashhurst Res**
Loudness N sone	41.8	47	35.8	47.4
N 5% sone	6.7	7.9	8.4	8.8
N 10% sone	6.4	6.7	7.2	8.2
S (Z&F)	1.5	1.6	1.4	1.4
S (A)	2.7	2.6	2.3	2.3
SDiss(H&K)	0.4351	0.5308	0.6749	0.6152
SDiss(S)	0	0	0	0
TDiss(H&K)	0.0432	0.0439	0.0338	0.0377
TDiss(S)	0	0.0002	8	0
Centroid	78	98	71	72
UBA*m* day iu	16.94	17.65	18.24	21.73
UBA*m* night iu	36.10	38.09	40.14	49.55
SenPleasantness pu	1.27	1.40	1.93	1.92
PsychoAnnoy	8.65	10.00	9.86	10.34
LA50	40.5	39.1	41.3	43.7
Leq dB(A)	40	42	41.7	43.8
PTonal	0.05	0.02	0.03	0.03
CTonal	0	0	0	0
MTones	0.68	0.27	0.45	0.48

Psychoacoustic Measures to PsySound2				
	Rural Café	Rural JN	Music Classical	Music Rock
Loudness N sone	49.3	47	62.3	43.8
N 5% sone	7.9	35	59.1	38.6
N 10% sone	6.9	28.4	57.7	37
S (Z&F)	1.4	1.4	1.7	1.6
S (A)	2.3	2.5	4.6	3.9
SDiss(H&K)	0.4921	0.6545	0.3086	0.5514
SDiss(S)	0.0011	0.0026	0.0257	0.0116
TDiss(H&K)	0.0397	0.0361	0.0449	0.0124
TDiss(S)	0	0.0085	0.1749	0.0355
Centroid	39	93	2670	766
UBA*m* day iu	17.23	123.75	526.01	243.01
UBA*m* night iu	37.48	418.68	2312.90	904.07
SenPleasantness pu	1.94	0.91	0.06	0.22
PsychoAnnoy	9.26	45.85	136.59	73.60
LA50	39.5	44.6	76.1	68.1
Leq dB(A)	42.7	63.2	76.8	67.6
PTonal	0.03	0.03	0.29	0.34
CTonal	0	0	0.04	0.06
MTones	0.42	0.38	1.93	2.04

Notes to Tables:
PsySound2 calculations include UBA*m* with ‘F’ as TDiss(S); ‘R’ as SDiss(S); 'S' as Aures 5%; 'N' as 10%; ‘iu’ is intrusion unit; dBSONIC and dBFA32 Sensory Pleasantness Tonality default is 0.2.

9.6 Evaluation of soundfile analyses

The analysed soundfiles present a wide range of information describing the character of the sounds. Measures such as loudness, fluctuation, roughness and sharpness have been previously described in this work. The individual soundfile analysis results presented allow comparison between measures and methods, calculation of new measures and evaluation of the perception values with physical values. The analysis of the measures identifies differences between the various soundfiles. The magnitude values in Tables 9.5.4.1 to 9.5.4.4 show the variation by which the different measures analyse the same sound. Figures 9.6.1 to 9.6.4 and Table 9.6.1 present a comparison of the application of different models of roughness, fluctuation strength, unbiased annoyance, psychoacoustic annoyance and sensory pleasantness.

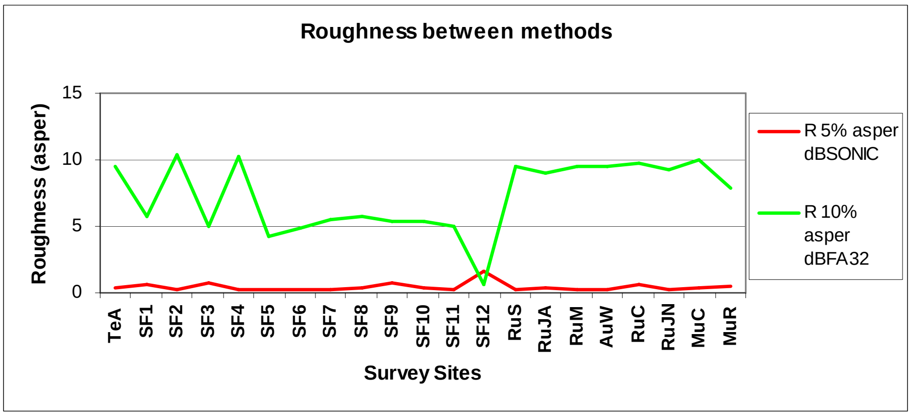

Figure 9.6.1: Comparison of roughness between different methods

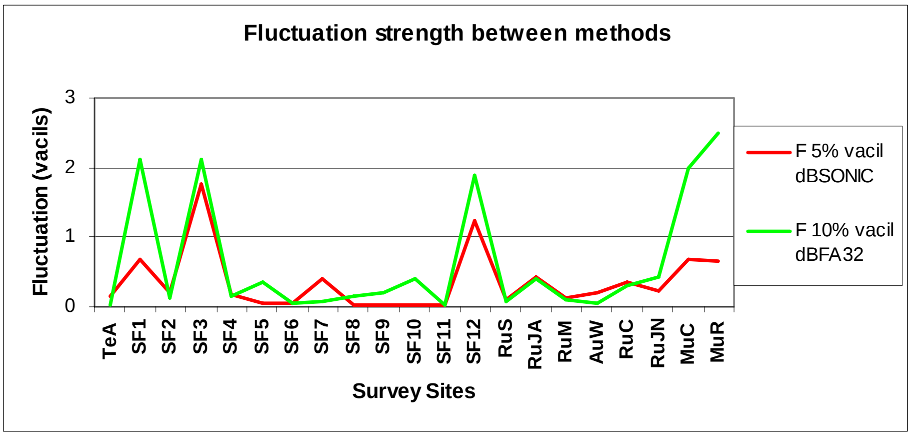

Figure 9.6.2: Comparison of fluctuation between different methods

The values in figures 9.6.3 and 9.6.4 have been derived from Table 9.6.1. In reading the psychoacoustic annoyance chart the lower the value the less annoying the sound is calculated to be.

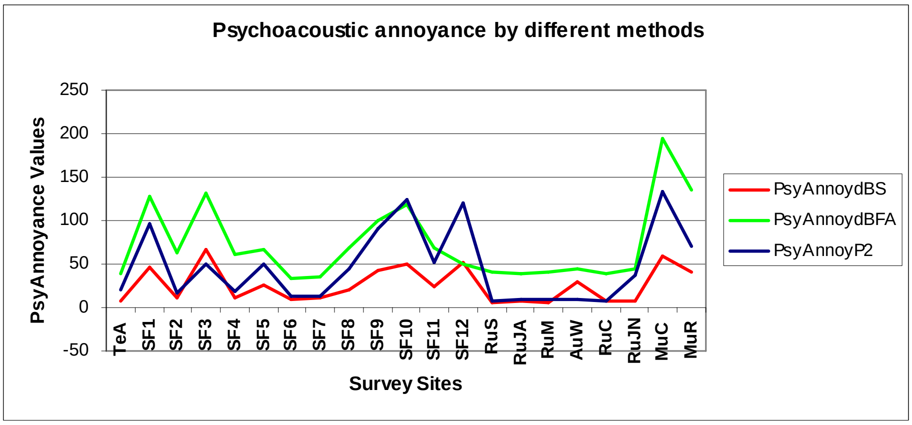

Figure 9.6.3: Comparison of psychoacoustic annoyance between different methods

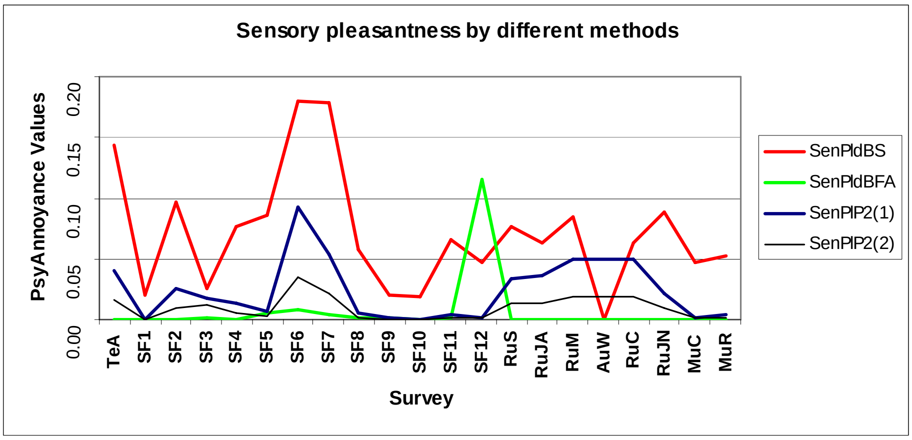

Figure 9.6.4: Comparison of sensory pleasantness between different methods

Table 9.6.1: Measures of annoyance and sensory pleasantness

SoundFile	UBA*m* day	dBFA32 PsychAnnoy	PsySound2 PsychAnnoy	dBSONIC SensPleas	Psy(1) SensPleas	Psy(2) SensPleas
TeAWT	59.71	39.28	19.6	14.32	4.03	1.61
SF1	314.64	127.91	97.1	2.02	0.05	0.02
SF2	41.99	62.31	16.36	9.67	2.46	0.95
SF3	186.31	131.67	50.14	2.47	1.76	1.22
SF4	47.17	60.64	18.53	7.72	1.44	0.56
SF5	163.76	65.88	50.72	8.64	0.71	0.30
SF6	32.28	33.50	12.51	18.05	9.17	3.53
SF7	33.1	35.53	13.11	17.78	5.42	2.08
SF8	130.5	67.93	44.39	5.75	0.50	0.19
SF9	290.5	99.68	91.51	2.04	0.05	0.03
SF10	414.44	118.24	124.79	1.87	0.01	0.01
SF11	159.64	68.08	52.23	6.63	0.42	0.17
SF12	506.69	49.95	120.17	4.68	0.09	0.16
RuS	16.94	41.42	8.25	7.64	3.30	1.27
RuJA	17.65	38.80	8.44	6.32	3.65	1.40
RuM	18.24	41.19	8.42	8.36	5.02	1.93
AshRes	21.73	44.80	9.62	8.90	5.00	1.92
RuCafé	17.23	38.54	8.06	6.34	5.04	1.94
RuJN	123.75	44.49	36.84	8.92	2.19	0.91
MuC	526.01	194.10	132.99	4.74	0.07	0.06
MuR	243.01	134.67	70.26	5.27	0.42	0.22

Notes to the Table:

1. *UBAm* is calculated with N10%, S (Aures), F (TDiss(S)).
2. *Psychoacoustic annoyance* calculated as dBFA32 by N10%, S10%, F10% and R10%; PsySound 2 by N10%, S(Aures), F(TDissS), R(SDissS)
3. *Sensory Pleasantness* calculated as dBSONIC by N5%, T0.2, F5% and R5%; Psy(1) by N5%, S(Aures), T0.2 and R(SDissS); Psy(2) by N5%, S(Aures), T(SDissS), R(SDissS); calculated values multiplied by 100 to present integer values
4. ‘N’ is loudness; ‘R’ is roughness; ‘S’ is sharpness; ‘T’ is tonality

Roughness as a measure is included in both dBSONIC and dBFA32, figure 9.6.1. Even allowing for the different loudness levels in the implementation methods the resultant patterns are quite different. For the purposes of this work all the analysis methods requiring roughness are treated as comparative. Psychoacoustic annoyance and sensory pleasantness both include roughness as one of the calculation parameters. Soundfile 9 is classified as being ‘rough’ and the calculation methods should show a higher value than for a sound classified as being ‘not-rough’ such as a rural environment (soundfile RuS). This is shown to be the case. Other sounds such as building clicks (soundfile 3) and sharp sound (soundfile 10) also show heightened sensitivity to roughness. A second method employing Sethares spectrum dissonance has good correlation with roughness for soundfile 9 and 10, but not for soundfile 3. It is concluded that roughness, as a practical working measure for an environmental noise decision process, does not have significant improvement over analysis incorporating Sethares spectrum dissonance.

Fluctuation strength, figure 9.6.2, has a good correlation between the two methods except for the amplitude modulated soundfile and one music soundfile. The measure is included in psychoacoustic annoyance and it is concluded that, as a practical working measure for an environmental noise decision process, does not have significant improvement over analysis incorporating Sethares tonal dissonance.

The sensory pleasantness measure is dependent on tonality. When referenced to the rural environment soundfiles the measure is ‘more pleasant’ the higher the value. The implemented methods of figure 9.6.4 present significantly different pattern values. The measure is not considered further in this work

Figures 9.6.5 to 9.6.7 illustrate the variation between unbiased annoyance measures calculated by different methods. The night-time vales show a similar pattern but with higher annoyance values. The comparison of dissonance methods of figure 9.6.5 presents a high level of similarity between the methods. Sethares tonal dissonance shows a higher value for soundfile 12, the calibration tones. This soundfile is extremely tonal. Hutchinson and Knopoff spectrum dissonance has a higher value for soundfile 3, building clicks. This soundfile is more tonal in nature. As a practical working measure for an environmental noise decision process, Sethares tonal dissonance is the preferred measure for ‘roughness’, ‘fluctuation’ and overall tonalness for assessment of a soundfile.

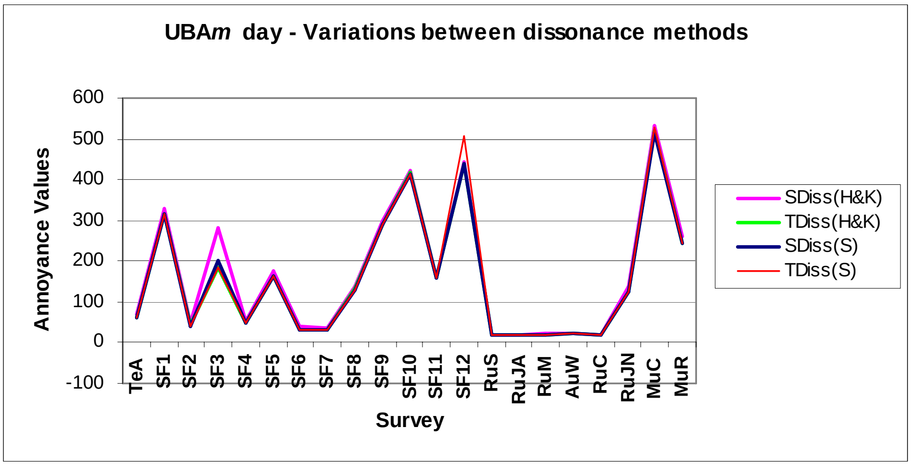

Figure 9.6.5: Comparison of unbiased annoyance between dissonance methods

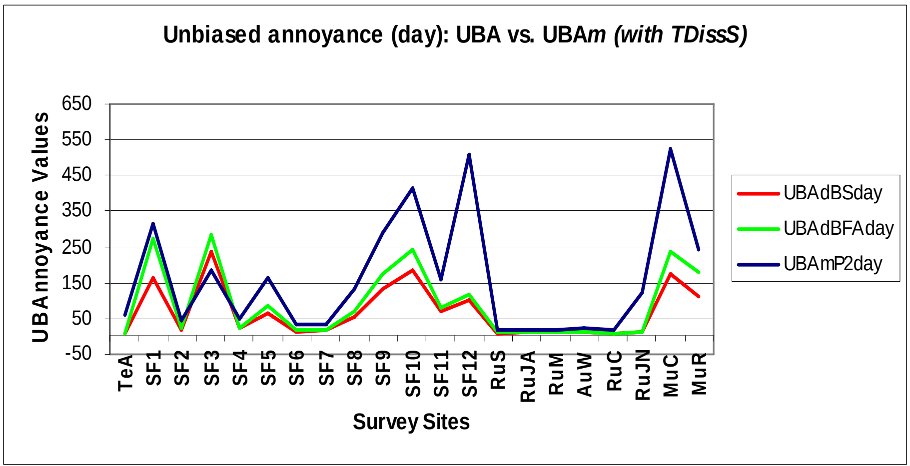

Figure 9.6.6: Annoyance UBA day vs UBA*m* day

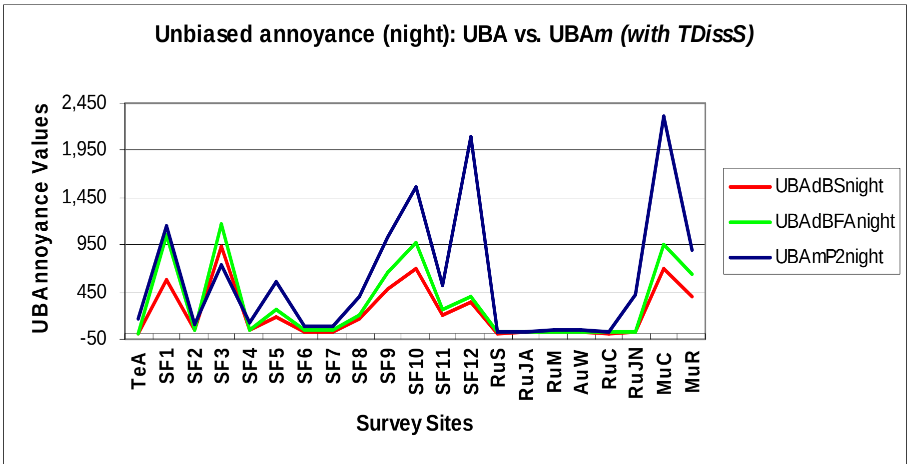

Figure 9.6.7: Annoyance UBA night vs UBA*m* night

Notes to the above figures:

'UBA' is unbiased annoyance calculated with dBSONIC values or dBFA32 values; 'UBA*m*' is modified unbiased annoyance; Hutchinson and Knopoff (H&K) and Sethares' (S); 'dBS' is dBSONIC; 'dBFA' is dBFA32; 'P2day' and 'P2night' is calculated with Sethares tonal dissonance (TDissS).

The values for unbiased annoyance in figures 9.6.6 and 9.6.7 present variation between the values for dBSONIC and dBFA32, both of which include fluctuation measures, and the implementation with Sethares tonal dissonance. The most significant variation is for soundfiles 1 (amplitude modulated sound), soundfile 3 (building clicks), soundfile 5 (tonal), soundfile 10 (sharp) and soundfile 12 (modulating tonal). The music soundfiles vary but are not considered for this environmental analysis. The program dBFA32 implements unbiased annoyance and it is with this method that the modified unbiased annoyance method of this work is compared. An analysis of the soundfiles and values indicates:

- For soundfile 1 the UBA/UBA*m* and loudness (N10) values are within ±7% of their average value. This is an acceptable variation for the purposes of this work.
- For soundfile 3 the UBA/UBA*m* variation is in the order of ±20% but the loudness is almost the same. This indicates that fluctuation does have a role when the sound is short and impulsive.
- With soundfile 5 the modified unbiased annoyance method gives significant weighting to the higher frequencies. Tones are at 990 Hz and 4000 Hz, frequencies that people are sensitive to. The method therefore is more sensitive to long duration sounds in the higher critical bands than is achieved with the fluctuation method.
- Both soundfiles 10 and 12 have sharp tonal nature. The method therefore is more sensitive to tonal sound than is achieved with the fluctuation method.

The rural environment values, unaffected by wind farm noise or bird song, have unbiased annoyance values in the order of 10 to 14 units measured to dBFA32 and 17 to 18 units measured by modified UBA. With staccato insect noise the rural measure was 14 units for dBFA32 and 124 units for modified UBA. In contrast, the Ashhurst residential measure without audible wind farm noise was 13 units for dBFA32 and 22 units for modified UBA. The variation between the measures can be attributed to the modified unbiased annoyance measure giving a higher weighting to sounds of higher frequencies and relatively long duration (in seconds rather than milliseconds).

The relationships between loudness, sound level and modified unbiased annoyance are presented in figure 9.6.8. There is a close relationship between loudness and modified unbiased annoyance with defined shifts in sound level.

