ASSESSING AURAL COMFORT OF HIGH-RISE APARTMENT DWELLERS IN THE TROPICS

SHEIKH MAHBUB ALAM

(B.Sc. (Civil), BUET ; M.Engg. (Structure), NUS)

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DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

Sk. M. Alam

Sheikh Mahbub Alam
25 February 2014

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SUMMARY

Noise is recognized as a key quality of life issue in a modern urban environment. In a dense high-rise urban environment with hot and humid tropical climatic condition, the need for natural ventilation in residential buildings poses challenges in the achievement of indoor aural comfort. As a result, aural comfort in a 'tropical high-rise environment' is different to that of a temperate urban zone. Hence, there is a need to redefine the context of 'aural comfort' in a high-rise built environment within a tropical climatic condition. In this thesis, the term 'aural comfort' is defined as the condition of mind which articulates satisfaction (or dissatisfaction) with the surrounding aural environment. Aural comfort does not solely depend on the physical noise levels, but also on the relationships between the factors that contribute to a person’s satisfaction in his/her surrounding aural environment. In the past, a little research have been carried out on the positive evaluation of the noise (aural comfort) in urban residential environment. This research study endeavours to assess the daytime 'Aural comfort' among high-rise apartment dwellers in tropical Singapore. The key objectives of this research are to establish a suitable framework, based on a sound theoretical basis, for the assessment of aural comfort and to develop an Aural Comfort Model (ACM). A novel comfort evaluation framework is proposed in this thesis which is rooted in Stallen's noise annoyance theory and is based on Eagly and Chaiken's Evaluation Response Model (ERM).

The developed aural comfort model established the hypothesis of this research by demonstrating that aural comfort is dependent on the noise exposure level, the subjective perceptions of the noisiness in the apartments due to the noise exposure, and the level of subjective disturbances due to Road Traffic noise and MRT (Mass Rapid Transit) train noise. The ACM was then validated using subjective comfort responses collected from the psychoacoustics experiments in a laboratory.

Analysis of the data revealed that the noisiness of an apartment subjected to Road Traffic noise was perceived as 'quiet' at a mean A-weighted noise exposure level of about 53 dB; also at a mean Loudness level of 7 sone and maximum Loudness level of 9 sone and at a mean Roughness level of 24 centi-Asper and maximum Roughness level of 27 centi-Asper. Noise disturbance due to road traffic was perceived as 'a little disturbing' at a mean A-weighted noise exposure level of about 57 dB , a mean Loudness level of 11 sone and at maximum Loudness level of 13 sone and at a mean Roughness of 26 centi-Asper. Analysis of the data has also shown that noisiness of an apartment subjected to MRT train noise was perceived as 'quiet' at a maximum Loudness level of 8 Sone and at a mean Sharpness level of 1.22 acum and at a maximum Roughness level of 33 centi-Asper whereas noise disturbance due to MRT train noise was perceived as 'a little disturbing' with a maximum Loudness level of 10 sone and at a mean Sharpness of 1.3 acum.

In addition to the development of a statistical model, aural comfort has been assessed in a semantic differential space comprising of twelve different bipolar adjective pairs. Relationships between these adjective parameters and different psychoacoustical quantities has been investigated in detail and are presented in this thesis.

For Road traffic noise, analysis showed that at an A-weighted equivalent noise level of 55 dB, 'moderately’ favourable subjective perceptions were observed across the twelve semantic adjective pairs. Furthermore, at a mean Loudness of 10 Sone and at a five percentile Roughness of 28 centi-asper 'moderately’ favourable subjective perceptions were observed across the twelve semantic adjective pairs. For MRT train noise, moderately favourable subjective perceptions across the twelve semantic adjective pairs were observed at an A-weighted equivalent noise level of 56 dB and at a five percentile loudness of 10 Sone, at five percentile Sharpness of 1.35 acum and at a Roughness of 26 centi-asper.

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LIST OF SYMBOLS

A	Room absorption
$deff$	Design effect
F	Fluctuation strength
F_{max}	Maximum Fluctuation Strength
F_{mean}	Mean Fluctuation Strength
F_{perc}	Percentile Fluctuation Strength
$F_{\_tnr}$	The frequency of the maximum tone to noise ratio (TNR)
$F_{\_tnr}$	The frequency of the maximum prominence
f_{mod}	Modulation frequency
$FSTC$	Field sound transmission class
IIC	Impact Insulation Class
$FIIC$	Field impact Insulation class
K_o	Directivity index
L_{max}	Maximum level of the signal
L_{mean}	Mean Level of the signal
L_{Aeq}	A-weighted equivalent continuous sound pressure level
$L_{Aeq,T}$	A-weighted equivalent continuous SPL for duration T
L_1	One percentile noise level
L_{10}	Ten percentile noise level
L_{50}	Fifty percentile noise level

L_{90}	Ninety percentile noise level
L_{DEN}	Day-evening-night average noise level
L_{DN}	Day-night noise average level
L_D	Day average noise level
L_N	Night average noise level
L_{NP}	Noise pollution level
L'_{nw}	Weighted normalized impact sound pressure level
MRT	Mass Rapid Transit
n	Sample size
NR	Noise Reduction
NIC	Noise Isolation Class
TNI	Traffic noise index
N	Loudness
$N^{'}$	Specific Loudness
N_{max}	Max Loudness
N_{mean}	Mean Loudness
$NISO532B$	Loudness according to ISO532B (Zwicker) standard
N_5	Five Percentile Loudness
P	Estimated prevalence of annoyance
PR_{max}	Maximum prominence
PR_{mean}	Mean Prominence

PR	Global Prominence
PA	Psychoacoustic Annoyance
R	Roughness
R_{max}	Max Roughness
R_{mean}	Mean Roughness
R_{perc}	Percentile Roughness
$R_w^{'}$	Weighted apparent sound reduction index
RT	Reverberation time
S	Sharpness
S_{max}	Maximum Sharpness
S_{mean}	Mean Sharpness
S_{perc}	Percentile Sharpness
SRI	Sound Reduction Index
STL	Sound transmission loss
T	Tonality
TNR	Maximum Tone-to-noise ratio
Z	Z-statistics (for % confidence intervals)

CHAPTER 1: INTRODUCTION

1.1 RESEARCH BACKGROUND

Residents in urban environment are exposed to several environmental stressors in recent days. Among these stressors, noise is recognized as the most notable, the most frequently mentioned and the one on which the most complaints are concentrated (Moser, 1992).

In a modern urban environment, noise is identified as a key quality of life issue (Atkinson 2007). In a high-rise densely populated tropical urban environment, the need for natural ventilation in residential buildings poses significant challenge in the achievement of aural comfort in the indoor environment. As such, the context of aural comfort in a tropical high-rise environment is different from that in a temperate urban zone. Consequently, there is a need to redefine the context of 'aural comfort' for high-rise built environments in tropical climatic conditions.

Human thermal comfort is defined by ASHRAE (ANSI/ASHRAE Standard 55) as the state of mind that expresses satisfaction with the surrounding thermal environment. Adopting this concept of thermal comfort, 'Aural comfort', in this thesis, may also be defined as the psychological state of mind which articulates the satisfaction (or dissatisfaction) with the surrounding noise environment. The definition itself illustrates the fact that aural comfort is related to the physical noise environment, the quantitative and qualitative aspects of noise, as well as the individuals' attitude (perception) towards the noise environment. Acoustic comfort is therefore a complex subject and its evaluation requires a comprehensive assessment of these aspects.

This research study focuses on the assessment of ***daytime 'Aural comfort'*** of the high-rise apartment dwellers in tropical Singapore. It aims to investigate the process and the key factors involved in aural comfort among the dwellers. The background of this research is presented in the following sections.

1.1.1 Noise in an Urban Environment

Generally, the dominant noise sources in the urban environment are the large systematic noise sources such as road traffic and trains. These are the key sources contributing to acoustic discomfort (Carter, 1996). This affirmation is on the basis of noise measurements and the corresponding intensity of noise annoyance due to these noise sources (Amando, 2006).

As indicated in the report 'The European Environment State and Outlook 2010 (EEA, 2010), road transport noise is the major source of noise disturbance in urban areas and approximately 56 million people in the largest cities in the 27 European Union countries (EU-27) are exposed to noise levels greater than 55 dB L_{DEN} (refer to Figure 1-1). The L_{DEN} (Day Evening Night Sound Level) is the average sound level over a 24 hour period.

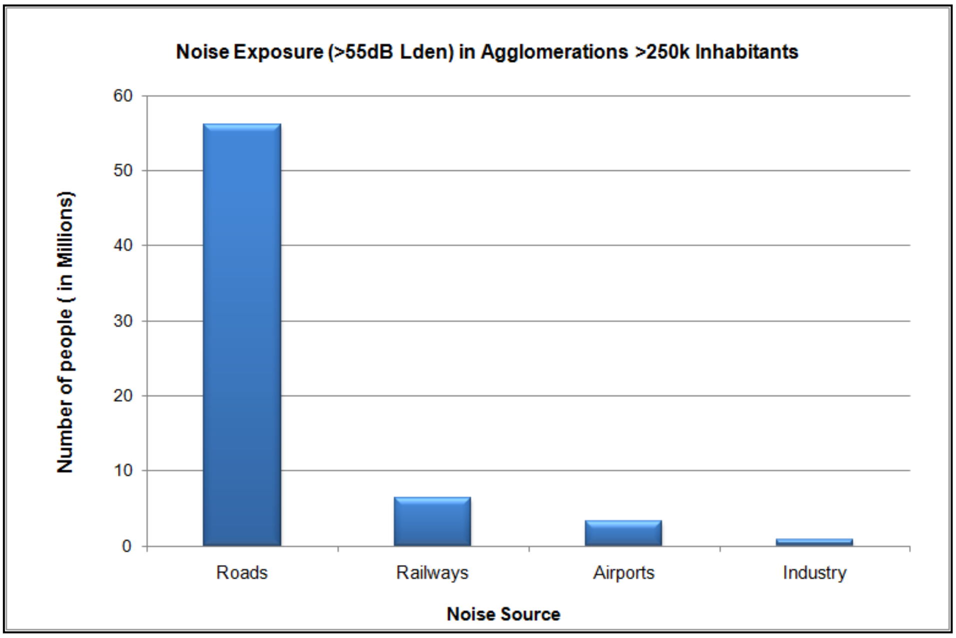
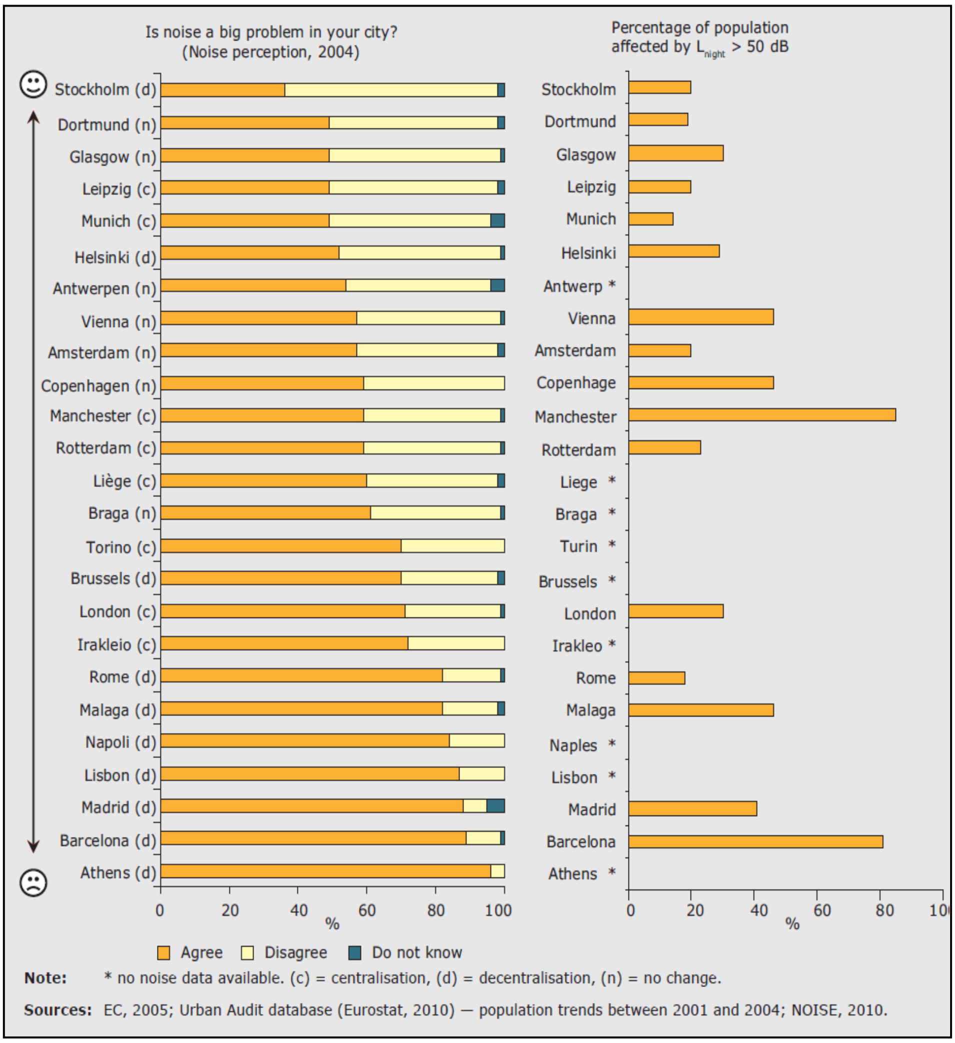


Figure 1-1: Noise exposure of L_{DEN} >55 dBA based on strategic noise mapping (Source: EEA, 2010)

The same report states that the findings of the 2004 Urban Audit Perception Survey (EEA, 2010) showed that the residents in many large cities believes that noise is a serious social problem (refer to Figure 1-2). In addition, numerous other studies have shown that the environmental noise sources (road traffic, train and aircraft) are the major source of community noise annoyance in modern cities (Jian Kang, 2010; Kryter, 2009; Maarten, 2008; Seto et al., 2007, Bluhm et al., 2007; Gorai et al., 2007, Moser, 2006; Babisch, 2005, Morillas, 2005; Marquis-Favre, 2005, Passchier, 2000; Fidell et al., 1991, etc).


Is noise a big problem in your city? (Noise perception, 2004)

Percentage of population affected by L_{night} > 50 dB

Note: * no noise data available. (c) = centralisation, (d) = decentralisation, (n) = no change.

Sources: EC, 2005; Urban Audit database (Eurostat, 2010) — population trends between 2001 and 2004; NOISE, 2010.

Figure 1-2: Perception of noise being a problem in the city (Source: EEA, 2010)

Amid the debate of sustainable development and urban compactness in recent years, there has been interests in the introduction of high-rise living in cities (Belinda, 2006). High-rise cities have been an inevitable development for many cities around the globe in fulfilling urban growth and resolve shortages in housing. The noise exposure and its level of annoyance in dense high-rise urban environments is more severe compared to less-dense cities. In a recent paper, while comparing the noise distribution between a high density city, such as Wuhan in China, and a low density city, such as Greater Manchester in the UK, Prof. Jian Kang (Jian Kang, 2011) demonstrated that other than the presence of busy transport network, urban morphology has a significant effect on the noise exposure level. Apart from the environmental noise in densely urbanized modern high-rise cities, noise caused by neighbours in the apartment building is becoming an increasing problem in society (Claude. 1991). It is a serious community concern in many cities. Neighbours' noise is associated with an inhabitant’s daily life and not easily solved by administrative regulation (Utley, 1988).

In an increasingly noisy urban environment, quietness has to be ensured at least in residential dwellings. Unfortunately not many people enjoy such living conditions (Ralf, 1997). Research in the past few decades has examined noise level and its relation to noise annoyance. ***However, little has been studied about the positive evaluation of the noise environment, i.e. aural comfort, in urban residential environment (Marquis-Favre et al. 2005).*** *As such, it is useful to examine and ascertain the acoustical and non-acoustical factors related to aural comfort in high-rise residential environment.*

1.1.2 The Need for a Holistic Approach to Assessing Aural Environment

The perception of the environmental condition in a building depends on the physical indoor environment and a host of physiological, psychological and behavioural factors of an individual (Raymond, 2008). Assessment of Sound in an indoor environment is hence related to the physical noise environment in the space evaluated, and the physiological, psychological behavioural attributes of an individual. Consequently, assessment of aural comfort should not be limited to the evaluation of noise exposure levels, but also requires the evaluation of temporal and spectral distribution of the stimulus, integrated with the individuals' perception and functional needs. *Assessment of aural comfort of high-rise residential dwellers in the tropics in such a holistic approach is missing in the literature.*

Numerous research studies have been conducted over the past three decades in an attempt to understand negative impact of noise on humans due to several environmental and neighbour related noise sources on an individual (Marquis-Favre et al. 2005; Miedema, 1998). Most of this research examined the factors influencing noise annoyance.

Typically, researchers have examined two sets of factors for assessment of noise annoyance. These are Acoustical Factors and Non-acoustical Factors. Acoustical factors generally refers to the physical characteristics of sound such as type of noise, noise level, duration of exposure, frequency spectrum, time of the day when exposure occurs and previous experience with noise source. Non-acoustical factors generally relate to individuals' physiological, psychological and social experience that affect the perception of noise and impair activities (communication, concentration, sleep, recreation or rest) (Ouis, 2001). Assessment of the noise environment (i.e. annoyance) with such factors in isolation does not evaluate the aural environment holistically. Maarten (2010) observed that, the determinants of residential satisfaction with the noise environment include both objective attributes and subjective assessments, both personal and environmental characteristics, and social and physical elements. *Guski (1999b) concluded that approximately one third of the variation in noise annoyance can be explained by acoustical factors. The second-third of the noise annoyance can be explained by the non-acoustical factors. The last third can either be attributed to measurement errors, the presence of yet unknown factors which* *influence noise annoyance or stochastic variation related to idiosyncrasies of individuals.*

Research in the last three decades has demonstrated that the correlations between noise annoyance and acoustical measures (i.e. $L_{Aeq,} L_{1,} L_{90,} L_{DEN,} L_{DN}\ etc$) are weak and the best correlation achieved is a Spearman correlation coefficient of 0.35 (Marquis, 2005). When the correlation coefficient is transformed into variance accounted for, (r^2), the relationship between annoyance and noise level is even more diluted (approximately 0.12). It is noted that L_{Aeq} is the equivalent continuous sound pressure level which would contain the same sound energy as the time varying sound. L_1 is the sound pressure level exceeded for 1% of the time. It is nearly the loudest noise recorded during a particular measurement period, since it is the level exceeded only 1% of the time; L_{90} is the sound pressure level exceeded for 90% of the time. It is generally considered to be representing the background or ambient level of a noise environment. L_{DN} is the Day-night noise level which is the average equivalent sound level over a 24 hour period. ***Maarten (2008) concluded that there is no one-on-one relationship established between noise exposure and noise annoyance.***

A good number of research studies, however, have shown that there are significant relationships between noise annoyance and several psychoacoustical parameters such as loudness, sharpness, roughness and fluctuation strength even though each of these indices is not able to explain noise annoyance on its own (Berglund et al., 1981; Namba et al., 1996; Carter, 1996; Weber, 1996; Fastl, 1997; Hellman and Broner, 1999; Daniel and Weber, 1997; Genuit, 1999). *However,* ***Marquis et al. (2005) has noted that most of these studies were carried out in a laboratory environment****, and that, except in the case of loudness, no investigation using these indices has been applied to field studies or to data resulting from in situ surveys.*

A large number of research has been carried out to investigate the relationship between noise annoyance and non-acoustical factors. Taylor (1984) observed that much of this research is based on path analysis and lacks sound theoretical basis; as such it is unable to explain the process of noise annoyance adequately. *Maarten (2008) explained that in many empirical models the correlations between noise annoyance and non-acoustical factors were established in exploratory manners and were based on implicit theory rather than a theory of noise annoyance.*

From the discussion above, it is apparent that there is a need for a holistic approach, integrating the acoustical factors with the non-acoustical subjective factors, to assessing aural comfort comprehensively. It requires not only the understanding of noise annoyance but also entails a detailed investigation of many physical, acoustical and non-acoustical factors involved in the delivery of aural comfort in dwellings.

1.1.3 The Need for Aural comfort Study in the Tropics

Despite of the many research conducted on the assessment of the negative impact of noise, i.e. annoyance, in past 30 over years, very limited research effort has been made in the positive evaluation of aural comfort in the residential environment, especially in the presence of dense urban environment. Jian Kang (2003) noted that only in recent days acoustics in non-acoustics building spaces (i.e. shopping mall atrium spaces, library reading rooms, football stadia, swimming spaces, churches and dining spaces etc) is receiving increasing attention. He has carried out a number of empirical studies on aural comfort considering various building types/spaces including shopping mall atrium spaces, library reading rooms, football stadia, swimming spaces, churches, dining spaces, as well as urban open public spaces. However, aural comfort among high-rise dwellers, especially in the dense urban residential environment has not been investigated. The presence of the tropical climatic condition and the need for natural ventilation creates a complex noise environment in high-rise residential dwellings. *Assessment of aural comfort holistically in such an environment has been entirely missing in the literature.*

Singapore is a city-state located at the southern tip of the Malay Peninsula, 137 kilometres north of the equator, in South East Asia. Under the Köppen climate classification system, Singapore has a tropical rainforest climate with no distinctive seasons, uniform temperature and pressure, high humidity, and abundant rainfall. Temperatures range from 22°C to 34°C (Wikipedia, 2011). The indoor aural environment in this high-rise city-state is influenced by the high temperature and humidity (mean annual RH 84%). In a tropical country like Singapore, where a large proportion of the population (approximately 82%) live in densely built up high-rise public housing estates, adequate natural ventilation for living comfort becomes a key design criterion. Amidst today's energy-economic crises, natural ventilation becomes an energy-efficient alternative in reducing the operational costs of building. It provides thermal comfort and maintains a healthy indoor environment (Wong, Feriadi, Lim, Tham, Sekhar, and Cheong, 2002).

In such a tropical climatic environment such as Singapore, the windows at the building facades are left open for the provision of natural ventilation and thermal comfort. As a result, aural comfort is compromised with relatively high noise levels in the apartments concerned. Apart from the large systemic noise sources (road traffic and train) in close proximity to the residential buildings, noise annoyance to the high-rise dwellers is also compounded by localized community noise sources, such as food courts, children's playgrounds, waste disposal trucks etc and from internally transmitted neighbour noise between apartments (Lee, 2008). As a result, a complex acoustic environment prevails in the high-rise residential apartments in tropical Singapore. It is noted that acoustical performance in residential buildings in Singapore is presently not being regulated under current building regulations in Singapore. There is no official guideline for an acceptable indoor aural environment for different needs and environmental conditions, with the exception of industrial noise with respect to noise induced hearing loss and factory boundary noise. Based on the above research background, it is apparent that there is a need to investigate aural comfort among high-rise apartment dwellers in the tropics, to identify the key factors involved in the quantification of aural comfort and to establish an aural comfort model based on a sound theoretical basis.

1.2 RESEARCH SCOPE AND OBJECTIVE

This study aims to expand knowledge on aural comfort of high rise dwellers in the tropics. ***The key objective of this thesis is to develop an aural comfort model for naturally ventilated high-rise apartment dwellers in the tropics.***

The establishment of the aural comfort model will involve the following tasks:

- To establish a suitable framework, based on a sound theoretical basis, for the assessment of aural comfort among high-rise dwellers in the tropics;
- To investigate the relationships between quantitative acoustical parameters and their corresponding subjective perceptions.

1.3 ORGANIZATION OF THE THESIS

This thesis is organized into eight chapters as follows:

Chapter 1 presents the background of this research and the research objectives.

Chapter 2 presents the literature review related to this research. In this chapter, a discussion is made on the condition of the current urban noise environment, the different factors affecting the noise environment, the methods of assessing noise environment and the models for the evaluation of noise annoyance. The knowledge gap is outlined on the available methods and approaches with respect to assessment of aural comfort, in particular, the needs of high-rise tropical climatic condition are discussed.

Chapter 3 presents the findings of a preliminary research investigation through a noise survey carried out to examine the indoor noise environment in high-rise residential environment in tropical Singapore. The investigation identifies the factors influencing the perception of the indoor aural environment. Based on the preliminary research investigation, a research hypothesis is established inductively and presented in this chapter. In addition, this chapter presents the research design and methodology that have been used to perform the entire study on aural comfort.

Chapter 4 presents the objective assessment of aural comfort based on the proposed aural comfort evaluation framework, as presented in Chapter 3. The objective assessments include the measurement and prediction of noise exposure levels of facades subjected to road traffic and train noise as well as the assessment of sound transmission loss performances of facades, and party walls and floors between apartments. The findings from these objective studies are used together with the subjective factors influencing aural comfort (identified in subjective studies) to establish the proposed aural comfort model.

Chapter 5 presents a subjective assessment of aural comfort. In this chapter, overall aural comfort is assessed through a stratified noise survey. The statistical analysis of the survey data serves identifying the key factors that are significantly correlated with aural comfort. These findings are then used to develop the Aural Comfort Model (ACM) in this chapter.

Chapter 6 presents the laboratory psychoacoustic experiment. A parametric study is also carried out in this chapter to investigate the factors in the aural comfort model and their relationships with different subjective and psychoacoustical indices. Regression models are developed to establish their relationships.

Chapter 7 presents the validation of the developed aural comfort model using subjective comfort responses from the psychoacoustic experiment, as presented in Chapter 6. In addition, multidimensional evaluation of road traffic and train noise are carried out in this chapter.

Chapter 8 is a concluding chapter and presents the key contribution of this research to existing knowledge, the current research limitations and the recommendations for further studies.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The subject of this current research embraces four important considerations namely aural comfort, assessment of comfort, high-rise residential environment and the tropical climatic condition. In the following sections, a literature review is made on these aspects to address the current research problems and recent research carried out in this field.

2.2 URBAN NOISE ENVIRONMENT AND AURAL COMFORT

With the rapid technological advancement and urban growth to meet residents housing shortage, superior transport system and improved quality of life, the cities around the world are becoming busy, crowded and dense. The presence of noise, beyond an acceptable level, and quality, is a key concern among the city dwellers since it causes notable annoyance in daily lives (Morillas et al., 2005).

A public survey of the citizens in the European Union (EU) shows that the problem of noise in daily lives is often rated as the utmost concern together with issues such as global warming (CALM, 2007). The report (CALM, 2007) revealed that, for the European Union, approximately 80 million people are exposed to unacceptable noise levels and this noise exposure has led to sleep disturbance and other adverse health effects. The report also stated that an estimated 170 million people live in 'grey areas' where noise produces annoyance at a 'serious' level. This demonstrates the severity of noise problem in the EU.

The European Environmental Agency (EEA) reported in the year 2000 that approximately 24 million out of 380 million people, in the European Union cities were highly annoyed due their exposure to road traffic noise levels greater than 55 dB for 24h (L_{DN}) (EEA, 2000). In another report published in 2003, EEA reported that the estimates of noise annoyance incidents was accelerating and had reached up to 30% of the population (EEA, 2003). Given the rapid urbanization, noise annoyance might increase among urban population in both developed and developing countries. The analysis of the SILENCE project in the EU showed that, based on the survey of 4,124 citizens in the 17 EU countries, 66.6% of the entire sample size was substantially annoyed (moderately, very, or extremely annoyed) due to road traffic and train noise (SILENCE, 2008).

Niemann et al. (2006) reported that in the LARES study (Large Analysis and Review of European housing and health Status), conducted between 2002 and 2003 in eight European cities, neighbour noise is the second major source of noise (followed by road traffic noise) in the residential environment. The study showed that approximately 39% of the sample was disturbed by road traffic noise. This was followed by 36% of the respondents who were disturbed most by neighbour noise. Neimann et al. (2006) noted that neighbour noise is generally produced by the daily living activities of the residents and it is therefore related to speech, music or impact noise within the residence. Because of such characteristics and information content of the neighbour transmitted noise, attention is drawn much more easily and therefore the potential of becoming annoyed by these noises is higher even at a relatively low noise level.

Langdon et al. (1983) conducted a noise survey among 709 English residents in the UK who lived in multi-storey dwellings. The survey results revealed that approximately 70% of the entire sample population heard noise from their neighbours. The survey also revealed that about 30% of the respondents rated poor sound insulation as the topmost defect in the building, due to neighbour transmitted noise, among a number of other building defects such as poor finishes and damp problems. Floor impact noise was found more serious in comparison to airborne noise through party walls. According to Utley and Buller (1988), noise annoyance due to neighbour noise is the second major source of annoyance followed by the noise annoyance due to road traffic noise, which is the major source of noise in the UK.

In Asia, with the rapid economic growth and development, the density of living and traffic is growing in an accelerated rate in the major cities. Like European cities, road traffic noise in China has been the key source of noise affecting residents. According to a survey in 1995 (China EPA, 1995), in cities > 1,000,000 population, 71.4% of the kerbside noise level was above the A-weighted noise level of 70 dB. The data of a large-scale noise survey in Beijing (Li et al. 2002; Li & Tao 2004) revealed that an average A-weighted noise level of 76 dB has been recorded in the curb side of the main roads. The contribution of individual noise sources to the urban environment were road traffic (61.2%), community (21.9%), construction (10.1%) and industry (6.8%) (Kang et al., 2006).