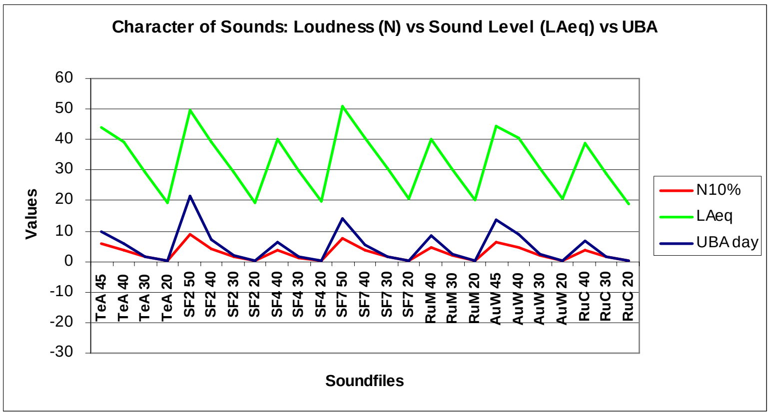

Figure 9.6.8: Character of sounds: loudness vs sound level vs unbiased annoyance

It is concluded from the observations, measurements and analysis that modified unbiased annoyance is an appropriate and acceptable measure for the purposes of unbiased environmental noise assessment.

Perception analysis

The May 2008 attitudinal survey contained a series of pre-recorded soundfiles, as previously recorded in this work. The purpose of the soundfiles was to present a consistent set of sounds that could be referenced for sound perception. A summary of the calculated magnitude or sound level verses the perceived character of the various soundfiles (figures 9.4.2.1 to 9.4.2.12) is presented in Table 9.6.2 and figure 9.6.9. In this Table the Manawatu and Brisbane responses are combined except for the two soundfiles where there are significant differences between the Manawatu (M) and Brisbane (B) responses for the same soundfiles. In order to group similar characteristics into a 'major' characteristic certain of the character responses are grouped: rough includes rumble and thump; sharp includes tonal and harsh; fluctuating includes beating and repetitive; unpleasant includes disturbing.

The values in Table 9.6.2 are derived from the combined responses of all the survey respondents for each major characteristic divided by the number of component characteristics comprising each major characteristic. The combined responses mean that a respondent may have 1 or more ‘positives’ for some of the major characteristics and this results in a fractional number for the response rate. In soundfile 1, for example, a total of 5 respondents found the sound rough and 4.7 found the sound unpleasant. In comparison, for soundfile 12 which is an alternating tone, only 1 respondent found the sound rough while 11.3 found the sound unpleasant.

Table 9.6.2: Soundfile perception – magnitude vs character

	Perceived Major Characteristics within a Soundfile					
Soundfile	**Rough**	**Sharp**	**Fluctuating**	**Unpleasant**	**Annoying**	**Pleasant**
SF1	5	8	11.7	4.7	6	1.3
SF2M	5	2.7	0	6	3.3	0
SF2B	0	0	0.3	0	0	10.3
SF3	2	10	3.7	6.3	5	0
SF4M	5	2.7	4	5.3	3.3	0.7
SF4B	0.7	0	0	0	0	5.3
SF5	7.7	9	5	8.3	5	0.7
SF6	6	3.7	5.3	6	4.3	4
SF7	1	7	8	5.7	5	1.7
SF8	5	6.3	3.7	7	5.3	0.3
SF9	5.7	7.3	5.3	9.7	7	0
SF10	2.7	13	3.3	10.7	5.3	1.3
SF11	5.7	7.3	9.7	11.3	6	1.3
SF12	1	13	6	11.3	5.3	2

The responses to soundfiles 2 and 4 present the most disagreement between the respondents in Manawatu compared to Brisbane. The Manawatu respondents had pre-knowledge and, it would appear, a pre-conception of the character of the sound illustrated by the soundfiles. This pre-knowledge and pre-conception did not exist for the Brisbane respondents who gained completely different perceptions. The clearly unpleasant and annoying sounds contain significant roughness or fluctuation, soundfiles 9 to 12. Soundfile 1 contains significant amplitude modulation and was judged to be highly annoying but not unpleasant. The measures indicate that the lower the modified unbiased annoyance value the higher the amenity of the soundscape in terms of ‘non-annoyance’. The responses are presented in figure 9.6.9 and illustrate the wide variation in perception.

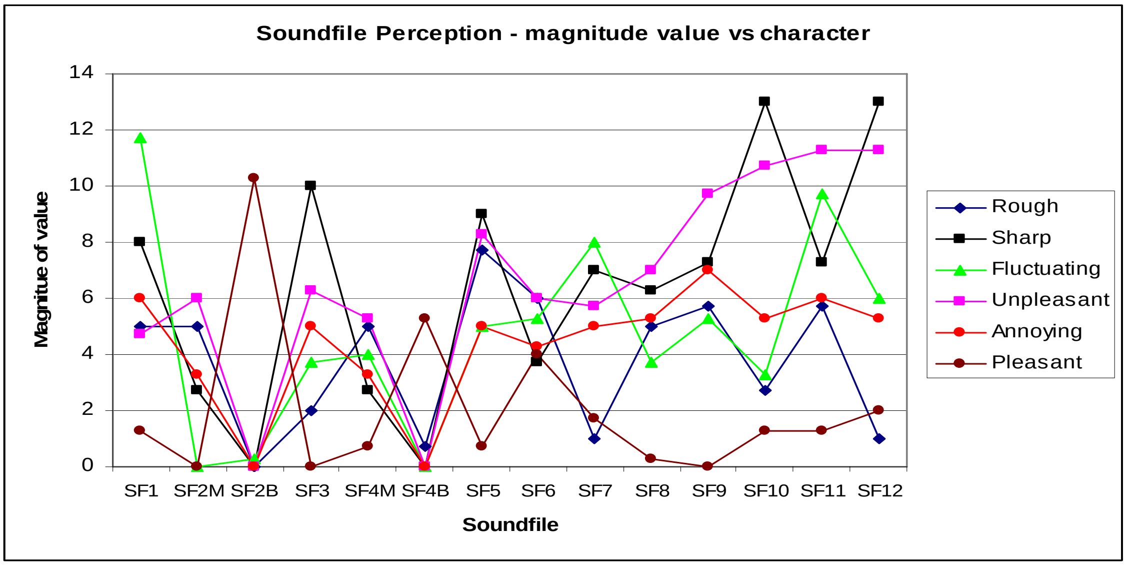

Figure 9.6.9: Soundfile perception – magnitude vs character

9.7 Soundscape analysis by modified unbiased annoyance

The surveys indicate that a rural environment unaffected by commercial or industrial noise has a high degree of positive amenity. The rural environments have modified unbiased annoyance values of less than 20 intrusion units. In comparison, the rural and urban environments that have wind farm noise overlaid have modified unbiased annoyance values in the range of 40-50 intrusion units. Sound perceived as being unpleasant and annoying has modified unbiased annoyance values of approximately 150-500 intrusion units.

It is concluded that modified unbiased annoyance is an acceptable and appropriate measure for the purposes of this work with respect to environmental sound analysis and perception. The measure is not suitable for music analysis.

CHAPTER 10: DECISION PROCESSES FOR NOISE ASSESSMENT

10.1 Decision processes

The starting point for consideration of the decision processes for noise assessment is to respond to the research question:

> Is it possible to develop a methodology incorporating a decision support system to integrate perceived noise with noise performance indicators, annoyance criteria and individual noise sensitivity?

The question raises more questions: what is a decision support system?; what is noise and how can it be perceived?; what are noise performance indicators and what criteria apply to annoyance? Individual noise sensitivity has a range of meanings. These questions have been answered in part in previous chapters and this chapter draws the themes together.

A decision support system is a methodology that combines models and data in an attempt to solve non-structured problems with extensive user involvement. In the context of this work the method assists in resolving noise problems by integrating subjective considerations with objective data against a background of standard measurement techniques, noise criteria and a decision matrix.

By far the most vexed issue is the assessment of noise is very difficult without a standard definition for ‘noise’. Everyone has a personal definition of noise and these can differ from standard community definitions. This work presents definitions based on the views of the persons interviewed in the course of the various studies.

Noise performance indicators are generally referenced to nominal community expectations and these can vary within communities and between countries. This issue is addressed further in this chapter.

Annoyance and noise sensitivity are not the same, as has been determined previously in the course of this work. Together, however, they must be considered as part of the decision process.

10.2 Individual amenity, noise and annoyance

The relationship between individual amenity and the adverse effects of noise is fundamental in the description of intrusive noise. For a sound to become noise, it must be unwanted by the recipient. Noise intrudes upon the amenity of a person and due to its unpleasantness causes annoyance and distress. The mechanism for this transformation of sound to noise varies widely from person to person. Because our hearing is functioning all the time we are continuously monitoring, analysing and responding to what we hear. Our environment is a complex of competing sounds, many are benign, and the sounds we hear are normally what we expect to hear. They are the common, everyday sounds that we are used to and generally accept and ignore. However, sometimes a sound or event occurs that triggers a warning or alert response within us. If the sound evokes a negative personal response the sound is unwanted and is noise. When an individual responds to intrusive sound or noise, the person is responding to a stimulus that is noticeable within the individual's environment. An individual may react differently to noise from a combination of sources than to noise from a single source at the same level. Significantly, other persons in the vicinity may not hear or be disturbed by the noise. There is, however, a stable personality trait for noise sensitivity that provides a foundation for the assessment of individual acceptability of a particular sound under general and specific conditions. Individual amenity is a complex mix of personal noise sensitivity, personal and cultural attitudes to noise in the environment, and habituation effects.

As noted previously in Chapter 2, many affected people do not know how to best describe the noise that they hear. Noise assessment for individuals is often confused with global noise exposure measures applied to communities. Individuals respond differently to noise depending on the "level" of the noise, its character, and the meaning or effect of the noise on the person. Many noise measures do not apply until the sound is quite loud whereas individuals can be considerably disturbed by noise that is only just audible to them. For a sound to be annoying it must intrude upon an individual. For the purposes of this work only audible sound is considered and inaudible sound or vibration of the body is not pursued. The question is, therefore, what are the mechanics of "intrusion"? The mechanism for this transform of sound to noise varies widely from person to person. The assessment of "intrusive" noise, or "nuisance" noise, is subject to individual sensitivity to the noise in question (that is, why is the sound noise?). Audibility and intrusive noise can therefore be defined in terms of effect, referenced to before, during and after some identified noise event. The reaction modifiers for individuals include:

- Attitude to noise source
- Attitude to information content in the noise
- Perceived control over the noise
- Sensitivity to noise (in general and specific)
- Sensitivity to specific character of the noise

Based upon the work described previously, these reaction modifiers can be integrated into definitions for intrusive sound, noise and intrusive noise that allow quantification in measurable terms and qualification as:

Intrusive sound

> Intrusive sound is a sound that, by its characteristics, is audible and intrudes upon the well-being or amenity of an individual.

Noise

> Noise is a sound that is audible to an individual and has definable characteristics that modify the individual's emotional and informational responses to that sound from pleasurable or neutral to adverse.

Intrusive Noise

> Intrusive noise, to an individual, is a sound whose variance in character (such as audibility, dissonance, duration, loudness, tonality, pitch or timbre) is perceived adversely compared to the character of the environment in the absence of that sound.

Amenity values are based upon how people feel about an area, its pleasantness or some other value that makes it a desirable place to live. Noise affects the way individuals and the community feel about their environment and how these “amenity” values form part of the economic values placed on the environment by the community as a whole. The adverse intrusion of a sound into the well-being or amenity of an individual is a significant precursor to annoyance. The amenity of an individual can, therefore, be defined in terms of the effects of sound exposure and character of sound in the environment-

- Significant adverse effect. The sound is deemed to be noise irrespective of subjective response causing annoyance or anger and has adverse health reactions including sleep disturbance;
- Nuisance adverse effect causing anger, annoyance, or adverse health reactions including sleep disturbance;
- Adverse effects more than minor;
- An adverse effect, but no more than minor (minor irritation);
- No adverse effect, pleasurable sounds or peace and tranquillity.

Based on the foregoing, it is practical to define “unreasonable noise” as being the first two dot points, the transition stage between unreasonable and reasonable noise as the third dot point “adverse effects more than minor”, and “reasonable noise” as being the fourth dot point. The fifth dot point infers no noise whatsoever.

In terms of noise, therefore, a person has cause for complaint about noise and is acting in a not unreasonable manner if he or she is:

- Awoken or suffering from disturbed sleep due to noise
- Disturbed by noise while relaxing within his or her home
- Annoyed by noise inside or outside the home
- Reacting to the sound because the individual finds that the sound contains perceptually negative information

An individual’s comfort within an environment and sensitivity to noise are affected by that individual’s exposure and habituation to different types of sounds. The subjective component of the methodology outlined in figure 10.2.1 presents the various indicators a person may subconsciously perceive and apply when listening to a sound. The criterion 'personal space' includes an individual's emotional state and sensitivity to a particular sound.

Having heard a sound and made an instantaneous value of that sound, an individual immediately characterises the sound as pleasant or unpleasant, acceptable or unacceptable, a sound that can be accommodated or intrusive noise. Figure 10.2.1 presents the relationships in a format to describe why the same sound does not always provoke the same intensity of disturbance or annoyance at different times in the same individual.

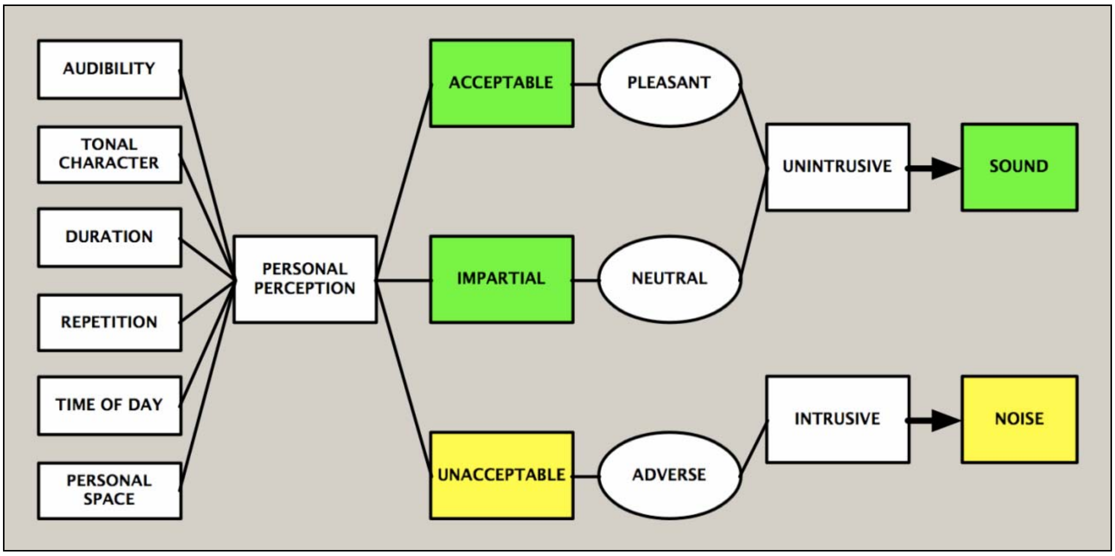

Figure 10.2.1: Subjective decision processes to differentiate between sound and noise.

The processes presented in figure 10.2.1 are common features in how an individual responds to a sound and makes perceptive choice that the sound is "good", "annoying but can be lived with" or "intrusive – get rid of it". A person can change his or her perception about a sound but tends towards a stable response with a set "value" for the sound. That is, ultimately, the sound is either accepted or rejected as a nuisance.

The audibility of a sound is its most common feature – a sound must be audible to be heard. This is the essential problem with all sound – noise assessment systems: a person is an individual and his or her responses cannot be mimicked by a machine. Equally, one individual cannot tell another individual what he or she hears and how he or she should respond to that sound. Audibility is aided by the character of the sound:

if the sound is similar to the locale then, even if the sound is audible, it is more likely to be accepted. If the character of the sound is foreign to the existing environment then it has less chance of being accepted. To an individual, the time of the day the sound is heard is important with unusual sounds in the early morning being less acceptable than if they are heard during the day. Sounds that disturb sleep are nearly always unacceptable even if they have some potential benefit to the individual. The number of times a sound is heard and the duration of the sound is important but, even though there are some studies for transportation noise they do not relate to low amplitude sound. If a sound affects the personal space of a person while at home, inside or outside, that sound has a high degree of probability as being a disturbance. Additionally, if the sound has information content that the person does not want to hear that sound is perceived negatively. Personal perception therefore combines a variety of attributes that cannot be measured by instrumentation.

In evaluating the ‘quality’ of a sound, the audibility of the sound is assessed by an individual by using different terms to describe the sound. The terms “loud”, “high volume”, “low pitch”, “low frequency” or “high pitch” are often used to describe sound and noise. Unfortunately, these terms do not readily correspond to the “normal” meaning given by the general population. That is, the terms will mean different things to different people. An individual may describe in many different ways the perceived character and any emotional value that person may give to the sound. The techniques of sound quality measurement provide a partial analogy for sensitivity.

10.3 Environmental noise assessment

Environmental noise assessment has long been the sole province of regulatory authorities. Over recent years, as found from the literature reviews pertaining to this work, people have been questioning not only the mandated noise criteria but also the why-and-how of the development of the criteria and the methodologies for measurement and assessment. This section reviews vary briefly two very different regulatory approaches to regulatory noise management and compares these approaches to the perceived needs of individuals and communities.

The first approach. Environmental noise assessment in New Zealand and internationally to a large degree, is management of sound from various sources to some pre-determined 'baseline' sound level. This level may be daily exposure (such as the United States' day-night level) or for some shorter or longer period of time. Implicit in the assessment is that a certain proportion of the community will be highly annoyed by the source of noise at the baseline sound level set. As stated previously in this work, this proportion is in the order of 10 to 20 percent of the exposed population depending on the source of noise and the baseline sound level. New Zealand district plans often refer to some statistical sound measure but, as stated previously:

> It was concluded from the investigations that there is no evidence that an external level of 45 dBA L10 is an acceptable or desirable night-time upper limit at a dwelling. Similarly, there is no evidence from the surveys that 55 dBA L10 is an acceptable or desirable daytime upper limit. These limits are those recommended in many New Zealand District Plans and various New Zealand standards for environmental noise.

New Zealand has a slightly different approach for some industrial activities that require resource consent under the Resource Management Act 1991. The approach is based upon an analysis of the nature of the sound source, the nature of the receiving environment and the potential for adverse effect due to the sounds. Section 17 of the Act defines "effect" as meaning:

> (a) Any positive or adverse effect; and
> (b) Any temporary or permanent effect; and
> (c) Any past, present, or future effect; and
> (d) Any cumulative effect which arises over time or in combination with other effects regardless of the scale, intensity, duration, or frequency of the effect, and also includes-
> (e) Any potential effect of high probability; and
> (f) Any potential effect of low probability which has a high potential impact.

The above process appears to have application only when an activity is referred to the Environment Court for decision. Experience within the Environment Court process indicates that this approach does not seek to protect individual values but rather something between individual amenity and the pre-determined baseline amenity for the community-at-large. Noise performance standards incorporated within district plans or New Zealand Standards are applied unless there is significant proven reason why some other indicator should be adopted. There appears to be little or no requirement within the New Zealand system for an applicant to provide a full and detailed assessment of an activity in terms of section 17 of the Act. Consequently, individuals and local communities in New Zealand appear to have very little redress against noise from industrial activities unless such noise is so unreasonable or excessive the territorial local authority is forced to take legal action for mitigation. In contrast New Zealand has a very robust and effective control process for noisy parties or loud music.

The second approach. Individual amenity is protected based upon an analysis of the nature of the sound source, the nature of the receiving environment and the potential for adverse effect on the individual due to the sounds. This approach is mandated in Queensland where environmental protection legislation is based on preventing nuisance and environmental harm. Environmental harm is any adverse effect or potential adverse effect of whatever magnitude, duration or frequency on an environmental value. Environmental nuisance is unreasonable interference or likely interference with an environmental value. As previously stated, the environmental values for noise stated in the Environmental Protection (Noise) Policy 1997 are:

> The environmental values to be enhanced or protected under this policy are the qualities of the acoustic environment that are conducive to-
> (a) the wellbeing of the community or a part of the community, including its social and economic amenity; or (b) the wellbeing of an individual, including the individual's opportunity to have sleep, relaxation and conversation without unreasonable interference from intrusive noise.

Intrusive noise is defined as meaning:

> Intrusive noise means noise, that because of its frequency, duration, level, tonal characteristics, impulsiveness or vibration (a) is clearly audible to, or can be felt by, and individual; and (b) annoys the individual.

The Environmental Protection Act binds all persons and the State. Local governments can set individual noise requirements within their planning schemes or refer to published state guidelines. Specific legislation also controls noise from many activities or potentially noisy machinery. Conversely, the policing of noise from music and parties is not as effective as in New Zealand.

As presented previously in this work, the two approaches tend to come together at approximately 50 to 55 dB(A) LAeq for transportation sources. Significant differences between the approaches appear, however, when low amplitude sound is considered. Sound levels from any source at the receiver of below 50 dB(A) are far more complex to assess and individual response becomes a major factor rather than the level of sound exposure. As sound levels approach 30 dB(A) at the receiver individual response and noise sensitivity become important considerations as well as the nature or characteristics of the sounds as heard by the individual. These levels are often below nominal baseline sound levels for a particular source and the questions arise whether the sounds are reasonable or unreasonable and whether the individual is reasonable or unreasonable in his or her responses.

The Queensland approach is significantly more complex in application and is often referenced to existing measured background sound levels with the activity limited to creating noise only a few decibels (0 dB to 5 dB) above the background. While the approach is complex compared to the New Zealand approach it presents, in my opinion, a better outcome for both individuals and industry as the rules are clearly defined, relatively inexpensive to progress, provide certainty and are effective. The Queensland legislation also sets noise emission criteria for a range of products, including domestic air conditioners. This approach integrates noise emissions at source to noise propagation analysis and noise immission at a receiver.

Individual and community expectations. Individuals, however, under either approach are relatively powerless to force change or obtain noise mitigation. Coincidently, based upon New Zealand and Queensland experiences, community groups also seem to experience the same problem. The fundamental issue both sectors have is significant difficulty in either sourcing relevant information or receiving the information in a form that makes sense to the persons involved. This section combines both of the regulatory approaches and provides methodologies for persons to investigate noise problems and compare results against amenity criteria and noise descriptors. The methodologies combine a heuristic search approach with sensitivity analysis to model reasonable noise – reasonable person interaction.

10.4 The reasonable person

All people are individuals and one person cannot, in terms of noise, state what another person hears or feels. The concept is important, however, in the assessment of low amplitude sound and noise because it has a direct relationship to the transitional phase of when adverse effects become more than minor. Various dictionary meanings of reasonable include: rational; governed by or being in accordance with reason or sound thinking; not excessive or extreme; fair; intelligent approach supported or justifiable by reason; possessing sound judgment. "Unreasonable" has dictionary meanings of: not governed by or acting according to reason; absurd; exceeding the bounds of reason or moderation. The decision relationships between reasonable noise and a reasonable person can be presented as-

- Reasonable noise – reasonable person
- Unreasonable noise – reasonable person
- Reasonable noise – unreasonable person
- Unreasonable noise – unreasonable person

In terms of noise, therefore, what guidance can a person have in order to at least feel comfortable that he or she has a reasonable concern and is acting in a reasonable manner with a reasonable complaint? The summary evidential requirements are:

- Evidence for definition of unreasonable – reasonable noise
- Evidence for definition of unreasonable - reasonable person
- Evidence for low amplitude sound – low amplitude intrusive noise
- Evidence to support definition of annoyance for low amplitude intrusive noise.

There is no defined relationship that can predict when a noise is reasonable or unreasonable; for this to happen, the sound must be intrusive and then have that added salience that makes it an adverse effect to the person listening. The person may or may not be unreasonable in their attitude. The environmental awareness and noise sensitivity questions of this work as presented in the next chapter presents a methodology providing objective measures to these highly subjective perceptions.

10.5 Assessing sound and noise in objective terms

The “level” of noise must be established in terms of fact and degree. A decision tree to assist this process is presented in figure 10.5.1. The processes described in the figure are referenced to the noise impact assessment methodology of USEPA *Guidelines for Noise Impact Analysis* 1982 (USEPA, 1982). The decision tree is significantly different to the 1982 guidelines by providing a lower criterion of less than 42 DNL; identifying attitudinal, noise sensitivity, community and individual responses; benefit-cost analysis; levels of adverse effect and unreasonable noise criteria. The decision processes in the figure are an overview and apply primarily to sounds above 50 dB(A). The concepts apply to low amplitude sound and intrusive noise by extension and consideration of the features of desirable amenity inside and outside a home. The standard of amenity and potential for noise mitigation can be assessed when the sounds from any particular source are heard at or within a home.

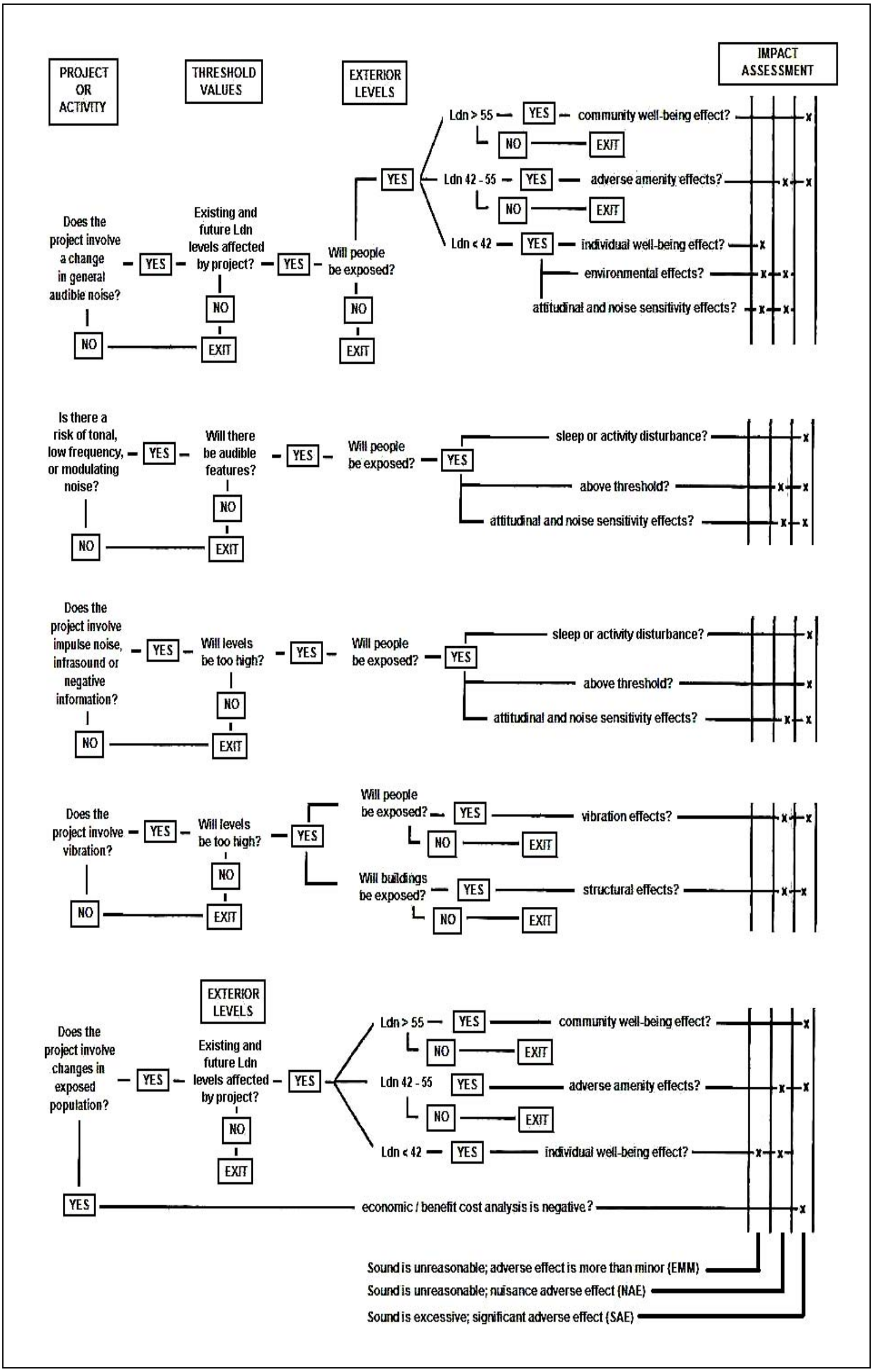

Figure 10.5.1: Decision processes for potential adverse effects of noise.

Amenity categories for average maximum and ambient levels applying to sounds when measured at a residence are expressed in Table 10.5.1. The categories and assessment methodology of the Table have been developed as outcomes from this work. The assessment starts at Category M1 and A1; if the sound levels or characteristics exceed a particular category then the next highest category applies.

Table 10.5.1: Categories for sound levels in dB(A) and amenity at a residence

Category	Average Maximum Sound Levels in dB(A) at a residence
M1	Soundscape neutral and sounds not intrusive inside or outside the residence,
M2	Not always audible inside a residence, with or without special audible characteristics
M3	Audible (below 45 dB LAmax inside a bedroom), may be moderately annoying with or without special audible characteristics
M4	Audible (45 - 55 dB LAmax inside a living room), may be moderately annoying with or without special audible characteristics
M5	Audible (65 dB LAmax or above outside a residence), may be highly annoying with or without special audible characteristics
Category	Average Leq Sound Levels in dB(A) at a residence
A1	Soundscape neutral and sounds not intrusive inside or outside the residence
A2	Not always audible inside a residence, with or without special audible characteristics
A3	Audible (below 35 dB LAeq inside a bedroom), may be moderately annoying with or without special audible characteristics
A4	Audible (below 40 dB LAeq inside a living room), may be moderately annoying with or without special audible characteristics
A5	Audible (55 dB LAeq or above outside a residence), may be highly annoying with or without special audible characteristics

Notes: (1) See Glossary for definition of “special audible characteristics”
(2) Low noise ambient soundscapes with low background (measured as either the L90 or L95 sound levels) are affected at Categories M2 and A2 of Table 10.5.1
(3) Sporadic complaint can be expected if single event maximum levels heard inside a bedroom are more than 5 dB(A) above night-time background levels (referenced to 10 minute measurement intervals)
(4) Complaint can be expected if LAeq levels containing distinctive adverse sound characteristics heard inside a bedroom are more than 5 dB(A) above night-time background levels (referenced to 10 minute measurement intervals)

Table 10.5.1 classifies two significant situations not clearly identified by existing environmental sound assessment methodologies are:

- Sound that is clearly audible but below the generally accepted assessment criteria or which has an identifiable character that is difficult to measure and assess.
- Sound that just intrudes into a person's consciousness. Such sound may be distinctly audible, or have a definable character, or it may be almost inaudible to others.

The "reasonable – unreasonable" complex is presented in Table 10.5.2 combining sound level, audibility, sound character and effect.

Table 10.5.2: Decision assessment of unreasonable – reasonable noise or person

Noise and Person	Category
Reasonable Noise - Reasonable Person Noise not intrusive, No complaint	1
Reasonable Noise – Unreasonable Person Noise sometimes intrusive - Complaint made without evidence	2
Reasonable Noise - Reasonable Person Transition Noise sometimes intrusive - Complaint made with evidence	3
Unreasonable Noise – Reasonable Person Noise often intrusive - Complaint made with evidence	4
Excessive Noise – Reasonable Person Noise often intrusive - Complaint made with evidence	5

Noise sensitivity lies outside the decision assessment as the trait informs about the person's potential to be disturbed, rather than the person's response to a particular sound. Noise sensitivity is considered as part of the assessment of noise intrusion.

The next chapter establishes the decision processes together with the analysis processes for intrusive noise and low amplitude sound.

CHAPTER 11: INTRUSIVE NOISE AND LOW AMPLITUDE SOUND

11.1 Introduction

The application of this work has been to explore methodologies incorporating a decision support system to integrate perceived noise with noise performance indicators, annoyance criteria and individual noise sensitivity and, consequently, to establish a methodology to assess low amplitude intrusive noise with respect to an individual. Conceptually, the methodologies must combine human perception with sound measurement and a process to integrate disparate information into a meaningful whole. The methodology follows the process illustrated in figure 11.1.1:

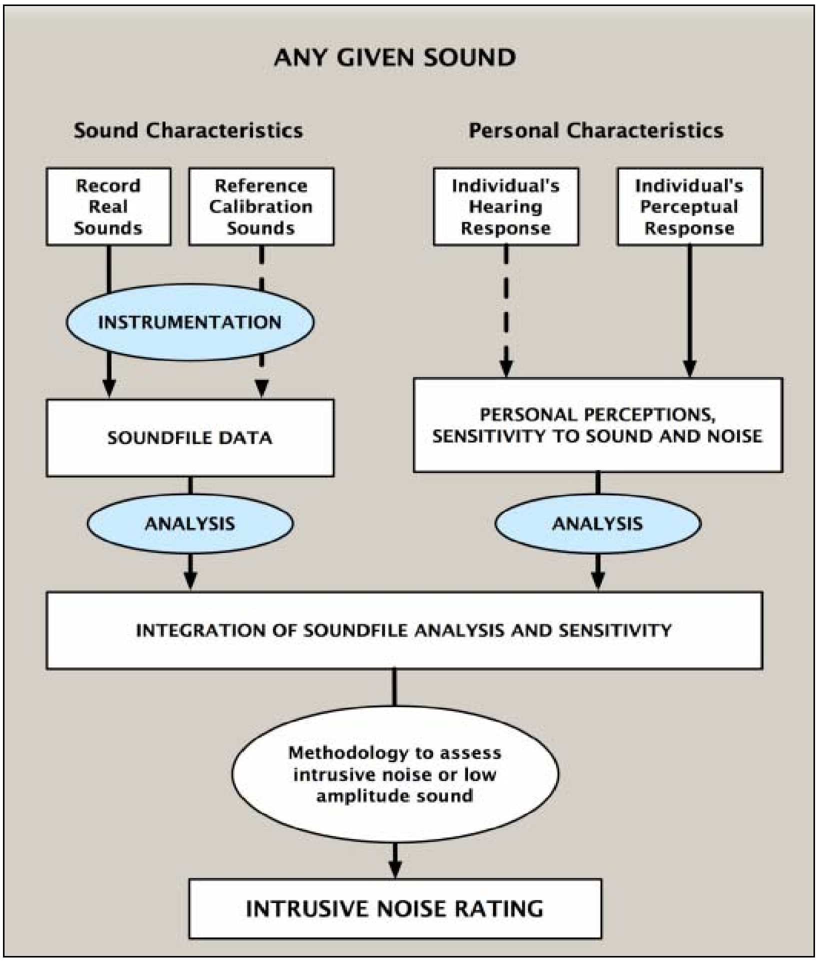

Figure 11.1.1: Method for measuring and assessing low amplitude sound and intrusive noise
Note: The dotted lines in figure 11.1.1 indicate desirable but not essential features.

The methodology presented in figure 11.1.1 is in three parts:

The first part is data gathering:

1. A sound is analysed in a structured, standard manner for its acoustic and sound quality characteristics.
2. The person who is interested in the sound is able to undertake a series of environmental and noise sensitivity tests in order to evaluate personal sensitivity and perceptions with respect to the sound.

The second part is data processing:

The sound quality measures and personal perceptions are integrated into a structured analytical methodology referenced to subjective analysis and objective criteria for which the relativities between non-parametric and parametric data are structurally encapsulated.

The third part of the methodology calculates an intrusive noise rating:

The information derived from the first two parts of the methodology is structured into a decision process for sound and intrusive noise, with special consideration given to low amplitude sound analysis.

11.2 Sound analysis

Sound analysis commences with the capture of the ‘sound of interest’, as presented in Chapter 5. The process takes real-world sounds presented in a Windows ™ PCM .wav format soundfile. The sound file is analysed for its overall character and then for those segments (if necessary) containing identified “noise” is analysed. Chapter 4 of this work present the varied measures that were considered for inclusion in the analysis methodology. The soundfile is automatically analysed in relation to the measures of dissonance, loudness, pitch and sound level. The objective component of the methodology, illustrated in figure 11.2.1, integrates common musical, acoustical and psychoacoustical attributes or measures. Based on the investigations made for this work the most relevant sound quality measures are loudness, loudness level, pitch salience, spectrum and tonal dissonance, tonality and modified unbiased annoyance.

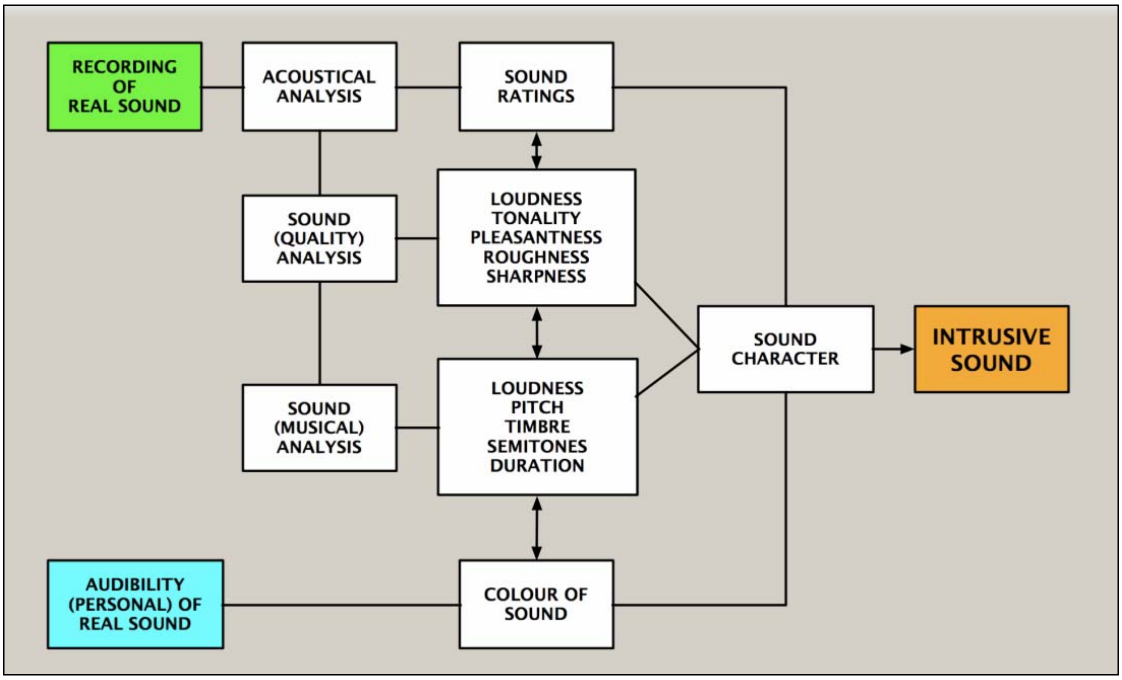

Figure 11.2.1: Objective and subjective decision processes to characterise intrusive sound

Intrusive sound is related to overall sound level; acoustical prominence features such as tonality or impulsiveness; audibility; and dissonance characteristics such as an audible beat, fluctuation, hum, modulation or rumble. The complete soundfile, or any distinct part of the soundfile, is analysed for all measures and all data is retained in a comma-separated variable summary format output file. Only some of the measures, however, are brought forward into a summary display output file.