More than a million of the Hong Kong population (about 7 million people) are affected by excessive noise exposure from road traffic. Due to its rapid development and vertical expansion to meet the housing shortage, the city-state has been developed in an unplanned way in earlier times. As a result, a number of major elevated roads can be found within a few meters of residential apartments, high-density residential buildings are located next to industry, construction sites have been located in residential developments for housing and infrastructure, and the airport is located in the middle of the city since before 1988. Besides the environmental noise, due to its high-rise living condition, residents are also exposed to different neighbour noise including pounding, ventilation systems, intruder alarm systems and other neighbour transmitted noise (EPD, Hong Kong). In addition, the presence of a warm and humid climatic condition makes the control of noise through window insulation undesirable as expensive air-conditioner needs to be used in this case (Wong, 2002). Hong Kong Planning Standards and Guidelines (PD, 1990) also described the acoustic insulation through windows as the "last resort" as it will practically deprive the resident of natural ventilation.

Singapore, a city-state island in the South East Asia, located one degree north of the equator, has a similar urban environment to Hong Kong. Singapore has tropical climatic weather and the majority (about 82%) of the population lives in the high-rise, naturally ventilated public housing. High-rise residential buildings are generally located at a curb distance between 5 meters and 25 meters of expressways and major arterial roads. Due to the close proximity of the residential buildings to the roads and elevated Mass Rapid Transport (MRT) track, residential apartments (naturally ventilated) are exposed to high noise level since outdoor noise is easily transmitted through the open windows. In addition, due to the high-rise living, neighbour noise has become a part and parcel of the living environment. The presence of tropical climatic condition, the need for natural ventilation in the residential building and the close proximity of the noise sources thus creates a complex aural environment in the high-rise apartments in Singapore. With the exception of the regulations on construction noise, there are no established acoustic performance criteria for residential building design. *As a result, the quality of the indoor aural environment in the residential dwellings in Singapore has been a challenging issue and has not received much attention to date.*

Extensive research has been conducted in the past 30 years on noise and its negative evaluation - annoyance. Most of this research has been involved with examining the relationships between noise annoyance and different acoustical and non-acoustical factors (Kang et al., 2011; Torija et al., 2011; Ryu et al., 2011; LI et al., 2010; Kang et al. 2010; Aslak, 2009; Jakovljevic et al., 2009; Lam et al. 2009, Kryter, 2009; Gerven et al., 2009; Kim et al., 2008; Maarten et al., 2008; David, et al., 2007; Moser and Robin, 2006; Morillas et al., 2005; Marquis-Favre, 2005; Klaeboe, 2004; Ali and Tamura, 2003; Botteldooren and Verkeyn, 2002; Ouis, 2001; Guski, 1999; Miedema, 1998, 1999; Guski, 1999; Staples, 1996; Khan and Sundback, 1996; Fields, 1993; Fidell, 1991; Claude, 1991; Job, 1988; Raw, 1985; Fields and Walker, 1982; Schultz, 1982; Kryter, 1982, 1983; Bradley, 1983; Langdon et al., 1981, Taylor et al., 1980; Alexandre, 1973, etc.). The purpose was to identify the key factors contributing to noise annoyance and disturbance.

Noise annoyance is defined as a feeling of displeasure or a negative attitude associated with exposure to an unwanted sound (Fields et al., 1987; Fidell et al., 1988). In contrary to noise annoyance, aural comfort can be regarded as a positive evaluation of a noise environment. As described in Chapter 1, borrowing the same concept of thermal comfort, 'Aural comfort' is defined as the psychological state of mind which articulates the satisfaction (or dissatisfaction) with the surrounding noise environment. *As a qualitative evaluation of the aural environment, aural comfort does not depend on the physical noise level alone. Rather it depends on the inter-relations between the factors that contribute to an individual's satisfaction in his/her surrounding aural environment. However, the terminology 'aural comfort' is rather a novel term and is not generally used for assessment of a noise environment.*

Recently, more and more scholars have shown interest in the indoor noise environment and comfort. Plenty of evidence shows that noise has an obvious impact on comfort and productivity (Chris et al, 1999; Dan and Richardson, 2002; Tang et al., 1998). Acoustics in non-acoustics building spaces is receiving increased attention. *Jian Kang (2006) noted that much attention has been given to acoustically designed spaces such as concert halls and recording studios, whereas research on non-acoustic buildings/spaces has been rather limited, especially from the viewpoint of aural comfort.* Recently a series of studies has been carried out on aural comfort in various spaces including shopping mall atrium spaces, library reading rooms, football stadia, swimming spaces, churches and dining spaces (Kang, 2006). However, most of these studies are limited to the different noise level indicators ($L_{Aeq}, L_{90}, L_{10}\ etc$)

and their correlations with subjective perceptions. *The studies were generally exploratory in nature and not founded on sound theoretical basis. Additionally, the meaning of comfort was not translated into psychoacoustical quantities and multi-dimensional perception perspectives which is present in 'soundscape' research.*

'Soundscape' is relatively a recent concept which accounts for meaningful acoustic environment, quantifies the sound and relates it to aural perception. The early investigations on soundscape research were more focused on noise, its mapping, related psychological effects and abatement procedures (Kang, 2001, 2007). The lesson learnt from recent soundscape research is, better aural comfort in urban areas may not be certainly achieved even with the reduction in noise level (De Ruiter, 2004). Soundscape research is different from conventional noise reduction in that it contemplates people's interactions with the sound (Kang et al. 2010). This means that soundscape does not only quantify the noise level, it also quantifies the qualitative aspects of the sound and establishes perceptual dimensions. *This is the missing link which is not connected to the assessment of aural environment of indoor residential environment. As a result, the evaluation of the indoor residential environment is limited to noise level assessment and its relation to several social, demographical and psychological factors in a disintegrated manner rather than in a holistic approach. In fact the assessment of aural comfort of high-rise apartment dwellers' in dense urban environment in the tropics has not yet taken place.*

With technological progression in many aspects of our living environment in recent years, quality of life matters become the prime concern. Aural comfort is a key aspiration of our living environment.

2.3 FACTORS AFFECTING EVALUATION OF THE NOISE ENVIRONMENT

Augoyard (1999) noted that people listen to sound inevitably and they perceive it based on their cognitive attitude towards it. The *physical signal* (noise) alone does not represent the perception quality; rather it depends on the *interaction* between sound and the listener resulting in a very complex process of evaluation of the noise environment. Raymond et al. (2008) observed that a host of physiological, psychological, cultural, behavioural and contextual factors shape a person's engagement, experience and enjoyment of environmental conditions in dwellings. This observation holds true for evaluation of the noise environment in a residential setting as well. Research on evaluation of noise environment (the negative evaluation - annoyance) has examined several acoustical and non-acoustical factors (Ouis, 2001). A review of this literature on noise annoyance and its relation to several acoustical and non-acoustical factors is presented below.

2.3.1 Acoustical Factors

Research on noise annoyance has shown that the correlations between global noise annoyance and acoustical factors are generally weak (Marquis et al. 2005). Generally the acoustical factors investigated are A-weighted equivalent sound pressure level (L_{Aeq}), statistical sound levels ($L_1, L_{10}, L_{50}, L_{90}$), Day-evening-night level (L_{DEN}), Day-night level (L_{DN}), Day level (L_D), Night level (L_N), Traffic noise index (TNI), Noise pollution level (L_{NP}) and Number Index (NNI) etc (Juhani, 2007; Marquis et al., 2005; Klaeboe et al. 2004; Ali and Tamura, 2003; Lawrence et al., 2002; Miedema et al., 2001; Miedema and Vos, 1998; Arana and Garcia, 1998; Fields, 1998; Fields, 1993; Fields, 1984; Kryter, 1982; Schultz, 1978; Griffiths and Langdon, 1968). *The maximum correlations achieved so far on an individual response basis is a spearman correlation of 0.35 (Marquis et al., 2005). Maarten et* *al. (2008) also noted that there is no one-one-one relationship between noise annoyance and acoustical factors*. The possible reason for such weak relationships may be the influence of other qualitative acoustical quantities (psychoacoustical parameters) and non-acoustical factors rather than the noise exposure quantities. *Guski (1999a-d) concluded that about one-third of the variation of the perceived noise annoyance can be explained by acoustical factors such as noise level, peak levels, noise spectrum and number of noise event. The second-third of the noise annoyance can possibly be explained by non-acoustical factors. Guski (1999a-d) noted that the last-third of the variation of the noise annoyance can either be attributed to measurement error, the presence of yet unknown factors which influence noise annoyance or stochastic variation related to the idiosyncrasies of individuals.* Berglund (1998), Job (1988) and Lercher (1998) confirmed this observation and noted that with the time average noise exposure level descriptors (L_{Aeq} and L_{DN}), noise annoyance can be explained between 20% and 30% at the most (though the relationships between acoustical factors and annoyance differ depending on the type of noise source, for example, peaks are often useful with aviation noise). However, among the acoustical factors investigated L_{Aeq}, L_{DNL}, L_{DN} and L_N have been found to have better correlations with noise annoyance (Miedema and Vos, 1998; Kryter, 1982; Schultz, 1978). The relationships between noise annoyance and several acoustical factors are shown in Figure 2-1 and Figure 2-2.

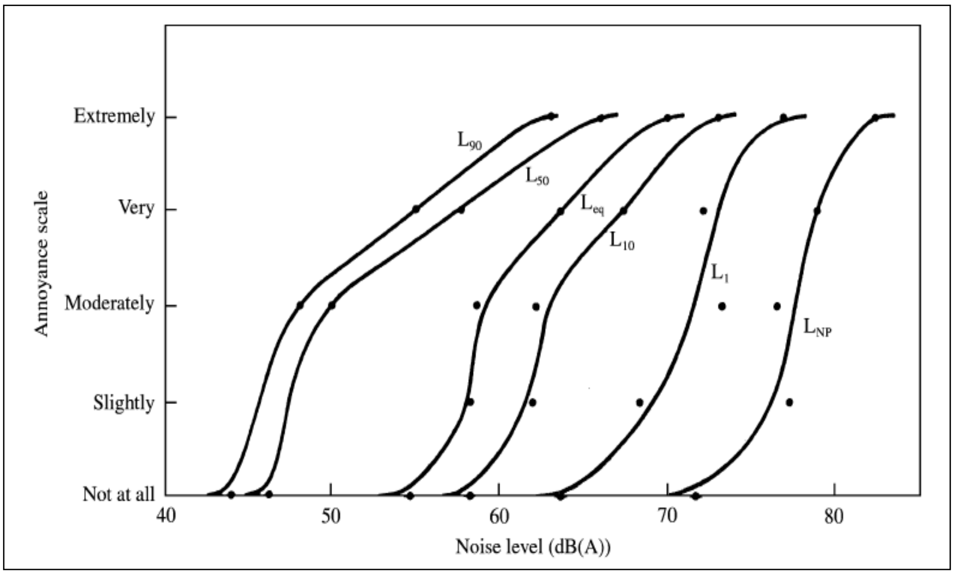


Figure 2-1: Annoyance as a function of noise level (Source: Crocker, 1997)

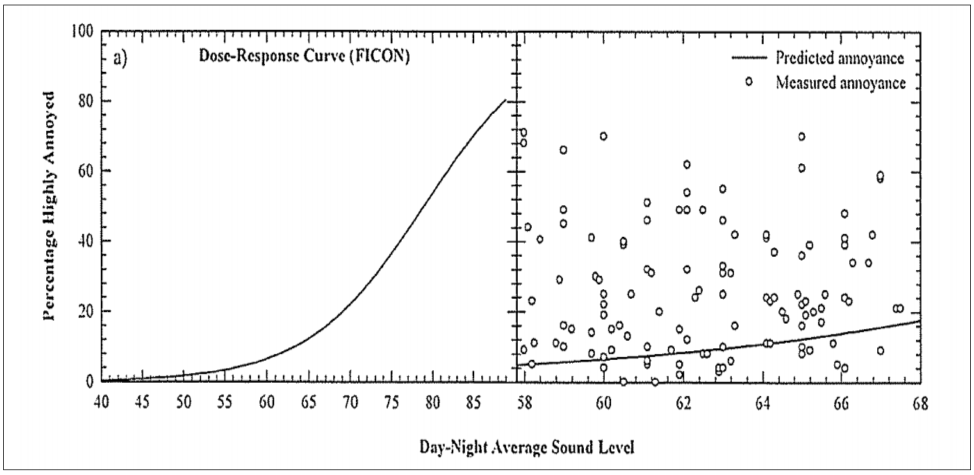


Figure 2-2: Percentage of exposed people highly annoyed of aircraft, road traffic and railway noise. (Fidell, 2003)

Lambert et al. (1984) observed that between the time period 8am and 8pm, no noise annoyance is perceived below 55 dBA (L_{Aeq}), whereas more sensitive people start to feel annoyed between 55 dBA and 60 dBA. Finally, definite noise disturbance is exhibited when noise level exceeds 65 dBA. Contrary to these findings, Fields (1993) noted that for a noise exposure level below 55 dB (L_{DNL}) there could be a correlation between noise annoyance and noise exposure level. However, other than these noise exposure parameters, the qualitative aspects of noise have an important role in the development of noise annoyance (Marquis et al. 2005).

Several studies have investigated the influence of the different types of noise sources on an annoyance rating known as the 'mode of transportation effect (Lambert et al., 1998). Lawrence et al. (2002) noted that since Schultz (1978) published his dose-response, controversy has continued over whether all types of transportation noise should be combined under "general transportation noise". In fact, many acousticians agree that aircraft noise is perceived as more annoying when compared to road traffic noise (Hall et al., 1981; Kryter, 1982) while road traffic noise was found more annoying when compared to railway noise (Guski, 1998; Herrmann et al., 1998; Fields and Walker, 1982; Schomer, 1998; Miedema and Vos, 1998). This is, however, found totally opposite in many research studies in Asian Context (Yano et al., 1996, Lim et al., 2006, Jiyoung et al., 2010). Yano et al (1996) explained that the factors influencing this judgement in Japan include differences in acoustical characteristics of road and train noise compared to European road and train noise, difference in attitude towards the noise sources, differences in housing factors such as windows insulation, difference in socio-cultural factors such as customs and lifestyles and difference in operation time of these noise sources.

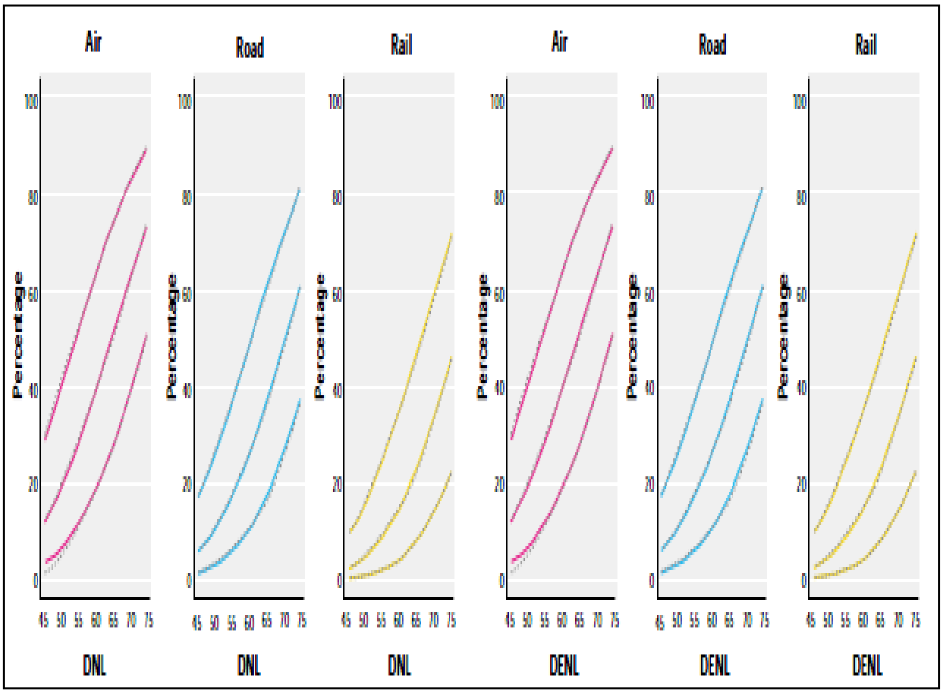


Figure 2-3: The estimated percentage of annoyed individuals as a function of DNL and DENL (annoyance curve: a little annoyed, annoyed and highly annoyed) (Source: Miedema et al., 2001)

As shown in Figure 2-3 Miedema et al. (2001) used different polynomial curves to describe different noise sources (aircraft, road traffic, and railway noise).

Table 2-1 : Summary of acoustical factors affecting noise annoyance

Acoustical Factors	**Relationship**	**References**
L_{Aeq}, L_1, L_{10}, L_{50}, L_{90}, L_{DEN}, L_D, L_N	No one-on-one relationship (max. spearman correlation 0.35) with noise annoyance	Maarten et al. (2008), Juhani (2007), Marquis (2005), Klaeboe (2004), Ali and Tamura (2003), Lawrence (2002), Miedema and Vos (2001, 1998), Arana and Garcia (1998), Fields (1998, 1993, 1984), Kryter (1982), Schultz (1978), Griffiths and Langdon (1968)
Mode of transportation (L_{DEN}, L_{DN})	Factors investigated for different modes of transportation effect on noise annoyance. No one-on-one relationship established.	Lambert (1998), Lawrence (2002), Schultz (1978), Miedema (2001)
Number of noise events	Once a certain number of events is reached, an increase in that number no	Bjorkman and Rylander (1996), Guski (1998)

Acoustical Factors	Relationship	References
	longer creates an annoyance increase. Number of noise event is not correlated with noise annoyance alone. Time of the day, *maximum sound level, rest time, duration of occasional events, spectral distribution of energy and number and duration of quiet periods etc* might also be involved.	
Ambient noise level	Annoyance is affected very little by the presence of another sound source qualified as ambient noise: a 20 dB increase would have approximately the same impact as a 1 dB drop in the studied annoying noise.	Fields (1998)

Marquis (2005) noted that other quantitative factors that have been used to evaluate noise annoyance include number of noise events, time of the day, maximum sound level, rest time, duration of occasional events, spectral distribution of energy and number and duration of quiet periods, etc (Fields et al. 1998, 1997; Vallet et al., 1996; Guski, 1998). A list of acoustical factors influencing noise annoyance (as discussed above) is tabulated in Table 2-1.

Table 2-1 *demonstrates that acoustical factors alone are not adequate to elucidate the evaluation of noise environment. Marquis (2005) commented that there is no "miracle" physical acoustical factor that could establish significant correlations between noise and annoyance. Apparently, in addition to the acoustical factors, other non-acoustical factors play an important role in noise annoyance evaluation (Jian Kang, 2006).*

2.3.2 Non-Acoustical Factors

Ouis (2001) illustrated that non-acoustical factors are generally person-related and they include physiological, psychological, and social factors that affect a person's perception of noise and impair activities (communication, concentration, sleep, recreation or rest). Numbers of researchers have concluded that the direction of the relationships between noise annoyance and non-acoustical factors remains unclear (Job, 1988). However, Miedema (2007) concluded that the influences of non-acoustical factors are of great importance for the evaluation of noise annoyance since several mechanisms explain the relationship with noise annoyance. According to Miedema (2007), noise annoyance is produced when the intruding sound/noise masks other sounds, makes intellectual activities complicated, agitates attention and concentration, leads to physiological stimulation, and generates “negative” or at least distressing affective/emotional reactions.

Fields (1993) concluded that demographic variables such as age, gender, socio-economic status, education, home ownership, type of dwelling, dependency of noise source etc. do not have a significant consequence on the evaluation of noise annoyance. Fields added that attitudinal variables such as fear of the noise source, feeling that noise annoyance is preventable and sensitivity to noise have considerable influence on noise annoyance. Finally, as noted by Nelson (1987), there are six aspects that researchers agreed influencing noise annoyance. The first aspect is related to the fear related to the noise source - i.e. people are more annoyed if they believe the noise source will affect them (Maarten, 2008; Job, 1988; Hellmann, 1996). The second aspect is dependency on the noise source - people who are dependent on the noise sources for their living are generally less annoyed (Miedema and Vos, 1999), people may be less annoyed if they are economically dependent on the activities generating the noise. The third aspect is sensitivity to noise - plenty of studies have shown that annoyance evaluation is significantly related to the noise sensitivity (Daniel, 2010; Dirk et al., 2010; Jakov et al., 2009; Van, 2004; Miedema and Vos,1999; Vallet, 1996 etc.). The type of activities affected by the intruding noise is the fourth aspect - intellectual tasks, rest time and communications are generally more affected by noise (David, 2007; Miedema, 2007; Hellmann, 1996; Schulte-

Fortkamp, 1996; Berglund, 1998). Perception of the neighbourhood is the fifth aspect - perception of the neighbourhood in a negative way increases the noise annoyance (Li et al., 2010; Lim et al., 2008; Langdon, 1976; Bertoni et al., 1993). The sixth aspect, as noted by Nelson (1987), is the global perception of the environment - the interaction between acoustics and other physical environmental factors that influence the perception of noise (Weber, 2001; Patsouras, 2002; Vallet et al., 1996; Sato, 1993; Yano et al., 1996 etc.). These factors are inter-related but the implication of the relationships between noise annoyance and these non-acoustical factors remains unclear (Maarten et al.,, 2008; Job, 1988; Alexandre, 1976; Fields and Walker, 1982).

Numerous studies have been made to evaluate noise annoyance with respect to several socio-demographic factors. Nelson (1987) concluded that generally no research has shown a strong and significant relationship between these factors and noise annoyance. *Fields (1993), Miedema and Vos (1999) also noted that, although results may differ, demographic factors do not have any crucial influence on the evaluation of noise annoyance.* A list of non-acoustical factors influencing noise annoyance is presented in Table 2-2.

From the above study (Table 2-2), it is apparent that the range of non-acoustical factors is wide and establishing their relationships with noise annoyance is a complex challenge. However, as Guski (1999) noted, only 30% of the variance of noise annoyance can be explained by non-acoustical factors alone. *As a result, it is important to consider both acoustical and non-acoustical factors for the evaluation of noise annoyance.*

There are several Psychoacoustical factors that are generally used for evaluation of sound quality of specific noise sources. There has been very limited application of *these factors to the evaluation of global noise annoyance in a residential context. The following section discusses these factors in relation to noise annoyance.*

Table 2-2 : Summary of non-acoustical factors affecting noise annoyance

Non-Acoustical Factors	Relationship	References
Age, Gender, Socio-economic status, Culture, Education, Home ownership, Dwelling size, Type of dwelling, Family size, Dependency of noise source, Length of residence etc	These factors do not have any significant effect on the evaluation of noise annoyance.	Fields (1993), Nelson (1987), Miedema and Vos (1999), Job (1988), Fields and Walker (1982), Bertoni (1993), Vallet (1996), Tonin (1996), Maurine and Lambert (1990)
Sensitivity to noise	Sensitivity to noise has significant influence on noise annoyance	Fields (1993), Daniel (2010), Dirk (2010), Jakovljevic (2009), Van (2004), Miedema and Vos (1999), Vallet (1996).
Perceived disturbance	Perceived disturbance and control influence level of noise annoyance	Stallen (1999)
Adaptive behaviours or habits	A couple of studies found significant influence of adaptive behaviours on noise annoyance.	Bertoni (1993), Lercher (1998)

2.3.3 Psychoacoustical Factors

The evaluation of the '*quality*' of a noise environment (for example '*aural comfort*') addresses three sets of factors: Acoustical Factors (related to physical sound evaluation), Non-acoustical Factors (psychological factors related to auditory evaluation) and Psychoacoustical Factors (related to auditory perceptions) (Genuit, 1996). Genuit commented that although "noise" is defined in (DIN 1320) as the sound occurring within the human hearing frequency range which disturbs silence or an intended sound perception and results in annoyance or endangers health - *no such definition can be given to the term 'acoustic quality'*. Genuit (1996) also commented that the acoustical quality of a sound environment is generally negative when the aural environment generates an auditory event as annoying while a positive acoustical quality means that the aural environment is not perceived as auditory event or not annoying and generates a pleasant aural impression.

Marquis et al. (2005) revealed that the psychoacoustical factors that have been investigated widely include Loudness, Sharpness, Roughness and Fluctuation Strength. A brief description of these factors is summarized below, based on the distinguished book 'Psychoacoustics: Facts and Models' by Fastl and Zwicker (2006).

Psychoacoustical analysis is not very common in research on noise annoyance or aural comfort in relation to environmental noise in residential perspective. Psychophysics can contribute substantially to the assessment of noise (Fastl and Zwicker (2006), Berglund (1975, 1976, 1981, 1991, 2006), Widmann (1996), Hellman and Broner (1999), Carter (1996), Weber (1996), Daniel and Weber (1997), Genuit (1999), Broner (1998). Marquis et al. (2005), Dittrich (2009), Kryter (2007), Botteldooren (2006), Bisping. (1997), Daniel (1997), Ellermeier (2004), Fastl (2006, 1997, 1989)).

With the advancement of signal analysis and hardware equipment, various technologies are available in the market for the measurement and evaluation of psychoacoustics magnitudes of a noise. The common method of psychoacoustic evaluation of noise is recording of a binaural sound either through an artificial manikin or through a binaural headset on a subject and post processing of the noise signal. However, jury testing is an essential part of the psychoacoustical evaluation of noise. Several methods are used for the subjective assessment which are presented in section 2.4 of this chapter.

However, since the perception of sounds is dependent on cognitive and emotional factors as well, additional measurements are needed to get the whole picture of sound quality

Loudness:

Human sensation perception that corresponds most closely to the sound intensity of the stimulus is loudness. The loudness of a sound is a perceptual measure of the effect of the energy content of sound on the ear. 'Sone' is the unit of loudness. The level of 40 dB of a 1 kHz sine tone is defined as a loudness of 1 sone. A tone which is perceived as having doubling the loudness (in sone) indicates that the level of the 1 kHz tone in a plane field has to increase by 10 dB. Using the reference point the loudness of a 40 dB 1kHz tone, corresponding to a loudness of 1 sone, the loudness function is calculated and shown in Figure 2-4.

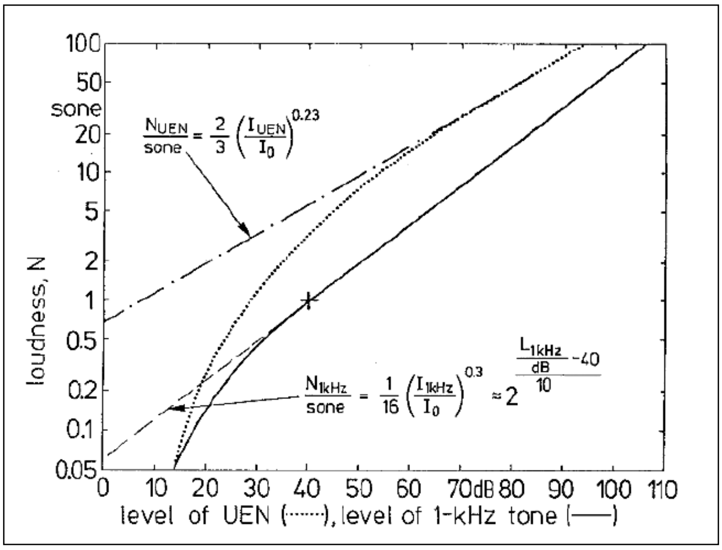


Figure 2-4: Loudness function of a 1-kHz tone (solid line) and uniform-exciting noise (dotted); loudness is given as a function of the sound pressure level. Approximations using power laws are indicated as broken and dashed-dotted lines together with their corresponding equations. (Source: Fastl and Zwicker, 2006)

'***Critical Band-Width***' plays an important role in the computation of more complex sound. It is a measure of the frequency resolution of the ear. The underlying assumption is that the part of a noise that is effective in masking a test tone is the part of its spectrum lying near the tone. Two tones of equal level with a frequency spectrum greater than the critical bandwidth produce a loudness which is larger than the loudness of a single tone with a frequency midway between that of the two tones, and with a level corresponding to the total intensity of the two tones. As a result, loudness is not produced from separate spectral components, but rather the two components influence each other, especially if their frequency separation is small. Only for quite large frequency separation, where the two single tones do not influence each other, does loudness value occur which corresponds to the addition of the loudnesses of each tone. Therefore, the loudness summation becomes a complicated process for complex sound. So, while it is more usual in acoustics to see the "loudness" of a signal expressed in dB(A), a better measure of the perceived loudness can be found by proper application of the critical bandwidths

The ***'Specific Loudness'*** exhibits the distribution of loudness across the critical bands. A specific loudness is calculated from the dB level for each third octave band using the assumption that a relative change in loudness is proportional to a relative change in intensity (Fastl and Zwicker, 2006). Its unit is “sone/bark”. The total loudness N is the result of the specific loudnesses N' through integration of the critical band rate (refer to Figure 2-5) and is shown in Eq. 2-1.

$$N = \int_0^{24\,Bark} N'dz \qquad \text{.....................................} \quad \text{[Eq. 2-1]}$$

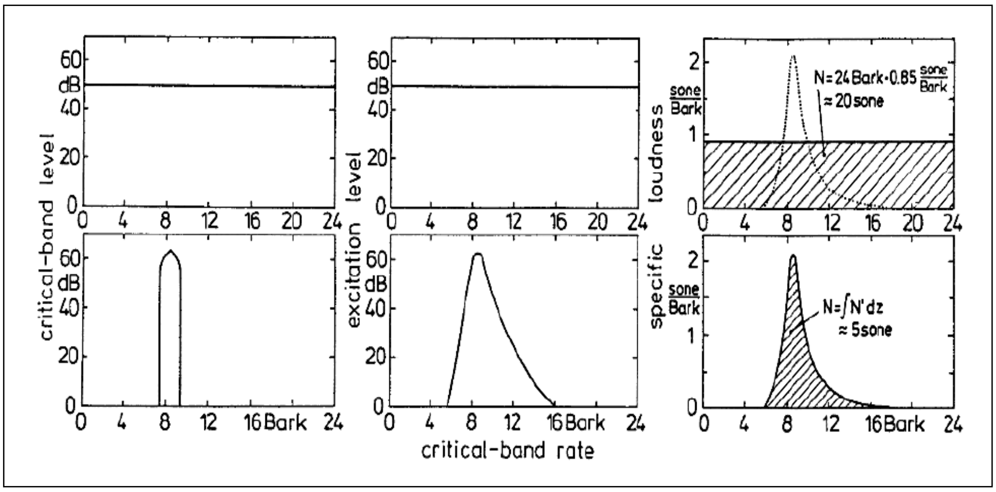


Figure 2-5: Schematic illustration of Zwicker Loudness model (Source: Fastl and Zwicker, 2006)

The procedure to evaluate loudness using Zwicker's method is shown in Figure 2-5. The left diagram shows a narrow band centred at 1000 Hz (corresponds to 8.5 bark). The central diagram in Figure 2-5 presents the narrow band of noise at 1000 Hz, including masking effects caused by spectral broadening in the cochlea due to inner ear mechanics. The rightmost diagram shows the specific loudness/critical band rate pattern (sone/bark), known as the ***Zwicker diagram***. The transition from the masking pattern, shown in the middle diagram, to the loudness pattern, shown in the rightmost diagram, can be considered to be obtained by taking the square root of the sound pressure or the fourth root of the sound intensity. The shaded area in the rightmost diagram in Figure 2-5 is directly proportional to the perceived loudness. There are several methods or algorithms for determining loudness. The Zwicker loudness method has been shown to have the highest correlation with human perceived loudness. Zwicker loudness can be used for both stationary and non-stationary sources. The computation procedure for Zwicker loudness for a stationary source has been standardized and illustrated in both ISO 532B and DIN 45631 standards.