The most relevant acoustical measures displayed are audibility, equivalent continuous sound pressure level (A-weighted), instantaneous sound pressure level (A-weighted), overall statistical measures (90% and 10%, A-weighted), a time history of sound levels (A-weighted) over the analysis period, and one-third octave bands (Z-weighted). The soundfile is analysed for the unbiased sound quality measures including sensory pleasantness (incorporating loudness, fluctuation, roughness and sharpness), psychoacoustic annoyance ((incorporating loudness, roughness, sharpness and tonality) and modified unbiased annoyance ((incorporating loudness, tonal dissonance and sharpness). Modified unbiased annoyance is the primary measure of sound intrusion and, combined with individual perception, the primary objective measure of noise intrusion. The calculated value for modified unbiased annoyance is displayed.

Measures that have a base in musical analysis calculate the potential prominence of different notes or narrow bands of noise. The primary measure is pitch salience with the calculations as prominence values in semitones. A semitone is nearly the same as a one-twelfth octave acoustical measure. Tonalness is calculated and this measure is referenced in comparison with acoustical tonality. Pitch salience is an excellent measure for visual display in 2D or 3D format to illustrate the potential for a sound to be noticed within the context of the whole soundfile.

The measures for this work have been calculated by reference to different analysis programs, including dBSONIC and dBFA32, NoiseLAB3 and PsySound2. The analysis programs have different FFT sample rates (from 65536 to 4096 points) and different calculation procedures for some of the measures. This work presents an analysis program referenced to Psysound2 and the measures are calculated with a 4096 point FFT.

The analysis program, *Analysis of Environmental Sound* (AES), is the practical implementation of the concepts, measures and methodologies of this work. The program is a work in progress with the FFT rate being increased to 32768 points in order to calculate the ISO 1996 tonality measure. The primary measures in the program are calculated to the measures of PsySound2 with a 4096 point FFT. AES utilises the FFT algorithm, statistical analysis and graphics routines from the Software Development Lohninger (SDL) suite implementations. The SDL suite has comprehensive graphic and data output support and provides magnitude and phase information not available in PsySound2.

The processing routines of AES follow the procedures in PsySound2:

- Read soundfile (*Microsoft .wav format*[34], 16-bit integer, 44100Hz, 1 or 2 channels)
- If 2-channels, then compare channels and mix to 1 channel
- FFT (4096-point Hanning window (= 93 ms)) - at 50 ms intervals
- Generate compact spectrum (108 components from 2048)
- Calculate L(A) from compact spectrum
- Calculate specific loudness from compact spectrum

[34] PsySound2 supports Apple or Macintosh AIFF soundfile format as standard

- Calculate loudness, sharpness, timbral width and volume from specific loudness
- Calculate spectrum dissonance from compact spectrum
- Extract tone components
- Calculate tone dissonance calculated from tone components
- Adjust tone components for masking effects
- Calculate audible pitches from tone components
- Calculate tonalness, multiplicity and salience
- Reduce pitches to 12-chroma and 88-pitch patterns
- Store L(A), N and ΔL for statistical measures.
- Calculate SPL, octave and 3rd-oct spectra from compressed compact spectrum
- Calculate tonicity and Maj/min from compressed chroma pattern.
- Accumulate means for overall results.
- Calculate background noise measures.
- Calculate tonality and chord from overall chroma pattern.
- Calculate statistical L(A), N and ΔL measures.
- Output summary results to summary datafile and graphics

Making a decisions about a sound requires listening to its audible characteristics but as the perception of these sounds vary from person to person other methods need to be made to communicate meaning or awareness. In the previous sections tables and line charts of summary values have been presented but these are often meaningless by themselves. A common analysis is in the form of a detailed acoustical chart, figure 11.2.2 that illustrates changes in sound level over time.

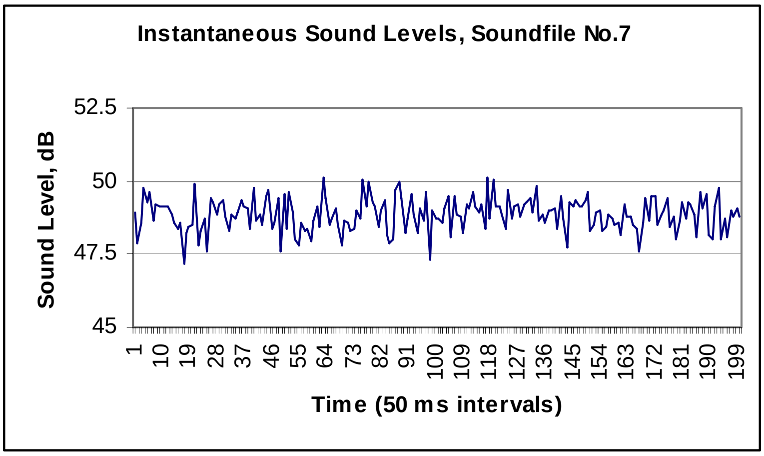

Figure 11.2.2: Example of a time-history sound level chart

This works presents acoustical information in a 3D format with musical notation. The methods are illustrated with respect to the outputs of the AES program with an instantaneous sound level time-history chart and two pitch salience charts, figures 11.2.3 and 11.2.4. The charts in figures 11.2.3 and 11.2 4 present examples of a different way of looking at a sound[35], in terms of mean pitch salience. Sound character is represented by the prominence of the semitones within the overall sound.

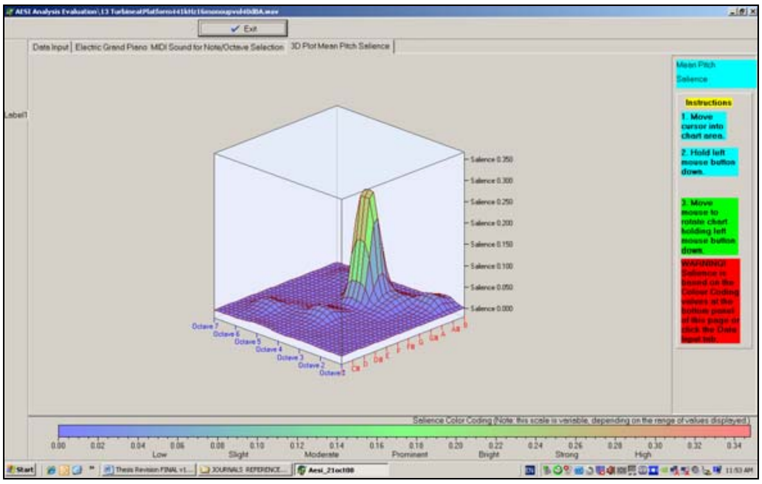

Figure 11.2.3: Example of a sound analysed in 3D mean pitch salience format

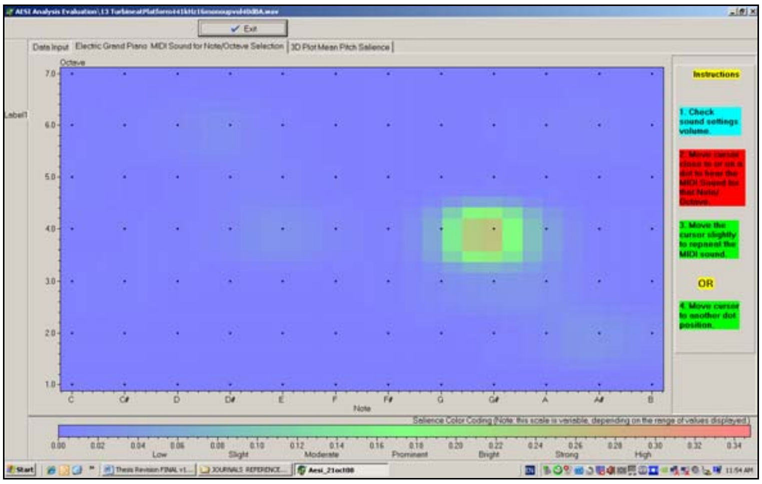

Figure 11.2.4: Example of a sound analysed in 2D mean pitch salience format

The visual format displays sound character in a meaningful way and the different charts provide visual indication as to the variability of the sound and its potential for intrusion. A variation in colour, for example green to red, indicates the semitones are

[35] The soundfile is the Te Apiti wind turbine with an overall level of 40 dB(A)

significantly different and the prominence of the notes / narrow-band sound is noticeable within the sound. The salience values indicate differing levels of prominence with some levels more noticeable than others. This does not mean that the sound is adverse in nature; it means that there is a method available to physically measure a variation in a meaningful way. Audibility is presented as an audibility chart, figure 11.2.5, where the sound of interest (red curve) adjusted third-octave ambient noise spectrum is plotted against the 20 phon equal loudness level contour – 35 dB(A) reference sound level (green curve) and threshold of hearing (orange curve).

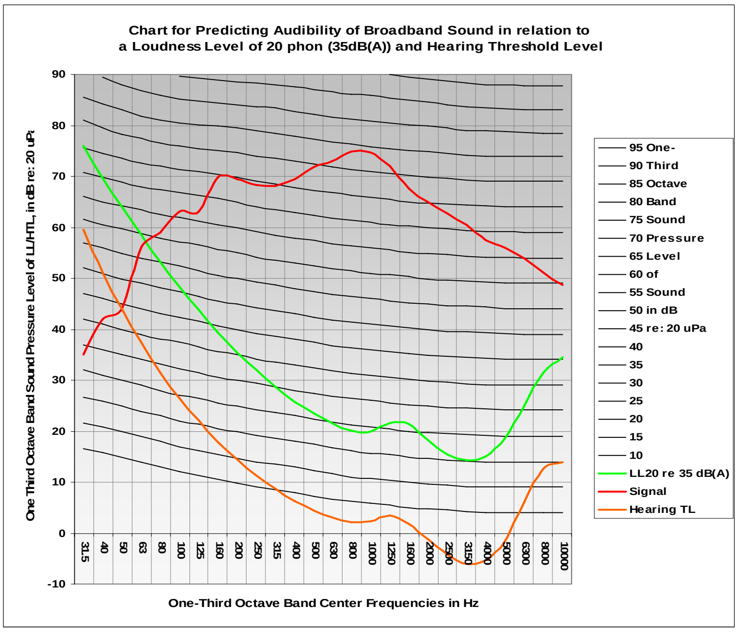

Figure 11.2.5: Audibility of a sound

It is concluded that a combination of the methods is necessary to describe the character of the overall sound and the prominence of the sounds in relation to each other in order that people may easily gain knowledge of the character of the soundscape and any sound of interest within that soundscape.

11.3 Analysis of low amplitude sound

The work applies audibility, loudness, salience prominence and modified unbiased annoyance as the most significant measures for low amplitude sound. Analysis of low amplitude sound presents significant issues recording and measurement instrumentation, methods of measurement and assessment. This work has identified the issues with recording and measurement instrumentation. Instrumentation usage can be readily divided into two parts: sounds above 20 dB(A) and sounds below 20 dB(A). Sounds above 20 dB(A) can be recorded and measured with standard commercial type 1 or 2 instruments or recorded within a computer audio system without significant degradation due to signal noise. For sounds below 20 dB(A) to the nominal threshold of hearing, however, specialised instrumentation is required to ensure a clean signal. Specialised calibration instrumentation is also necessary and is described in this work.

Figure 11.3.1 presents the data of representative soundfiles recalculated to lower (quieter) sound levels using dBFA32. The dataset is referenced from Table 9.5.4.3. The primary values are loudness, overall equivalent sound level (LAeq) and unbiased annoyance (UBA*m*). Both loudness and unbiased annoyance are physical measures that can be assessed with personal sound perception. Analysis of the soundfiles indicates that low amplitude sound – which would be the normal case inside a dwelling – have relatively low loudness and modified unbiased annoyance values. In Table 9.5.4.3 the levels for the Ashhurst locale, with or without wind farm noise, are below 1.0 UBA*m* for a sound level of 20 dB(A). The environment, however, has distinctive acoustical character in terms of one-third or one-twelfth octave band levels. Audibility even at 20 dB(A) presents a distinctive analysis pattern and is described by one-third octave band analysis (the audibility chart) or as represented in semi-tones by mean pitch salience.

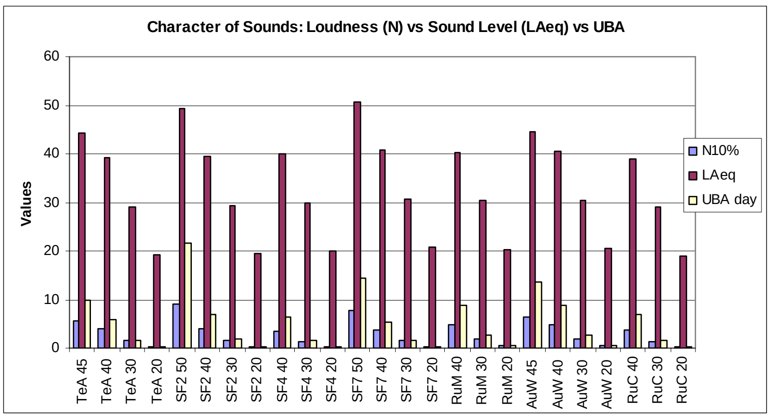

Figure 11.3.1: Loudness vs sound level vs unbiased annoyance of low amplitude sound

The charts in figures 11.2.3 and 11.2 4 present a different way of looking at the sound, in terms of mean pitch salience. Sound character is represented by the prominence of the semitones within the graphic. This format allows very low amplitude sound character to be displayed in a meaningful way and the charts provide visual indication as to the variability of the sound and its potential for intrusion. A person sees that the quieter the sound the lower the value of the salience values. It is concluded that the presentation methodology is appropriate for the purposes of defining and integrating noise performance indicators and annoyance criteria for low amplitude sound.

11.4 Perception of a sound and Intrusive Noise Rating

Personal perception of a sound is investigated through assessment of personal noise sensitivity, personal perception of the characteristics of the sound. Personal response questionnaires developed from the questionnaires presented in the course of this work are compiled in Annex E. The perceptual response questionnaires are designed to describe an individual's:

- sensitivity to the disturbance created by the sound, such as sleep disturbance or annoyance, as indicated by a personal noise response assessment
- sensitivity to noise, as indicated by the NoiSeQ noise sensitivity questionnaire
- perception of the sound as indicated by the soundfile analysis questionnaire

The perception analyses assess personal responses to avoid, remedy or mitigate sleep disturbance or disturbance with relaxation or enjoyment of the property. Intrusive sound is defined as such by the person affected by the sound. The program, however, uses the modified unbiased annoyance calculation to establish the potential for intrusive sound and, by correlation with the personal perception assessments, provides refined analysis.

Personal perception of the sound and the environment in which the sound is heard is fundamental to assessing the potential for noise intrusion and annoyance. This work establishes a defined methodology for sound and noise perception through application of perception – sensitivity questionnaires. The questionnaires (Annex E) are:

1. A simple personal questionnaire that links sex and age with hearing response.
2. A locality questionnaire. The questionnaire assists in defining the potential for masking sound that may - or may not - mask noise. The responses assist in defining a nominal ambient sound level for the person's locale and this is associated with previous socio-acoustic studies.
3. A noise in the environment questionnaire. The questionnaire asks about noise in the person's environment and links to the noise sensitivity analysis.
4. An 'are you disturbed by noise' questionnaire. The questionnaire asks about noise that may disturb or annoy the person while relaxing or sleeping. This questionnaire links to the noise sensitivity analysis questionnaire.
5. A personal noise sensitivity questionnaire. The questionnaire asks 35 specific questions and all questions must be answered in order to obtain a noise sensitivity analysis. This questionnaire links to the personal noise disturbance questionnaire.
6. A sound perception questionnaire. This questionnaire is designed to identify the character of the sound and is used to compare different sounds and characterise a particular sound that concerns the person.

There are no 'right or wrong' answers to the questionnaires. The fundamental purpose of the decision process is confirming that a particular sound exists. If the person can hear a sound and analyse it then that is all that is needed to establish effect.

A perceived sound is quantified in terms of amenity and potential for noise intrusion when the sound(s) from any particular source are heard at or within a home. The decision process is presented in Chapter 10. The categories and assessment methodologies presented in Tables 10.5.1 and 10.5.2 have been developed as outcomes from this research work.

The New Zealand – Brisbane reference amenity sound levels and modified unbiased annoyance values established by this work are:

- The levels for better than average environmental amenity is an environment with an exterior night-time background (L95) level of 33 dB(A) ± 4.7 dB(A) or less for most weather conditions. In the alternative, an exterior night-time average (LAeq) level of 40.4 dB(A) ± 4.3 dB(A) or less for most weather conditions. The modified unbiased annoyance exterior night-time value is less than 50 *iu*

- The level for average environmental amenity is an environment with an exterior night-time background (L95) level of 29.9 dB(A) ± 4.9 dB(A) for most weather conditions. In the alternative, an exterior night-time average (LAeq) level of 45.5 dB(A) ± 8.9 dB(A) or less for most weather conditions. The modified unbiased annoyance exterior night-time value is 50 to 100 *iu*
- The levels for less than average environmental amenity is an environment with an exterior night-time background (L90) level of 42.2 dB(A) ± 5.3 dB(A) or more for most weather conditions. In the alternative, an exterior night-time average (LAeq) level of 55.0 dB(A) ± 5.9 dB(A) or Ldn 62.9 ± 5.7 dB(A) for most weather conditions. The modified unbiased annoyance exterior night-time value is more than 100 *iu*

Intrusive Noise Ratings

The Intrusive Noise Ratings derived from the amenity values and these works are:

1. ***No adverse effect***, pleasurable sounds or peace and tranquility; modified unbiased annoyance exterior night-time value of less than 50 *iu*
2. ***Minor adverse effect, minor irritation***; modified unbiased annoyance exterior night-time value of less than 50 *iu*, minor intrusion of noise on occasion external to the home, no modulation or distinctive tonality
3. ***Adverse effects more than minor***; modified unbiased annoyance exterior night-time value of 50 to 100 *iu*, intrusive noise audible on occasion within the home, no modulation or distinctive tonality
4. ***Nuisance adverse effect***; modified unbiased annoyance exterior night-time value of more than 100 *iu*; intrusive noise heard within or exterior to the home on a regular or definable basis, modulation or distinctive tonality may be present; causing anger, annoyance, or adverse health reactions including sleep disturbance
5. ***Significant adverse effect***; modified unbiased annoyance exterior night-time value of more than 100 *iu* irrespective of sound character causing annoyance or anger and or adverse health reactions including sleep disturbance

11.5 Integration of sound analyses and personal perception

The integration of sound analyses and personal perception is developed under the IEDIS (Intelligent Environmental Decision Information System) protocols for a structured analytical methodology referenced to subjective analysis and objective criteria for which the relativities between non-parametric and parametric data may be culturally, environmentally or structurally encapsulated.

The decision processes involved in determining intrusive sound or noise use Rules to create a decision support system (as described by Turban, 1990, or as applied in EXSYS Professional, for example) and knowledge base consisting of the acoustical, musical and sound quality parameters described in this work. Rules can be expressed as simple 'yes' or 'no' answers, or confidence values from 1 to 10 for relative likelihood, dependent probabilities or independent probabilities. Increment and decrement systems and custom formula systems provide further analysis flexibility. The general format for the construction of Rules within the decision process to integrate sound and sensitivity analyses is:

```
IF
    expression      <test>   expression
AND
    qualifier       {value}
AND
    qualifier       {value}
THEN
    [probability expression]
ELSE
    choice          [probability expression]
```

The primary Rules are defined by reference to the personal, environmental, noise sensitivity and sound character questionnaires (Annex E questionnaire coding), amenity reference sound levels (section 11.4), the Intrusive Noise Ratings (section 11.4), sound analysis outputs (audibility, loudness, tonalness), calculated sound levels, sound quality as pitch salience and modified unbiased annoyance. The primary decision table to define Intrusive Noise Ratings by integrating sound levels (LAeq), personal perception (LE), personal noise sensitivity (ns_overall) and sound character

(SC) with amenity and soundscape is presented in Table 11.5.1 and Annex E. The table does not include viable alternative choices or decisions.