Sharpness

Sharpness is a measure of the high frequency content of a sound. If one sound signal has more high-frequency content than another, it is said to have more *sharpness* than the other. Sharpness has been used to partially quantify sound quality. It is employed in the computation of a sensory pleasantness metric and an unbiased annoyance metric (refer to the next Section 2.4 for further illustration).

Unit of sharpness is 'acum'. As shown in Figure 2-6, one acum is defined as a narrow band noise one critical band wide at a centre frequency of 1kHz (8.5 Bark) having a level of 60 dB. The formula for computation of sharpness according to Fastl and Zwicker (2006) is shown in Eq. 2-2.

$$S = 0.11 \frac{\int_0^{24\,Bark} N' g(z) z dz}{\int_0^{24\,Bark} N' dz} \quad \text{......................................} \text{[Eq. 2-2]}$$

In the above equation, the numerator is similar to the first moment of specific loudness over critical-band rate, but uses an additional factor, $g(z)$, that is critical-band-rate dependent while the denominator is the total loudness. To account for the increased sharpness of high-frequency sounds, the weighting function $g(z)$ is used. From Figure 2-7 it is obvious that when a low frequency noise is added to a high-pass noise, the centre of gravity shifts downwards. As a result, a smaller sharpness value is generated compared to dotted and dashed arrows. This implies that sharpness can be reduced by addition of low frequency components which is useful for sound quality control.

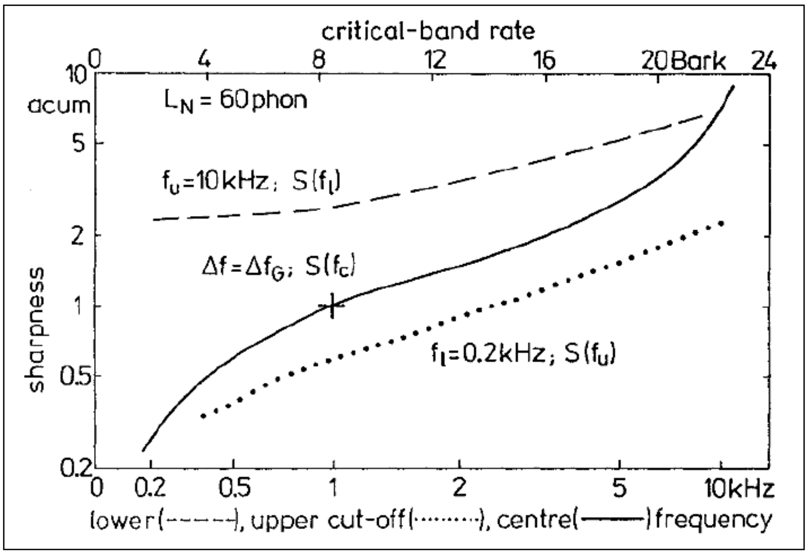


Figure 2-6: Sharpness of narrow-band noise (solid), high pass noise (dashed), and low-pass noise (dotted) (Source: Fastl and Zwicker, 2006)

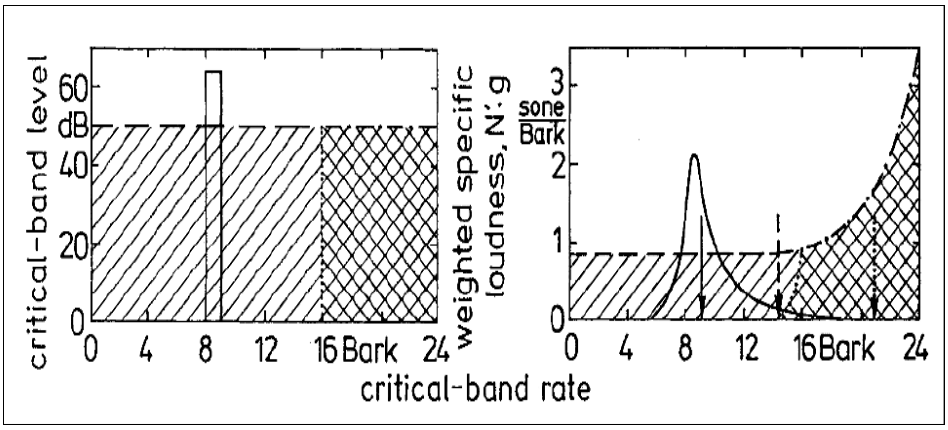


Figure 2-7: Model of sharpness for narrow-band noise (solid), broadband noise (dashed), and high-pass noise (cross hatched) (Source: Fastl and Zwicker, 2006)

Fluctuation Strength

Another key psychoacoustic metric is fluctuation strength. A sound which has a strong time-dependent fluctuation in sound pressure level is more annoying than a steady sound (Fastl and Zwicker, 2006). The unit of fluctuation strength is 'vacil'. One vacil is defined as the fluctuation strength generated by a 1000Hz tone of 60dB which is 100% amplitude modulated at 4Hz. According to Fastl and Zwicker (2006), the fluctuation strength (F) is defined as:

$$F \sim \frac{\Delta L}{\left(\frac{f_{mod}}{4Hz}\right) + \left(\frac{4Hz}{f_{mod}}\right)} \quad \text{.. [Eq. 2-3]}$$

Where, ΔL is the masking depth and f_{mod} is the modulation frequency.

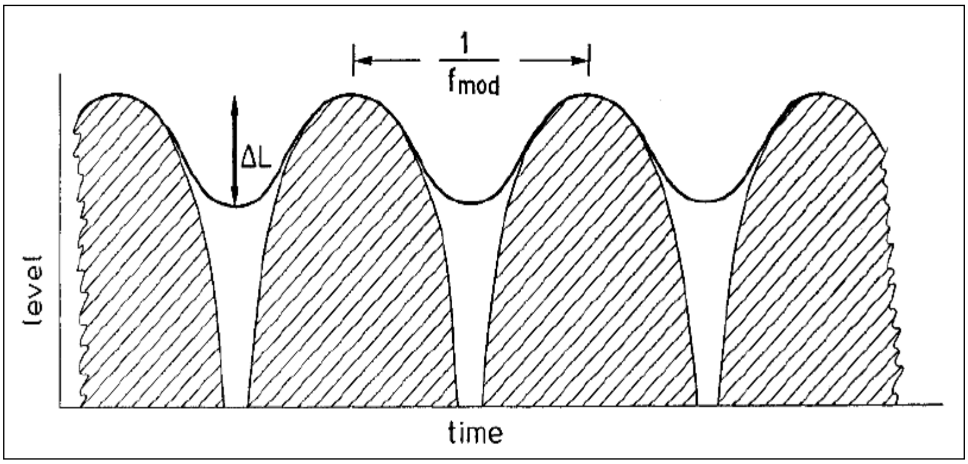


Figure 2-8: Model of fluctuation strength: temporal masking pattern of sinusoidal amplitude-modulated masker leading to temporal masking depth ΔL (Source: Fastl and Zwicker, 2006)

Fluctuation strength is used for developing an unbiased annoyance metric (refer to section 2.4). Fluctuation strength is similar to roughness except it quantifies the subjective perception of slower (up to 15Hz) amplitude modulation of a sound. The sensation of fluctuation strength continues up to 15Hz and then the sensation of roughness takes over (Fastl and Zwicker, 2006).

Roughness

Roughness is another important psychoacoustic quantity that quantifies the subjective perception of rapid (15-300 Hz) amplitude modulation of a sound. 'Asper' is the unit of roughness. One asper is defined as the roughness produced by a 1kHz tone of 60dB which is 100% amplitude modulated at 70Hz (Fastl and Zwicker, 2006). Roughness is used for the development of an unbiased annoyance metric (refer to section 2.4). Roughness depends on modulation depth and the sound pressure level. An approximate relationship for roughness is given in Eq. 2-4.

$$R \sim \Delta f_{mod} \quad \text{[Eq. 2-4]}$$

Tonality

Tonality is another psychoacoustic aspect which examines the tonal prominence of a sound. Tonality is a measures for audibility, amenity and pleasantness. Tone-to-Noise Ratio (TNR Method, ANSI S1.13) and Prominence Ratio (PR Method, ANSI S1.13) are two different measures of Tonality. The tone-to-noise (TNR) ratio 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 that 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 ration (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.

Table 2-3 : Summary of psychoacoustical factors affecting noise annoyance

Psychoacoustical Factors	Relationship	References
Loudness, Sharpness, Roughness, Fluctuation Strength, Impulsiveness	A number of studies underline the relation between annoyance and the significant values given by psychoacoustic indices.	Fastl and Zwicker (2006), Berglund (1975, 1976, 1981), Widmann (1996), Hellman and Broner (1999), Carter (1996), Weber (1996), Daniel and Weber (1997), Genuit (1999), Broner (1998). Marquis et al. (2005)

Marquis (2005) noted that one has to underline the fact that most of the research (refer to Table 2-3) related to these psychoacoustical factors has been carried out in laboratories, i.e. in a controlled environment, and that except in the case of loudness, no investigation using these indices has been applied to field studies or to data resulting from in situ surveys.

Each of the mentioned psychoacoustic indices, on its own, is not sufficient to predict the annoyance felt, but the relevance of one or of many indices depends on the type of noise, and for the same noise, on its level. Psychoacoustical metrics are unable to consider the non-sensory aspects used in the evaluation of a noise environment (Ellermeier et al., 2004; Jekosch, 1999), though some researchers argue that psychoacoustical metrics can covary with non-sensory aspects such as noise sensitivity and its relationship with fluctuation strength, roughness and annoyance (Stansfeld et al, 2006). However, consideration of the attitude towards the noise environment together with the quantitative acoustical and psychoacoustical parameters are important for a complete evaluation of noise environment.

2.4 METHODOLOGIES FOR EVALUATION OF NOISE

There are basically two different approaches to the evaluation of a noise environment or noise annoyance. They are the ***Unidimensional Psychophysical Analysis*** and

Multi-dimensional Psychophysical Analysis evaluation methods. The Unidimensional method establishes relationships between each acoustic factor and perception dimensions. On the other hand the multi-dimensional method is concerned with various perception dimensions of the noise under investigation. *A brief summary of these methods is illustrated in the following sections based on the literature of Marquis et al. (2005) and Kang et al. (2006).*

2.4.1 Uni-dimensional Psychophysical Analysis

According to Marquis et al. (2005), most of the unidimensional psychophysical analysis methods are derived from analyses and procedures established in general psychophysics (Stevens, 1951; Torgerson, 1958; Luce and Galanter, 1963; Coombs et al., 1970; Falmagne, 1985; Bonnet, 1986). Depending on the measurement methods, there are three classes of Unidimensional psychophysical scale. These are ***Category Scale***, ***Discrimination Scale*** and ***Ratio scales***. These are discussed in short in the following:

Category Scales: This is a classical method of psychophysics in which scaling is universally recognized by scientists for carrying out reliable surveys. This is a relatively quick and reliable approach (Fields, 1996). Verbal or numerical scales are used for the representation of different categories. Fields (1984) concluded that multipoint scales are more dependable when compared to dichotomous measures for evaluation of noise annoyance. Yano et al (1996) demonstrated that the formulation of descriptors ('not at all annoyed', 'a little annoyed'...) are more important compared to the numbers assigned to the descriptor in the category scale. Comparable results were found with category scale having 4, 5, 6 and 7 points. Several studies (Cf. Kuwano and Namba, 1978; Kuwano et al., 1988; Fastl, 1989) have demonstrated that the use of an analog scale, a line with the ends clearly defined, is appropriate to collect continuous judgments for unsteady sounds (noise, speech, music, etc.).

Discrimination Scales: The discrimination scale is based on a paired comparison method (Thurstone, 1927b; Baird and Noma, 1978; David, 1988). Two stimuli are compared in pairs in different perception scales in this method. This method generally produces robust results for untrained subjects compared to the category method, given that there is possibility of confusion generated between scales in the category method (Khan et al., 1996).

Ratio Scales: The ratio estimation method includes the *magnitude estimation method* and the *ratio production method*. In the magnitude estimation method, subjects are required to rate a real positive number relative to a reference stimulus such as pink or white noise (Yamada, 1985; Bisping, 1997; Fields, 1996). This method has been used to calibrate different community noises or a combination of several community noises so as to develop a common unit of subjective assessment measurement for comparison of the different noises (Berglund et al., 1975, 1976, 1981). When no reference is used, the method is known as the absolute magnitude estimation method (Cf. Canévet, 1996; Zeitler and Hellbrück, 1999). In the ratio production method a subject adjusts the stimulus (based on his own perception) such that its value is a ratio or a whole part of the reference stimulus.

A combination of different methods has also been used for evaluation of noise annoyance. The ***Category Partitioning*** scale method is another kind of unidimensional psychophysical scaling method that is a combination of category scales and magnitude estimation methods (Guski, 1997). In this method, there are five verbal categories each of which has ten levels. Subjects are required to give a global evaluation first by choosing a verbal category followed by a more precise rating - that is choosing one of 10 points in that particular category. Guski (1997) underlines that the method is imprecise on its metric properties.

2.4.2 Multidimensional Psychophysical Analysis

The Semantic Differential Method: The semantic differential method, proposed by Osgood et al. (1957), is a widely used multidimensional evaluation method (Kuwano and Namba, 1990; Zeitler and Hellbrück, 2001; Viollon et al., 2000; Lopez et al., 2003; Kang, 2006). In this method, a seven point scale is used where subjects are required to rate two opposing terms on a scale in the same dimension. When evaluating stimuli, subjects describe their perceptions in the form of imagination, metaphors and comparisons so that a list of representative adjectives can be established that describes the perception dimensions of the stimuli (Schulte-Fortkamp, 1999).

Multidimensional Analysis: In this method estimation is made on the similarities of pairs of sounds to describe the auditory space of the stimulus (Axelsson et al. 2003, Susini et al. 2001). The dimensions of the space are obtained using a statistical procedure known as multidimensional scaling techniques (Kruskal and Wish, 1978).

2.5 MODELS FOR EVALUATION OF NOISE ANNOYANCE

There are basically three categories of models (specifically used for outdoor road traffic noise, train noise and aircraft noise) - ***Quantitative Models, Qualitative Models and Psychoacoustics Models***. The *quantitative* models, in general, mathematically relate the overall noise annoyance to noise exposure, corresponding annoyance and loudness of each individual noise source. On the other hand, the *qualitative* models account for the cognitive and perceptual mechanism relating to different noise sources and combine them for an overall annoyance rating. The psychoacoustical models relate the noise perception with different psychoacoustical parameters. A brief summary of these model is found below.

2.5.1 Quantitative Models:

As summarized by Marquis et al. (2005), in the ***Energy Summation Model,*** global noise annoyance is related to the noise levels resulting from the energy summation. In the ***Independent Effect Model,*** annoyance is presented as a linear combination of the functions representing the equivalent noise level of each source. The ***Energy Difference Model*** presents the overall noise annoyance as the summation of the functions representing the total equivalent noise level and of the difference between the equivalent noise levels of individual sources. In the ***Model of Response Summation,*** a correction factor is added to the equivalent total level (Ollerhead, 1978) to account for the differences in the equivalent noise levels of individual noise sources. In ***Dominant Source Model,*** noise annoyance is expressed as the annoyance of the most annoying noise source. In the ***Summation and Inhibition Model*** (Powell, 1979), the total annoyance is evaluated according to the total equivalent noise level with a correction factor. The ***Quantitative Model*** (Vos, 1992) is in principal very similar to the subjectively corrected models, except that the correction factor depends on the equivalent noise level of each individual noise source.

2.5.2 Qualitative Models:

As summarized by Marquis et al. (2005), ***Subjectively Corrected Models*** use correction factors to approximate the difference in noise perception due to individual noise sources. In the ***Vector Summation Model,*** the total annoyance is expressed as the square root of the sum of squares of perceptual variables of an individual noise source (Berglund et al., 1981). In the ***Structural Equation Model*** (also known as Path Model), overall noise annoyance is correlated with different non-acoustical factors through simultaneous multiple regression or path analysis.

2.5.3 Psychoacoustical Models:

Sensory Pleasantness Model: This model was developed by Zwicker (please refer to Fastl and Zwicker, 2006) to estimate the pleasantness of a noise by relating perception dimension with relative values of Sharpness (S), Roughness (R), Loudness (N) and Tonality (T). The relative sensory pleasantness, according to Zwicker was defined as:

$$\frac{P}{P_0} = e^{\frac{-0.7R}{R_0}} \; e^{\frac{-10.8S}{S_0}} \left(1.24 - e^{\frac{-2.43T}{T_0}}\right) e^{-\left(0.023\frac{N}{N_0}\right)2} \text{ .... [Eq. 2-5]}$$

Experimental results relating relative pleasantness with relative sharpness, relative roughness, relative loudness and relative tonality are presented in Figure 2-9. As described by Fastl and Zwicker (2006), sensory pleasantness depends mostly on sharpness, a little on roughness and tonality and on loudness having a value above the normal loudness of communication between two people in quiet.

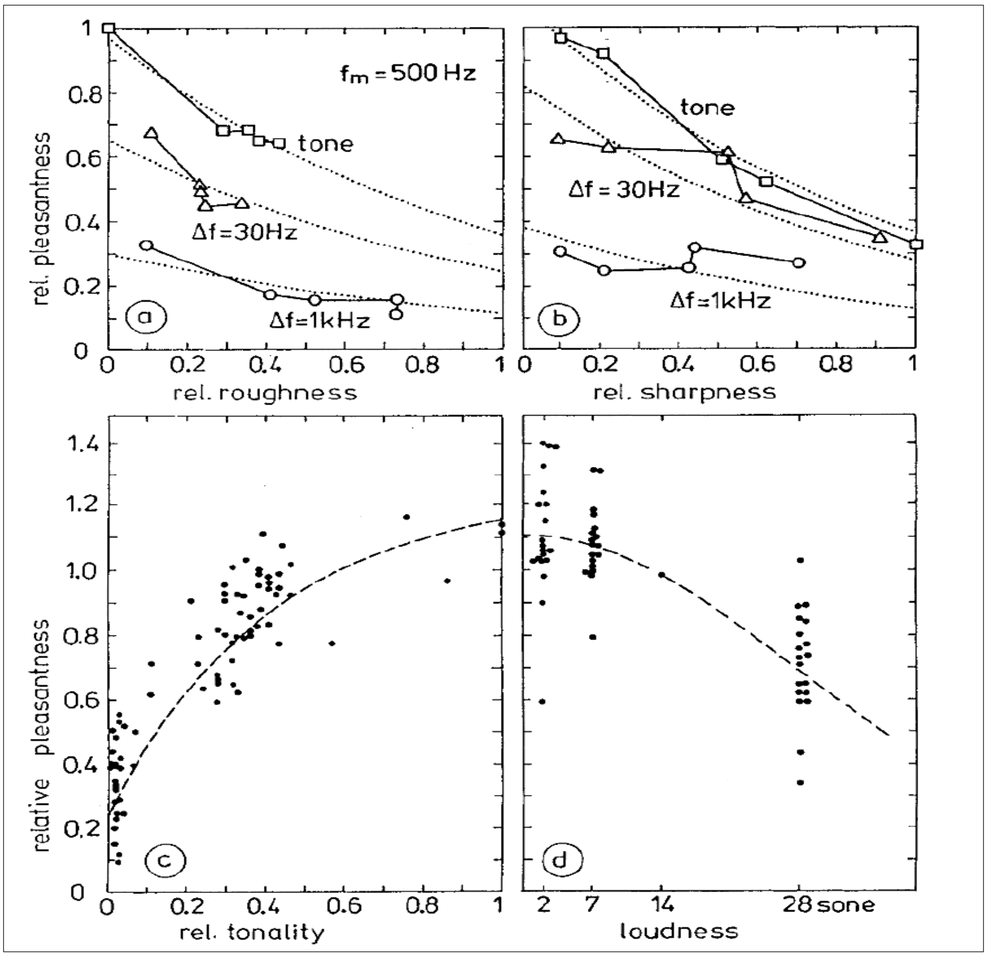


Figure 2-9: Relative pleasantness as a function of relative roughness, sharpness, tonality and loudness (Source: Fastl and Zwicker, 2006)

Perceived Annoyance Model:

A psychoacoustics annoyance model was developed by Zwicker (Fastl and Zwicker, 2006) which relates Psychoacoustic Annoyance with five percentile Loudness (N_5), Sharpness (S), Fluctuation Strength (F) and the Roughness (R) of the sound as shown below:

$$PA = N_5\left(1+\sqrt{w_S^2+w_{FR}^2}\right) \text{ .... [Eq. 2-6]}$$

Where, $w_S = \left(\frac{S}{acum}-1.75\right).0.25lg\left(\frac{N_5}{sone}+10\right)\ for\ S > 1.75\ acum$ ....

[Eq. 2-7]

and $w_{FR} = \frac{2.18}{(N_{5/sone})^{0.4}}\left(0.4\frac{F}{vacil}+0.6\frac{R}{asper}\right)$ .... [Eq. 2-8]

Eq. 2-6 is used for evaluating psychoacoustic annoyance of synthetic sound as well as sounds like car noise, air conditioner noise, noise from circular saws, drills, etc (Fastl and Zwicker, 2006). This model is not widely used, but several examples explain the annoyance behaviour of different transportation noise (Fastl and Zwicker, 2006; More and Davies, 2007).

2.6 LIMITATIONS OF THE NOISE ANNOYANCE EVALUATION METHODS

From the literature study it is understood that simple energy summation generates poor prediction of noise annoyance while independent effect models and energy difference models provide a better prediction of noise annoyance. Ronnebaum (1996) concluded that the dominant source model provides the best prediction of noise annoyance. However, Izumi (1988) observed that there is no significant difference among these models in predicting overall noise annoyance due to multiple noise sources. The annoyance equivalent model Miedema (2004) has developed (on the basis of energy summation) has resulted in the revision of ISO-1996 which is meant for the measurement and assessment of environmental noise. However, Jin (2010) noted that it remains unclear about the model's accuracy in predicting global noise annoyance due to multiple noise sources and the suitability of the models for evaluation of indoor noise environment of residential premises. Maarten (2008) pointed that qualitative research that involves non-acoustical factors is highly inductive and lacks a sound theoretical foundation. Additionally, correlations between noise annoyance and non-acoustical factors might lead to misapprehension as the effect of the factor under consideration is not controlled (Alexandre, 1976).

From the literature review, it was also observed that *the inclusion of neighbour noise is missing in the development of overall noise annoyance models.* Rather, noise annoyance due to neighbour noise has been investigated in isolation by many authors emphasizing the relationship between noise levels, level of disturbance, audibility, etc, to establish sound isolation requirements (Langdon et al., 1981, 1983; Bodlund, 1985; Rindel et al., 1997, 1999; Jeon et al., 2006*). Jin (2010) found that the neighbour noise annoyance evaluation was not included it in the computation of overall indoor noise annoyance in a residential environment. Rather it was used for the evaluation of individual sound or building elements.*

Maarten et al. (2008) developed a noise annoyance evaluation model which is based on a conceptualization of noise annoyance by Stallen (1999). Stallen's conceptualization model is rooted in the psychological stress theory of Lazarus (1966) which underlines that noise annoyance is a kind of psychological stress which is determined by the extent to which a person perceives a threat (i.e., perceived disturbance) and the possibilities or resources that a person has with which to face this threat (i.e., perceived control). *According to Maarten (2008), Stallen's (1999) conceptual model is, as of yet, the only theory that gives an explanation for noise annoyance.*

With regards to Psychoacoustical models, *Marquis et al. (2005) has pointed out that psychoacoustical indices have been investigated in laboratory conditions and no research has been made on the psychoacoustical quantities (except loudness) in the field condition or the use of data resulting from field survey*.

From the literature review, it is observed that the study of noise annoyance is limited to relating annoyance with specific acoustical and non-acoustical factors involved in the annoyance process, in isolation. *Marquis (2005) noted that one often speaks about annoyance (the negative perception of noise) and less about the positive perception of noise as a comfort.* ***She added that certain authors however insist upon the need to learn to listen again, especially to repossess the soundscape and to work more on the prevention and the quality of the environment*****.** Marquis (2005) emphasized that the evaluation of the indoor aural environment in residential dwellings due to multiple noise source exposure is relatively unstudied and further investigation is required. *In the multidimensional context of a complex environment, the importance of other sensory aspects which could figure in a more general methodology must be emphasised.*

2.7 HIGH RISE LIVING, TROPICAL CLIMATE AND AURAL COMFORT

While researchers, engineers, planners, architects and politicians have been engaged in the debate of sustainable development, green environment and urban compactness, there has been huge interest in initiating high-rise living in the cities (Belinda, 2006). According to city planners, developers and mayors, who took part in the MIPIM 2011 conference, the world's big cities are already bursting at the seams but are set to grow even larger. In 1900, around 14% of the world's population lived in cities, by 1950 this had risen to 30% percent and today is about 50%. Currently, there are more than 400 cities with a population over a million, 19 of which have over 10 million inhabitants. Experts are predicting that about 70% of the world's population will be urban by 2050 (Yahoo News, March 11, 2011). Therefore, the unfolding trend is towards taller buildings as an inevitable housing solution. As part of their urban planning to meet housing demand, many European cities including London and Manchester are building high-rise residential buildings. High-rise housing (generally public housing) is often infused with alternative images in many Western cities (Church and Gale, 2000; Costello, 2005). As Helleman and Wassenberg (2004) put it – ‘High-rise estates are associated with problematic living conditions, deprived areas, isolated locations, a poor population, a negative image, social isolation, pollution and crime . . . In short, they are not the most popular areas in town’. However, this is not the end of High-rise housing. In Asia, Hong Kong and Singapore are distinguished by their high-rise public housing developments. Singapore and Hong Kong have similarly experimented the urban-style living in high-rise housing to meet housing shortage due to the land scarcity and increased population growth. A high level of residential satisfaction has been achieved for living in high-rise buildings in both countries. The demands of limited land space, a growing population and the need for improved housing conditions have launched these cities into experiencing and celebrating vertical development (Belinda, 2006). Over a period of 40–50 years, high-rise public housing has become, not just the lifestyle of the majority of the population, but also the dominant building form in these cities.

The tropical climatic condition in the high-rise urban residential environment demands energy-efficient provision of thermal comfort which poses a challenge in the delivery of aural comfort among the high rise dwellers. With the windows left open for natural ventilation, dwellers in the high-rise environment are exposed to relatively high outdoor noise levels in the apartments and aural comfort is compromised. In the temperate countries, for most part of the year, windows and doors are kept closed and well sealed to prevent heat loss. In the tropical context, where apartments' openings in close proximity are opened for natural ventilation, airborne flanking paths between residential units can significantly compromise sound insulation between apartments. Owing to the tropical climatic conditions and the high density living in Singapore, and most major tropical cities, achieving high aural comfort and acoustical privacy may be more expensive compared to the temperate zone. Therefore, it is important to investigate the factors related to aural comfort among the high-rise dwellers in the context of tropical environment which might be different from that in the world's most temperate zones. Given the extensive high-rise living in Singapore, the findings of aural comfort assessment among high-rise dwellers in the tropics shall stand to offer important implications on aural comfort to cities considering high-rise housing.

2.8 IDENTIFICATION OF KNOWLEDGE GAP

As seen from the literature study, research on positive evaluation of sound, such as aural comfort, is rather limited and nascent. Research on aural comfort among high-rise apartment dwellers in the tropical climatic condition is missing in literature. *Since research on aural comfort is promising, there is a quest for a comprehensive evaluation framework and a comfort model developed on sound theoretical basis.*

The literature lacks an integrated approach for evaluation of the noise environment. Evaluation of the noise environment, especially noise annoyance, is generally based on a subjective or an objective assessment of outdoor transportation noise in isolation. As such, Jin (2010) commented that the suitability of the established noise annoyance models for evaluation of the indoor noise environment of residential premises is in question. Additionally, the established noise annoyance models did not include neighbour noise in their evaluation framework for the computation of overall noise annoyance. Moreover, psychoacoustical quantities have never been included in the noise annoyance models for defining perceptual dimensions in a residential context.

Based on the above arguments, a holistic approach is required for the integration of the perceptual dimension of noise and its quantitative aspects for assessment of aural comfort in a high-rise residential dwelling. As discussed earlier, Maarten (2008) found that Stallen's (1999) conceptual model is the only theory that gives an explanation for noise annoyance. The use of such a theoretical framework for the assessment of aural comfort (or discomfort) has never been applied in research. *A sound theoretical basis is therefore indispensable for psychophysical explanation of evaluation of comfort and development of an aural comfort model.*

Apart from the issues discussed above, indoor noise evaluation in high-rise residential living condition in the tropical climatic environment is absent in the literature of noise annoyance evaluation. The context of this research is Singapore, having a tropical climatic condition and more than 82% of the residential population living in the naturally ventilated high-rise public housing apartment. The provision of windows at high-rise building façade is a key bio-climatic building design criterion for natural ventilations in Singapore. As previously mentioned, these high-rise apartments are located in close proximity (between 5m and 25 m) to different transport noise sources (e.g. road and train), community noise sources (playground, food centre etc.) and are subjected to neighbour noise due to its high-rise living. *As a result, the tropical climatic condition and high-rise living condition make the context of the aural comfort study more complicated which has never been addressed before and must be re-defined. This study will therefore, be useful in expanding knowledge for planning, design and development of new residential estates and high rise buildings, and to ensure aural comfort among the high-rise dwellers in tropical countries like Singapore.*

Figure 2-10: Noise sources in the vicinity of high-rise public housing in Singapore

2.9 SUMMARY

Evaluation of a noise environment, especially noise annoyance, is generally based on a subjective or an objective assessment of outdoor transportation noise in isolation. As Jin (2010) pointed out, suitability of the established noise annoyance models for the evaluation of an indoor noise environment of residential premises is in question. Moreover, psychoacoustical quantities have never been included in the noise annoyance models for defining perceptual dimensions in a residential context (Marquis, 2005). *Based on the above arguments, a holistic approach is required for the integration of the perceptual dimension of noise and its quantitative aspects for the assessment of aural comfort in a high-rise residential dwelling*. Additionally, the use of a theoretical framework for the assessment of aural comfort (or discomfort) has never been studied.

Apart from the issues discussed above, indoor noise evaluation in high-rise residential living condition in the tropical climatic environment is absent in the literature of noise annoyance evaluation. *As a result, aural comfort in the tropical climatic high-rise living condition, which has never been addressed before, is in need of investigation.*

CHAPTER 3: PRELIMINARY INVESTIGATION AND RESEARCH DESIGN

3.1 INTRODUCTION

This chapter presents the details and findings of a noise survey conducted for the research project "Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments (Project Ref. R-296-000-100-490)" by Housing and Development Board (HDB) and Department of Building, National University of Singapore.

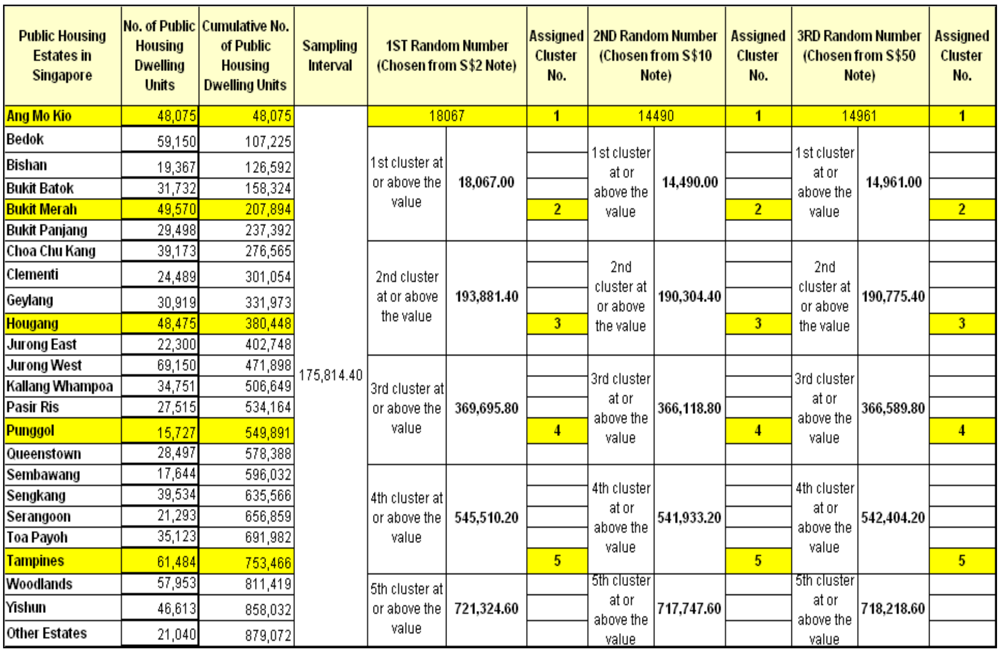
To embark on an aural comfort research study, it is essential to examine the factors influencing the perception of the indoor noise environment in high-rise residential environment in Singapore. To do this, a cluster sampled noise survey was carried out. A number of factors influencing the evaluation of indoor aural environment have been identified through literature study and the preliminary investigation. A Research hypothesis is established inductively based on the key findings from this noise survey. The way in which these factors are investigated for the assessment of aural comfort is discussed in research design section of this chapter.

3.2 SAMPLING TECHNIQUE

A cluster sampling technique was adopted for the noise survey where subjects were selected in groups or clusters of households. This approach allowed overcoming the constraints of costs and time associated with such a dispersed population. The sample frame (879,072 households) for the study was chosen from the total number of public households (public residential dwellings) listed in the HDB Annual report (2005-2006).

Table 3-1: Identification of clusters for noise survey

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)



Public Housing Estates in Singapore	No. of Public Housing Dwelling Units	Cumulative No. of Public Housing Dwelling Units	Sampling Interval	1ST Random Number (Chosen from S$2 Note)		Assigned Cluster No.	2ND Random Number (Chosen from S$10 Note)		Assigned Cluster No.	3RD Random Number (Chosen from S$50 Note)		Assigned Cluster No.
Ang Mo Kio	48,075	48,075	175,814.40	18067		1	14490		1	14961		1
Bedok	59,150	107,225		1st cluster at or above the value	18,067.00		1st cluster at or above the value	14,490.00		1st cluster at or above the value	14,961.00	
Bishan	19,367	126,592										
Bukit Batok	31,732	158,324										
Bukit Merah	49,570	207,894				2			2			2
Bukit Panjang	29,498	237,392										
Choa Chu Kang	39,173	276,565		2nd cluster at or above the value	193,881.40		2nd cluster at or above the value	190,304.40		2nd cluster at or above the value	190,775.40	
Clementi	24,489	301,054										
Geylang	30,919	331,973										
Hougang	48,475	380,448				3			3			3
Jurong East	22,300	402,748										
Jurong West	69,150	471,898		3rd cluster at or above the value	369,695.80		3rd cluster at or above the value	366,118.80		3rd cluster at or above the value	366,589.80	
Kallang Whampoa	34,751	506,649										
Pasir Ris	27,515	534,164										
Punggol	15,727	549,891				4			4			4
Queenstown	28,497	578,388										
Sembawang	17,644	596,032		4th cluster at or above the value	545,510.20		4th cluster at or above the value	541,933.20		4th cluster at or above the value	542,404.20	
Sengkang	39,534	635,566										
Serangoon	21,293	656,859										
Toa Payoh	35,123	691,982										
Tampines	61,484	753,466				5			5			5
Woodlands	57,953	811,419		5th cluster at or above the value	721,324.60		5th cluster at or above the value	717,747.60		5th cluster at or above the value	718,218.60	
Yishun	46,613	858,032										
Other Estates	21,040	879,072										

In order to assign clusters, a sampling interval and a random number were determined. The sampling interval (SI) was used to systematically assign clusters from the sampling frame. The SI was determined by dividing the sampling frame (879,072) by the total number of clusters (5) targeted to survey. The random number (its value ranges between zero and SI) was used to determine the starting point for the first cluster. A random number was generated from a few currency notes (A two dollar, a ten dollar and a fifty dollar). The random number was taken as a five digit numbers to ensure that all the public housing towns had equal probability of being selected. Each random number was chosen as the last five digits of each note in reverse order. Table 3-1 shows that irrespective of using any of the three random numbers, the clusters found were *Ang Mo Kio*, *Bukit Merah*, *Hougang*, *Punggol* and *Tampines* residential towns. It was noted that all these areas included a mix of recently developed and old residential public housing buildings.

3.2.1 Determination of Sample Size

The trade-off between cost and precision in determining sample size may be derived using the Central Limit Theorem (Tan, 2004). The sample size value derived from the Cochran formula (Cochran, 1977) is valid only for simple random or systematic random sampling methods. The cluster sampling method requires a larger sample size to achieve the same precision. Therefore, the calculated sample sizes using the Cochran formula needed to be adjusted by the design effect (*deff*) (Cochran, 1977).

The appropriate sample size for a population-based survey is determined largely by three factors: a) the estimated prevalence of the variable of interest; b) the desired level of confidence; and c) the acceptable precision factor. For a survey design based on a simple random sample, the sample size required can be approximated using the formula given by Cochran, in Equation 3-1.

$$n = \frac{Z^2 P(1-P)}{d^2} \quad \text{..} \text{ [Eq. 3-1]}$$

Where, n is the required sample size, Z is the Z-statistic for 95% confidence intervals, P is the estimated prevalence of annoyance in the project area (20%) and d is the precision factor.

The prevalence of annoyance (i.e. noisy) was estimated from a Sample Household Survey conducted by Housing and Development Board Singapore in 2003 and another survey conducted on 347 people (Yuen, 2005). A precision value was estimated 5%. Therefore, the calculated sample size is 246. The above sample size calculation formula was based on the assumption of normal distribution.

As the noise survey was designed using the cluster sampling technique, to correct for the difference in design, the sample size (n) was multiplied by the design effect ($deff$) which was assumed to have a conservative value of 2 (Bennet, 1991). The sample was further increased by 5% to account for contingencies such as non-response or unreasonable data. Therefore, the total sample size calculated was 517. Finally, the total sample size was rounded up to the closest number that matches well with the number of clusters (five areas) to survey. The final Sample Size (N) was 520 households. As a result, 104 households to be randomly chosen per cluster.

3.3 QUESTIONNAIRE DESIGN AND SURVEY PROCEDURE

The survey questionnaire was structured into four sections. The first section of the questionnaire was related to the respondents' personal profile, type of apartment, interview location and working environment in relation to noise. The second section of the questionnaire involved subjective assessment of the respondents' apartment and the surrounding living environment with respect to noise, ranking of noise, respondents' annoyance rating and identifying the noisy part of their apartment. The third section involved questions for the subjective assessment of different noise sources, the annoyance rating, the frequency of occurrence of noise and the nature of annoyance. The final section of the questionnaire involved an objective noise measurement at the interview location (just outside the entrance of the apartment) together with resident's subjective rating of the exposed noise level during the measurement.

The survey was conducted by face-to-face interview, with the questionnaire being completed by the five trained interviewers. Interviewers were equipped with a Type 1 integrating sound level meter to measure $L_{Aeq,1\min}$ at the end of the interview. Noise measurements were carried out in bright and sunny days during the noise survey. The survey was conducted between 10am and 6pm during Monday to Saturday between November 2007 and January 2008. This study was carried out entirely to investigate daytime aural comfort, hence night time noise measurement and relevant comfort studies were excluded from this research. The average temperature during these period was approximately 27^0C and mean wind speed 4km/hr. The entire questionnaires were vigorously checked on the spot, after each survey, to confirm that all the feedback was received accurately. Cases of incomplete information was rejected on the spot and a replacement interview was carried out in another apartment in compensation. Eventually, it was found that a total of 522 questionnaire forms had been collected with realistic information. At the end of each interview during the noise survey, a background noise measurement was carried out $(L_{Aeq,1min})$ just outside the entrance of the apartment and the subjective rating of the respondents were recorded. The objective of these measurements was to understand subjective perceptions of the measured noise levels and establishment of an acceptable outdoor noise level from the measured data. The locations of the measurements were the front entrance of the apartments as it was convenient to measure the background noise in presence of the subject and note his immediate response on the observed sound.

Survey sites were selected such that there were no existing nearby construction sites in the vicinity of the residential development under investigation during the survey. Aircraft noise was probably unavoidable in some housing estates. However, noise annoyance due to these two sources were also investigated through the noise survey in this research

3.4 FINDINGS FROM NOISE SURVEY

3.4.1 General Observations

The respondents constituted 61.7% female and 38.3% male all aged above eighteen years. Due to the nature of the noise survey during day-time, many working male and females were not included in the survey. In addition, it is noted that all male Singapore Citizen (and non-first generation permanent residents) who have reached the age of 18 are required to enrol for National Service which is for a period of 24 months. This results in a good number of male population away from home each year. Considering the above, the sample size of this composition is considered unbiased. The noise survey also reveals that 26.2% of the respondents were housewives, 24.9% work in quiet office environments, 22.8% were students, 19% were non-working, retired and care takers of apartments, 5.6% people work in noisy factory environment and 0.4% people work in noisy construction environment.

In response to the perception of noisiness in the apartment, 83% of respondents rated their apartments very quiet to acceptable. 15.5% of the entire cohort of respondents rated their apartment ‘Noisy**’** and 1.5% respondents rated their apartment ‘Very Noisy**’.** Figure 3-1 below presents the apartments’ rating with regards to noisiness of the apartment and it generally shows a normal distribution.

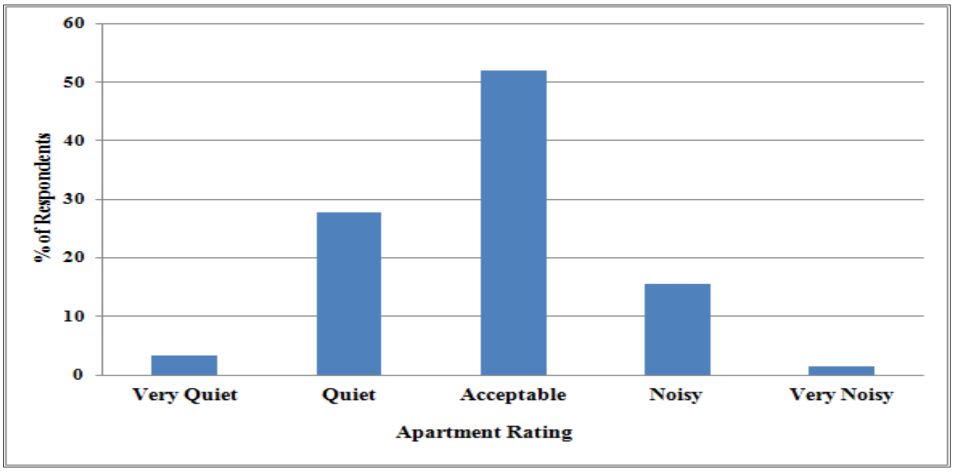


Figure 3-1: General rating of the apartments with respect to indoor noise level

Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

The survey results showed that 38% of respondents felt ‘Disturbed’ by noise in their living environment while 61% felt ‘Not Disturbed’ and the remaining 1% of respondents were unsure about their disturbance. About 36% of the respondents considered their ‘Living rooms or Halls’ as the 'noisy' part of their apartments followed by about 14% respondents who considered this to be their ‘Bedrooms’. *The Spearman Rank Correlation test showed that* ***rating of the 'noisiness of the apartment' is significantly correlated to the 'disturbance by noise in the living environment'*** *with a level of significance of 0.01.*

It is noted that Spearman Rank Correlation test is used in the analysis of noise data since it is computed on ranks and depicts monotonic relationship as opposed to Pearson correlation test which is computed on true values and depicts linear relationships.

The survey revealed that 36.8% of respondents felt that ‘Road Traffic Noise’ was the major source of noise in their living environment. This was followed by 14.2% for ‘Construction Noise’, 7.7% for ‘Aircraft Noise’, 7.3% for ‘Mass Rapid Transit (MRT) Train Noise’, and 6.1% for ‘Renovation Noise’ and by ‘Neighbour's Activity’. *The Spearman Rank Correlation test showed that* ***'noisiness of the apartment' was significantly correlated with the major sources (road traffic and train) of noise with a level of significance of 0.01****.*

The survey results revealed that approximately 68% respondents felt 'the noisiest period' was during the daytime (6 am to 6pm) followed by 16% sample population who felt the noisiest period was during the night (11pm to 6am). Another 9% of the respondents felt the noisiest period was the evening (6pm to 11pm). The rest of the sample population did not feel affected by noise in their living environment.

It was noted from the survey results that 90% of the entire cohort generally open at least one window during their stay at home while the remaining 10% generally leave the windows closed.

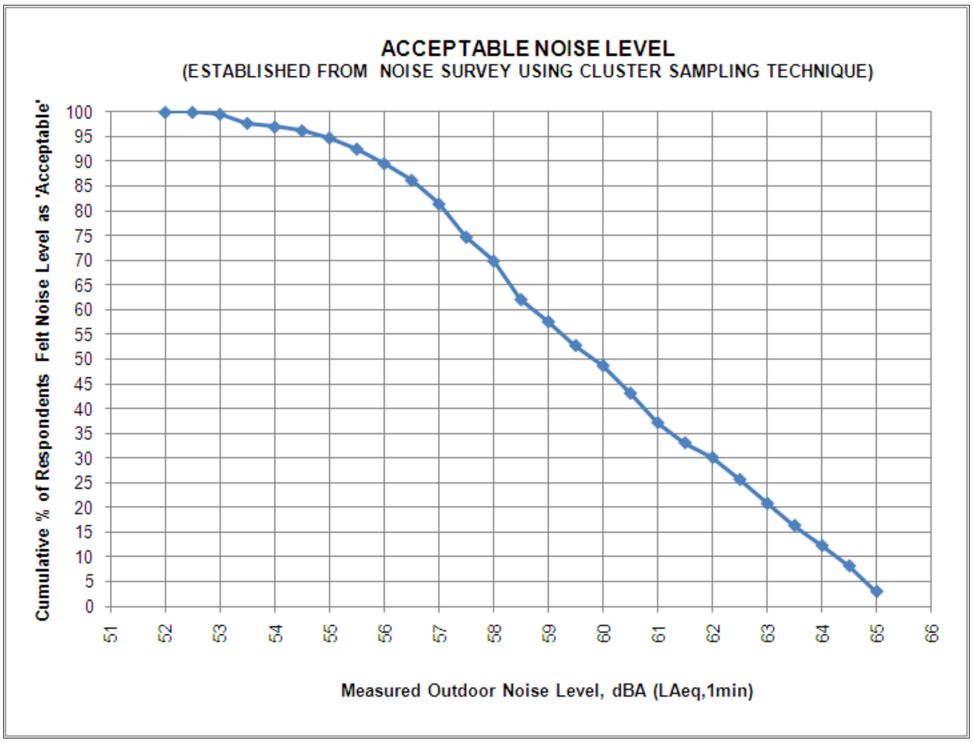


Figure 3-2: Acceptable noise levels

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

During the noise survey, at the end of each interview a background noise measurement was carried out ($L_{Aeq,1min}$) just outside the entrance of the apartment and the subjective rating of the respondents were recorded. The cumulative data, presented in Figure 3-2 shows that an outdoor measured A-weighted noise level of 55 dB is found as an 'acceptable' noise level to 95% of the entire sample size. It is noted that this acceptable noise level is established based on the measured noise data collected between 10am and 6pm during the noise survey.

3.5 ANALYSIS OF THE NOISE SURVEY DATA

3.5.1 Assessment of the Overall 'Noisiness' of the Indoor Aural Environment

Table 3-2 lists several acoustical and non-acoustical factors that are correlated (tested using Spearman Rank correlation test) to the overall 'noisiness' of the apartment.

Table 3-2: Factors correlated to overall noisiness of the apartment

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Type of Factor	**Factors**	**Correlation Coefficient**	**Level of Significance**
Non-Acoustical	*Sensitivity to noise*	0.280	0.01
Non-Acoustical	Consideration of noise as an important aspect in living environment	0.227	0.01
Non-Acoustical	*Rating of disturbance by noise in surrounding living environment (outdoor noise)*	0.308	0.01
Non-Acoustical	*Rating of Disturbance by major noise source*	0.290	0.01
Acoustical	Noisiest period for the major source of noise	0.131	0.01
Non-Acoustical	Activities disturbed by the major source of noise	0.211	0.01

From the analysis, it is observed that 'noisiness' of the indoor environment of an apartment is significantly correlated to the sensitivity of the inhabitants. The 'noisiness' perception tends to reduce for people who are less sensitive to noise. The cognitive response, for example, belief of noise as an important aspect in the living environment, is also found significantly correlated to 'noisiness' of the apartment. It is observed that respondents who rated noise as an important aspect in the living environment showed a higher incidence of finding their apartment noisy.

It is also found that the 'noisiness' of the apartment is significantly correlated to the perceived disturbance by noise in the general surrounding living environment. Inhabitants who are disturbed by noise in their general surrounding living environment generally find their apartment noisier.

The disturbance by particular major noise source (e.g. road traffic) is found significantly correlated to the 'noisiness' of the apartment. It is observed that inhabitants who are disturbed by a major source of noise find their apartment less acceptable with regards to 'noisiness' of the apartment. 'Noisiness' is also found significantly correlated with the noisiest period by the particular major source of noise. It is observed from this study that the inhabitants who found the indoor noise environment noisy felt that the noisiest period of the particular major noise source is mostly during the daytime (6am to 6pm) rather than in the evening and night time. Besides, activity disturbance was found correlated to the 'noisiness' of the apartment. Sleep disturbance was found higher for inhabitants who were disturbed by a particular major noise source.

A one way Anova test (refer to Table 3-3*) shows that* ***rating of the 'noisiness' of the indoor aural environment is not influenced differently by gender, age, level of the apartment of residence. Length of residence and the belief in the importance of noise as an important aspect****.* ***Noisiness of the indoor environment was rated differently by inhabitants with different noise sensitivity and the people who stayed in different types of the apartment*** *(for example, 3 room apartment, 4 room apartment etc).* For the latter, it was observed from a Tukey t-test that the mean rating of the indoor noise environment by inhabitants residing in 3 rooms apartment and 4 rooms apartment significantly differs at an alpha level of 0.05. A one way Anova test showed that the mean background noise levels across different types of apartments are significantly different ($p<0.05$). The A-weighted mean background noise level for a 3 room apartments (59 dB) was found lower compared to that of the 4 rooms apartments (61 dB).

Post-Hoc analysis was carried out using Tukey's Honesty Significant Difference (HSD) test in order to identify that Type 1 (considering significant a difference that actually is not significant) error is not made. Test results are presented in Table 3-4. The analysis shows that there are significant differences in rating noisiness of apartment by different noise sensitive groups namely 'non sensitive', 'average sensitive' and 'sensitive' group.

Table 3-3: Influence of factors to overall rating of noisiness of the apartment

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Type of Factor	Factors	F	Significance	Remarks
Non-Acoustical	***Consideration of noise as an important aspect in living environment***	3.535	$p < 0.05$	***Significantly important***
Non-Acoustical	Rating of apartment by different gender	0.395	$p > 0.05$	Rating of apartment equal across groups
Non-Acoustical	Rating of apartment by different age group	1.877	$p > 0.05$	Rating of apartment equal across groups
Acoustical	Rating of apartment by residents staying at different level of the building	1.156	$p > 0.05$	Rating of apartment equal across groups
Non-Acoustical	Rating of apartment by residents of different length of stay	1.114	$p > 0.05$	Rating of apartment equal across groups
Acoustical	***Rating of apartment by residents staying in different types of apartments***	2.967	$p < 0.05$	***Rating of apartment different across groups***
Non-Acoustical	***Rating of apartment by residents with different sensitivity to noise***	21.653	$p < 0.05$	***Rating of apartment different across groups***

Table 3-4: Post-Hoc analysis for noise sensitivity

(I) Noise Sensitivity	(J) Noise Sensitivity	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Non Sensitive	Average	-.362*	.075	.000	-.54	-.19
	Sensitive	-.584*	.094	.000	-.80	-.36
Average	Non Sensitive	.362*	.075	.000	.19	.54
	Sensitive	-.223*	.087	.029	-.43	-.02
Sensitive	Non Sensitive	.584*	.094	.000	.36	.80
	Average	.223*	.087	.029	.02	.43

*. The mean difference is significant at the 0.05 level.

Another one way Anova test (refer to Table 3-5) revealed that the Nationality (Singaporean/PR/Foreigner) does not have any significant influence on rating of different subjective quantities. For example, the rating of noisiness of the apartment, noise sensitivity, rating of disturbance by noise in surrounding living environment, rating of disturbance by major source of noise, and the adaptive behaviour like opening or closing of windows by different nationality groups are equal.

Table 3-5: Influence of nationality to different subjective ratings

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Type of Factor	Factors	Significance	Remarks
Acoustical	Rating of overall noisiness of apartment	$p > 0.05$	Equal across different nationality group (Singaporean/PR/Foreigners
Non-Acoustical	Rating of noise sensitivity	$p > 0.05$	Equal across different nationality group (Singaporean/PR/Foreigners
Non-Acoustical	Rating of disturbance by noise in surrounding living environment	$p > 0.05$	Equal across different nationality group (Singaporean/PR/Foreigners
Acoustical	Rating of disturbance by Major source of noise	$p > 0.05$	Equal across different nationality group (Singaporean/PR/Foreigners
Acoustical	Opening or closing of window	$p > 0.05$	Equal across different nationality group (Singaporean/PR/Foreigners

3.5.2 Evaluation of Apartments' Noisiness for Different Categories of Noise Source

Table 3-6 summarizes the factors that are correlated (tested using Spearman Rank correlations) to the rating of 'noisiness' of the apartments while outdoor ***environmental noise*** is considered as the major category of noise source.

Apart from the factors that have been discussed in the earlier section relating to the overall noisiness of the apartment, it is observed from Table 3-6 that the rating of noisiness of the apartment is moderately correlated to the disturbance due to the major ***environmental*** noise source which in turn strongly correlated to the disturbance by noise in the general surrounding living environment. It is found that the acceptability of the indoor noise environment (in terms of noisiness of the apartment) reduces with the increase in disturbance by particular major environmental noise source.

Table 3-6: Factors related to rating of 'noisiness' of the apartment when *environmental noise* is considered as the major category of noise source

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Dependent Variable	Type of Factor	Factors	Correlation Coefficient	Significance
Rating of Apartment (Noisiness)	Non-Acoustical	Sensitivity to noise	0.286	0.01
Rating of Apartment (Noisiness)	Non-Acoustical	Consideration of noise as an important aspect in living environment	0.241	0.01
Rating of Apartment (Noisiness)	Non-Acoustical	Disturbance by noise in surrounding living environment (outdoor noise)	0.303	0.01
Rating of Apartment (Noisiness)	Acoustical	Part of the apartment considered noisy	0.123	0.01
Rating of Apartment (Noisiness)	Acoustical	Type of major noise source	0.214	0.01
Rating of Apartment (Noisiness)	***Non-Acoustical***	***Disturbance by major noise source***	***0.315***	***0.01***
Rating of Apartment (Noisiness)	Non-Acoustical	Activities disturbed by the major source of noise	0.220	0.01
Disturbance by major noise source	Non-Acoustical	Sensitivity to noise	0.256	0.01
Disturbance by noise in surrounding living environment	***Non-Acoustical***	***Disturbance by major noise source***	***0.458***	***0.01***
Activities disturbed by the major source of noise	***Non-Acoustical***	***Disturbance by major noise source***	***0.497***	***0.01***

Table 3-7 summarizes the factors that are correlated (Tested using Spearman Rank correlations) to the rating of the apartments' noisiness when ***neighbour noise*** is considered as the major category of noise source. The type of activity disturbed by the major neighbour noise source is correlated with the disturbance by major neighbour noise source. It was observed that sleep disturbance was mostly affected by the noise from the floor directly above the apartment.