Table 11.5.1: Primary decision table for Intrusive Noise Rating

Line	Decision action IF-AND	Statement THEN
5	IF ns_overall >= 1.11 AND <=1.63	ns_overall = "average noise sensitivity"
10	IF ns_overall > 1.63	ns_overall = "more than average noise sensitivity"
15	IF ns_overall < 1.11	ns_overall = "less than average noise sensitivity"
20	IF exterior LAeq < 35.0 AND LE24 = true AND LE25 = true	"better than average soundscape and amenity"
25	IF exterior LAeq >= 35.0 AND <= 55.0 AND LE26 = true	"average soundscape and amenity"
30	IF exterior LAeq > 55.0 AND LE27 = true AND LE28 = true	"less than average soundscape and amenity"
35	IF exterior UBA*m* night < 50.0	"better than average amenity"
40	IF exterior UBA*m* night >= 50.0 AND <= 100.0	"average amenity"
45	IF exterior UBA*m* night > 100.0	"less than average amenity"
50	IF exterior UBA*m* night < 50.0 AND Line 20 = true	"INR=1=no adverse effect expected"
55	IF exterior UBA*m* night < 50.0 AND LE31 = true AND SC76 = true AND Line 25 = true	"INR=2=minor adverse effect"
60	IF exterior UBA*m* night >= 50.0 AND <= 100.0 AND LE31 = true AND SC76 = true AND SC78 = true AND exterior LAeq >= 35.0 AND <= 55.0	"INR=3=adverse effects more than minor"
65	IF exterior UBA*m* night > 100.0 AND LE32 = true AND SC76 = true AND SC78 = true AND exterior LAeq >= 35.0 AND <= 55.0	"INR=4=nuisance adverse effect expected"
70	IF exterior UBA*m* night > 100.0 AND LE32 = true AND SC76 = true AND SC78 = true AND exterior LAeq > 55.0	"INR=5=significant adverse effect"

Figure 11.1.1 and Table 11.5.1 present the overall methodology of this work for a decision support system that integrates perceived noise with noise performance indicators, annoyance criteria and individual noise sensitivity.

Analysis of Environmental Sound

The complete sound intrusion - perception - decision support methodology is implemented in an analysis program, *Analysis of Environmental Sound* (AES). The program is designed to implement standard measures and, apart from the length of the soundfile to be analysed, measures can not be changed. This ensures that the program remains ‘standard’.

To find the character of the sound you are interested in all you need to do is to play the sound through the analyser and it will give graphics of what the soundfile “sounds” like plus a numeric summary of primary indicators. Different parts of the soundfile can be compared by selecting different times and analysing, say, the start of the soundfile with middle. A different set of results will be given each time. The program is under development and soundfile calibration is not available unless an external calibration signal with a known sound level and frequency output is recorded at the same time as the sound recording.

There is a set of questions for personal noise sensitivity and personal perception of your environment and a set of questions concerning the sound you are interested in. Each questionnaire needs to be answered for an analysis to be produced.

An outcome of the research is the *Analysis of Environmental Sound* (AES) program which implements the decision methodology presented in figure 11.1.1 and Table 11.5.1 of this work.

CHAPTER 12: SYNOPSIS

This work presents acoustical, musical, psychoacoustic and sound quality methods to objectively and subjectively measure and assess sound and noise. The objective methods, however, are not complete in themselves as the measures do not determine a sound as being intrusive nor whether a person would consider a sound as being noise. Subjective measures help identify an individual's response to sound and noise and his or her sense of amenity.

A new approach to the measurement and assessment of sound, including low amplitude sound, is presented by way of:

- Sound is described and visually presented in musical and sound quality measures
- New definitions for 'intrusive sound', 'noise' and 'intrusive noise'
- Application of elements of musical expression to provide a keystone for a translation process to "describe" sound and noise in other than acoustical terms
- Individual amenity assessed with respect to personal noise sensitivity and personal attitudes to sound in the environment and the environment itself

The development of the intrusive sound methodology for consideration of ambience, amenity and context has been sourced in part from the world of music. The methodology acknowledges techniques that characterise the sound of music, such as timbre, pitch, loudness and dissonance, and places them into relationships with descriptions of acoustical sound and annoyance.

Acoustical analysis has little meaning to a person unless it is has a real relationship with an individual's responses to intrusive sound and can be described or explained in a way that the individual understands. Individuals understand intuitively what "noise" is to them personally, and this distinction may change day-by-day even to the same sound. Individual amenity is assessed as an *intrinsic* value reflecting personal noise sensitivity, personal and cultural attitudes to sound in the environment, the environment itself, and habituation effects. The *extrinsic* values that affect individual amenity are presented as community values that may have potential effect on the individual.

The presence of a noise and its subjective perception are identified by an individual through a set of personal environmental and noise sensitivity questionnaires. A person gives emotional weighting to noise heard and it is this highly variable weighting that is identified as an individual's sensitivity and potential for annoyance to noise. The techniques of sound quality measurement provide a partial analog for sensitivity.

The research presents a new definition of ***intrusive sound***:

> Intrusive sound is a sound that, by its characteristics, is audible and intrudes upon the well-being or amenity of an individual.

And that:

> The adverse intrusion of a sound into the well-being or amenity of an individual is a significant precursor to annoyance.

Consequently, a new definition for ***Noise*** is proposed:

> Noise is a sound that is audible to an individual and has definable characteristics that modify the individual's emotional and informational responses to that sound from pleasurable or neutral to adverse.

Intrusive noise is defined as:

> Intrusive noise, to an individual, is a sound whose variance in character (such as audibility, dissonance, duration, loudness, tonality, pitch or timbre) is perceived adversely compared to the character of the environment in the absence of that sound.

Zwicker's unbiased annoyance (UBA) is modified as a primary measure for noise assessment. The modified unbiased annoyance UBA*m* measure applies loudness (N10 in sones), Aures sharpness (in acums) and a new approach to fluctuation by implementing Sethare's Tonal Dissonance, *TD(S)* in *sets*, to account for frequency as well as amplitude fluctuation. The UBA*m* measure has an effect on soundfile measured values by emphasising the contribution of dissonance and tonalness. The calculation is given in 'intrusion units, *iu*':

$$UBAm = d(N10)^{1.3} \cdot \left\{1 + 0.25(S-1) \cdot \lg(N10+10) + 0.3TD(S) \cdot \frac{1+N10}{0.3+N10}\right\} \quad \text{iu}$$

(eqn 9.5.3.1)

Loudness (N10) is the loudness in sone which is exceeded for 10% of the time. (The exponent in the first expression is 1.3). UBA*m* is modified for night-time. The value of '*d*' in equation 9.5.3.1 for the day is 1, for night-time the value of $d = 1 + (N10/5)^{0.5}$.

Research Questions

The question posed at the commencement of the research was: 'Is it possible to develop a methodology incorporating a decision support system to integrate perceived noise with noise performance indicators, annoyance criteria and individual noise sensitivity?'

- The research question is answered in the affirmative. The primary Decision Table that integrates measured sound levels with personal amenity, noise performance indicators, personal noise sensitivity and annoyance criteria is presented in Chapter 11. The component assessment methods are presented in Chapter 10. Assessment outcomes are presented visually as tonal salience charts as well as numeric levels.

As the research into perceived noise progressed it drew the emphasis of the work into the nature of noise and then into low amplitude intrusive sound and noise. A second research question was then postulated: 'Can low amplitude intrusive sound affecting individuals can be measured and assessed in a consistent manner.'

- The research question is answered in part in the affirmative. Low amplitude sound can be measured and assessed in a consistent manner as described in this work. The methodology, however, is not predictive because intrusion is a human perception.

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GLOSSARY

Specific definitions are drawn from international standards or from authoritative sources, with the source acknowledged in the Table. In some instances definitions vary between sources and the definition most appropriate to the research is applied.

Term	Definition	Reference
Acoustic environment	The part of the environment of a place or locality characterised by the noise that may be experienced there (*cf. soundscape*)	Thorne
A-weighting	A-frequency weighting signifies the use of an electrical filter incorporated in a sound level meter which modifies the response of the instrument to correspond to the 40-phon equal loudness contour of the human ear	Dickinson; IEC61672-1:2002 Table 2 refers
Algorithm	A well-defined procedure to solve a problem	Thorne
Ambience	Our physical surroundings and personal perception of those surroundings; sense of place	Thorne
Amenity	Pleasantness or a useful feature of a place	Concise Oxford
Amenity values	Means those natural or physical qualities and characteristics of an area that contributes to people's appreciation of its pleasantness, aesthetic coherence, and cultural and recreational attributes.	Resource Management Act s.2. New Zealand
Amplitude	The equivalence of "loudness" and "volume" to intensity in decibels *(colloquial)*	Thorne
Annoyance	A feeling of displeasure associated with any agent or condition, known or believed by an individual or group to adversely affect them	WHO 2000
Attribute	Property, e.g., the pitch, loudness or timbre of a sound sensation	Parncutt
Audible	Capable of being heard	Concise Oxford
Audible level	Level of a pure tone (component) above masked threshold	Parncutt

Aural texture	The perception by a person of the interaction of the characteristics of all the sounds in a particular environment at a particular time	Thorne
Background sound level (L90 or L95)	An indicator of the quietest times of day, evening or night. The L90 (or L95) level is calculated as the noise level equalled and exceeded for 90% (or 95%) of the measurement time. The level is recorded in the absence of any noise under investigation. The level is not adjusted for tonality or impulsiveness.	Thorne
Bark	Unit of critical band rate equal to one critical bandwidth	Parncutt
Beats	Periodic variations that result from the superposition of two simple harmonic quantities of different frequencies f_1 and f_2. They involve the periodic increase and decrease of amplitude at the beat frequency ($f_1 - f_2$)	ANSI S3.20-1973
Cent	1/100 of an equal temperament semitone	Helmholtz (Ellis)
Character	Distinctive features	Thorne
Chroma (1)	Pitch class without the specification of octave register, eg “C” instead of “C_4”	Parncutt
Chroma (2)	Interval in semitones between a pitch category and the nearest “C” below	Parncutt
Chroma salience	Measure of the perceptual importance of a particular chroma in a musical sound or sequence, as perceived by an average or “ideal” listener	Parncutt
Complex sound	Sound whose pressure waveform is not sinusoidal, and whose spectrum therefore contains more than one pure tone component	Parncutt
Complex tonalness	Measure of tonalness; the audibility of the most audible complex tone sensation of a sound	Parncutt
Consonance	How well the tones of a simultaneity or sounds in a sequence sound together, depending on roughness, tonalness, pitch commonality, pitch	See section 4.5

	distance, context, familiarity and cultural conditioning (*cf. sensory consonance*)	
Costs and benefits	Includes costs and benefits of any kind, whether monetary or non-monetary, and valuation of amenity	Thorne
Critical band	Maximum range of frequencies over which the ear is like a single band-pass acoustic filter (so loudness is independent of bandwidth); at wider ranges, it is like a bank of band-pass filters (so loudness increases with increasing bandwidth)	Parncutt
Critical bandwidth	Width of a critical band (in semitones or Hz), equal to about 3 semitones above 500 Hz, and 50 - 100 Hz below 500 Hz; contains a constant number of pitch difference thresholds	Parncutt
Day-Night Level or DNL	Day-night average sound level; the cumulative 24-hour level is calculated by the hour or second and sound exposure levels at night (10pm to 7am) are weighted by +10dB	ANSI S12.9-1988
dB	decibel; one-tenth of a bel	ANSI S3.20-1973
dB(A)	decibel, where the sound pressure is A-frequency weighted	Dickinson
Decision support systems	computer based information systems that combine models and data in an attempt to solve non-structured problems with extensive user involvement	Turban
Dissonance	Roughness, unpleasant *(cf sensory dissonance)*	See section 4.5
Environment	Ecosystems and their constituent parts, including people, their communities, and their amenity values and the social, economic, aesthetic, and cultural conditions which affect them.	NZ Resource Management Act (s2)
Environmental value (personal)	The qualities of the acoustic environment that are conducive to the well-being of an individual, including the individual's opportunity to have sleep, relaxation and conversation without unreasonable interference from intrusive noise.	Qld EPP (Noise) Policy 1997

Environmental value (community)	The qualities of the acoustic environment that are conducive to the well-being of the community, or part of the community, including its social and economic amenity	Qld EPP (Noise) Policy 1997
Equal temperament	Term for the 12-tone tuning system of 12-TET that divides the octave into 12 equal parts	Sethares
Equivalent frequency	Measure of pitch; frequency of a standard reference tone whose pitch is the same as that of a particular tone sensation	Parncutt
Erb	Equivalent rectangular bandwidth. The Erb of a given auditory filter using Patterson’s method are typically between 11% and 17% of the centre frequency.	Moore
Expert system	A computer based system that applies reasoning methodologies on knowledge in a specific domain in order to render advice or recommendations, much like a human expert.	Turban
Extrinsic	Not inherent or essential	Concise Oxford
FFT	Fast Fourier Transform. A mathematical algorithm to compute the discrete Fourier transform (frequency domain) from a digital (time domain) signal or soundfile	Thorne
Forward masking	The condition in which the masking sound appears before the masked sound	Yost
Fundamental	First harmonic; lowest pure tone component of a full complex tone	Parncutt
Harmonic	Whole multiple of a specified number; pure tone component whose frequency is (close to) n times the waveform (fundamental) frequency of a complex tone	Parncutt
Harmony	General term embracing consonance	Parncutt
Hearing threshold level	The hearing level at which a tone of specified frequency is heard by an ear in a specified fraction of trials	ANSI S3.20-1973

Heuristics	Decision rules regarding how a problem should be solved	Turban
High amplitude sound	Sound levels above 80 dB	Thorne
Holistic	The treating of the whole person including mental and social factors rather than just the symptoms of a disease *(cf. wholistic)*	
Hz	Hertz; frequency in cycles per second	ANSI S3.20-1973
Intensity	Of a sound: amount of energy transmitted per unit time, per unit area perpendicular to the direction of propagation	Parncutt
Intrinsic	inherent, essential, belonging naturally	Concise Oxford
Intrusive sound	A sound that, by its characteristics, is audible and intrudes upon the well-being or amenity of an individual	Thorne
Intrusive noise	To an individual, is a sound whose variance in character (such as audibility, dissonance, duration, loudness, tonality, pitch or timbre) is perceived adversely compared to the character of the environment in the absence of that sound	Thorne
ISO	International Organization for Standardization	ISO
Just noticeable difference (1)	The differential threshold, or difference limen, is the change in stimulus that can be correctly judged as different from a reference stimulus in a specified fraction of trials	ANSI S3.20-1973
Just noticeable difference (2)	Under careful testing, the just noticeable difference can be 2 to 3 cents	Sethares
Knowledge base	A collection of facts, rules, and procedures organized into schemas. The assembly of all information and knowledge of a specific field of interest	Turban
L10, L90, L95	The time-weighted and frequency-weighted sound pressure level that is exceeded for 10%, 90% or 95% of the time interval considered, in decibels	ISO 1996-1

LAeq	See Time-average sound level	IEC 61672-1
Loudness	Attribute of auditory sensation by which different sensations may be ordered on a scale extending from "soft" to "loud"	Parncutt
Loudness Level (1)	Value in phons that has the same numerical value as the sound pressure level in decibels of a reference sound, consisting of a frontally incident, sinusoidal plane progressive wave at a frequency of 1000 Hz, which is judged as loud as the given sound	ISO 226
Loudness Level (2)	Normal equal-loudness-level contour	ISO 226
Low amplitude	Sound levels below 50 dB to nominal threshold of hearing	Thorne
Masked threshold	Threshold of audibility in the presence of maskers	Parncutt
Masker	A sound that masks other sounds	Parncutt
Masking	Complete or partial "drowning-out" of one tone by another	Parncutt
MIDI	Musical Instrument Digital Interface – a communication protocol for electronic musical devices	Sethares
Moderate amplitude sound	Sound levels ranging between 50 dB to 80 dB	Thorne
Modulation	Periodic change in the amplitude or frequency of a sound (beating)	See section 4.12
Modulation frequency	The difference between the frequencies of two beating pure tone components	Parncutt
ms	milli-second (1/1000 of a second)	
Noise	A sound that is audible to an individual and has definable characteristics that modify the individual's emotional and informational responses to that sound from pleasurable or neutral to adverse.	Thorne

Noise annoyance	An emotional and attitudinal reaction from a person exposed to noise in a given context.	Pedersen, 2007
Noise sensitivity	A person’ condition enhancing their reactivity to noise	Schütte
Normal equal-loudness-level contour	Equal-loudness-level-contour that represents the average judgment of otologically normal persons within the age limits from 18 years to 25 years inclusive	ISO 226
Octave	Distance between two tones or frequencies corresponding to a frequency ratio of 2:1; a frequency level difference of 12 semitones	Parncutt
Perceive	To understand; to apprehend	Concise Oxford
Phon	The loudness level of a given sound or noise	AS 1633
Pitch (1)	Attribute of a tone sensation by which it may be ordered on a scale from “low” to “high”	ANSI S3.20-1973
Pitch (2)	An auditory attribute in terms of which sine tones can be ordered on the low-high dimension *(cf. spectral pitch and virtual pitch)*	Terhardt
Pitch (3)	Perceived fundamental frequency of a sound	
Pitch difference thresholds	Just noticeable difference in pitch, smallest perceptible physical change in a stimulus	Parncutt
Pitch prominence	Audibility, salience of a pure tone	Parncutt
Psychoacoustics	The science that deals with the psychological correlates of the physical parameters of acoustics	ANSI S3.20-1973
Psychophysics	The science that deals with the qualitative relationships between physical and psychological events	ANSI S3.20-1973
Pulsing	A rhythmic beat or vibration; as in a pulsating sphere	Chapter 5.2.1, ENC
Pure tone	Tone whose pressure waveform is sinusoidal	Parncutt
QEPA	Environmental Protection Agency, Queensland, Australia	QEPA

Qld EPP (Noise)	Environmental Protection (Noise) Policy 1997, Queensland, Australia	QEPA
Root mean square (RMS)	Average value of a waveform calculated by taking the square root of the mean of the square of the function	Parncutt
Roughness	Sensation associated with beating at frequencies in the range 20 – 300 Hz	See section 4.16
Rule	A formal way of specifying a recommendation, directive or strategy, expressed as IF premise, AND statement(s), THEN conclusion	Turban
Salience	Perceptual importance or prominence of a stimulus; probability of being noticed or sensation being experienced	Parncutt
Semitone	Unit of frequency level; twelfth part of an octave; equal to 100 cents (equal temperament)	Sethares
Sensation	The consciousness of perceiving or seeming to perceive some state or condition of one's body or its parts or senses or of one's mind or its emotions	Concise Oxford
Sensory consonance	The absence of dissonant beats	Helmholtz
Sharpness	Sharpness is a measure of the high frequency content of a sound, the greater the proportion of high frequencies the 'sharper' the sound.	Salford
Significant	(in statistics) most unlikely to have occurred by chance (e.g., $p<0.05$ means that the probability of a given result occurring by chance is less than 5%.	Parncutt
Socio-acoustic	Social attitudinal study combined with an acoustical survey within the same community	Thorne
Sone	Loudness. The numerical definition of the strength of a sound which is proportional to its subjective magnitude as estimated by normal observers. One sone is the loudness of a sound whose loudness level is 40 phons.	AS3652-2
Sound exposure	The total sound energy produced from a sound	IEC61672-1

	source over a specified time or event	
Soundfile	Sound recording in Microsoft PCM .wav format	Thorne
Soundscape	The part of the environment of a place or locality characterised by the sounds that may be experienced there (*cf. acoustic environment*)	Thorne
Special audible characteristics	Sound that has distinct features such as impulsiveness, modulation or tonality that makes the sound stand out from other sounds in the same soundscape	Thorne
Spectral pitch	An elementary auditory object that immediately represents a spectral singularity, e.g., a sine tone *(cf virtual pitch)*	Terhardt
Subharmonic	Whole multiple of a particular number (e.g., 2.5 is the 4^{th} subharmonic of 10)	Parncutt
Threshold of audibility	Threshold sound pressure (defined for an average “ideal” listener) below which a pure tone is inaudible, expressed as a function of its frequency *(cf Hearing threshold level)*	Parncutt
Threshold of hearing	Level of a sound at which, under specified conditions, a person gives 50% of correct detection responses on repeated trials	ISO 226
Threshold of pitch	Lowest (20 Hz, E_0) or highest (16 kHz, C_{10}) audible pitch	Parncutt
Timbre	Timbre or tone quality or tone colour is a function in time of the frequency content or spectrum of a sound, including its transients and pitch, loudness, duration and manner of articulation. Timbre allows a person to distinguish between different sounds, instruments and voices.	Thorne
Time-average sound level	Time-average sound level or equivalent continuous sound level, no frequency weighting stated but normally A-weighted	IEC 61672-1
Tonal	Evoking pitch or tone sensation(s)	Parncutt

Tonality	Pitch structure in music in which some pitches are more important (salient, stable) than others	Parncutt
Tonalness	The extent to which a sound evokes (pure or complex) pitch or audible tone sensations	Parncutt
Tone (1)	Sound which evokes a tone sensation; approximately or exactly periodic sound in the audible range of frequencies; sound whose various possible pitches belong mostly to a single … chroma	Parncutt
Tone (2)	A sound sensation having pitch	ANSI S3.20
Tone sensation	Auditory sensation having one, unambiguous pitch; other attributes include loudness or salience, timbre, and apparent duration	Parncutt
Unbiased Annoyance	The response of subjects annoyed exclusively by sound under describable acoustical circumstances in laboratory conditions without relation to the nature of the source	Zwicker
USEPA	United States Environmental Protection Agency	USEPA
Virtual Pitch	An attribute of auditory sensation with the fundamental pitch 'extracted' by the auditory system from a range of the Fourier spectrum that extends above the fundamental	Terhardt
.wav	Microsoft uncompressed PCM audio file format for storing audio in digital format in a computer	Thorne
WHO	World Health Organization	WHO
Wholistic	Whole, complete, comprising or involving all parts	NSOD
Z-weighting	Z- weighting (very similar to the previous 'Lin' or 'Flat' response) gives the unweighted sound pressure with a lower and an upper cut-off as specified by the manufacturer; usually 16 Hz and 20,000 Hz to limit measurements to within the audible frequency range	Dickinson; IEC61672-1:2002 Table 2 refers

Notes to Glossary:

(a) 'NSOD' refers to The New Shorter Concise Oxford Dictionary, Clarendon Press Oxford 1993.