Table 3-7: Factors related to rating of 'noisiness' of the apartment when *neighbour noise* is considered as the major category of noise source

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Dependent Variable	**Type of Factor**	**Factors**	**Correlation Coefficient**	**Level of Significance**
Rating of Apartment (Noisiness)	***Non-Acoustical***	***Disturbance by major noise source***	***0.275***	***0.01***
Rating of Apartment (Noisiness)	***Acoustical***	***Noisiest period for the major source of noise***	***0.313***	***0.01***
Rating of Apartment (Noisiness)	Non-Acoustical	Activities disturbed by the major source of noise	0.253	0.01
Activities Disturbed by Major Noise Source	***Non-Acoustical***	***Disturbance by major noise source***	***0.430***	***0.01***

Table 3-8: Factors related to rating of 'noisiness' of the apartment when *community noise* is considered as the major category of noise source

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Dependent Variable	**Factors**	**Type of Factor**	**Correlation Coefficient**	**Level of Significance**
Rating of Apartment (Noisiness)	Sensitivity to noise	Non-Acoustical	0.431	0.01
Rating of Apartment (Noisiness)	Disturbance by major noise source	Non-Acoustical	0.281	0.05
Rating of Apartment (Noisiness)	Level of apartment	Acoustical	0.281	0.05
Activities Disturbed by Major Noise Source	Disturbance by major noise source	Non-Acoustical	0.372	0.01

Table 3-8 presents the factors that are correlated (Tested using Spearman Rank correlations) to the rating of apartments' noisiness when ***community noise*** is considered as the major category of noise source. Similar to neighbour noise sources, it is observed that the overall acceptability of the indoor noise environment (noisiness) is correlated to disturbance due to community noise sources which in turn is correlated to disturbance of activities. It is found that the rating of apartments' noisiness increases with the increase in disturbance by the particular community noise source.

It is also noted that the overall noisiness of the apartment increases for inhabitants who are sensitive to noise and for those who reside in the lower floors (below seventh floor) of the building. The latter may be due to the fact that, at lower apartments, the noise exposure levels might be relatively higher. This is investigated in Chapter 4.

3.6 RESEARCH HYPOTHESIS

The key findings from the preliminary noise survey are as follows:

- Rating of 'noisiness' of an apartment is correlated to subjective 'disturbance' due to the major noise sources. Respondents who were less disturbed by different types of noise sources rated their apartments less noisy.
- Environmental noise sources (e.g. Road traffic noise, MRT Train noise) are found as the major sources of noise disturbance and are found correlated to the rating of noisiness of an apartment.
- Respondents who rated their apartment 'noisy' felt that the noisiest period is during the daytime (6am to 6pm) rather than in the evening and night time. This indicates that the reduction of overall noisiness of an apartment (in other words, the increase of aural comfort) depends on the 'daytime' noise exposure of the apartments.

The noise survey thus establishes that the rating of apartments' noisiness, disturbance due to major noise sources and daytime noise levels are found to be significantly related to the assessment of the indoor aural environment.

Based on the literature review and the preliminary research study, a research hypothesis is inductively established as follows:

> ***'Daytime subjective aural comfort in high-rise naturally ventilated residential dwellings can be defined as a function of the daily average indoor noise exposure level, the perception of the overall noisiness at the apartment and the noise disturbance caused by road traffic and Mass Rapid Transit (MRT) train noise'.***

As observed from the discussions above, the evaluation of sound is a complex. A number of physiological, psychological, behavioural and contextual factors affect the evaluation of noise environment. In addition to the understanding of the process of noise annoyance, the evaluation requires a detailed investigation on many physical, acoustical and non-acoustical factors that are involved in the delivery of aural comfort in dwellings. Hence, there is a need for a holistic framework that is able to assess the indoor aural comfort in an integrated manner considering all the acoustical and non-acoustical factors involved in its evaluation.

3.7 PARAMETERS INFLUENCING ASSESSMENT OF THE AURAL ENVIRONMENT

The factors influencing the assessment of one's aural environment, investigated during the preliminary study, is summarized in Table 3-9 below.

Table 3-9: Factors influencing assessment of aural environment

S/N	Factors influencing noise annoyance	Significant influence on noise annoyance (Yes/No)		Factors for further investigation
		Literature Study	Preliminary Noise Survey	
1	Gender	No*	No	-
2	Nature of working environment	No*	No	-
3	Age	No*	No	-
4	Nationality	No*	No	-
5	No. of occupants	No*	No	-

S/N	Factors influencing noise annoyance	Significant influence on noise annoyance (Yes/No)		Factors for further investigation
		Literature Study	Preliminary Noise Survey	
6	Level of apartment	No*	No	-
7	Length of residence	No*	No	-
8	Type of Apartment	No*	No	-
9	Noise Sensitivity (Non-acoustical)	Yes*	Yes	Included
10	Rating of noisiness of apartment (acoustical)	Yes*	Yes	Included
11	Consideration of noise as an important aspect in living environment (non-acoustical)	Yes*	Yes	Included
12	Disturbance by noise (non-acoustical)	Yes*	Yes	Included
13	Location within apartment considered noisy (acoustical)	Yes*	Yes	Included
14	Door opening condition (acoustical)	Yes*	Yes	Included
15	Windows opening condition (non-acoustical)	Yes*	Yes	Included
16	Sources of environmental noise (acoustical)	Yes**	Yes	Included
17	Sources of neighbour noise (acoustical)	Yes**	Yes	Included
18	Sources of community noise (acoustical)	Yes**	Yes	Included
19	Key noise source causing noise annoyance (acoustical)	Yes**	Yes	Included
20	Time period for noise annoyance (acoustical)	Yes**	Yes	Included
21	Noise exposure level (LAeq) (acoustical)	Yes**	Yes	Included

*Refer to Table 2-2 for relevant research papers.

**Refer to Table 2-1 for relevant research papers.

It is noted from Table 3-9 that there are several acoustical and non-acoustical factors influencing the aural environment. Evaluation of acoustical factors, such as noise exposure levels, locations of apartments considered noisy, sources of noise and time period of noise exposure, require an extensive investigation of the noise environment of high-rise dwellings and their vicinity. On the other hand, evaluation of non-acoustical factors, such as thoughts about the noise environment, subjective rating of noisiness of the apartment and disturbance due to noise, requires an understanding of the dwellers' attitude towards the noise environment. As a result, a comprehensive objective and subjective assessment of the high-rise noise environment is required for the assessment of aural comfort. A research framework is proposed in the following section that describes the fundamental theory behind the assessment of an aural environment and demonstrates how several acoustical and non-acoustical factors are integrated for the assessment of aural comfort.

3.8 PROPOSED AURAL COMFORT ASSESSMENT FRAMEWORK

3.8.1 Theory of Noise Annoyance

Stallen (1999) developed an explicit theoretical framework for unfolding the process of noise annoyance based on the psychological stress theory of Lazarus (1966). As Maarten (2008) noted, this is the only theory that gives an explanation for noise annoyance.

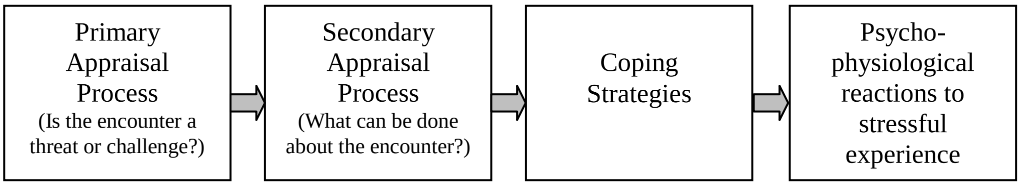


Figure 3-3: Lazarus's (1996) conceptual model for psychological stress and coping

Lazarus (1996) used the term cognitive-motivational-relational theory to describe stress as an outcome, subject to the balance of coping which exists between environmental demands, constraints, and resources, and the ability of the person to manage them. An illustration of his model is presented in

Figure 3-3. According to his theory, cognition is central to the process of “primary appraisal,” in which events are evaluated in terms of impact and meaning with respect to the individual’s goals and beliefs. Cognition is also involved in “secondary appraisal,” which concerns evaluation of the available options for dealing with the perceived demands. Cognitive-motivational-relational theory does three important things: First, it highlights the complexity of the stress process; second, it locates the process within the individual rather than in the environment; and third, it explicitly incorporates mental activity as a driving force in the stress process.

Empirical research by Lazarus (1966) established that there are two key determinants of stress namely ***Perceived Threat*** and ***Perceived Control***. According to Lazarus (1996), 'Perceived control' is a generic term applicable to several cognitive and/or affective mechanisms that come into play when exposed to a particular threat or confronted with the possibility of consequential change. On the other hand, 'Perceived Threat' is stressful depending upon the perceived possibilities to stand up against the disturbance or cause of dissatisfaction. In general, psychological stress will be higher for lower levels of perceived control. High disturbance and high control may be less annoying than moderate disturbance and no control.

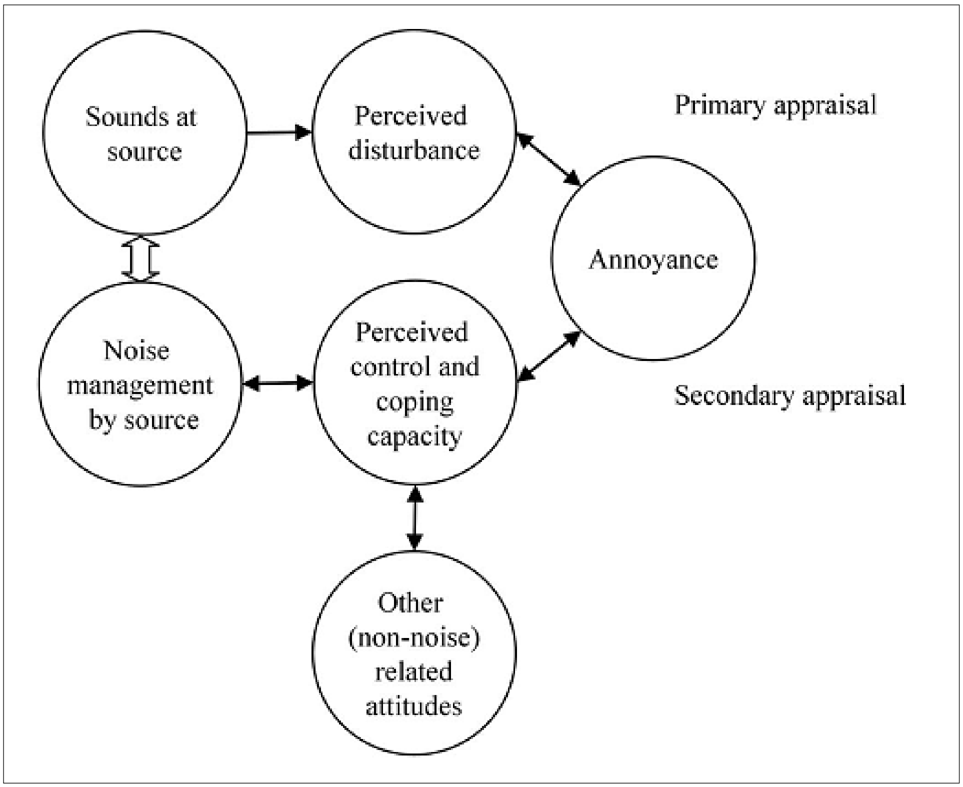


Figure 3-4: Stallen’s (1999) conceptual model for noise annoyance

In his theoretical framework, Stallen (1999) (refer to Figure 3-4) demonstrated that perceived disturbance is a similar concept as perceived threat. Based on the Lazarus's theory, Stallen argued that the perceived disturbance and the available resources to tackle the disturbance determine the extent of the noise annoyance. Stallen concluded that when the perceived resources (such as perceived control and coping capacity) are insufficient to tackle the perceived disturbance, noise annoyance in the form of psychological stress will arise. Stallen also mentioned that there shall be no noise annoyance if there are sufficient resources to tackle the noise even though the level of perceived disturbance is very high. Stallen (1999) underlined the fact that as the perceived control and coping capacity is in constant flux, multiple reciprocal relationships exist in the theoretical framework of noise annoyance.

In his conceptual model, Stallen demonstrated that evaluation of noise annoyance requires the subjective assessment of perceived disturbance due to noise. As such, it is important to understand the theory behind the evaluation response of human beings. Eagly and Chaiken (1993) developed the evaluative response model (ERM) that explains the underlying factors influencing subjective assessment (of a noise environment). According to the ERM, evaluation plays a significant role in how people make sense of what they experience. As shown in Figure 3-5, Evaluative Response Model (ERM) illustrates that the responses to the 'attitude object' reveal the existence of an 'attitude' that is expressed through 'evaluation'. According to Eagly and Chaiken, the 'attitude object' is defined as any tangible item (e.g. noise exposure) presented to an individual to determine their opinion of the item and thus their 'attitude' towards the item. According to Eagly and Chaiken, people's ideas, opinions and perspectives about the 'attitude object' shape their 'attitude' towards the attitude object. They illustrated that 'attitude' is a latent processes in human's minds that is articulated only when the 'attitude object' (for example noise) is perceived. Eagly and Chaiken defined 'Attitude' as the psychological tendency that is expressed by evaluating a particular entity with some degree of favour or disfavour.

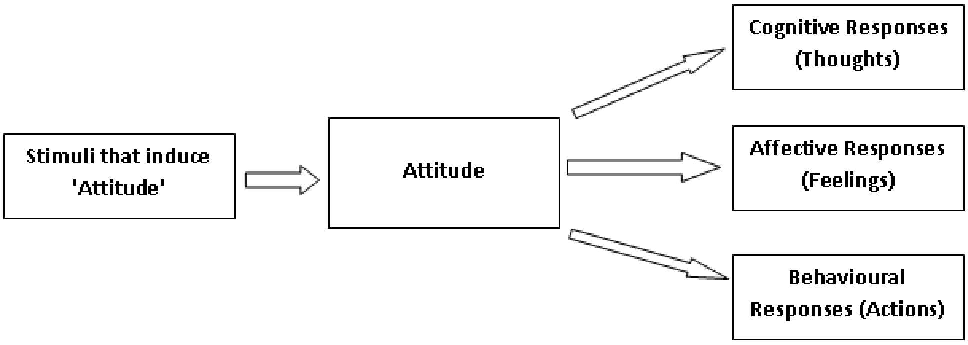


Figure 3-5: Eagly and Chaiken's (1993) model of 'attitude'

Eagly and Chaiken (1993) illustrated that Cognitive Responses, Affective Responses and Behavioural Responses are the three key elements of the evaluation responses that shape the foundation of the ERM model. They defined these key responses as follows.

a) ***Cognitive Responses*****:** These are conceptualized as knowledge, opinions, beliefs, information and inferences that reflect the thoughts and ideas of a human being about an attitude object (i.e. noise). These cognitive responses establish the links between the attitude object and the various attributes of the attitude objects. Therefore, favourable evaluations are connected with positive attributes and vice versa. Evaluation of the importance of noise in the living environment is related to cognitive response.

b) ***Affective Responses*****:** These are emotions, feelings and moods that are experienced with regard to the evaluation of the attitude object. Eagly and Chaiken (1993) illustrated that both extremely positive and extremely negative experiences are related to the evaluation and a favourable evaluation is generally linked with positive attributes and vice versa. Sensitivity to noise, subjective assessment of the noisiness of the apartment and perceived disturbance due to noise are related to affective response of human.

c) ***Behavioural Responses*****:** Behavioural response are related to the intentions to act or to the overt action associated with the attitude objects. Generally, an attitude object is evaluated favourably with the support of positive behaviour and vice versa. Likeliness of closing doors, windows in relation to noise annoyance are some adaptive activities related to the behavioural response. In addition, likeliness of making complaint or moving house are other behavioural responses with respect to noise annoyance.

Recently, Andringa and Lanser (2013) has extended Stallen's (1999) theory of noise annoyance. They have further extended the idea of 'Perceived Control' (as used by Stallen, 1999 in his noise annoyance model) in terms of 'Core Affect' which is defined as the combination of perceived viability and resource allocation. Human behavioural options to noise complies with the demand that they preserve viability and help to regulate core affect. Noise annoying is interpreted as the challenges to self regulate viability. Noise annoyance reduces the number of options for restoration and other forms of viability self-regulation. According to Andringa and Lanser (2013), the processes of hearing and listening, different forms of attention, meaning giving and associated effortful and less effortful mental states, core affect regulation, basic emotions, viability and health, and the restoration of the capacity for directed attention are the factors that contribute in predictable ways to how humans respond to sound.

Andringa and Lanser's (2013) theoretical model for noise annoyance is presented in Figure 3-6. It illustrates the causal routes from sound exposure to sound annoyance through reduced restoration. The model connects (cortical) attention states with (sub-cortical) motivational drives as estimated by core cognition. The different attention states correspond to qualitatively different modes of cortical activity: sleep, automated task performance, single task performance, and multi-tasking. While these different modes are separate, they form in actuality a continuum that corresponds to progressively higher arousal and alertness. The arousal and safety (both aspects of core affect) determine which mind-states are accessible (Andringa and Lanser, 2013).

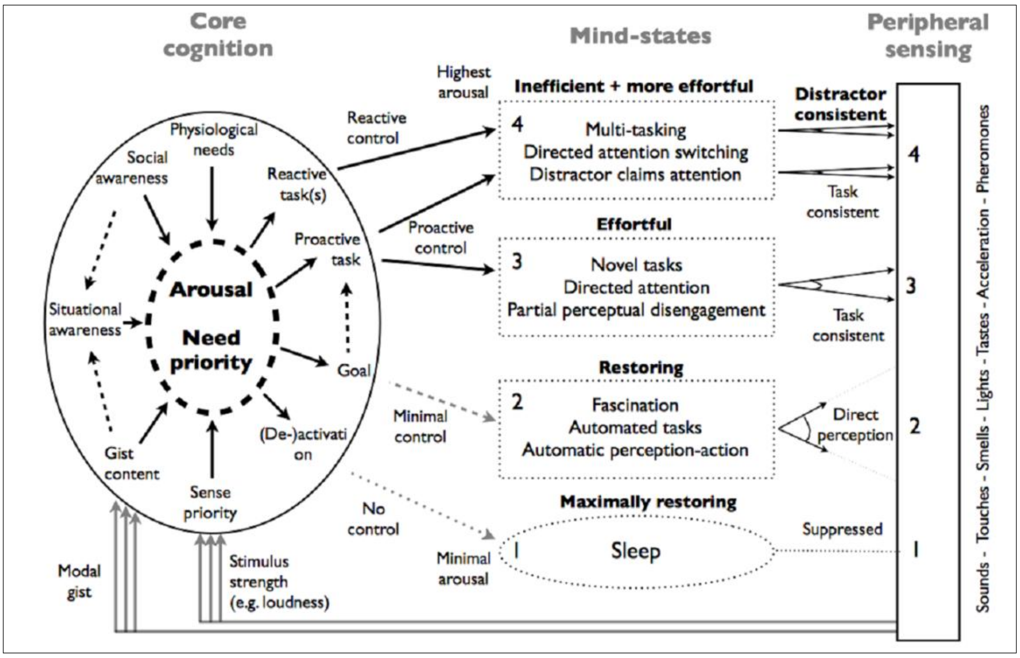


Figure 3-6: Andringa and Lanser (2013) model of noise annoyance and quietness

According to Andringa and Lanser (2013), the model illustrates that conscious mind-states serve self-selection of adaptive behaviour either proactively, to address long-term needs, or reactively, to serve immediate needs. These mind-states need to be based in situational awareness. According to Job (1999), situational awareness has two components. One component tracks the overall properties of the environment and relies mainly on the ambiance and the subtle sounds and corresponds to proximal situational awareness. The second component is aimed at specific events within the environment and is typically directed towards the processes that correspond to the loudest (often distal) sounds in the environment. Appraising a situation as safe allows for mind-states for (mental) restoration and proactive adaptive behaviour. Diminished safety guarantees, in either the proximal or distal component of noise sensitivity, arouse and lead to mind-states that switch between vigilance and self-selected tasks.

If high switching costs, arousal, and vigilance prevent the execution of self-selected tasks: one is dominated by (annoying) sound.

3.8.2 Comfort Assessment Framework

From the literature study and preliminary investigation, it is established that several acoustical and non-acoustical factors (refer to Table 3-9) influence the assessment of aural environment. For the development of an aural comfort model, acoustical factors are further evaluated through an objective assessment approach whereas non-acoustical factors are evaluated through 'Attitude' evaluation (explained by both Stallen's (1999) noise annoyance theory and Eagly and Chaiken's (1993) ERM model). The aural comfort evaluation framework is structured based on the fundamental process of controlling environmental disturbance to achieve a level of comfort, as demonstrated by Dean (1982) in Figure 3-7.

Dean (1982) illustrated (Figure 3-7) that *D* is a set of environmental disturbances (e.g. noise) which impinge upon a person, *C* are the physiological/psychological variables which determine his state of comfort, *N* is the channel (e.g. human) through which *D* is transmitted to *C* and is a combination of the physical environment and the individual's physiology. Dean (1982) illustrated that the precise state of *N* depends upon certain parameters and these are represented by *P*. The minimal environmental control system described by Dean (1982) indicated the opportunities for control of individual's environment by R_o (e.g. building design, control of noise at source or at transmission path or regulation of adaptive activities and behaviours).

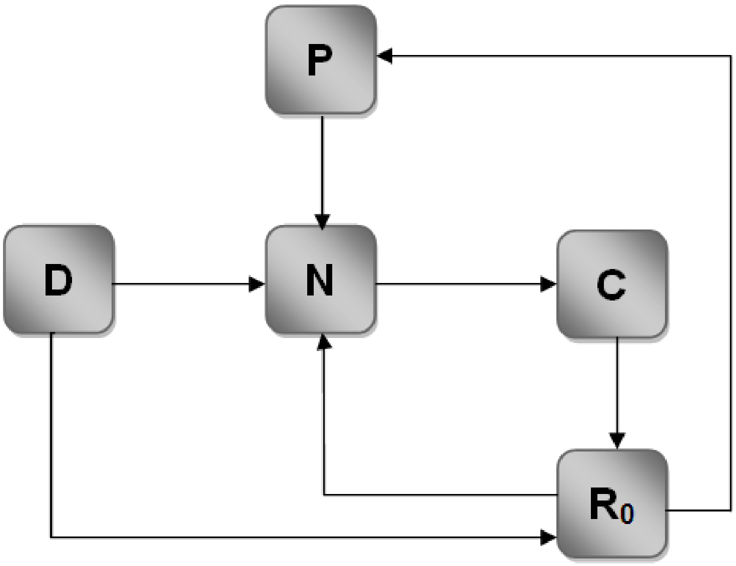


Figure 3-7: Environment control system (Source: Dean, 1982)

In Figure 3-8, a comprehensive framework is proposed for the assessment of aural comfort of high-rise dwellers in Singapore. Figure 3-8 exemplifies that noise in an indoor environment, considered as 'perceived disturbance' or an 'attitude object', impinges on the 'human interface' which is surrounded by its relevant physical and environmental conditions and depends on the individuals' attitude response. The 'human interface', in other words, refers to the residential dwellings of the individuals in high-rise naturally ventilated buildings in tropical Singapore and the 'attitude' of the individuals towards the noise exposure in their dwellings. In such a residential setting, the indoor noise is attributed to outdoor environmental and community noise sources as well as neighbours transmitted noise from immediate neighbouring apartments.

The physical environment of the residential dwellings influences the indoor noise exposure which, also in turn depends on the type and characteristics of noise sources, their proximity to dwellings, the level of noise exposure, acoustical performance of the building components, and the geographical and the climatic requirements for building design. The assessment of this physical environment for overall assessment of aural comfort is defined as the 'Objective assessment' in this proposed framework.

The 'Subjective assessment' of the aural comfort is fundamentally the assessment of the 'attitude' response of the individuals towards the aural environment they are exposed to in their dwellings. According to Eagly and Chaiken (1993), an individual’s attitude towards this noise environment is an evaluative process which is founded on several psychological and physiological variables that determine the individual's state of aural comfort.

As illustrated in the Evaluation Response Model (ERM), the fundamental components of an individual’s attitude towards the noise environment include cognitive responses (thoughts - importance of noise in the living environment) to noise, affective responses (feeling - noisiness of the apartment, noisiest time of the day, noise sensitivity, perceived disturbance due to noise) to noise and behavioural responses (adaptive behaviours - likeliness of closing doors, windows, etc.) to noise.

A comprehensive assessment of the aural comfort in dwellings thus necessitates an integrated evaluation approach which is founded on an objective assessment of the physical environment and subjective assessment of the individual's attitude towards the objective noise exposure that influence's aural comfort. It is only possible to understand the 'experience' of the dweller's aural comfort condition through such an integrated evaluation approach. Once such 'acoustical experience' is defined through acoustical and non-acoustical factors, an aural comfort assessment model can be developed.

In the following sections, detailed research methodology for each component of the proposed evaluation framework is discussed.

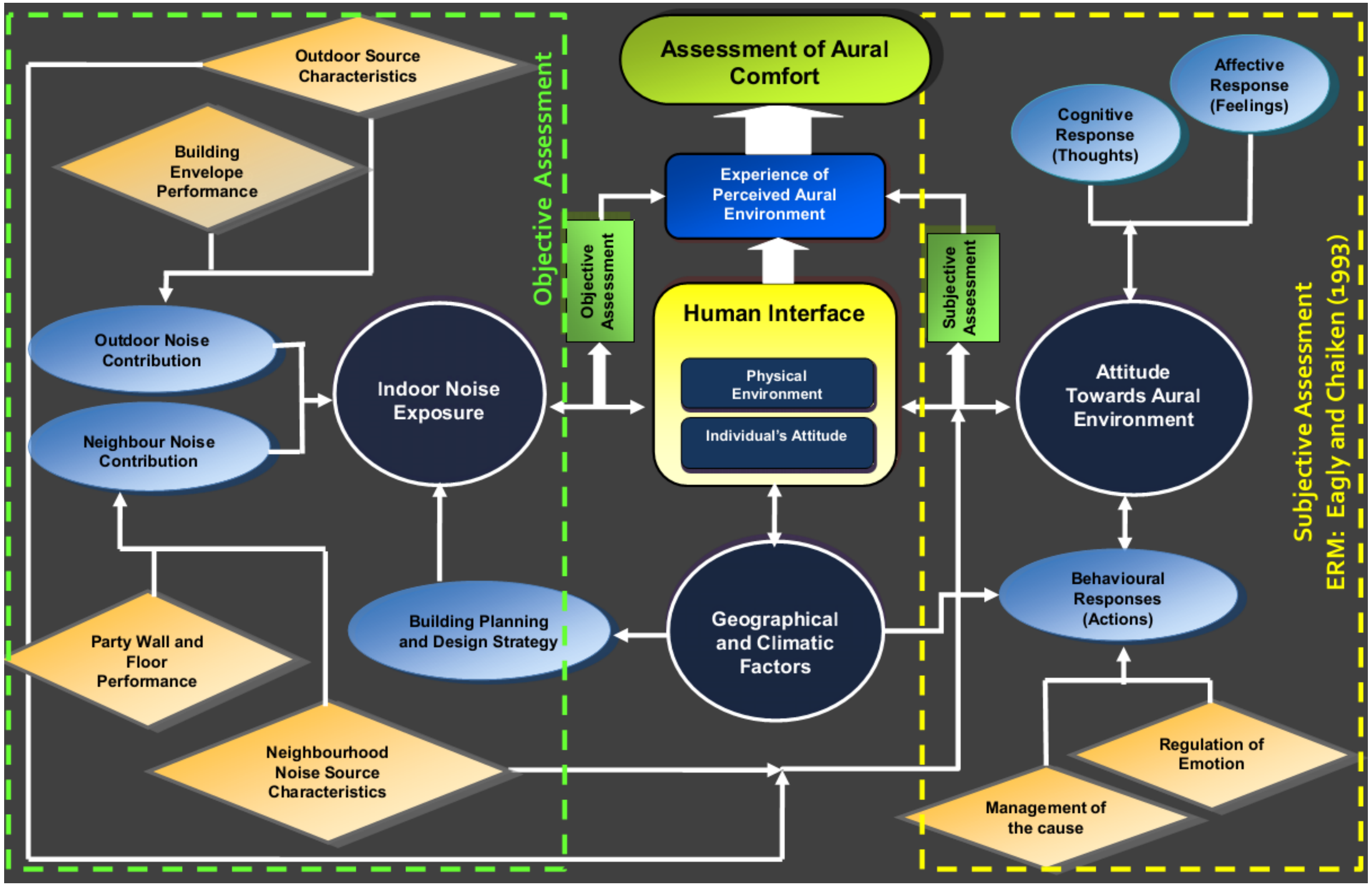


Figure 3-8: Proposed conceptual framework for aural comfort assessment

3.9 RESEARCH DESIGN AND METHOD

Figure 3-9: Land transport network in Singapore showing major roads and MRT Train lines (Source: retrieved from onemap.com.sg on the 16th March 2011)

From the preliminary research study it is obvious that the large systemic noise sources such as Road Traffic and MRT train are the major sources of environmental noise in Singapore and they are correlated to the noise disturbance in high-rise apartments. Road Traffic and MRT shape the backbone of the land transport system in Singapore and thus form the majority of the background noise in the living environment. Singapore is a city-state with a population density of approximately 7,148 people per square kilometre, making it one of the most densely populated countries in the world. Due to the high-density living and land scarcity (a total land area of 710.2 square kilometres, 23% of which is forest and natural reserve), the city has a vertical growth to meet the housing demand for its residents. High-rise apartments (generally 20 to 30 storeys) are in close proximity (5m to 25m) to roads, highways and elevated tracks. It was therefore interesting to assess the acoustic of comfort of high-rise apartments dwellers in the presence of this background noise, formed from the presence of nearby roads and trains.

This study was undertaken for high-rise naturally ventilated public housing apartments (known as HDB apartments), in which where more than 85% of the resident population lives. For the subjective assessment of the aural comfort of high-rise apartment dwellers in the vicinity of roads and MRT trains, a stratified sampled population was chosen. However, the stratification criteria were road and MRT train noise with varying levels of noise exposures of residents. For road traffic noise, residential buildings were stratified according to their exposure levels which are directly affected by the volume of traffic along the road (in other words, varying noise exposure levels). As such, the stratification was based on the five different road categories in Singapore, namely Expressway, Major Arterial Road, Minor Arterial Road, Primary Access Road and Local Access Road. For MRT noise, distance to the MRT tracks was the main factor affecting the noise exposure of the residential buildings. Therefore residential buildings were selected based on their distances to the MRT tracks at distances of 30m, 40m, 50m, 60m, and 70m. Other criteria for selection of buildings included:

a. Existence of party walls between apartments facing noise sources;
b. Living areas in apartments with windows front facing towards the noise source;
c. No mixed developments of commercial & residential buildings;
d. High rise buildings with 10 storey and above;
e. At least 30 units per building;
f. No major obstructions between buildings and the main noise source.

The research scope area for the aural comfort investigation is described above. In the following few sections, detailed research design and methodologies are discussed on the various components of objective and subjective assessment for aural comfort (as illustrated in Figure 3-8).

3.10 RESEARCH METHODOLOGY FOR OBJECTIVE ASSESSMENT

The purpose of the objective assessment is to determine the background indoor noise levels (due to road traffic and train) that the dwellers are exposed to in the study area. This involved characterization of road traffic and train noise sources, establish apartments’ facade noise exposure levels due to these outdoor noise sources and evaluation of the sound insulation performances of different types of facades. The objective assessment also examined the airborne and impact sound transmission performance of the party walls and floors to investigate the neighbour noise impact.

3.10.1 Characterization of Road Traffic and Train Noise

To examine the objective noise exposure levels of high-rise apartments subjected to different roads and train noise sources, two basic research methods are adopted. The first is the measurement method, and the other is a predictive approach using computer simulations. The predicted results are validated with measured data. The prediction method used for the traffic noise propagation study is the standard UK method for Calculation of Road Traffic Noise (CRTN). MRT train noise is predicted using the standard UK method for Calculation of Railway Noise (CRN).

In Singapore, there is no established prediction model for the computation of facade noise exposure levels of high-rise apartments subjected to different environmental noise sources. Therefore, it was crucial to establish the noise exposure profiles of high rise apartments for the estimation of indoor noise exposure levels.

A. Method of noise measurements

To evaluate facade noise exposure levels, noise measurements were carried out at different elevation of buildings facing the noise sources (road or train). To avoid possible inconvenience to the residents due to instrument setup and operation, noise measurements were carried out either at the opening area within the staircase or at the common corridor at each level of the building (whichever convenient on site). A schematic diagram of the measurements are presented in Figure 3-10 and Figure 3-11. Microphones are generally placed half a meter away from the corridor (approximately 1.5m away from façade) in open areas where there is no immediate reflection from the nearby parapet wall. The schematic diagrams show the general height of the microphones which varied on site to site basis.

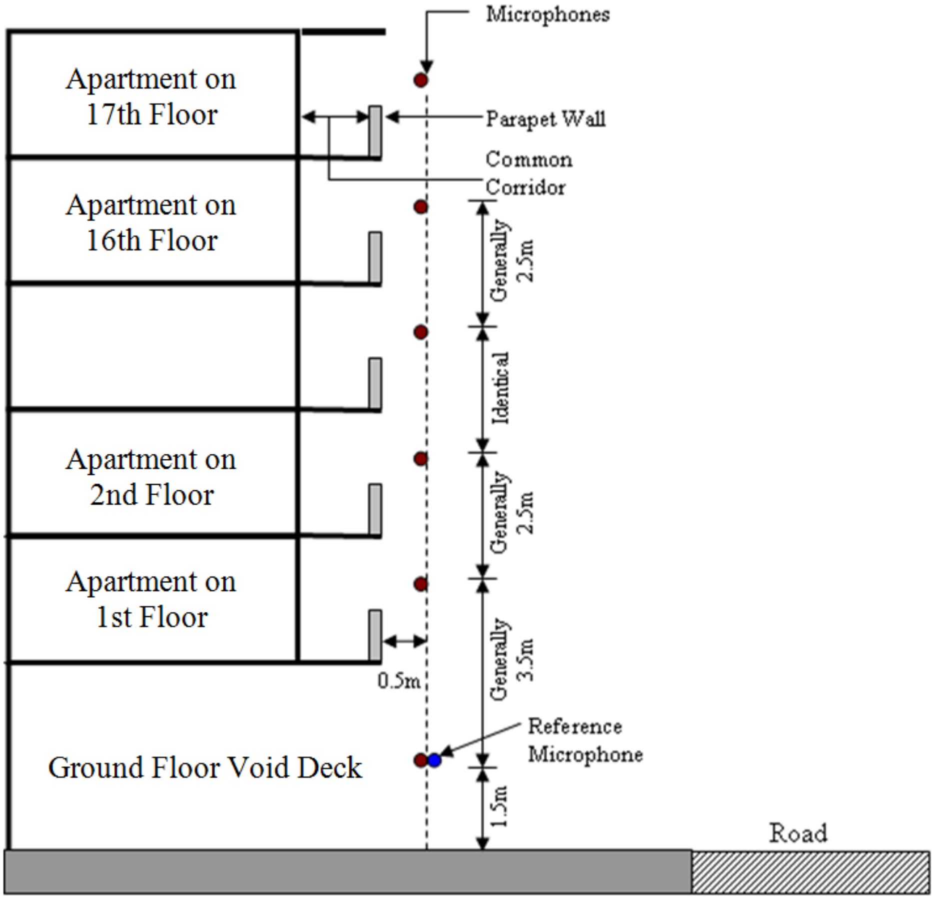


Figure 3-10: Schematic diagram of measurement setup where common corridor is available for site access and measurement

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

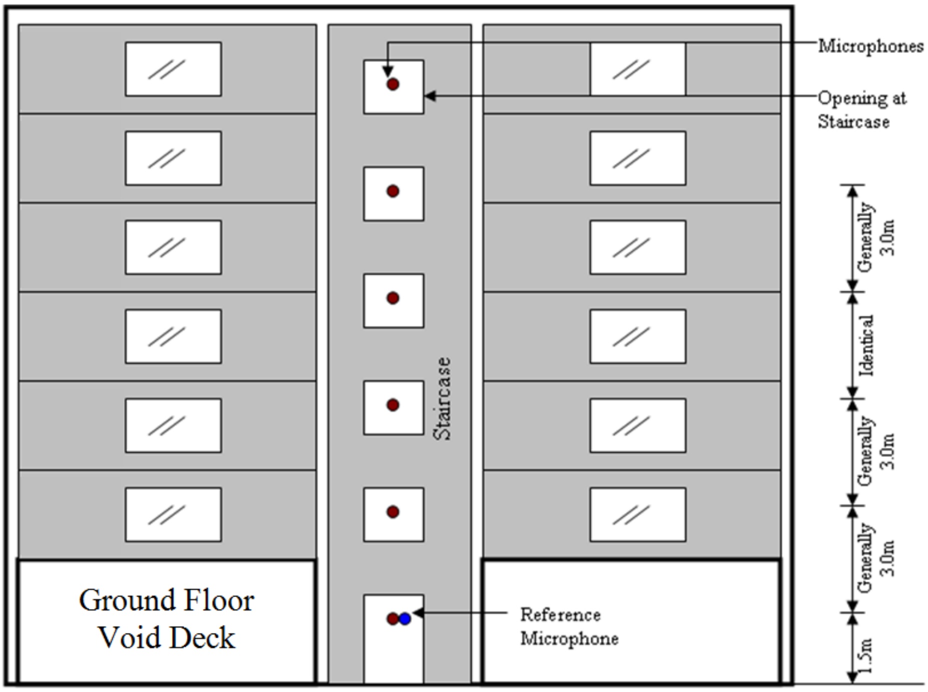


Figure 3-11: Schematic diagram of measurement setup where staircase opening is available for site access and measurement

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Most of the buildings where noise measurements were carried out are sixteen stories high. The measurements were carried out mostly at all the levels of the buildings. A-weighted equivalent continuous sound pressure levels (L_{Aeq}) were measured. To examine the vertical noise propagation, a sound level meter was set at the ground floor of the building and another sound level meter was set to each floor above in order to compute the change in noise level with vertical distance as from the noise level at the ground floor.

For road traffic noise, five minute A-weighted equivalent continuous sound pressure level ($L_{Aeq,5min}$) were measured to capture the change in noise level along the elevation (vertical height) of the building with respect to the reference microphone located at the ground floor. This measured change in noise level is added to the measured 12-hr noise level at the ground floor to estimate the noise level at different apartment floor level. Similarly, to compute such changes in noise level due to MRT

Train, A-weighted equivalent sound pressure levels were measured for a period of twenty seconds ($L_{Aeq,20sec}$). Generally a MRT train takes approximately 20 sec to pass by a high-rise building facing the track.

For quantification of the noise sources, another sound level meter (called 'reference' sound level meter) was placed at the ground floor at a height of 1.5m above the ground to measure the noise level from the source during its operating hours. The measurement parameter was $L_{Aeq,T}$ where T refers to the operational hours during the day of the particular noise source. For traffic noise, T was 12 hours from 0600 hrs to 1800 hrs. For MRT Train noise T was twenty seconds for fifteen MRT runs to establish the daily average noise level.

B. Modeling, simulation and prediction methods

Road traffic noise was predicted using CRTN standard while the MRT Train noise was predicted using CRN standard. A commercial software, CadnaA, was used for the modeling of the acoustic environment which incorporated CRTN and CRN calculation algorithm. Actual road dimensions, building dimensions, source to receiver distance, microphones height, etc, were measured on site prior to the computer modeling. A true scale locality map (retrieved from Singapore Land Transport Authority website) was used as a background to model the exact locations of the noise sources, obstacles and buildings and thus the actual site conditions. The noise sources were also modelled in CadnaA using their respective noise emission levels and by defining the physical geometry (length, width, height etc.) of each. The noise emission levels of the noise sources were measured on site. Road traffic noise was modelled using CadnaA with the 18-hr traffic flow input, percentage of heavy vehicles and average traffic speed information (obtained from measurements by the Singapore Land Transport Authority (LTA) on the specific sites).

The road traffic noise emission measurements were carried out in general accordance with the British Standard CRTN. According to CRTN, the reference noise level (basic noise level) is measured at a reference distance of 10m away from the nearside road curb at a height of 1.5m at grade above ground. 18-hour A-weighted equivalent continuous sound pressure level was measured to quantify the noise emission level of the road.

The MRT train noise emission measurements were carried out in accordance with the British Standard CRN. According to CRN, the reference noise level is measured at a reference distance of 25m away from the nearside rail head at a height of 3.5m above the railhead.

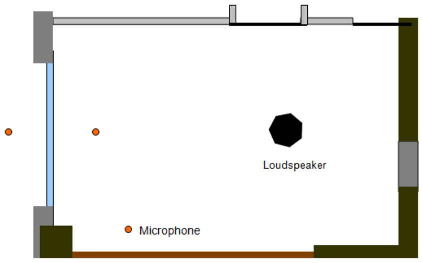
3.10.2 Method of Measurement - Sound Insulation Performance of Building Envelope

There is no established dataset or published data on the acoustical performances of building façade, in terms of sound insulation, in Singapore. Because of the tropical climatic environment, Singapore’s high rise residential public housing apartments are designed to perform with natural ventilation. Therefore, the provisions of open windows at the building facade provide an easy transmission path for the outdoor noise to the indoor living environment. It was, therefore, important to conduct acoustical tests to determine the sound transmission performance of these commonly used building elements in high-rise public housing apartments in Singapore.

Table 3-10: Measurement setup for façade acoustical performance evaluation

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

Parameter	Background noise	Sound Transmission Loss
Noise type	Continuous	Pink noise
Bandwidth	1/3 octave	1/3 octave
Frequency band	16 Hz – 16 kHz	63 Hz – 5 kHz
Measurement period	300 s	30 s (each test)

Parameter	Background noise	Sound Transmission Loss
Values to record	L_{Aeq} at microphone position	L_{Aeq} at microphone position
Microphone position	Fixed	Fixed
Method	• 1 microphone position each at source (S) and receiving (R) room • 1 test taken at each position • Total 2 sets of measurement	• 1 loudspeaker position • 1 microphone position outside façade (R) & inside room (S) • 3 tests taken at the microphone position • Total 3 sets of measurements (all windows closed) • Repeat measurements with 1 window open
Measurement Setup Diagram		

The measurement of the sound insulation of a façade in a high rise apartment in Singapore requires the placement of a sound source outside the façade according to ISO 140-5:1998 (Acoustics - Measurement of sound insulation in buildings and of building elements - Part 5: Field measurements of airborne sound insulation of façade elements and façades) which is not practical in high rise apartments. Additionally, there is generally no apartment at the ground floor of the building under investigation. Therefore, calculation of the weighted apparent sound reduction index according to ISO 140-5:1998 was not feasible.

In order to judge the sound insulation of the façade, a sound source was placed inside the room while the instrument side of façade is subjected to the test signal. Noise measurements were carried out at both side of the façade. This arrangement allowed measuring the Noise Reduction (NR) provided by the façade. The sound insulation of the façade is reported in terms of Noise Isolation Class (NIC) as per ASTM E 413-10 (Classification for Rating Sound Insulation). Generally Sound Reduction Index (SRI) is approximately 5 dB higher than the NIC value. Setup for facade insulation measurements are presented in Table 3-10.

3.10.3 Method of Measurement - Sound Insulation Performance of Party Walls and Floors

Airborne sound transmission loss of party walls and floors were carried out in general accordance with ISO 140-4: Acoustics - the measurement of sound insulation in buildings and of building elements – Part 4: Field measurements of airborne sound insulation between rooms (2nd Ed); and ISO 717-1: Acoustics- Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation (2nd Ed). ASTM standards (E336-97: Standard test method for measurement of airborne sound insulation in buildings and E413-04: Classification for rating sound insulation) were also used for the measurement and rating of the walls for ease of comparison and evaluation. The general measurement setup for airborne sound transmission loss measurement is presented in Table 3-11 below.

Field impact sound transmission measurements of floors were carried out in general accordance with ISO 140-7: Acoustics - Measurement of sound insulation in buildings and of building elements – Part 7: Field measurements of impact sound insulation of floors; and ISO 717-2: Acoustics - Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation. ASTM standards (E 1007 – 04: Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures1 and E 989 – 89: Standard Classification for Determination of Impact Insulation Class) were also used for the measurement and rating of the walls, for ease of comparison and evaluation. The general measurement setup for impact sound transmission measurement is presented in Table 3-11.

Table 3-11: Measurement setup for airborne sound transmission performance of party walls

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

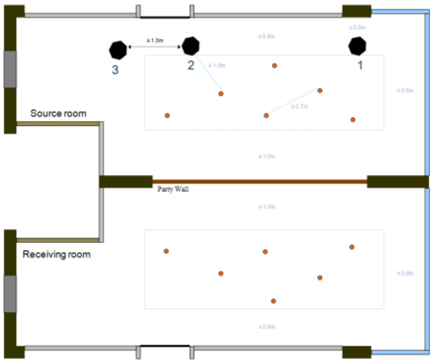
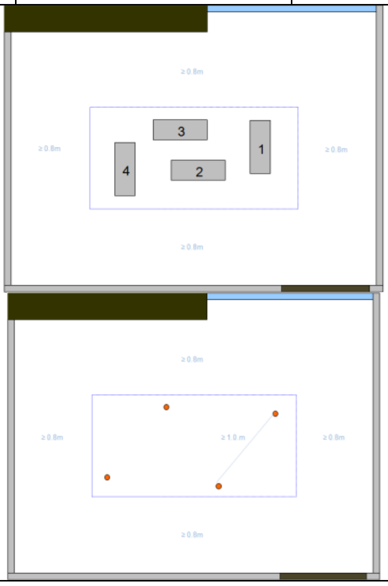
Parameter	**Background noise**	**Reverberation Time**	**Sound Transmission Loss**
Noise type	Continuous	Impulsive	Pink noise
Bandwidth	1/3 octave	1/3 octave	1/3 octave
Frequency band	16 Hz – 16 kHz	63 Hz – 5 kHz	63 Hz – 5 kHz
Measurement period	300 s	30 s (each test)	30 s (each test)
Values to record	L_{Aeq} at microphone position	Decay time	L_{Aeq} at microphone position
Microphone position	Fixed	Fixed	Fixed
Method	• 1 mic position each and source (S) room and receiving (R) room • 1 test taken at each position • Total 2 set of measurement	• 1 loudspeaker position • 3 microphone positions (R room) • 3 tests taken at each position • Total 9 sets of measurements	All windows closed: • 3 loudspeaker positions • 6 microphone positions (in each R & S) • 1 test taken at each position • Total 18 sets of measurements
Measurement Setup Diagram			

Table 3-12: Measurement setup for impact sound transmission performance of floors

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

Parameter	Background noise	Reverberation Time	Sound Transmission Loss
Noise type	Continuous	Impulsive	Impact
Bandwidth	1/3 octave	1/3 octave	1/3 octave
Frequency band	16 Hz – 16 kHz	63 Hz – 5 kHz	63 Hz – 5 kHz
Measurement period	300 s	30 s (each test)	30 s (each test)
Values to record	LAeq at microphone position	Decay time	LAeq at microphone position
Microphone position	Fixed	Fixed	Fixed
Method	• 1 microphone position each and source (S) room and receiving (R) room • 1 test taken at each position • Total 2 set of measurement	• 1 loudspeaker position • 3 microphone positions (R room) • 3 tests taken at each position • Total 9 sets of measurements	• 4 Tapping machine positions • 4 microphone positions (R room) • 1 tests taken at each position • Total 16 sets of measurements
Measurement Setup Diagram			

3.11 RESEARCH METHODOLOGY FOR SUBJECTIVE ASSESSMENT

A noise survey, based on stratified sampled population, was conducted for the research project " Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore (Project Ref. R-296-000-121-490)" by Building and Construction Authority (BCA), Housing and Development Board (HDB) and Department of Building, National University of Singapore. I acknowledge the support of the research collaborators for allowing me to use the project data for my PhD research.

The noise survey evaluated the 'Attitude' about the indoor aural environment of the high-rise dwellers in Singapore. The data from the noise survey was analysed to investigate the relationship between indoor aural comfort and the factors established by the literature study and preliminary noise survey. This forms the basis for the establishment of an aural comfort model. The other objectives of the survey were to study the influence of environmental noise, neighbour noise and adaptive behaviours on overall aural comfort. The method of data collection and analysis are discussed below.

3.11.1 Sample Size

The sample size calculation is as described in Chapter 3. However, the sample size value was derived using Cochran formula which is valid for simple random sampling methods. A stratified sampling method requires a larger sample size to achieve the same precision. Therefore, the calculated sample sizes using the Cochran formula needed to be adjusted by the design effect ($deff$) (Cochran, 1977).

Assuming the percentage of prevalence 15% (rating of the indoor noise environment as 'noisy' estimated from the earlier noise survey in cluster sampling technique) and a precision value of 5%, the calculated sample size (for random sampling), based on the Cochran formula (Eq. 3-1), was 195 (n). This was further multiplied by the design effect ($deff$) of 1.5 and further increased by 3% to account for contingencies (such as non-response or unreasonable data). The sample size for the stratified sample was found to be 302 households each for Road and MRT noise exposed areas (i.e. about 60 households for each of the five different categories of roads and five different classification of MRT train distances).

A total of 302 households in public housing apartments were selected for the study in the vicinity of the 5 different categories of roads. Therefore a total of 10 locations – 2 for each road category were chosen and 30 households were surveyed at each of these locations. Similarly, a total of 302 HDB households were surveyed in buildings at different distances to the MRT tracks – 30 households at each of the 10 locations. Hence, a total of 604 households were surveyed for public residential dwellings subjected to road traffic noise and MRT train noise. The distribution of the noise survey locations is shown in Figure 3-12. The buildings under study included a good mix of old and new residential buildings.

Figure 3-12: Distribution of noise survey locations (shown in black circles)

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

3.11.2 Data Collection - Questionnaire Design and Survey Procedure

The questionnaire consisted of 21 questions and was categorized into 4 sections. The first section of the questionnaire focused on the overall rating of noise and aural comfort (long term) in their living condition at home. The second section of the questionnaire involved subjective assessment of the noise from immediate neighbours' apartments. Respondents were asked to rate the noise heard from their immediate neighbours' instead of the sound performance of the separating elements for a more accurate and consistent result. The third section investigated the subjective assessment of different outdoor noise sources. The final section of the questionnaire consisted of an objective noise measurement inside the resident's apartment together with the subjective rating of the exposed noise level during the measurement. The survey questions were closed ended and designed with a five point Likert rating scale for subjective assessment of the noise environment.

The survey was generally conducted by personal interviews and the questionnaires were completed by trained interviewers. Interviewers were equipped with Type 1 integrating sound level meters to measure indoor noise exposure levels (for 30 sec) at the end of the interview. Each questionnaire was vigorously checked on the spot to ensure that the feedback received was accurate. Questionnaires with incomplete information were rejected on the spot and separate interviews were carried out in other apartments for replacement purposes.

3.11.3 Data Analysis

Data collected from the noise survey was analysed statistically to establish a relationship between aural comfort and other influencing factors including perceived responses from the dwellers (from noise survey) and measured objective acoustical quantities (indoor noise levels, sound transmission loss of walls and floors). The analysis method included trend analysis, spearman rank correlation test, factor analysis, one way Anova test and linear regression. The statistical software package SPSS (Statistical Product and Service Solutions) was used for the data analysis. It is noted that Spearman Rank Correlation test is used in the analysis of ordinal noise data since it is computed on ranks and depicts monotonic relationship as opposed to Pearson correlation test which is computed on true values and depicts linear relationships.

3.12 METHODOLOGY FOR ESTABLISHMENT OF EXPERIENCE ABOUT THE PERCEIVED AURAL ENVIRONMENT

Dwellers' perceived experiences of the indoor aural environment is established through the development of an aural comfort model. The aural comfort model is developed based on the statistical relationship (or integration) between the perceived aural comfort response from the noise survey, non-acoustical factors that were found significantly related to aural comfort (from statistical analysis of noise survey data) and the objective noise exposure data (from objective assessment).

Multinomial Logistic Regression (MLR) was used for the development of the aural comfort model. A multinomial logistic regression model, also known as multinomial logit model, is a regression model which generalizes logistic regression by allowing more than two discrete outcomes. That is, the model determines the probabilities of the different possible outcomes of a categorically distributed dependent variable, given a set of independent variables (which may be real-valued, binary-valued, categorical-valued, etc.). Multinomial logistic model is used to predict categorical data. MLR assumes that the dependent variable (aural comfort) cannot be perfectly predicted from the independent variables for any case and from this, a probability is predicted for each categories. MLR does not make any assumptions of normality, linearity, and homogeneity of variance for the independent variables (Chatterjee and Ali, 2006). Since the acoustic comfort of residents is evaluated on a category scale, MLR is the appropriate regression model that can be used to develop aural comfort model.

3.13 METHODOLOGY FOR VALIDATION OF THE AURAL COMFORT MODEL

Based on the preliminary noise survey, it can be concluded that the aural comfort model might be dependent on the A-weighted indoor noise exposure levels, sound transmission performance of party walls and floors and some non-acoustical factors which are subjective in nature (perceived responses). In order to validate such a model, which is founded on the field measured dwellers' responses about the aural environment, a subjective laboratory test was designed in which another group of subjects (not residents from the noise survey area) were exposed to the same road traffic and train noise (through binaural headphones) as the noise survey sites. Perceived responses from these subjects about the indoor aural environment were then used to validate the model. The research methodology for the laboratory subjective test is discussed below.

3.13.1 Laboratory Subjective (Psychoacoustical) Testing

3.13.1.1 Location of binaural recording of sounds

In laboratory psychoacoustics tests, subjects were exposed to binaurally presented road traffic and train noise. Binaural recording of the sounds was carried out at the locations where the noise survey in the stratified sample was conducted. These included ten locations near different categories of roads (expressway, major arterial, minor arterial, primary access and local road) and another ten locations at varying distances (30m, 40m, 50m, 60m and 70m) from the ten MRT track. Recording of these sounds was generally carried out in front of the open window of the apartments (generally on the 10th floor of the building), facing the respective noise source. This was to ensure that the psychoacoustical evaluations were made for those stimuli which are experienced by the residents during their living in high-rise naturally ventilated buildings. Binaural recording of the sounds was carried out using the

Binaural Recording System from 01-dB Metravib which uses a binaural headset to record the sound through dBSonic software.

3.13.1.2 Instrumentation and methodology for binaural recording

The system for binaural recording of road traffic and train sounds comprised of a binaural recording headset, a sound card and an analysis software package known as dBSonic from 01 dB Metravib, France (refer to Figure 3-13). The recording microphones on the headset are located on the outer sides of the headphone which are near the entrance of the ear cannels to capture noise entering the ears. Binaural recordings were carried out using dBSonic software and through a Binaural Microphone Headset (BMH) which was connected to the dBSonic software through a 24 bit Professional Sound Card. Integrated microphones in the BMH had a microphone sensitivity of 20mV/Pa. The headset was calibrated prior to the measurements using B&K Class 1 Acoustical Calibrator (ref 94dB@1Khz). The frequency range of the binaural microphones is 20 Hz to 18 KHz. The sampling frequency of the sound card is 48 kHz per channel.

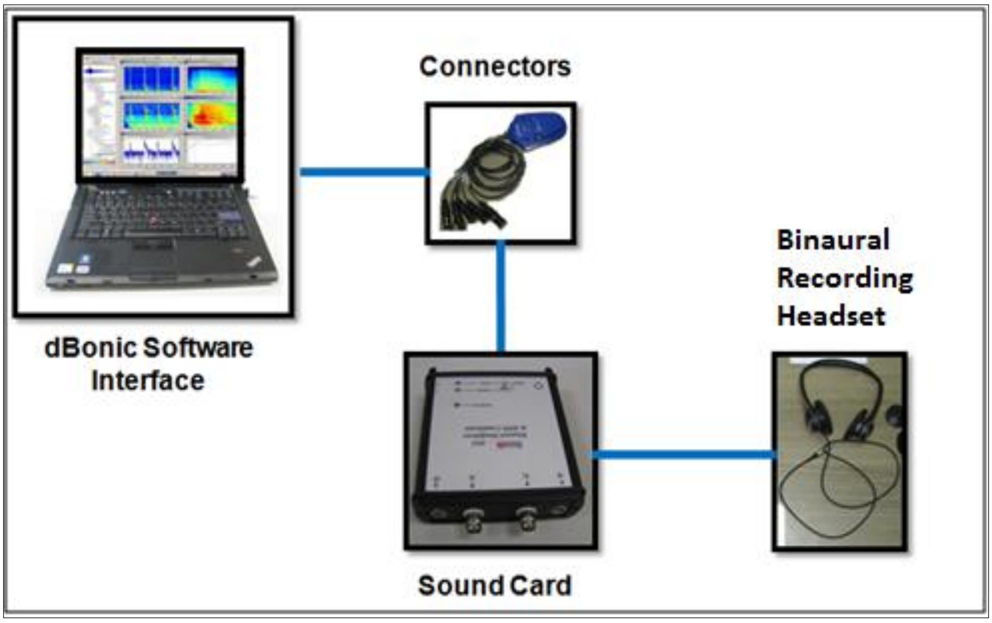


Figure 3-13: Recording system (from 01-dB Metravib) used for binaural recording of sounds

On site, each binaural recording (both road traffic and train noise) was carried out for a period of 1 minute. After the recording of the sounds, each recorded signal was equalized (in a laboratory), both in duration and magnitude, prior to its psychoacoustic evaluation (Stephan et al., 2008). The equalization was done through the dBSonic software. Each sound was equalized for a duration of 6 seconds and an amplitude of A-weighted equivalent noise level of 75 dB. After equalization, each of these sounds was referred to as the 'Reference Level' (also called 'Ref + 0 dB') for each respective class of road and MRT train noise. After equalization and calibration, the equivalent noise level of each stimulus was changed to four different levels such as +3 dB, 0 dB, -3 dB and -6 dB relative to the reference level (L_{Aeq}). As a result, a total of 40 binaural road traffic sounds and 40 binaural MRT train sounds were generated for psychoacoustic evaluation.