(b) 'ENC' is *Engineering Noise Control Theory and Practice*, third edition, Bies, DA and Hansen CH, 2003, Spon Press

(c) The authors referenced are identified in the Reference List.

(d) A definition that has been formulated for, or from, this research is referenced as 'Thorne'.

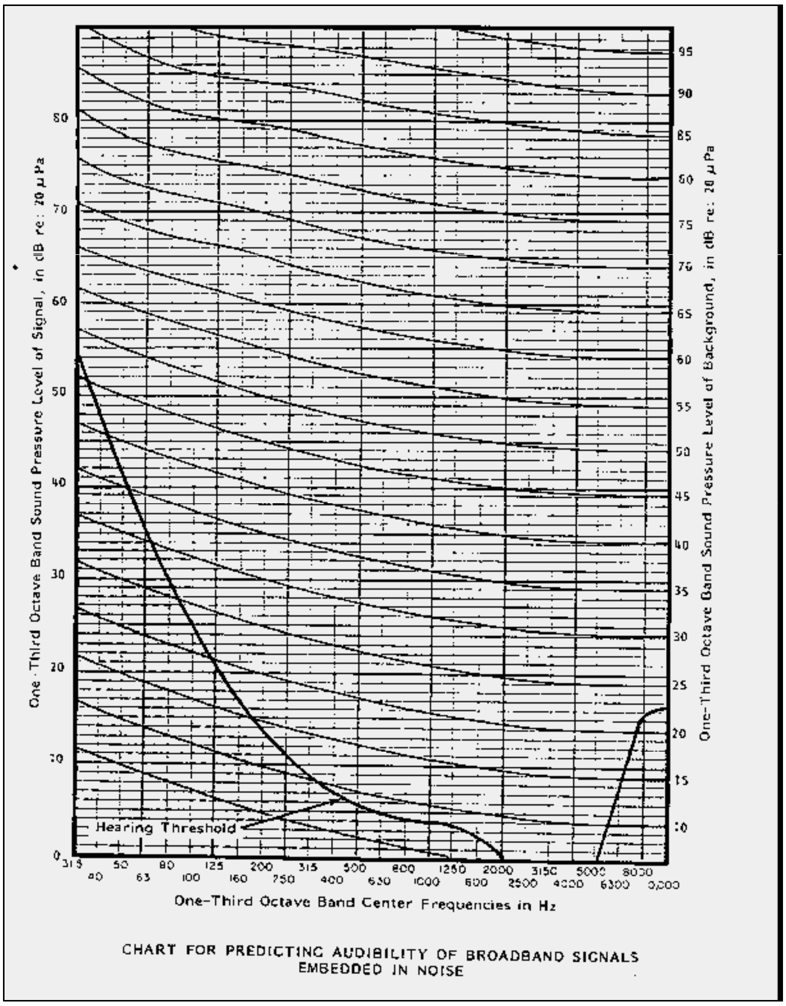
Glossary of Notes and Associated Frequency Values

The values in the Table are referenced for the pitch salience charts. Each Note row is presented by equal temperament note, octave number and pitch in hertz, e.g., C_4 has a pitch of 261.6 Hz and, for this work, a semitone note value, e.g., "60"

	Octave										
	-1	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Note											
C	8.2 0	16.3 12	33 24	65 36	131 48	**261.6** **60**	523 72	1046 84	2093 96	4186 108	8372 120
C♯/D^b	8.6 1	17.3 13	35 25	69 37	139 49	277 61	554 73	1109 85	2218 97	4435 109	8870 121
D	9.2 2	18.3 14	37 26	73 38	147 50	294 62	587 74	1175 86	2349 98	4699 110	9397 122
D♯/E^b	9.7 3	19.5 15	39 27	78 39	156 51	311 63	622 75	1245 87	2489 99	4978 111	9956 123
E	10.3 4	20.6 16	41 28	82 40	165 52	330 64	659 76	1319 88	2637 100	5274 112	10558 124
F	10.9 5	22 17	44 29	87 41	175 53	349 65	698 77	1397 89	2794 101	5588 113	11176 125
F♯/G^b	11.6 6	23 18	46 30	92.5 42	185 54	370 66	740 78	1480 90	2960 102	5920 114	11840 126
G	12.3 7	24.5 19	49 31	98 43	196 55	392 67	784 79	1568 91	3136 103	6272 115	12544 127
G♯/A^b	13 8	26 20	52 32	104 44	208 56	415 68	831 80	1661 92	3322 104	6645 116	13290
A	13.8 9	27.5 21	55 33	110 45	220 57	**440** **69**	880 81	1760 93	3520 105	7040 117	14080
A♯/B^b	14,6 10	29 22	58 34	116.5 46	233 58	466 70	932 82	1865 94	3729 106	7459 118	14917
B	15.4 11	31 23	62 35	123.5 47	247 59	494 71	988 83	1975.5 95	3951 107	7902 119	15804

Note: the semitone note values are only for the purposes of this work

Glossary: Audibility chart for Chapter 4.4



The above chart is required for the assessment of audibility for this work.

Annex A: Southern Scene Attitudinal and Acoustical Surveys

The general design of the questionnaire follows. The analysis coding numbers employed are the primary question as [Q#] and the question response coding in (brackets) adjacent to each question.

ENVIRONMENTAL NOISE SURVEY

Council is undertaking an environmental noise survey as part of its review of the District Plan. Environmental noise means noise from everything: Cars, Trucks, Motorbikes, Birds, Dogs, Loud Stereos, Industry, etc. Before proposing any controls, council needs to know if noise is a problem in the community and, if so, what you would like us to do about it. Please help us by filling out and returning this questionnaire

Q1. Do you think noise is a problem?

To You	YES (1)	NO (0)	SOMETIMES (8)	[Q1]
To Others	YES (1)	NO (0)	SOMETIMES (8)	[Q2]

Q2. Are you ever annoyed by noise? YES (1) NO (0) [Q3]

If YES: What sort of noise? At what time of day?

	Morning	**Afternoon**	**Evening**	**All the time**	
Traffic	4TM	4TA	4TE	4TAll	[Q4]
Motorcycles	-	-	-	-	[Q5]
Dogs	6DM	6DA	6DE	6DAll	[Q6]
Lawnmowers	7LCM	7LCA	7LCE	7LCAll	[Q7]
Aeroplanes	-	-	-	-	[Q8]
Loud music	9MM	9MA	9ME	9MAll	[Q9]
Other	10IM 11PinM	10IA 11PinA	10IE 11PinE	10IAll 11PinAll	[Q10] [Q11]

(Please mark one column)

[Coding comment: initial response analysis from this question set and Question set 23 indicated traffic and motorcycles could be combined as Q4, lawnmowers and chainsaws as Q7, Other as "Industrial noise Q10", Persistent intrusive noise Q11"

Q3.	Have you ever complained about noise?		YES (1)	NO (0)	[Q12]
	To Whom:	Police	YES (1)	NO (0)	[Q13]
		Local Council	YES (1)	NO (0)	[Q14]
		Other	YES (1)	NO (0)	[Q15]

Q4. Does noise affect you-

While reading	YES (1)	NO (0)	[Q16]
While watching TV	YES (1)	NO (0)	[Q17]
While listening/talking	YES (1)	NO (0)	[Q18]
While relaxing	YES (1)	NO (0)	[Q19]
While at work	YES (1)	NO (0)	[Q20]
While at school	YES (1)	NO (0)	[Q21]
While sleeping	YES (1)	NO (0)	[Q22]

Q5. Is there any particular type of noise that can really annoy you? [Q23]

(Please write down as many as you like)

[The coding of the "types of noise" responses to this question set are correlated to the "time of day" responses for questions Q4 to Q11]

Q6. What do you think is a good way to control noise? [Q24]

(Please write down as many as you like)

COULD YOU PLEASE TELL US A LITTLE ABOUT YOURSELF?

Q7. How long have you lived in the area? _______ years [Q25]

Q8.	Do you live near a main road or a busy local road?	YES (1)	NO (0)	[Q26]
Q9.	Do you live in a rural area?	YES (1)	NO (0)	[Q27]
Q10.	Do you live in an urban area?	YES (1)	NO (0)	[Q28]

Q11. Are you? MALE (1) FEMALE (0) [Q29]

Q12. Could you please note your age group [Q30]

Under 12	(1)	12-16	(2)	17-19	(3)	20-29	(4)
30-39	(5)	40-49	(6)	50-59	(7)	60-69	(8)
70-79	(9)	80 plus	(10)				

Thank you very much for your help. Your reply will be kept strictly confidential

Annex B: Auckland Attitudinal Survey Pilot

B.1: Introduction

The general design of the questionnaire is presented in this Annex. The analysis coding numbers employed are the primary question as [Q#] and the question response coding in (brackets) adjacent to each question.

ENVIRONMENTAL NOISE SURVEY

The Public Health Protection Service of Auckland Healthcare would like your help with a survey of the effects of environmental noise in the greater Auckland region. Noise is widespread in the community- we would like to know if it affects you and how you would like to see it controlled. This survey is about noise from all sources in the environment, including cars, trucks, aircraft, loud music, industry, etc. Please encourage and help your whole family/household to answer this survey. We would like to find out how community noise affects a wide range of people, including children. *Kids- please ask your parents first.*

PERSONAL NOISE SURVEY - *please tick your reply*

1. Do you find noise in your environment (including your home, work and social environment) a problem?

YES (1Y) NO (1N) SOMETIMES (1S) [Q1]

2. Thinking about where you live, could you please say how quiet or noisy you think your area is? [Q2]

Very quiet	(2VQ)	Quiet	(2Q)
Moderately noisy	(2MN)	Noisy	(2N)
Very noisy	(2VN)		

3. Thinking about the last 12 months or so, when you are at home, how much does the noise from the following sources bother/disturb/annoy you? [Q3]

Please tick the boxes that apply

Source*	Extremely	Very much	Moderately	Slightly	Not at all
Cars	3CX	3CVM	3CM	3CS	3CN
Trucks	3TX	3TVM	3TM	3TS	3TN
Planes	3PX	3PVM	3PM	3PS	3PN
Trains	3TnX	3TnVM	3TnM	3TnS	3TnN

Helicopters	3HX	3HVM	3HM	3HS	3HN
Industry	3IX	3IVM	3IM	3IS	3IN
Loud music	3MX	3MVM	3MM	3MS	3MN
Sports venues	3SX	3SVM	3SM	3SS	3SN
Neighbours	3NX	3NVM	3NM	3NS	3NN
Other*	3?X	3?VM	3?M	3?S	3?N
Other*	3??X	3??VM	3??M	3??S	3??N

** Please add any other noises that bother, disturb or annoy you.*

4. Does noise from your neighbourhood (not including from those living in your household) affect you- [Q4]

While reading	YES (4RY)	NO (4RN)
While watching TV	YES (4TvY)	NO (4TvN)
While listening/talking	YES (4TY)	NO (4TN)
While relaxing	YES (4XY)	NO (4XN)
While at work	YES 4(WY)	NO (4WN)
While at school	YES (4ScY)	NO (4ScN)
While sleeping	YES (4SlY)	NO (4SlN)

5. Are you ever disturbed or annoyed by noise at home (not including from those living in your household)? YES (5Y) NO (5N) [Q5]

If yes- Could you please tell us what sort of noise and at what time of day? Some typical noise sources (in no particular order) may be from-

Please tick the boxes that apply

Source*	Morning 6 am -12 noon	Afternoon 12 noon - 6pm	Evening 6pm - 10pm	Night 10pm - 6am	All the time
Cars	5CM	5CA	5CE	5CN	5CAll
Trucks	5TM	5TA	5TE	5TN	5TAll
Planes	5PM	5PA	5PE	5PN	5PAll
Trains	5TnM	5TnA	5TnE	5TnN	5TnAll
Helicopters	5HM	5HA	5HE	5HN	5HAll
Industry	5IM	5IA	5IE	5IN	5IAll
Loud music	5CM	5CA	5CE	5CN	5CAll
Sports venues	5SM	5SA	5SE	5SN	5SAll
Neighbours	5NM	5NA	5NE	5NN	5NAll
*	5?M	5?A	5?E	5?N	5?All
*	5??M	5??A	5??E	5??N	5??All

** Please add any other noises that bother, disturb or annoy you.*

6. What do <u>you</u> think is a good way to control noise? [Q6]

Please use extra paper if necessary

7. Where do you live? (just the general area/suburb is OK) [Q7]

(This question was replaced in the final questionnaire with Q9)

Could you please tell us a little about yourself?

8. How long have you lived in the area?_ years Q8 (<1, 1-5, >5)

9. Where do you live? *Please tick the boxes that apply*

Near a main road or a busy local road?	YES (9RY)	NO (9RN)
Near or in an industrial area?	YES (9IY)	NO (9IN)
Under or near aircraft overflight?	YES (9AY)	NO (9AN)
In an urban or rural area?	Urban (9U)	Rural (9R)

10. Generally, how would <u>you</u> rate your area as a place to live?

1	2	3	4	5
Rate it low				Rate it high

Question 10 is coded as 10 plus number 1 to 5

11. Are you? MALE (11M) FEMALE (11F)

12. Please tick your age group- (CODED AS 12 and AGE group)

Under 10 (1)	10-14 (2)	15-19 (3)	20-29 (4)
30-39 (5)	40-49 (6)	50-59 (7)	60-69 (8)
70 and over (9)			

PLEASE MARK THE AREA WHERE YOU LIVE

THANK YOU VERY MUCH FOR YOUR HELP.

Your response to this questionnaire will be kept strictly confidential.

(Questionnaires are individually coded to help with analysis,
but we do not know who filled in each questionnaire.)

Annex C: Manawatu Pilot Study

The introduction to the Manawatu Pilot study is presented flowing. An explanation of the coding and analysis of the questionnaires is given in this Annex but was not provided to the respondents. The response zone map is included.

PhD PROJECT: REACTION TO SOUND QUESTIONNAIRE

Bob Thorne is a PhD student with Massey University studying community noise. As part of his thesis he is conducting some surveys around the Manawatu and Tararua region and your assistance with completing the attached surveys would be most appreciated. We have included 4 copies of the survey sheets and would ask each member of your family who is willing and over the age of 15 years to complete all 4 survey sheets.

On the following pages, we will ask for your opinion with respect to a variety of sounds. Please try to imagine the situation presented in each statement, and indicate to which extent you agree with it. We are interested in **your own personal assessment** of the topics presented here, so there are *no right or wrong* answers only your opinion. Please give your opinion spontaneously by marking that answering option which best reflects your opinion. Please answer all statements in turn, always marking a single option only. If you are unsure as to which option to mark, please choose that option which comes closest in reflecting your opinion. All surveys will be confidential to the researchers and only the aggregated data will be made available to others. Participants will not be able to be identified in the thesis or any subsequent publications. Thank you for your participation. Please return your completed surveys in the attached reply paid envelope. We would appreciate it if you could return your surveys within a week.

QUESTIONNAIRE 1: LEF NOISE SENSITIVITY QUESTIONNAIRE

Coding: Agree Fully (3) Rather Agree (2) Rather Disagree (1) Disagree Fully (0)	Factor
1. Before I start work I try to turn off all sources of noise.	F1
2. When I am exhausted loud music has an invigorating effect on me.	
3. Healthy sleep is only possible in completely quiet surroundings.	F2
4. A slamming door does not make me jump.	
5. In a restaurant, I find it inconsiderate of people at the neighbouring table to talk loudly.	
6. I am able to listen to the radio while reading the newspaper.	
7. On weekends I like to be in quiet places.	
8. I often long for peace and quiet.	
9. No matter how excellent the food, I lose my appetite whenever a place is noisy.	
10. I get fidgety if I hear somebody talking while I am falling asleep.	
11. Sound protection is being taken too seriously.	
12. I do not like to go to public events if they are noisy.	
13. I cannot fall asleep with even the slightest noise around.	F2
14. In my opinion, even extreme background noise does not impair my performance.	F1
15. It is no fun keeping up a conversation while the radio is on.	
16. At a dance, it does not matter how loud the music is.	F3
17. I am more relaxed in quiet places.	
18. Not even a thunderstorm can wake me up.	
19. In noisy surroundings, I often make slips of the tongue.	F4
20. Eating out in a noisy place upsets my stomach.	F4
21. I am able to fall asleep only if there is complete quiet.	F2
22. I like listening to loud music while doing my household chores.	F3
23. I am of the opinion that loud music in a café does not disturb a conversation.	
24. Noisy colleagues make me nervous.	F4
25. I try to get away from everyday street noise as fast as possible.	
26. While working, background music does not bother me.	F1
27. I tend to notice disturbing sounds later than do other persons.	
28. It is no fun to talk to somebody in a noisy place.	
29. Noise makes you aggressive.	
30. I avoid noisy pastimes such as going to sports matches or fairs.	F4
31. background noise at my work place makes me aggressive.	
32. Neighbours should be as quiet as if they were not in.	
33. I wake up at the slightest sound.	F2
34. Even in noisy surroundings, I am able to work quickly and with concentration.	

35. Music ought to be listened to at full blast.	F3
36. On doing my shopping in the city, I hardly hear the street noise.	
37. After having passed an evening in a noisy pub I feel drained.	
38. When I want to fall asleep, hardly any sound can disturb me.	F2
39. Intellectually demanding tasks call for quietness.	F1
40. Loud music does not damage my hearing.	
41. I get annoyed at a dog barking below my window while I am reading the newspaper.	
42. I like to have the radio or TV on in the background all day long.	
43. Loud music in a pub makes me stop talking.	
44. I can concentrate on a book even if there is music in the background.	
45. If the volume at a party goes up, I quit.	
46. After work, I like to listen to loud music.	F3
47. In my opinion, the nocturnal peace must not be disturbed.	
48. When there is loud music I would like to do something about it.	
49. Clearly, one cannot communicate in noisy environments.	
50. If I am absorbed in a conversation, I do not notice whether a pub is noisy or not.	
51. Loud music helps me unwind.	F3
52. Noise makes you ill.	