3.13.1.3 Instrumentation and methodology for subjective assessment

Instrumentation: Psychoacoustic tests were carried out in a controlled environment where respondents were not exposed to any intrusive noise except for the sound under investigation. The acoustical criterion for selection of the test environment was a signal-to-noise ratio of 10 dB. The test environment was also 'comfortable' with respect to thermal, visual and spatial aspects. As a result the psychoacoustic test is designed to be conducted in a conducive environment. The detail of the test environment is discussed in Chapter 6 of thesis.

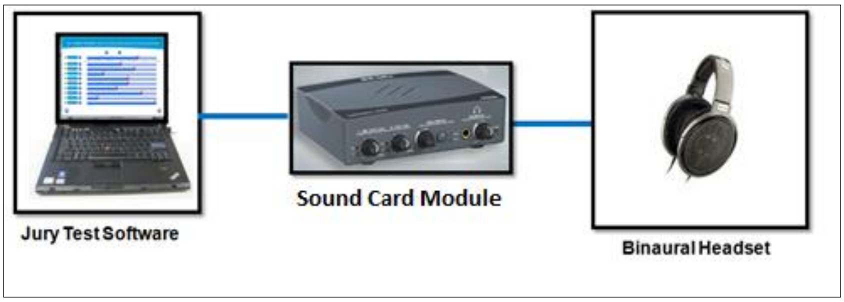


Figure 3-14: Listening system (from 01-dB Metravib) used for binaural listening of sounds

The listening system for the stimulus evaluation was operated and controlled by the Jury Test software package from 01 dB Metravib (Figure 3-14). According to the system, stimuli are sent from notebook computers equipped with a 24 bit professional sound card to a binaural headset (Sennheiser HD650) for listening. The headset is factory calibrated. dBSonic software is used for editing, analysis and calculation of the psychoacoustical quantities. Stimuli sent by the Jury Listening Software were listened to by the subjects through the Binaural Headset and they rated their perception on a continuous scale shown on the computer screen. The psychoacoustic analysis of the recorded signals were carried out in dBSonic software.

Criteria for Subject Selection and Sample Size: For inclusion in the psychoacoustic experiment sample set, each subjects was required to undergo a audiometric test to confirm that they have normal hearing conditions. Normal hearing is defined as the mean hearing threshold level, computed based on Goodman (1965) criteria (average of 500 Hz, 1000 Hz and 2000 Hz).

A total of 30 subjects were chosen for the experiment. Daniel (1997), in the book 'Music, Cognition and Computerized Sound: An Introduction to Psychoacoustics' recommended that for a descriptive psychoacoustics experiment, where the outcomes are expected to be invariant across people, only a few (i.e. five) subjects is sufficient. Daniel (1997) added that for psychoacoustics experiments where a large variation in individuals perception is expected, for a mean with relatively smaller error variance, at least five to ten subjects is required in each experimental condition. Since, the study of aural comfort is subjective in nature and even though the comfort perceptions are not expected to vary on a wider range, the minimum number of subjects required for the study is 10 according to the recommendation by Daniel (1997). However, the experimental design for the aural comfort study is made for a total of 30 subjects and is thus justified.

Methods of Evaluation: There were a total of 80 stimuli (40 road sound signals and 40 train sound signals) for evaluation. The noise exposure levels (LAeq) of the stimuli were between 45 dBA and 75 dBA. Each stimulus was 6 seconds in length. It is important to note, studies have shown that the duration of a listening session (length of stimuli) does not influence the ratings of noise annoyance if the evaluation question refers to the home situation (Poulsen, 1990). As a result, a shorter session length with the evaluation question relating to home environment, reduces the experimental time significantly.

Psychoacoustic evaluation (Jury testing) was planned to be carried in three different approaches - Absolute evaluation approach, Mixed evaluation approach and Paired comparison approach. A brief summary of these approaches is given below.

A. Absolute evaluation method:

This is also known as the Direct Evaluation Approach. In this approach the subjective responses are collected using a category scale. The detail of this technique was discussed in the literature review (in Chapter 2). In the aural comfort study, the absolute evaluation method was used to evaluate the three aspects of road traffic and train noise - overall aural comfort, noisiness of the apartment and disturbance due to the noise. All 40 different road traffic stimuli and 40 different train stimuli were evaluated in this approach. The 'aural comfort' responses collected from this approach were used for the verification of the aural comfort model. The other two subjective responses - 'noisiness of the apartment' and 'disturbance by the noise' correlated with different psychoacoustical quantities for parametric studies to establish their relationship.

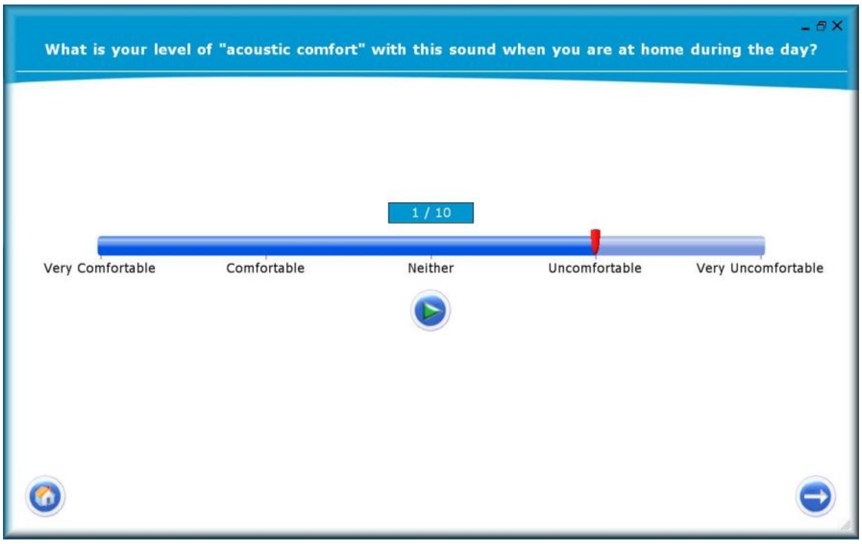
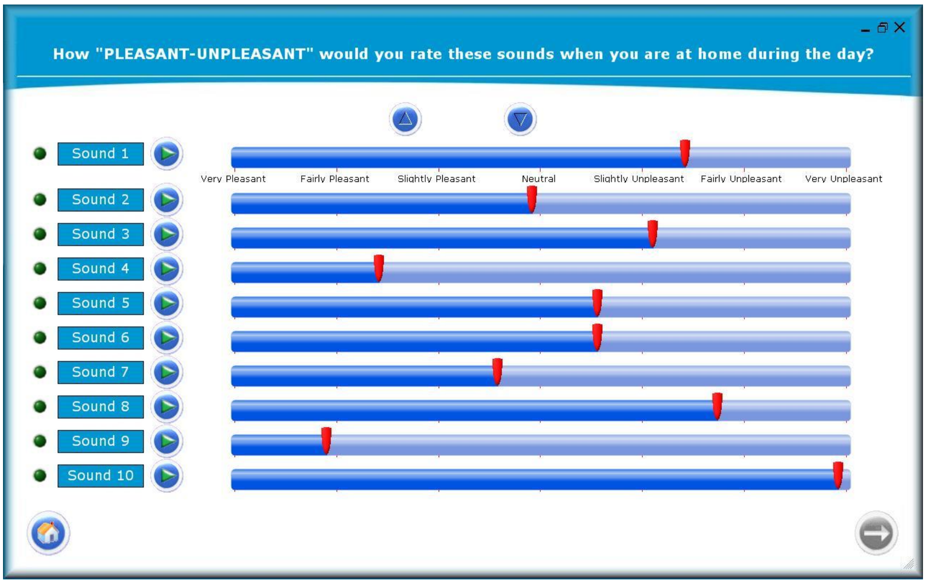

What is your level of "acoustic comfort" with this sound when you are at home during the day?

Figure 3-15: Absolute evaluation of a stimulus in Jury Testing Software

In the Jury Testing Software, absolute evaluation of the recorded 80 stimuli was programmed in 8 sessions (4 sessions consisting of road traffic sound signals each having 10 sound signals, and same for the train sound). *It is noted that Jury Testing is an advanced software for the ranking of sound on a perceptual scale. The software graphical user interface allows to program a psychoacoustic experiment in different evaluation approach (i.e. absolute evaluation, paired comparison evaluation, mixed evaluation, etc) through integration of the test signals with the rating scale and test question.* Based on the experimental design, each subject evaluated all 8 sessions with respect to aural comfort, noisiness of apartment and disturbance by noise. A snapshot of the evaluation of a stimulus in the absolute evaluation method in the Jury Testing Listening Program is shown in Figure 3-15.

B. Mixed Evaluation Approach

A mixed approach is a combination of direct and paired comparison approaches. In this approach the subject has the opportunity to evaluate a sound in the direct evaluation method and at the same time to compare it with other sounds in order to provide a comparative evaluation. This approach is a relatively new approach which has been introduced by 01-dB Metravib in the Jury Listening Software. In the mixed evaluation method, subjects can listen to any of the sounds and compare it with other sounds to provide a comparative evaluation on a continuous scale. Parizet et al. (2005, 2007) demonstrated that this method allowed for a good trade-off between quick assessment and precise pair comparison. A snapshot of the evaluation of stimuli in the mixed evaluation method in the Jury Testing Listening Program is shown in Figure 3-16.



How "PLEASANT-UNPLEASANT" would you rate these sounds when you are at home during the day?

Figure 3-16: Mixed evaluation of stimuli in the Jury Listening Software

Osgood's (1957) semantic differential (SD) scale was used for the mixed evaluation of different road traffic and train sounds in this study. This method has been used widely for different multi-dimensional evaluation studies including sound quality, soundscape etc (Kang et al, 2010; Lopez et al., 2003; Zeitler et al., 2001; Viollon et al., 2000; Kuwano et al, 1990; etc,). As shown in Table 3-13, a total of twelve adjective pairs are chosen for the multi-dimensional evaluation of the characteristics of different road traffic and MRT train noises investigated in this research. These included some common characteristics (adjective pairs) that are generally used for perceptual evaluation of sound (for example Kuwano, 2000; Schulte-Fortkamp, 1999; Fastl, 1997). The characterization of different types of sounds through such multi-dimensional evaluation is expected to be a useful tool for classifying different types of noises, their relationship with aural comfort and establishing the meaning of the sound heard.

Table 3-13: Bipolar adjectives for the semantic differential study

Evaluation	Potency	Activity
Pleasant-Unpleasant	Soft-Loud	Quiet-Busy
Relaxing-Stressful	Weak-Strong	Ignoring-Distracting
Bearable-Unbearable	Dull-Sharp	Smooth-Rough
Peaceful-Violent	Mild-Intense	Calm-Exciting

Osgood (1957) illustrated that the factor analyses of different adjectives used for affective evaluation typically return three dimensions: evaluation, potency, and activity. Here 'evaluation' is concerned with the subjects' preferences (e.g. pleasant-unpleasant, relaxing-stressful) about the attitude object (for example, noise). 'Potency' is the perception of the subjects about the strength of the attitude object (e.g. soft-loud, weak-strong). 'Activity' is concerned with whether the attitude object is perceived as active or passive (e.g. quiet-busy, ignoring-distracting). Through the evaluation of these three dimensions, as suggested by Osgood, the connotative meaning of the different types of sounds (road traffic and MRT train) were expected to be established in this research investigation.

The bipolar adjective pairs discussed above are used for establishment of the meaning of the sound heard in qualitative space. In recent psycho-physiological research studies, these dimensions are often found related to emotions.

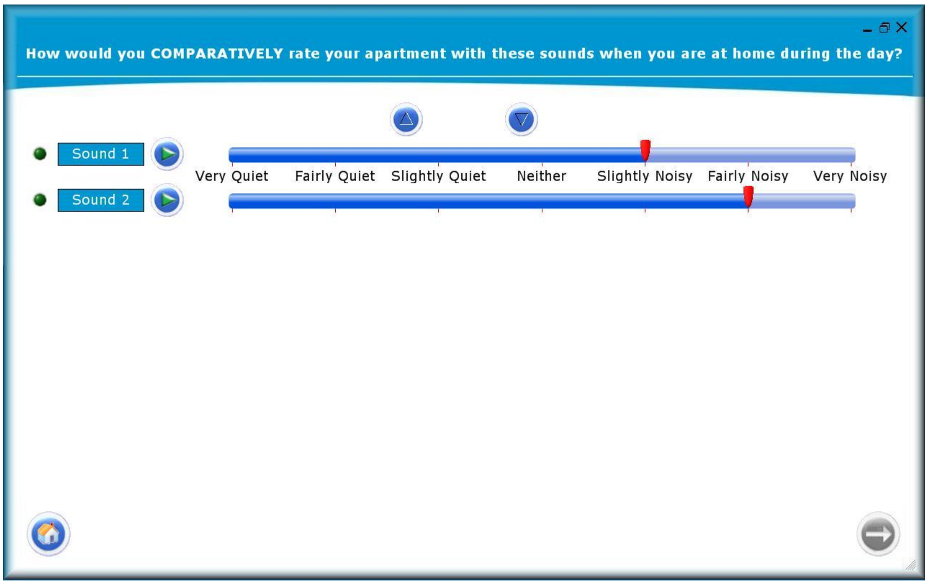
The “biphasic theory of emotion” proposed by Lang et al. (1998) describes emotion from a from a motivational perspective which states that the emotion is as a behavioural tendency of a subject to approach or avoid/withdraw from a stimulus. According to Bradley and Lang (2000), emotions are organized in two motivational systems of the brain that respond adaptively to two basic types of stimulation, appetitive and aversive. All emotional expressions (overt and covert) are determined by the dominant motivational system in the subject and by the intensity level of such a system. Hence, emotions can be organized according to this classification as pleasant/appetitive or unpleasant/aversive, and this disposition constitutes the first bipolar dimension of the model—the affective valence. As each motivational system can mobilize energy, and therefore, the activation or intensity level can vary, the model establishes a second bipolar dimension arousal whose poles are defined as calm and excitation (Lang et al., 1998). Taking into account these two orthogonal dimensions, a two-dimensional space is defined in which all emotions are located according to their affective valence and arousal (Lang et al., 1992). This affective space supports the biphasic motivational organization (appetitive and aversive) of the emotion (Bradley et al., 2000).

In this research, a mixed assessment approach was used to examine the semantic space of different road traffic and MRT train sounds for parametric studies. A total of 3 sessions were designed in this mixed approach for subjective assessment. Each session consisted of 5 road traffic sound signals and 5 MRT train sound signals in random order. As a result, for each of the twelve adjective pair evaluations a subject was required to evaluate all three sessions every time. As discussed earlier, Road Traffic sound signals were recorded at buildings facing five different categories of roads while MRT Trains sound signals were recorded at building located at different distances (between 30m and 70m at 10m interval) from the MRT track.

C. Paired Comparison Approach

The paired comparison evaluation that was used in this research was basically included in the mixed evaluation approach. This method was chosen since only two sounds could be evaluated at a time - one being road traffic sound and the other is MRT train sound - both having the same equivalent continuous sound pressure level (L_{Aeq}). This approach allowed the evaluation each of the two sounds independently on a direct evaluation scale based on a paired comparative judgment.

A snapshot of the evaluation of stimuli in the paired comparison method in the Jury Testing Listening Program is shown in Figure 3-17. Five pairs of sounds were evaluated in the paired comparison method. The first pair consisted of road traffic sounds from the expressway and train noise at 30m from the track, both having the same equivalent continuous sound pressure level (L_{Aeq}). The second pair comprised of road traffic sounds from a major arterial road and train noise at 40m from the track, both having the same L_{Aeq}.



How would you COMPARATIVELY rate your apartment with these sounds when you are at home during the day?

Figure 3-17: Paired evaluation of stimuli in the Jury Listening Software (using the mixed method)

The third pair comprised of road traffic sounds from a minor arterial road and train noise at 50m from the track, both having the same L_{Aeq}. The fourth pair consisted of road traffic sounds from a minor arterial road and train noise at 60m from the track, both having the same L_{Aeq}. The last pair comprised of road traffic sounds from local road and train noise at 70m from track, both having the same L_{Aeq}. In the paired evaluation method, 10 sound signals were programmed into the Jury Testing Software in total of 5 sessions where each session comprised of 1 road sound signal and 1 train sound signal.

Each subject was expected to evaluate a maximum of 10 sessions per day which resulted in a 30 minute 'Experimental Block' a day for a subject. The total experimental duration was about a month, starting from 18th October 2010 to 11th November 2010. A maximum of 13 subjects were scheduled per day (during weekdays only) starting from 10am.

3.14 METHODOLOGY FOR PARAMETRIC STUDIES

Examinations of psychoacoustical quantities and their inclusion in the overall aural comfort model were beyond the scope of the noise survey. This was due to the fact that it was not possible to examine the different psychoacoustical quantities of individual noise source in a complex noise environment and therefore the influence of the specific noise source on overall aural comfort remained unclear. As such, it was of utmost importance to integrate the subjective quantities of aural comfort with psychoacoustic quantities through laboratory psychoacoustic tests.

Table 3-14: Psychoacoustical quantities evaluated for road traffic and MRT train noise

Acoustical Quantities	Acoustical Indices and Description
Level	○ Lmax: Maximum level of the signal ○ Lmean: Mean Level of the signal
Loudness	○ Nmax: Max Loudness of signal ○ Nmean: Mean Loudness (or Loudness), taking into account temporal masking (ideal for non stationary signals) ○ NISO532B: Loudness according to ISO532B (Zwicker) standard ○ N_5 : Five Percentile Loudness
Sharpness	○ Smax :Max Sharpness ○ Smean: Mean Sharpness ○ S_5: Five Percentile Sharpness
Fluctuation Strength	○ Fmax: Max Fluctuation Strength ○ Fmean: Mean Fluctuation Strength ○ F_5: Five Percentile Fluctuation Strength
Roughness	○ Rmax: Max Roughness ○ Rmean: Mean Roughness ○ R5: Five Percentile Roughness
Tonality	○ F_tnr: Frequency of the maximum Tone to Noise Ratio (TNR) ○ TNR : Maximum TNR
Prominence	○ F_pr : The frequency of the maximum prominence ○ PRMax: Maximum prominence

Acoustical Quantities	Acoustical Indices and Description
	○ PRmean: Mean Prominence ○ PR: Global Prominence
Note: The definition of the psychoacoustical quantities are given in Literature Review (Chapter 2).	

For parametric studies, subjective noisiness of the apartment and disturbance due to road traffic noise and MRT train noise were evaluated in different psychoacoustical perspectives. Statistical analysis (linear regression, correlation tests) was carried out for the development of models that relate these subjective responses (noisiness and disturbance) with several psychoacoustical factors. All 80 different binaurally recorded sounds were analysed using the dBSonic software for the calculation of different psychoacoustical quantities, listed in Table 3-14.

The psychoacoustical indices that were computed to examine *Loudness* include: a) Maximum loudness of the sound signal (N_{max}), b) Mean loudness of the sound signal (N_{mean}), c) Zwicker's loudness ($NISO532B$) and d) Five percentile loudness (N_5). Zwicker's loudness ($NISO532B$) is used for stationary sound signals and the computation procedure has been standardized in DIN 45631 and ISO 532B. The dBSonic software used the standard computation method (according to DIN 45631 and ISO 532B) to compute Zwicker's loudness. Even though the sound signal under investigation is non-stationary in nature (road traffic and MRT train noise), this parameter is still used in the aural comfort study since the nature of some road traffic noise is roughly steady-state (i.e. due to constant uninterrupted traffic flow in expressway) and it may be interesting to investigate the correlations between this parameter and aural comfort. Loudness for non-stationary signals is denoted by N_{mean}. The five percentile loudness (N_5) is also examined as much research has shown its correlation with perceived noise annoyance (Fastl and Zwicker, 2006).

To examine the relationships between *Sharpness* and the independent variables in the aural comfort model, three psychoacoustical indices relating to sharpness were computed using dBSonic. These include, a) Maximum sharpness (S_{max}), b) Mean sharpness (S_{mean}) and c) Five percentile sharpness (S_5).

Almost all signals technically show modulations and fluctuations produced by periodic or stochastic processes. Therefore, in addition to Loudness and Sharpness, Roughness and Fluctuation strength were of interest for non stationary signal such as road traffic and train noise. Research has shown the relevance of these parameters in noise annoyance. The maximum, mean and five percentile roughness and fluctuation strength were computed in dBSonic and were examined for their relationship with the independent variables of the aural comfort model in this thesis.

Tonality is another psychoacoustic aspect which examines the tonal prominence of a sound. The prominence of tonal components was examined by the Tone-to-Noise Ratio (TNR) and Prominence Ratio (PR). TNR is the ratio of the power of a test tone to the power of the critical band centred on that particular tone. In dBSonic, The TNR is computed in accordance with E DIN 45681- 2002 or ANSI S1.13-1995. On the other hand, PR is defined as the ratio of the power in the critical band cantered on the tone under investigation to the mean power of the two adjacent critical bands. In dBSonic, PR is computed in accordance with the ANSI S1.13 - 1995 standard which states that a tone is prominent if its PR exceeds 7 dB (01-dB dBSonic user manual, 2005).

The models used for the computation of *Roughness* and *Fluctuation Strength*, used in dBSonic, are presented in Appendix A.

3.15 SUMMARY

Results of a preliminary noise investigation is presented in the first part of this chapter. A number of factors affecting indoor aural comfort are identified through the noise survey. Survey results revealed that 'noisiness' of an apartment is correlated to the noise 'disturbance' due to major noise sources. Daytime (6am to 6pm) has been identified as the noisiest period affecting indoor aural comfort. A research hypothesis has been proposed in this chapter which states that 'Daytime subjective aural comfort in high-rise naturally ventilated residential dwellings can be defined as a function of the daily average indoor noise exposure level, the perception of the overall noisiness at the apartment and the noise disturbance caused by road traffic and Mass Rapid Transit (MRT) train noise'.

Second part of this chapter presents the research design for assessment of aural comfort of high-rise apartment dwellers in Singapore. A novel framework is proposed for assessment of aural comfort, which is rooted in Stallen’s (1999) theory of noise annoyance and based on the theory of the Evaluation Response Model (ERM) (Eagly and Chaiken, 1993). The framework is founded on the objective and subjective assessment which are integrated for assessment of aural comfort and establish a statistical comfort model. Research methods are outlined in this chapter illustrating the approaches for objective measurement of indoor noise exposure levels, sound insulation performance of facades, party walls and floors. In addition, method for recording of binaural sounds (road traffic and train noise), their analysis and relevant psychoacoustical indices for aural comfort study is also discussed in this chapter. A multinomial logistic regression analysis is proposed for the development of an aural comfort model using subjective response data. A psychoacoustic experiment is also designed and discussed in this chapter in relation to assessing aural comfort subjected to road traffic and train noise and eventually validating the aural comfort model.

CHAPTER 4: OBJECTIVE ASSESSMENT

4.1 INTRODUCTION

This chapter presents the details and findings of the objective measurements carried out for the research projects "Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments (Project Ref. R-296-000-100-490)" by Housing and Development Board (HDB) and Department of Building, National University of Singapore and "Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore (Project Ref. R-296-000-121-490)" by Building and Construction Authority (BCA), Housing and Development Board (HDB) and Department of Building, National University of Singapore.

As discussed in Chapter 3, there is no valid tool established in Singapore to predict the façade noise exposure levels of high-rise apartments subjected to road traffic and train noise. As such, road traffic noise and train noise exposure for high-rise apartments in Singapore are therefore predicted using CRTN (UK Calculation of Road Traffic Noise standard) and CRN (UK Calculation of Railway Noise standard) standards respectively and validated through field measurements. As illustrated in the research methodology, such validation was carried out for five different categories of roads in Singapore. Noise exposures from train at different distances to buildings were also validated through extensive field investigation.

4.2 FEATURES OF HIGH-RISE BUILDINGS IN SINGAPORE

As discussed in Chapter 1, more than 80% of the resident population in Singapore live in high-rise public housing apartments. Public housing is divided into several towns which are then subdivided into neighbourhoods and precincts.

Depending on the size, a town may be divided up to nine neighbourhoods. Each neighbourhood is served by a neighbourhood commercial centre. A neighbourhood may comprise of 600 to 800 residential apartments in a number of high-rise residential buildings. Each neighbourhood is again subdivided into a number of precincts. Public housing precincts in Singapore are clusters of public housing blocks arranged as a single unit. Comprising an average of 10 blocks per precinct, they are collectively grouped into up to nine neighbourhoods. Precincts are generally designed to physically envelop a common space, or centred around some kind of communal facility.

Each public housing block is considered a vertical community, with common area built into the design to promote social interaction. Void decks, a term unique to Singapore, refers to the first level which are often left devoid of housing units, hence the word "void". These open, sheltered spaces are intentionally left empty to provide convenient spaces for communal activities such as weddings, funerals, parties, bazaars and even as polling stations. Other common permanent facilities built in void decks may include Residential Committee facilities and offices, kindergartens, medical centres, Neighbourhood Police Posts, fire posts and so on.

The objective of the public housing is to provide affordable housing based on the needs of Singapore's population. It also aims creating vibrant and sustainable towns and to ensure vibrant, active and cohesive communities. The average height of most public housing apartment blocks is 12 stories with some, the more recent development, rising to 30-50 stories. The trend is towards taller buildings with increased population growth.

Singapore has a tropical climatic condition. Tropical climate is generally characterised with uniformly high relative humidity and air temperature. Thermal uniformity in Singapore is generally emphasised by the observation that the mean monthly temperature varies by only 1.1^0C from the mean annual value of 26.6^0C. The tropical climatic condition thus pose uncomfortable hot and sticky conditions which require higher velocity of wind flow over the human body to increase efficiency of sweat evaporation.

Natural Ventilation is a key factor in achieving energy efficient design of buildings in tropical climate zones. Natural Ventilation enable occupants to reduce reliance on mechanical ventilation systems and thus reduce energy dependency and cost. Tall buildings have the advantage of being able to generate higher pressure differentials across the dwelling, making it potentially easier to achieve thermal comfort for occupants by means of natural ventilation. As such, high-rise buildings in Singapore are designed for Naturally Ventilated condition.

The key characteristics of tropical high-rise buildings are openness and shading as they are designed to provide efficient natural ventilation, and protection from the sun, rain and insects. This is why the windows at the building facades are left open for most part of the day and night time. The close proximity of these naturally ventilated high-rise buildings to major sources of noise (such as road traffic, MRT train etc.) thus expose the residents to high noise exposure level and hence compromise acoustic comfort.

4.3 METEOROLOGICAL CONDITION

All the field noise measurements were carried out between Monday and Friday in March to August 2008. Noise measurements were carried out in bright and shiny days during these months. Temperature, relative humidity and wind speed measurements were carried out at different height of the buildings at different study locations (for a period of five minutes each) during the noise measurements and are presented in Figure 4-1 to Figure 4-3.