[Note: in the coding the responses to the above questions are denoted by a “1” in the relevant column and row]

QUESTIONNAIRE 2: NOISE AT HOME

PLEASE INDICATE HOW MUCH NOISE BOTHERS, DISTURBS OR ANNOYS YOU WHEN YOU ARE HERE AT HOME.

1. Do you find noise in your environment (including your home environment) a problem?

YES (1Y) NO (1N) SOMETIMES (1S) [Q1]

2. Thinking about where you live, could you please say how quiet or noisy you think your area is? [Q2]

Very quiet (2VQ) Quiet (2Q) Moderately noisy (2MN)

Noisy (2N) Very noisy (2VN)

3. Thinking about the last 12 months or so, when you are here at home, <u>how much</u> does the noise from the following sources bother/disturb/annoy you? [Q3]

Please tick the boxes that apply

Source*	Extremely	Very much	Moderately	Slightly	Not at all
Cars	3CTX	3CTVM	3CTM	3CTS	3CTN
Trucks	-	-	-	-	-
Planes	3PX	3PVM	3PM	3PS	3PN
Trains	3TnX	3TnVM	3TnM	3TnS	3TnN
Helicopters	3HX	3HVM	3HM	3HS	3HN
Industry	3IX	3IVM	3IM	3IS	3IN
Loud music	3LMX	3LMVM	3LMM	3LMS	3LMN
Sports venues	3SX	3SVM	3SM	3SS	3SN
Neighbours music	3MX	3MVM	3MM	3MS	3MN
Boy racers	3BX	3BVM	3BM	3BS	3BN
Wind turbines	3WX	3WVM	3WM	3WS	3WN
Animals outside	3AX	3AVM	3AM	3AS	3AN
Other*	3?X	3?VM	3?M	3?S	3?N
Other*	3??X	3??VM	3??M	3??S	3??N

** Please add any other noises that bother, disturb or annoy you.*

[Note: in the coding cars, motorbikes and trucks are combined into Q3CT]

4. Does noise from your neighbourhood (not including from those living in your household) affect you- [Q4]

While reading	YES (4RY)	NO (4RN)
While watching TV	YES (4TvY)	NO (4TvN)
While listening/talking	YES (4TY)	NO (4TN)

While relaxing YES (4XY) NO (4XN)
While at work YES 4(WY) NO (4WN)
While at school YES (4ScY) NO (4ScN)
While sleeping YES (4SlY) NO (4SlN)

5. Are you ever disturbed or annoyed by noise at home (not including from those living in your household)? YES (5Y) NO (5N) [Q5]

6. If yes- Could you please tell us what sort of noise and at what time of day?

Please tick the boxes that apply

Source*	Morning 6 am -12 noon	Afternoon 12 noon - 6pm	Evening 6pm - 10pm	Night 10pm - 6am	All the time
Wind turbines	6WM	6WA	6WE	6WN	6WAll
Music	6MM	6MA	6ME	6MN	6MAll

** Please add noises that bother, disturb or annoy you.*

[Note: the coding provides for two sources – wind turbines and music as these are two sources that are of interest to the work.]

7. What do <u>you</u> think is a good way to control noise? [Q7]

Could you please tell us a little about yourself?

8. How long have you lived in the area?_ years 8 (<1, 1-5, >5)

9. Where do you live? *Please tick the boxes that apply*

Near a main road or a busy local road? YES (9RY) NO (9RN)
Near or in an industrial area? YES (9IY) NO (9IN)
Under or near aircraft overflight? YES (9AY) NO (9AN)
In an urban or rural area? Urban (9U) Rural (9R)

10. Generally, how would <u>you</u> rate your area as a place to live?

1 2 3 4 5

Rate it low Rate it high

Question 10 is coded as 10 plus number 1 to 5

11. Are you? MALE (11M) FEMALE (11F)

12. Please tick your age group- (CODED AS 12 and AGE group)

10-14 (1) 15-19 (2) 20-29 (3) 30-39 (4)
40-49 (5) 50-59 (6) 60-69 (7) 70 and over (8)

QUESTIONNAIRE 3: WE WOULD LIKE TO KNOW ABOUT THE CHARACTER OF SOUND FROM THE LOCALITY WHEN YOU ARE HERE AT HOME.

1. Please select the best description(s) for sounds heard in your local environment. You can choose as many words as you like. My local environment is-

□ Quiet	(1Q)
□ Sometimes noisy	(1SN)
□ Noisy	(1N)
□ Pleasant	(1P)
□ Often pleasant	(1OP)
□ Unpleasant	(1U)

2. Please select the best description(s) of sounds heard in your local environment. You can choose as many words as you like. I find the sounds are-

□ Pleasant	(2P)
□ Sometimes pleasant	(2SP)
□ Often pleasant	(2OP)
□ Sometimes disturbing / irritating	(2SDI)
□ Sometimes annoying	(2SA)
□ Ugly / negative	(2UN)
□ Intrusive	(2I)
□ Able to be ignored	(2AI)
□ Disturbing my sleep	(2DS)
□ Disturbing my rest or conversation	(2DR)
□ Making me anxious	(2MA)
□ I'm sensitized to a particular sound	(2SS)

3. Please choose, from the following list, the words that best describe the quality or character or "soundscape" of your environment that you hear when you are here at home. You can choose as many words as you like. The usual character of the soundscape is-

□ Smooth	(3S)
□ Bright	(3B)

□ Warm	(3W)
□ Gentle	(3G)
□ Rich	(3Rh)
□ Powerful	(3P)
□ Rough	(3R)
□ Other (please state)	(3?)

4. Please choose, from the following list, the words that best describe any one sound that is clearly noticeable when you are here at home. You can choose as many words as you like. The sound is from: [name] The sound is-

□ Smooth	(4S)
□ Bright	(4B)
□ Warm	(4W)
□ Gentle	(4G)
□ Rich	(4Rh)
□ Powerful	(4P)
□ Rough	(4R)
□ Sharp or metallic	(4SM)
□ Percussive	(4Per)
□ Dull	(4D)
□ Tonal	(4T)
□ Harsh	(4H)
□ A distinctive hum or drone	(4Hum)
□ Fluctuating, undulating or beating	(4F)
□ Impulsive	(4I)
□ Repetitive	(4Rep)

5. My home is in a locality that is rural □ (5R)
urban (town) □ (5U)

[Note: the question coding has identified wind turbines (4WIND) and lawnmowers (4OTHER) as being the two sources of interest]

QUESTIONNAIRE 4: WEINSTEIN'S NOISE SENSITIVITY SCALE

Please circle the number corresponding to how well you agree or disagree with the question.

No.	Question	**Strongly**	Responses						**Strongly**
1	I wouldn't mind living on a noisy street if the apartment I had was nice	Agree	1	2	3	4	5	6	Disagree
2	I am more aware of noise than I was 3 years' ago	Agree	6	5	4	3	2	1	Disagree
3	No one should mind much if someone turns up his stereo full blast once in a while	Agree	1	2	3	4	5	6	Disagree
4	At movies, talking and crinkling wrappers disturbs me	Agree	6	5	4	3	2	1	Disagree
5	I am easily woken by noise	Agree	6	5	4	3	2	1	Disagree
6	If it is noisy where I am studying, I try to close the door or window or move somewhere else	Agree	6	5	4	3	2	1	Disagree
7	I get annoyed when my neighbours are noisy	Agree	6	5	4	3	2	1	Disagree
8	I get used to most noises without much difficulty	Agree	1	2	3	4	5	6	Disagree
9	How much would it matter to you if an apartment you were interested in renting was located across from a fire station	A lot	6	5	4	3	2	1	Not much
10	Sometimes sounds I hear get on my nerves and get me irritated	Agree	6	5	4	3	2	1	Disagree
11	Even music I normally like will bother me if I am trying to concentrate	Agree	6	5	4	3	2	1	Disagree
12	It wouldn't bother me to hear the sounds of every day living from my neighbours (such as footsteps, running water, quiet voices)	Agree	1	2	3	4	5	6	Disagree
13	When I want to be alone, it disturbs me to hear outside voices	Agree	6	5	4	3	2	1	Disagree
14	I am good at concentrating no matter what is going on around me	Agree	1	2	3	4	5	6	Disagree
15	In a library, I don't mind if people carry on a conversation if they do it quietly	Agree	1	2	3	4	5	6	Disagree
16	There are often times when I want complete silence	Agree	6	5	4	3	2	1	Disagree
17	Motorcycles ought to be required to be quieter	Agree	6	5	4	3	2	1	Disagree
18	I find it hard to relax in a place that is noisy	Agree	6	5	4	3	2	1	Disagree
19	I get mad at people who make noise that keeps me from falling asleep or getting work done	Agree	6	5	4	3	2	1	Disagree
20	I would not mind living in an apartment with thin walls	Agree	1	2	3	4	5	6	Disagree
21	I am sensitive to noise	Agree	6	5	4	3	2	1	Disagree

Coding and Analysis

Notes to Questionnaire 1: LEF Questionnaire

This noise sensitivity questionnaire (Zimmer & Ellermeier 1997, 1998, 1999) encompasses statements about a wide variety of environmental noises in a range of situations that affect the whole population. The authors state that for every item as score was assigned to each response item so that the higher its numerical value the more noise sensitive the respondent. The LEF ordinarily scores from 0 to 156 points (coding noted in the form) and four different factors (F1, Achievements and general attitudes; F2, Sleep; F3, Music and F4, Social and public context). On the basis of the questionnaire design information the questionnaire following has four questions marked as showing a higher degree of confidence for each of the factors.

Notes to Questionnaire 2: Noise At Home

The analysis coding numbers employed are the primary question as [Q#] and the question response coding in (brackets) adjacent to each question. Survey responses to Questions Q1, Q2, Q4 (all), and Q5 are analysed. The responses to these questions are correlated to the similar questions in Annexes A and B.

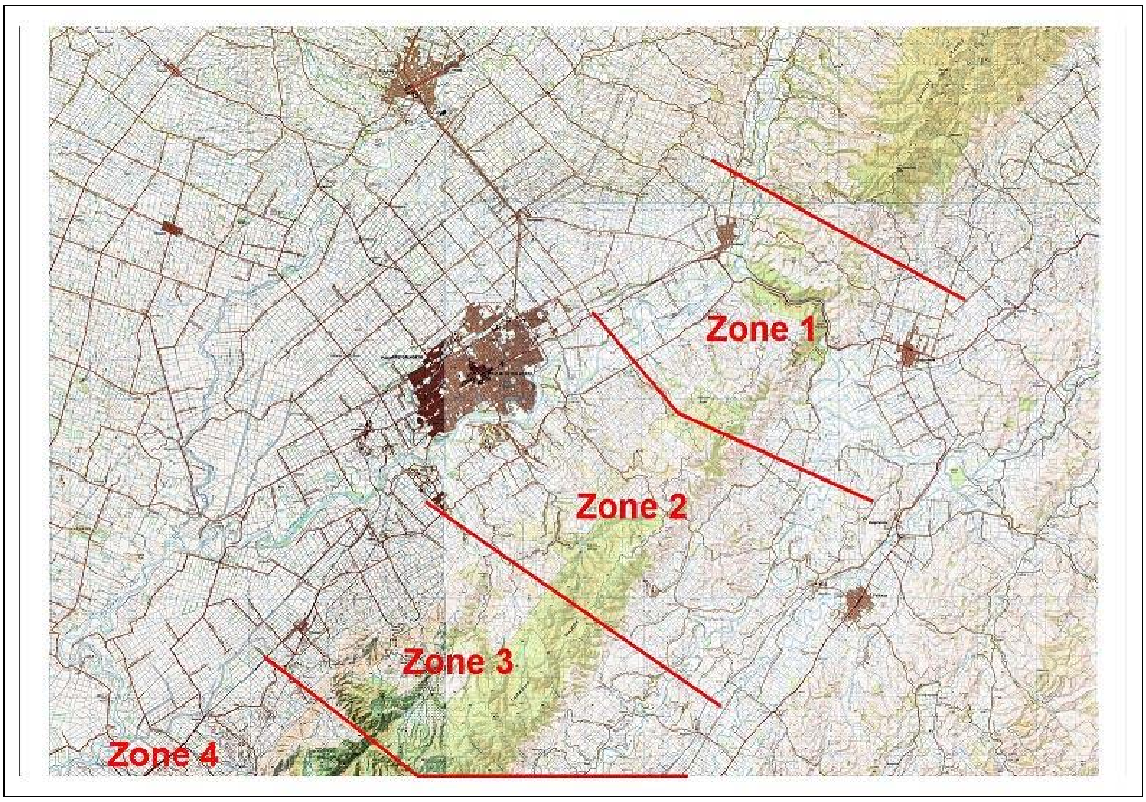
Notes to Questionnaire 3: Character of Sound

The questionnaire contains repeated questions in different sections as cross-checks to responses. The summary characteristics are categorised for sound perception.

Notes to Questionnaire 4: Weinstein's Noise Sensitivity Scale (WNSS).

Weinstein found the group mean score for the noise sensitive group was 67.9 and the group mean score for the noise insensitive group was 39.8. The highest possible noise sensitive score is 126. There is no significant difference between male and female response.

Zone Map for Coding of Responses



Zones 1 and 2 are potentially affected by wind farm noise, Zone 3 is greenfields but may be affected by wind farm noise to the north. Zone 4 is greenfields and unaffected by wind farm noise.

Annex D: Sensitivity and Sound Perception Survey

Introduction to the Survey.

The aim of this survey is to assist in the development of sound perception analysis instrumentation and methodologies. Two questionnaires are provided to ascertain your perceptions of real life experiences of sounds at home and while relaxing or at work. A set of soundfiles are included and your opinion of the character of the sounds is needed. This survey is to be incorporated in the PhD research work of Bob Thorne, Massey University, Wellington (May 2008 survey).

Ethics Approval

Ethics approval for the trial of instrumentation and methodology for assessing low amplitude sound as a low risk project was received on 18 October 2007.

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Professor Sylvia Rumball, Assistant to the Vice-Chancellor (Ethics and Equity), telephone 06 350 5249, email humanethics@massey.ac.nz

All surveys will be confidential to the researcher and only the aggregated data will be made available to others, within publications. Participants will not be able to be identified in the thesis or any subsequent publications. Thank you for your participation.

Please return to Bob Thorne, 5 Pryce Road, Lake Okareka, RD5, Rotorua

NoiSeQ Questionnaire

In the following questionnaire your opinion is asked concerning a variety of sounds. Please try to imagine the situation presented in each statement, and indicate to which extent you agree or disagree with it. It is **your own personal assessment** of the topics presented here that is of interest, so there is *no right or wrong* answer, only your opinion. Please give your opinion spontaneously by marking that answering option which best reflects your opinion. Please answer all statements in turn, always marking a single option only. If you are unsure as to which option to mark, please choose that option which comes closest in reflecting your opinion.

No	Item	Strongly disagree	Slightly disagree	Slightly agree	Strongly agree
1	I find it hard to relax in a noisy environment	0	1	2	3
2	I need peace and quiet to do difficult work	0	1	2	3
3	For a quiet place to live I would accept other disadvantages	0	1	2	3
4	I am very sensitive to neighbourhood noise	0	1	2	3
5	I find it hard to communicate while it is noisy	0	1	2	3
6	I have no problems to do routine work in a noisy environment	0	1	2	3
7	I become very agitated if I can hear someone talking while I am trying to fall asleep	0	1	2	3
8	When I am absorbed in a conversation I do not notice if it is noisy around me	0	1	2	3
9	I can fall asleep even when it is noisy	0	1	2	3
10	My performance is much worse in noisy places	0	1	2	3
11	Listening to loud music helps me relax after work	0	1	2	3
12	In a restaurant I cannot concentrate well on my conversation when people are talking loudly at other tables	0	1	2	3
13	I need quiet surroundings to be able to work on new tasks	0	1	2	3
14	When people around me are noisy I don’t get on with my work	0	1	2	3
15	I need an absolutely quiet environment to get a good night’s sleep	0	1	2	3
16	Even the slightest noise can prevent me from falling asleep	0	1	2	3

17	When I am at home, I become accustomed to noise quickly	0	1	2	3
18	In the cinema I am annoyed by other people whispering and by rustling paper	0	1	2	3
19	I think music interferes with conversations	0	1	2	3
20	I find it very hard to follow a conversation when the radio is playing	0	1	2	3
21	If my workplace was noisy I would always try to find a way for me to change this	0	1	2	3
22	When dancing I don't mind how loud the music is	0	1	2	3
23	It would not bother me to live in a noisy street	0	1	2	3
24	When other peoples' children are noisy I would prefer that they should not play in front of my house	0	1	2	3
25	At weekends I prefer quiet surroundings	0	1	2	3
26	I do not feel well rested if there has been a lot of noise the night before	0	1	2	3
27	When I am at home I find it uncomfortable if the radio or TV is left on in the background	0	1	2	3
28	Loud music in a restaurant makes me stop my conversation	0	1	2	3
29	I can do complicated work even while background music is playing	0	1	2	3
30	I wake up at the slightest noise	0	1	2	3
31	I avoid leisure activities which are loud	0	1	2	3
32	I don't like noisy activities in my residential area	0	1	2	3
33	Noises from neighbours can be extremely disturbing	0	1	2	3
34	The sound of loud thunder does not usually wake me up	0	1	2	3
35	High noise levels make it hard for me to concentrate on my conversation	0	1	2	3

PLEASE INDICATE HOW MUCH NOISE BOTHERS, DISTURBS OR ANNOYS YOU WHEN YOU ARE HERE AT HOME.

1. Do you find noise in your environment (including your home environment) a problem? YES ☐(1Y) NO ☐ (1N) SOMETIMES ☐ (1S)

2. Thinking about where you live, could you please say how quiet or noisy you think your area is?

Very quiet ☐ (2VQ)
Quiet ☐ (2Q)
Moderately noisy ☐ (2MN)
Noisy ☐ (2N)
Very noisy ☐ (2VN)

3. Does noise from your neighbourhood (not including from those living in your household) affect you-

While reading YES ☐ (3RY) NO ☐ (3RN)
While watching TV YES ☐ (3TvY) NO ☐ (3TvN)
While listening/talking YES ☐ (3TY) NO ☐ (3TN)
While relaxing YES ☐ (3XY) NO ☐ (3XN)
While at work YES ☐ (3WY) NO ☐ (3WN)
While at school YES ☐ (3ScY) NO ☐ (3ScN)
While sleeping YES ☐ (3SlY) NO ☐ (3SlN)

4. Are you ever disturbed or annoyed by noise at home (not including from those living in your household)? YES ☐ (4Y) NO ☐ (5N)

5. If yes - Could you please tell us what sort of noise and at what time of day?
Please mark the boxes that apply

Source*	**Morning** 6 am - 12noon	**Afternoon** 12 noon - 6pm	**Evening** 6pm - 10pm	**Night** 10pm - 6am	**All the time**

**Please add noises that bother, disturb or annoy you.*

6. Where do you live? *Please mark the boxes that apply*

Near a main road or a busy local road? YES ☐ NO ☐
Near or in an industrial area? YES ☐ NO ☐
Under or near aircraft overflight? YES ☐ NO ☐
In an urban or rural area? Urban ☐ Rural ☐

7. Generally, how would <u>you</u> rate your area as a place to live?

1	2	3	4	5
Low				High

8. Are you? MALE ☐ FEMALE ☐

9. Please mark your age group-

10-14 ☐ 15-19 ☐ 20-29 ☐ 30-39 ☐
40-49 ☐ 50-59 ☐ 60-69 ☐ 70 and over ☐

SOUNDFILE QUESTIONNAIRE - INTRODUCTION

A series of 12 soundfiles are included in this survey. Please listen to ALL the soundfiles and write your comments on the response sheets. You can listen to the soundfiles in any order. The soundfiles are in Microsoft .wav format and need to be played through a computer. Computer soundcards and speaker systems are generally not of a high quality and, except for two soundfiles, the soundfiles have been chosen to reproduce sounds clearly. The two exceptions are environmental sounds which are a mix of quiet sounds. Each soundfile is 2 minutes long. Please listen to the soundfile as many times as you like before completing the response sheet.

It is recommended that the sounds be recorded into a playlist, such as iTunes, and the soundfile name MUST be written onto the soundfile response sheet. When playing the soundfile the sound level should be relatively “quiet” and just below the level normally set when watching TV or listening to the radio or music system. You may need to adjust the sound level for the two environmental soundfiles. The sounds can be played through speakers but headphones or earbud-headphones are recommended. The soundfiles are:

No 1: Amplitude modulated fluctuating noise
No 2: Ashhurst2Febafternoon 441k16bitstereo
No 3: Building component clicks 441k16stereo
No 4: Café Wind Turbines1Feb 441k16stereo
No 5: NoiseLab031asC3 441k16stereo
No 6: NoiseLab032asC4 441k16stereo
No 7: NoiseLab071asC6 441k16stereo
No 8: Pink noise 5Hz to 20kHz 441k16stereo
No 9: Rough noise 441k16stereo
No 10: Sharp noise 441k16stereo
No 11: Wind turbine noise simulation 441k16stereo

In addition there is a calibration tone sequence of 440Hz at -2.5dB and then -12.5dB; and 1000Hz at -2.5dB and then at -12.5dB. This sequence is continued for the whole of the soundfile. Each individual tone is 1.5 seconds in duration. The recordings are saved in both wav and mp3 formats. The soundfiles are numbers 12W and 12M.

SOUNDFILE QUESTIONNAIRE

In the following questionnaire your opinion is asked concerning the character of a specific soundfile. It is **your own personal assessment** of the sound presented that is of interest, so there is *no right or wrong* answer, only your opinion.

- □ I listened to the soundfile while using headphones or earbuds
- □ I listened to the soundfile using speakers

Soundfile Name / Number:

Please select the best description or descriptions concerning the character of the sound. The descriptions are in no particular order. The sound is-

- □ Smooth
- □ Bright
- □ Warm
- □ Gentle
- □ Waterfall
- □ Rich
- □ Powerful
- □ "Wind in trees"
- □ Rough
- □ Sharp or metallic
- □ Percussive
- □ Dull
- □ Tonal
- □ Harsh
- □ A distinctive hum
- □ Fluctuating, undulating or beating
- □ Rumble
- □ Impulsive
- □ Repetitive
- □ Thumping
- □ Annoying
- □ Disturbing
- □ Unpleasant
- □ Pleasant
- □ Any other description that you feel is better than the general terms above

This section is not part of the questionnaires or survey.

NoiSeQ Questionnaire Analysis

A rating value of 0 always indicates "strongly disagree", a rating value of 1 always indicates "slightly disagree", a rating value of 2 indicates always "slightly agree" and a rating value of 3 always indicates "strongly agree". Items 6, 8, 9, 11, 17, 22, 23, 29, 34 are reverse-scored. To calculate the subscale scores or the global noise sensitivity score the rating values of the above mentioned items have to change since a high score indicates high noise sensitivity. For example: if a person says that he/she strongly agrees concerning item 22 "when dancing I don't mind how loud the music is" then he/she is not noise sensitive. Therefore when calculating the subscale scores use the value "0" and so on (if they give a rating of 0 "strongly disagree" use the value 3 when calculating the subscale score and so on). The subscales are

Subscale	Question Numbers
Communication	5, 8, 12, 19, 20, 28, 35
Habitation	3, 4, 17, 23, 24, 32, 33
Leisure	1, 11, 18, 22, 25, 27, 31
Sleep	7, 9, 15, 16, 26, 30, 34
Work	2, 6, 10, 13, 14, 21, 29

The Annoyance Questionnaire is slightly revised version of the questionnaire issued in the previous Manawatu Survey and is presented to allow comparison between this questionnaire set and the earlier questionnaires. The analysis coding numbers employed are the primary question as [Q#] and the question response coding in (brackets) adjacent to each question. Survey responses to Questions Q1, Q2, Q3 (all), and Q4 are analysed. The responses to these questions are correlated to the similar questions in Annexes A, B and C.

The Soundfile analysis questionnaire is to assist in sound perception. The responses to the noise sensitivity and disturbance questionnaires, plus the responses to the soundfiles' characteristics (e.g., bright, pleasant) inform the psychometric measures within the perception templates.

Annex E: Sensitivity and Sound Perception Analysis Tables

The Tables in this Annex present the questions and coding for the decision processes linking individual perception and soundfile analysis.

Table E1: Personal and environmental information

PLEASE PROVIDE A LITTLE INFORMATION ABOUT YOURSELF AND WHERE YOU LIVE								
	Are you	Female	Male					
		1	2					
	Please mark your age group	under 20	20-29	30-39	40-49	50-59	60-69	70 or above
		3	4	5	6	7	8	9
Please answer each question. If you are unsure as to which option to mark, please choose that option which comes closest in reflecting your opinion.								
Do you live-								
	Near a main road, railway or airport?	No	Yes					
		10	11					
	Near large industries or industrial activity?	No	Yes					
		12	13					
	In a city or large urban area?	No	Yes					
		14	15					
	In a village or small residential area?	No	Yes					
		16	17					
	In a rural or similar sort of area?	No	Yes					
		18	19					
YOUR LOCAL ENVIRONMENT								
Please answer each question. If you are unsure as to which option to mark, please choose that option which comes closest in reflecting your opinion.								
Thinking about the last 12 months or so, when you are here at home-								
	Do you find noise in your environment a problem?	No	Not Often	Sometimes	Often			
		20	21	22	23			
	How quiet or noisy do you think your neighbourhood is?	Very Quiet	Quiet	Moderately noisy	Noisy	Very noisy		
		24	25	26	27	28		
	Are you disturbed or annoyed by noise at home?	No	Not Often	Sometimes	Often			
		29	30	31	32			
Please answer each question. If you are unsure as to which option to mark, please choose that option which comes closest in reflecting your opinion.								
Thinking about the last 12 months or so, when you are here at home, how much does noise from outside your home bother, disturb or annoy you-								
	while reading?	Not at all	Slightly	Moderately	Very	Extremely		
		33	34	35	36	37		
	while watching TV?	Not at all	Slightly	Moderately	Very	Extremely		
		38	39	40	41	42		
	while listening or talking?	Not at all	Slightly	Moderately	Very	Extremely		
		43	44	45	46	47		
	while relaxing?	Not at all	Slightly	Moderately	Very	Extremely		
		48	49	50	51	52		
	when sleeping?	Not at all	Slightly	Moderately	Very	Extremely		
		53	54	55	56	57		

Table E2: Personal noise sensitivity

PERSONAL NOISE SENSITIVITY											
	In the following questionnaire your opinion is asked concerning a variety of sounds. Please try to imagine the situation presented in each statement, and indicate to which extent you agree or disagree with it. It is your own personal assessment of the topics presented here that is of interest, so there is *no right or wrong* answer, only your opinion. Please give your opinion spontaneously by marking that answering option which best reflects your opinion. Please answer all statements in turn, always marking a single option only. If you are unsure as to which option to mark, please choose that option which comes closest in reflecting your opinion.										
									Subscales		
		Strongly disagree	Slightly disagree	Slightly agree	Strongly agree		Comm	Habit'n	Leisure	Sleep	Work
1	I find it hard to relax in a noisy environment	0	1	2	3				x		
2	I need peace and quiet to do difficult work	0	1	2	3						x
3	For a quiet place to live I would accept other disadvantages	0	1	2	3			x			
4	I am very sensitive to neighbourhood noise	0	1	2	3			x			
5	I find it hard to communicate while it is noisy	0	1	2	3		x				
6	I have no problems to do routine work in a noisy environment	3	2	1	0						x
7	I become very agitated if I can hear someone talking while I am trying to fall asleep	0	1	2	3					x	
8	When I am absorbed in a conversation I do not notice if it is noisy around me	3	2	1	0		x				
9	I can fall asleep even when it is noisy	3	2	1	0					x	
10	My performance is much worse in noisy places	0	1	2	3						x
11	Listening to loud music helps me relax after work	3	2	1	0				x		
12	In a restaurant I cannot concentrate well on my conversation when people are talking loudly at other tables	0	1	2	3		x				
13	I need quiet surroundings to be able to work on new tasks	0	1	2	3						x
14	When people around me are noisy I don't get on with my work	0	1	2	3						x
15	I need an absolutely quiet environment to get a good night's sleep	0	1	2	3					x	
16	Even the slightest noise can prevent me from falling asleep	0	1	2	3					x	
17	When I am at home, I become accustomed to noise quickly	3	2	1	0			x			
18	In the cinema I am annoyed by other people whispering and by rustling paper	0	1	2	3				x		
19	I think music interferes with conversations	0	1	2	3		x				
20	I find it very hard to follow a conversation when the radio is playing	0	1	2	3		x				
21	If my workplace was noisy I would always try to find a way for me to change this	0	1	2	3						x
22	When dancing I don't mind how loud the music is	3	2	1	0				x		
23	It would not bother me to live in a noisy street	3	2	1	0			x			
24	When other peoples' children are noisy I would prefer that they should not play in front of my house	0	1	2	3			x			
25	At weekends I prefer quiet surroundings	0	1	2	3				x		
26	I do not feel well rested if there has been a lot of noise the night before	0	1	2	3					x	
27	When I am at home I find it uncomfortable if the radio or TV is left on in the background	0	1	2	3				x		
28	Loud music in a restaurant makes me stop my conversation	0	1	2	3		x				
29	I can do complicated work even while background music is playing	3	2	1	0						x
30	I wake up at the slightest noise	0	1	2	3					x	
31	I avoid leisure activities which are loud	0	1	2	3				x		
32	I don't like noisy activities in my residential area	0	1	2	3			x			
33	Noises from neighbours can be extremely disturbing	0	1	2	3			x			
34	The sound of loud thunder does not usually wake me up	3	2	1	0					x	
35	High noise levels make it hard for me to concentrate on my conversation	0	1	2	3		x				
					sum of rows	Overall	Comm	Habit'n	Leisure	Sleep	Work
					Median/n	1	2	3	4	5	6

Table E3: Sound character

CHARACTER OF THE SOUND THAT YOU ARE INTERESTED IN						
In the following questionnaire your opinion is asked concerning the character of the sound that you are interested in. It is your own personal assessment of the sound that is of interest, so there is *no right or wrong* answer, only your opinion. Please mark the descriptions that best describe the character of the sound.						
The sound is	smooth	bright	warm	gentle	rich	powerful
	58	59	60	61	62	63
The sound sounds like	wind in trees	rough	sharp or metallic	dull	tonal	harsh
	64	65	66	67	68	69
The sound is	a hum	beating or fluctuating	rumble	impulsive	repetitive	thumping
	70	71	72	73	74	75
To me the sound is	annoying	disturbing	unpleasant	pleasant	enjoyable	relaxing
	76	77	78	79	80	81

Reference sound levels or soundfiles for different locales can be determined and substituted for the New Zealand – Brisbane reference levels or sounds.

APPLICATION OF QUESTIONNAIRES FOR INTRUSIVE NOISE RATING

Table 11.5.1 is presented, following, in descriptive terms:

Line 5

IF noise sensitivity overall is greater than or equal to 1.11 AND less than or equal to 1.63 THEN a person's noise sensitivity is "average"

Line 10

IF noise sensitivity overall is greater than 1.63 THEN a person's noise sensitivity is "more than average"

Line 15

IF noise sensitivity overall is less than or equal to 1.11 THEN a person's noise sensitivity is "less than average"

Line 20

IF the exterior LAeq sound level is less than 35 dB(A) AND the answer to the question ‘How quiet or noisy do you think your neighbourhood is?’ is ‘very quiet’ OR ‘quiet’ THEN the person has a “better than average soundscape and amenity”

Line 25

IF the exterior LAeq sound level is greater than or equal to 35.0 dB(A) AND less than or equal to 55 dB(A) AND the answer to the question ‘How quiet or noisy do you think your neighbourhood is’ is ‘moderately noisy’ THEN the person has an “average soundscape and amenity”

Line 30

IF the exterior LAeq sound level is greater than 55 dB(A) and the answer to the question ‘How quiet or noisy do you think your neighbourhood is?’ is ‘noisy’ OR ‘very noisy’ THEN the person has a “less than average soundscape and amenity”

Line 35

IF exterior night-time modified unbiased annoyance is less than 50 THEN a person has “better than average amenity”

Line 40

IF exterior night-time modified unbiased annoyance is greater than or equal to 50 AND less than or equal to 100 THEN a person has “average amenity”

Line 45

IF exterior night-time modified unbiased annoyance is greater than 100 THEN a person has “less than average amenity”

Line 50

IF exterior night-time modified unbiased annoyance is less than 50 AND the exterior LAeq sound level is less than 35 dB(A) AND the answer to the question ‘How quiet or noisy do you think your neighbourhood is?’ is ‘very quiet’ OR ‘quiet’ THEN the person has an Intrusive Noise Rating of ‘1’ meaning “no adverse effect expected”

Line 55

IF exterior night-time modified unbiased annoyance is less than 50 AND the answer to the question ‘Are you disturbed or annoyed by noise at home?’ is ‘sometimes’ AND the answer to the character of the sound question ‘To me the sound is’ is ‘annoying’ AND the exterior LAeq sound level is greater than or equal to 35.0 dB(A) or less than or equal to 55 dB(A) AND the answer to the question ‘How quiet or noisy do you think your neighbourhood is’ is ‘moderately noisy’ THEN the person has an Intrusive Noise Rating of ‘2’ meaning “minor adverse effect”

Line 60

IF exterior night-time modified unbiased annoyance is greater than or equal to 50 AND less than or equal to 100 AND the answer to the question ‘Are you disturbed or annoyed by noise at home?’ is ‘sometimes’ AND the answer to the character of the sound question ‘To me the sound is’ is ‘annoying’ AND the answer to the character of the sound question ‘To me the sound is’ is ‘unpleasant’ AND the exterior LAeq sound level is greater than or equal to 35.0 dB(A) AND less than or equal to 55 dB(A) THEN the person has an Intrusive Noise Rating of ‘3’ meaning “adverse effects more than minor”

Line 65

IF exterior night-time modified unbiased annoyance is greater than 100 AND the answer to the question ‘Are you disturbed or annoyed by noise at home?’ is ‘often’ AND the answer to the character of the sound question ‘To me the sound is’ is ‘annoying’ AND the answer to the character of the sound question ‘To me the sound is’ is ‘unpleasant’ AND the exterior LAeq sound level is greater than or equal to 35.0 dB(A) AND less than or equal to 55 dB(A) THEN the person has an Intrusive Noise Rating of ‘4’ meaning “nuisance adverse effect expected”

Line 70

IF exterior night-time modified unbiased annoyance is greater than 100 AND the answer to the question ‘Are you disturbed or annoyed by noise at home?’ is ‘often’ AND the answer to the character of the sound question ‘To me the sound is’ is ‘annoying’ AND the answer to the character of the sound question ‘To me the sound is’ is ‘unpleasant’ AND the exterior LAeq sound level is greater than 55 dB(A) THEN the person has an Intrusive Noise Rating of ‘5’ meaning “significant adverse effect”

Annex F: Glossary of statistical measures

Sample Size for Attitudinal Studies

The probability level for this work is set at 95 percent. The table values are calculated from the following formula, based on the standard error of a proportion:

Range $= \pm z \ (pq / n)^{1/2}$ where:

z = standardised score representing the area under the normal curve for a given probability level. When 95% level, $z = 1.96$, at 90% level, $z = 1.645$.

p = proportion of sample having a characteristic.

q = (l-p), proportion of sample not having the characteristic.

n = number of completed interviews.

Table F.1: sample sizes vs probability levels

	n = 100	200	500	1,000
95%	0.098	0.069	0.044	0.031
90%	0.082	0.058	0.037	0.026

The random surveys of Annexes A and B were designed with a goal of not less than two hundred completed responses giving a maximum range of ±7% at the 95% level for each district within the Region.

Statistical methods

The statistical methods of this work use non-parametric methods as well as simple parametric methods such as average, percent exceeded and standard deviation. Analysis of variance (ANOVA) assumes that the underlying distributions are normally distributed, as in the case of long-term sound level measurements. Non-parametric methods are used to study populations that have a ranked order (such as a scale of some sort). The attitudinal studies, annoyance and sound perception studies are of this nature.

The Kruskal-Wallis H test is a one-way analysis of variance. It is the non-parametric equivalent of ANOVA for testing equality of population medians among groups. The test does not assume a normal population but does assume an identically shaped distribution for each group except for any difference in medians.

The Mann-Whitney U test is a non-parametric test for assessing whether two samples of observations come from the same distribution. The null hypothesis is that the two samples are from a single population and their probability distributions are equal.

The Bonferroni correction is a safeguard against multiple tests of statistical significance on the same data falsely giving the appearance of significance.

Confidence Intervals (or Limits)

The confidence interval is the likely range of the true value. “Likely” is usually a probability of .95 (defining 95% limits). The confidence limits (upper and lower bounds) do not have to be evenly spaced, although in a normal distribution the observed value falls in the middle of a confidence interval. The correlation coefficient is in the range of ±1. If the confidence interval does not overlap zero the effect is statistically significant; that is, there is a real effect. Confidence intervals indicate whether a result could be trivial.

Correlation coefficient

A correlation coefficient is a single number that describes the degree of relationship between two variables. The confidence limits of the correlation coefficient are defined with the Fisher z transformation.

Hypothesis Testing

A hypothesis is an idea whose merit requires testing; conceptually, is there an effect? The outcome of the hypothesis must be unknown when it is framed. The first step is to state the alternative hypothesis (H_A); that is, the hypothesis that is predicted or supported. The second step is to state the null hypothesis (H_0); that is, the hypothesis that there is no effect and that describes the remaining possible outcomes. Convention has the null hypothesis stated first. Depending on how the null hypothesis is framed it could have a ‘direction’ and be referred to as being one- or two-tailed. If the prediction specifies a direction, the null hypothesis is the no-difference (or no effect) prediction and the prediction of the opposite direction. The hypotheses must be tested so that one is accepted and the other rejected. For this work the null hypothesis for the noise sensitivity responses is that there is no significant difference between the groups. The alternative hypothesis is that there is significant difference between the groups. No direction is specified so the hypothesis is two-tailed.

Standard deviation

The standard deviation is a measure of the dispersion of values. For a normal distribution, one standard deviation (σ) from the mean (average) accounts for 68.27% of the set, 1.645 σ accounts for 90% and 2 σ accounts for 95.45% of the set. In Microsoft Excel, used in this work, the calculation of the standard deviation uses the equation:

$$\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}}$$

where x is the sample mean AVERAGE(number1,number2,…) and n is the sample size.

Statistical significance *p* value

Statistical significance is reported by the generation of a *p* (probability) value from a test statistic. It is a test of whether the effect is greater than zero for an observed positive effect. A value of $p>0.05$ is often taken as 'acceptance of the null hypothesis' and a value of $p<0.05$ as 'rejection of the null hypothesis'. Acceptance of the null does not necessarily mean there is no effect. Rejection means that the effect is not zero. Statistical significance does not indicate whether a result could be trivial or how big or small the effect could be on the population. The p values of this work, derived from one-tailed tests, represent the probability that the true value of the effect is of sign opposite to the observed value. The level of significance (alpha level) of the tests is 5% and therefore any result with a *p* value of less than 0.05 is significant. For the noise sensitivity responses the p-value gives the probability of a Type 1 error; that is, saying the null hypothesis is false when in fact the null is true. If the probability of a Type 1 error is below 5% (alpha = .05) then it is safe to reject the null hypothesis. If the *p* value is over .05 then the null hypothesis is accepted; that is, the hypothesis of no difference.