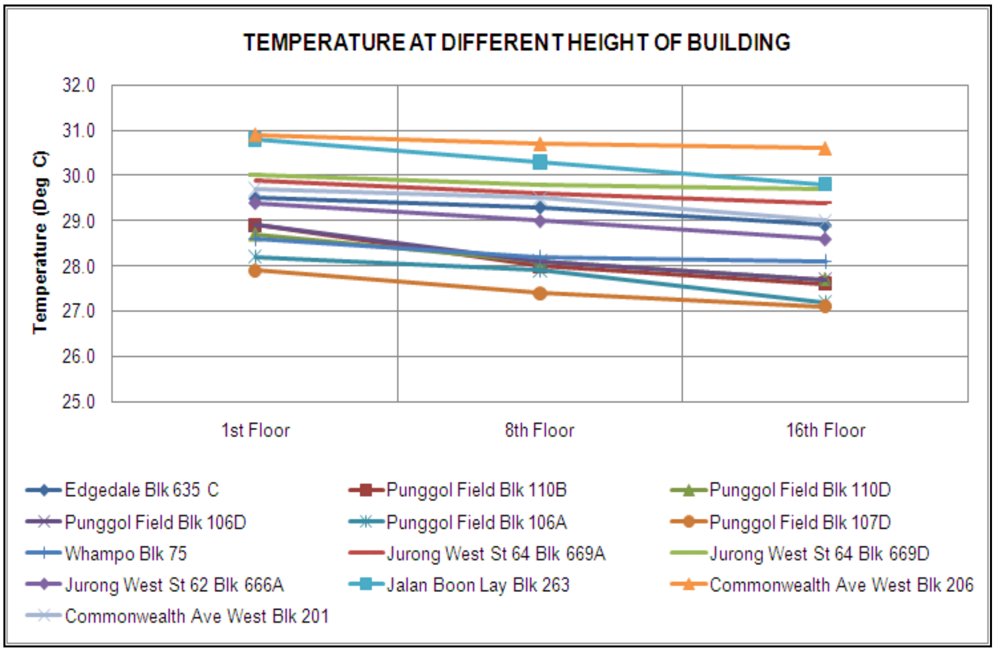


Figure 4-1: Measured temperature profile on site

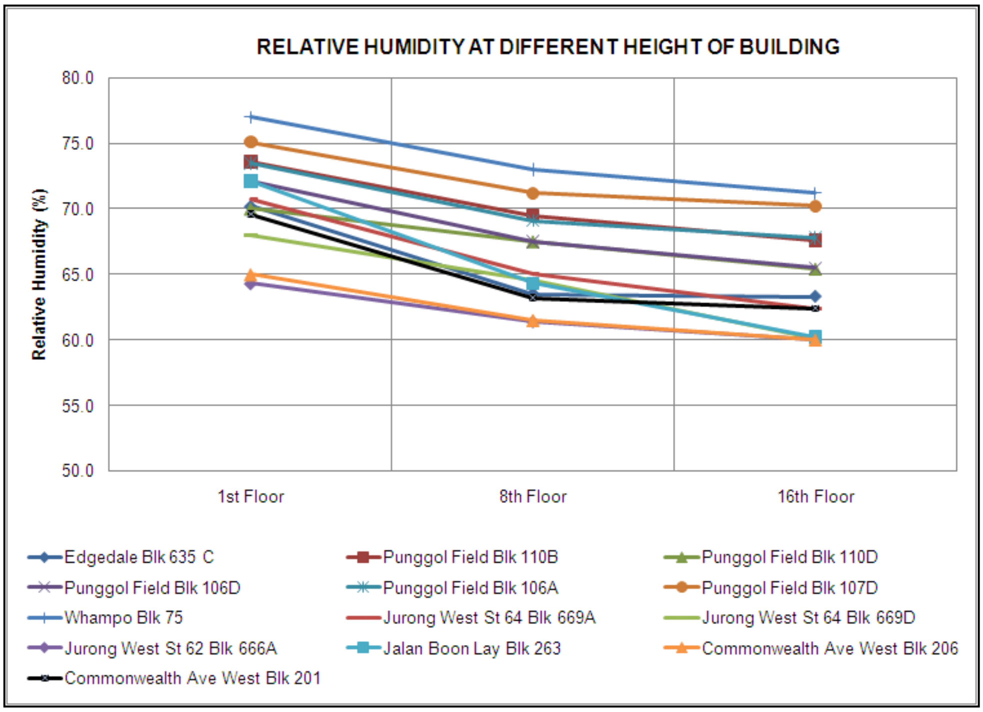


Figure 4-2: Measured relative humidity profile on site

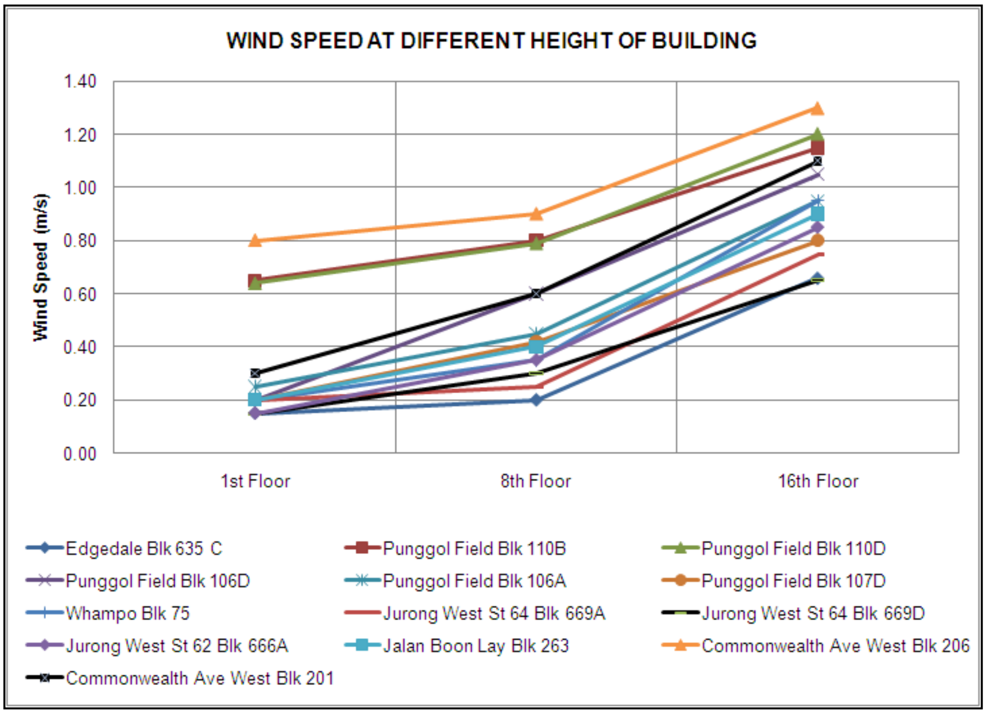


Figure 4-3: Measured wind speed profile on site

Temperature and Relative Humidity measurements were carried out with Vaisala HM34C Humidity and Temperature Meter (Accuracy: Temperature $\pm 0.3℃$ and Relative Humidity $\pm 1\% RH$). Wind Speed measurements were carried out with VelociCALC Air Velocity Meters (Accuracy: $\pm 0.015 m/s$)

4.4 EVALUATION OF FACADE NOISE LEVELS SUBJECTED TO ROAD TRAFFIC NOISE

As discussed in Chapter 3, for objective noise exposure levels of high-rise apartments subjected to different roads, two basic research methods are adopted: measurement method and predictive approach using computer simulations. The predicted results are validated with measured data. Road traffic noise was predicted using UK CRTN standard using commercial software, CadnaA. Acoustical modelling of the road traffic noise in CadnaA was carried out in two different approaches namely a) Noise Emission Method and b) Flow Input Method. For noise emission method, 18-hr noise emission levels of the noise sources were measured on site (10m away from curb, according to CRTN standard) and used in the development of the model. In contrary, road traffic noise was modelled in traffic flow input method in CadnaA using measured 18-hr traffic flow input, percentage of heavy vehicles and average traffic speed information (obtained from on site measurements by the Singapore Land Transport Authority (LTA) using smart integrated sensor system).

4.4.1 Building Facade Subjected to Expressway Road Traffic Noise

This study was carried out at Blk 75 Whampo, located next to the Central Expressway (CTE). Whampoa is an old public housing estate where a number of high-rise residential buildings are located next to the expressway. The road traffic flow count and speed of the expressway are provided by the Singapore Land Transport Authority (LTA, Singapore). The traffic data were collected using LTA's integrated road sensors and traffic camera system. The 18-hrss traffic volume (between 0600 hrs and 2400 hrs) was 240,714 vehicles and the average traffic speed (between 0600 hrs and 1800 hrs) was 79 km/hr.

The measured and predicted facade noise levels at different elevations of the building are graphically presented in Figure 4-4. The test statistics for the mean difference between the measured and predicted noise level at all the receiver locations are presented in Table 4-1. The test statistics demonstrate that the predicted facade noise levels modelled with the noise emission level are in very good agreement with the measured noise levels (maximum mean difference 1.19 dB) whereas predicted facade noise levels modelled with traffic flow vary appreciably (maximum mean difference 9.9 dB) and therefore have been excluded from this research.

To examine the propagation of noise levels from the Expressway, receivers were modelled in CadnaA at different intervals from the nearside road curb and along the elevations of the building. Predicted façade noise levels are graphically presented in

Figure 4-5. The noise profiles established in this figure help in estimating the façade noise exposure level of apartments located at varying distances between the road and the building. The noise profiles established in this study are of very similar nature of the same studied by Chew (1994) for buildings up to a height of 30m along expressway.

According to the recent building design guideline (URA, 2011), a buffer distance of 30m between the residential building and the nearside curb of the expressway is required. In earlier days, the building to road distance was even as low as 5 meters.

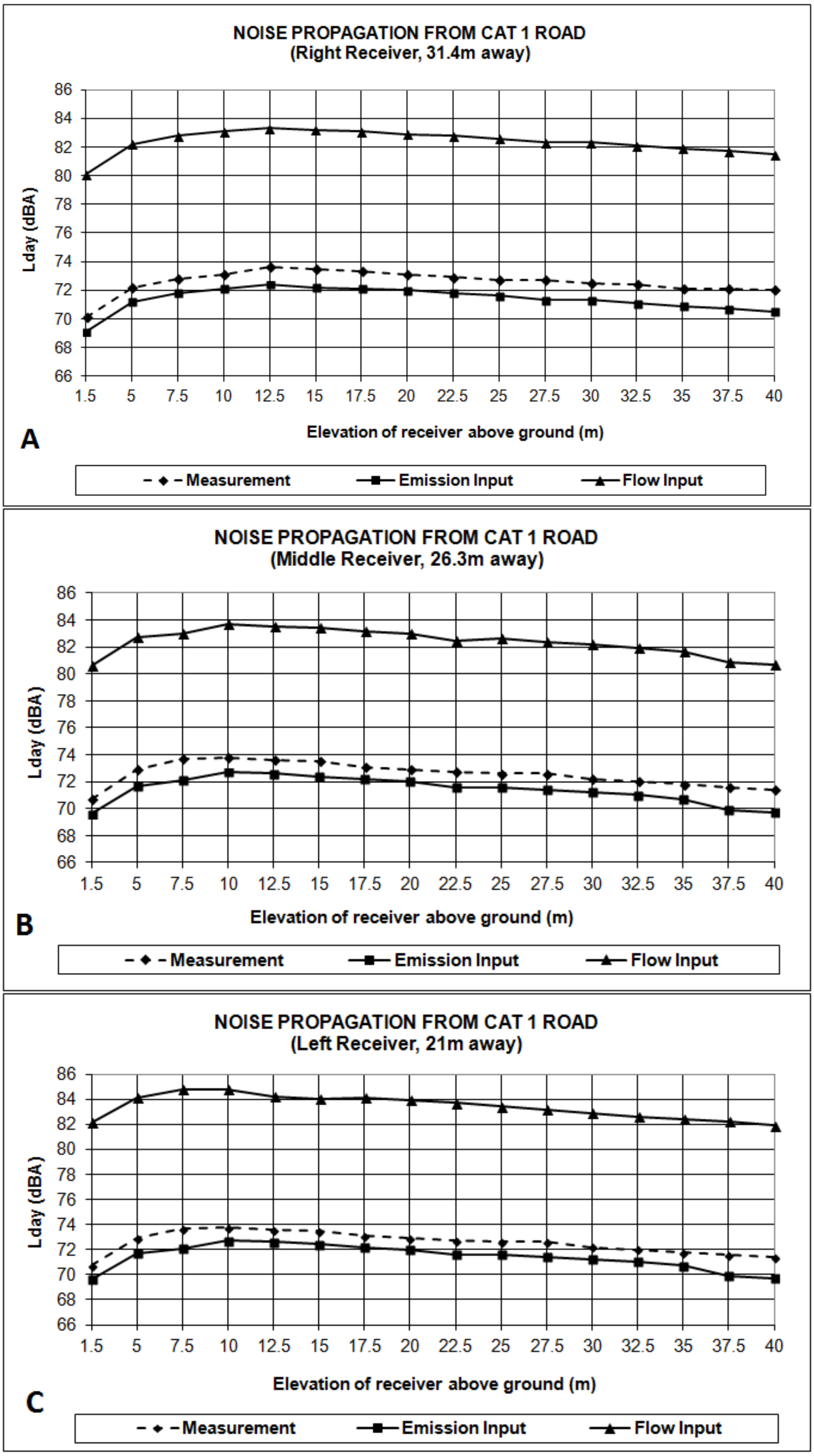


Figure 4-4: Predicted and measured façade noise levels subjected to expressway

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Table 4-1: Statistics for variation between measured and predicted results

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

		Mean Difference Between Measured and Predicted (Emission Input) Noise Level	**Mean Difference Between Measured and Predicted (Flow Input) Noise Level**
Right Receiver, 31.4m away	Mean	1.19	-9.80
	95% CI	0.08	0.08
Middle Receiver	Mean	1.17	-9.81
	95% CI	0.14	0.14
Left Receiver	Mean	1.03	-9.90
	95% CI	0.16	0.16

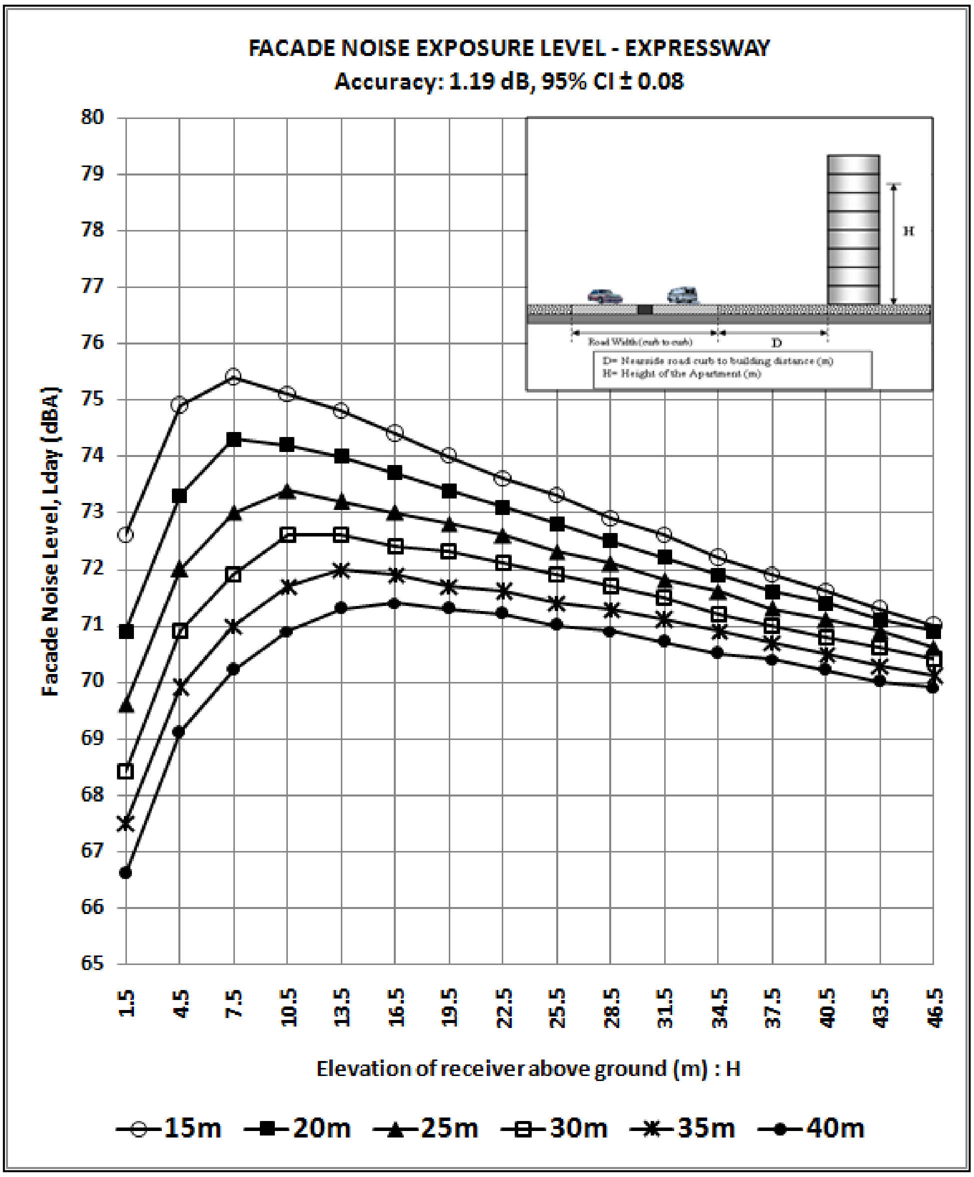


Figure 4-5: Noise profile of high-rise apartments subjected to Expressway noise

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

However, from Figure 4-5 it can be seen that the facade noise levels of building located at 30m (assuming a similar road traffic flow condition) ranges between A-weighted noise levels of 68 dB and 73 dB. *As a result, naturally ventilated buildings located next to the expressway are exposed to very high level of noise (as compared to an acceptable outdoor A-weighted noise level of 55 dB).*

4.4.2 Building Facade Subjected to Major Arterial Road Traffic Noise

Building facade subjected to major arterial road were evaluated at Clementi along the Commonwealth Avenue West road. Clementi is an old public housing estate where a number of high-rise residential buildings are located next to the road. The measurement location, traffic flow information and measured road noise emission levels are presented in Appendix B. Predicted and measured noise levels along the building elevation are presented in Figure 4-6 (A and B).

Statistical analysis showed that the maximum mean difference between predicted and measured facade noise levels for the acoustical model with noise emission information was found to be 0.34 dB with a 95% confidence interval of ±0.13. On the other hand, the maximum mean difference between measured and predicted noise levels with traffic volume modelling was found 1.77 dB with a 95% confidence interval of ±0.13. The predicted noise levels with noise emission model were therefore found in very good agreement with the measured noise level from the Major Arterial road.

A noise profile chart has been established in Figure 4-7 to predict the façade noise levels of high-rise apartments for different road (major arterial road) to building distances. According to the building design guideline (URA, 2011), a buffer distance of 15m is required for buildings near major arterial road. It is, however, noted from Figure 4-7 that the facade noise levels of the building located at this distance (assuming similar road traffic flow condition) range between A-weighted noise levels of 65 dB and 69 dB. *As a result, buildings located next to major arterial roads are exposed to very high level of noise (as compared to the acceptable outdoor A-weighted noise level of 55 dB) due to the provision of open windows for natural ventilation.*

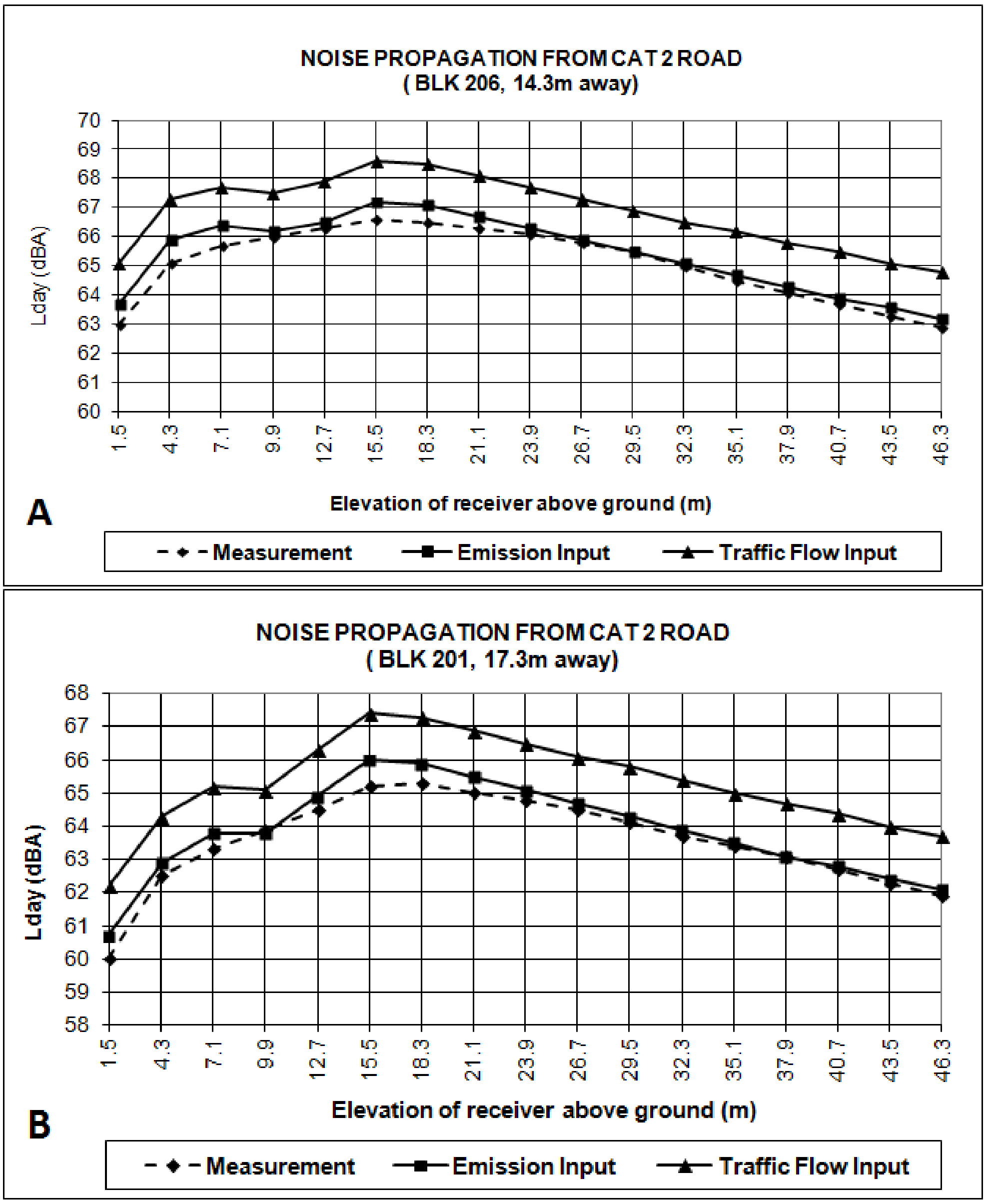


Figure 4-6: Predicted and measured façade noise levels for a Major Arterial Road

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

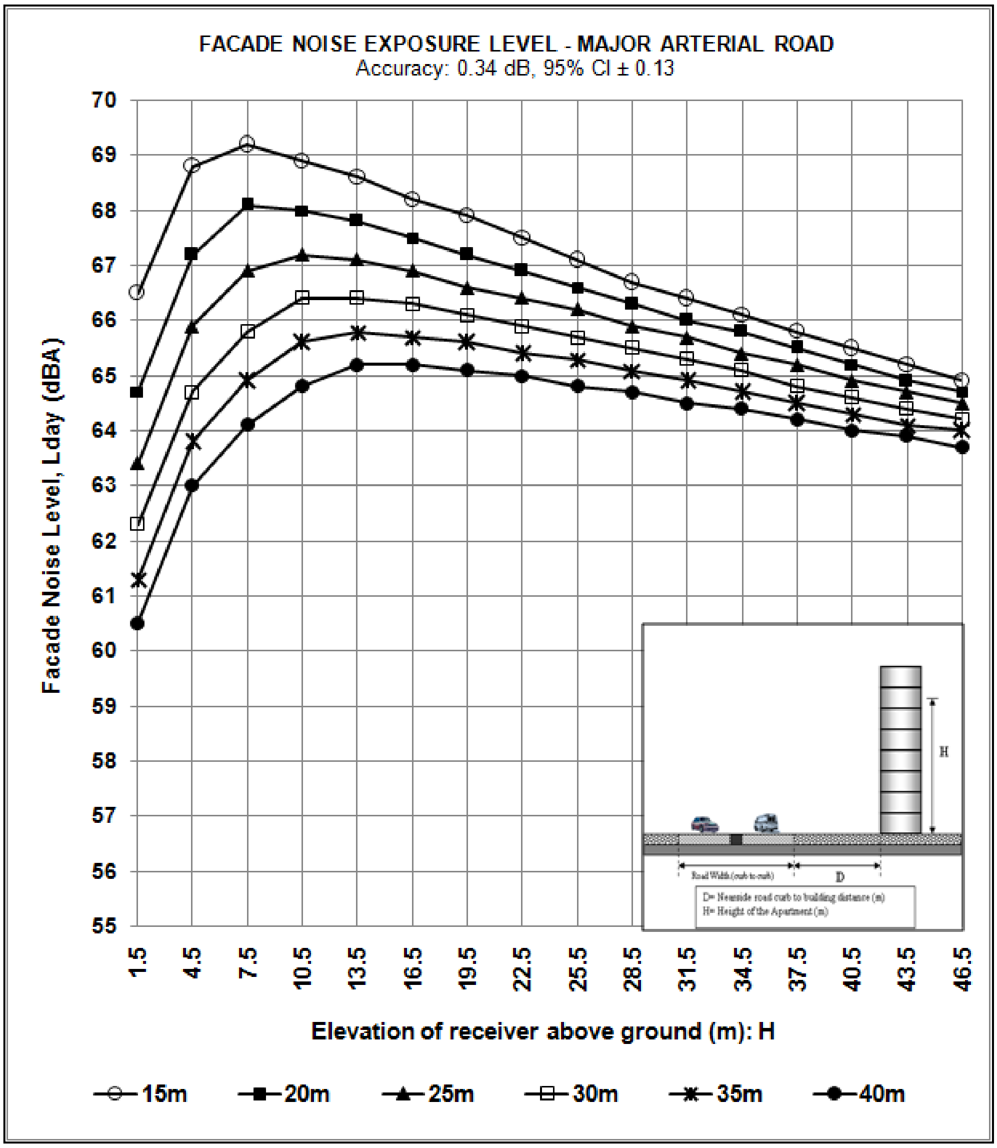


Figure 4-7: Noise profile of high-rise apartments subjected to a Major Arterial Road Noise

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

4.4.3 Building Facade Subjected to Minor Arterial Road Traffic Noise

Traffic information and measured road noise emission level for this study is presented in Appendix B. Measured and predicted facade noise levels at different receiver locations at the study site are presented in Figure 4-8. Statistical analysis showed that the maximum mean difference between predicted and measured noise levels with the noise emission model was found to be 0.23 dB with a 95% confidence interval of ±0.06.

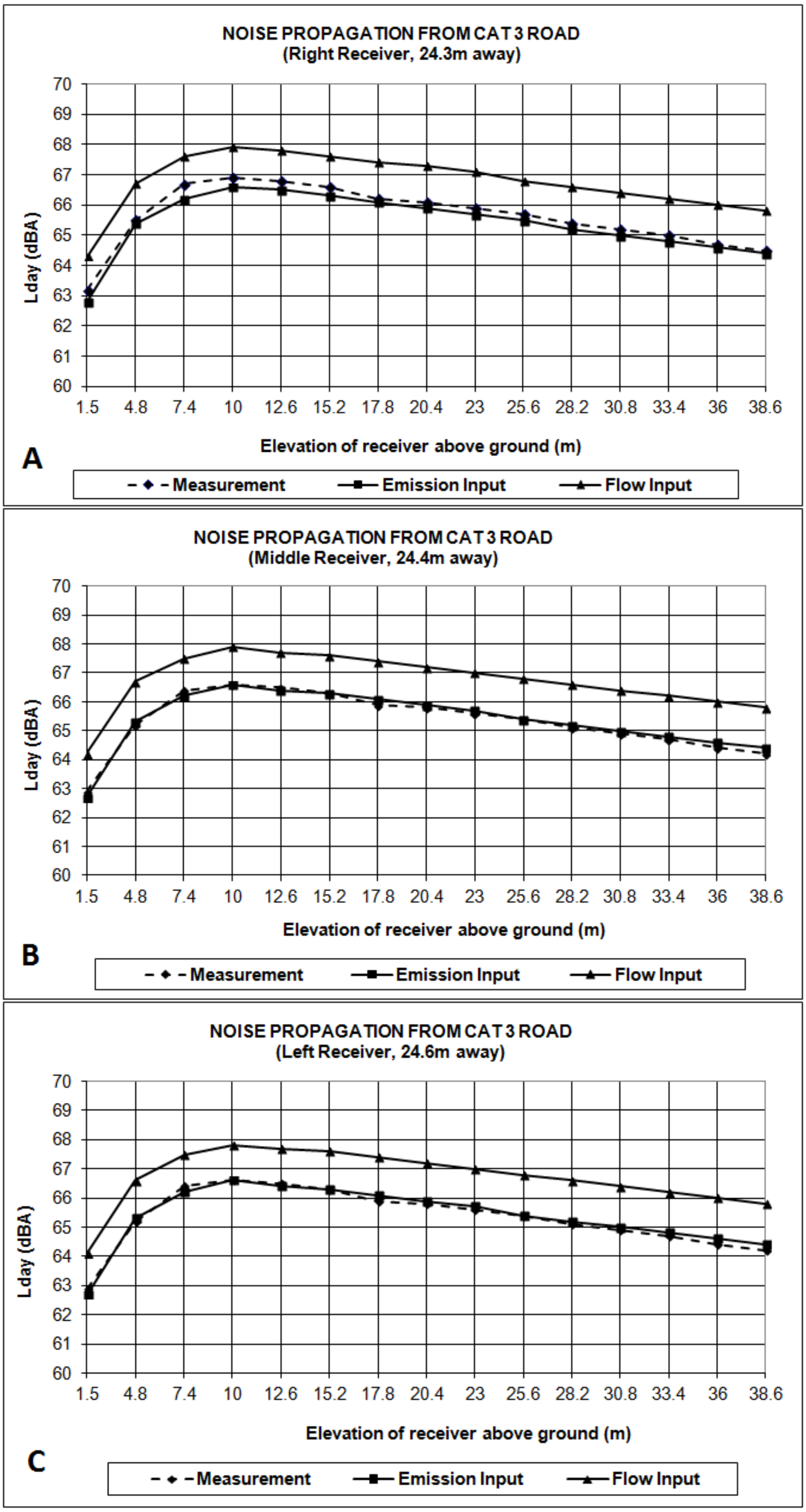


Figure 4-8: Predicted and measured façade noise levels for a Minor Arterial Road

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

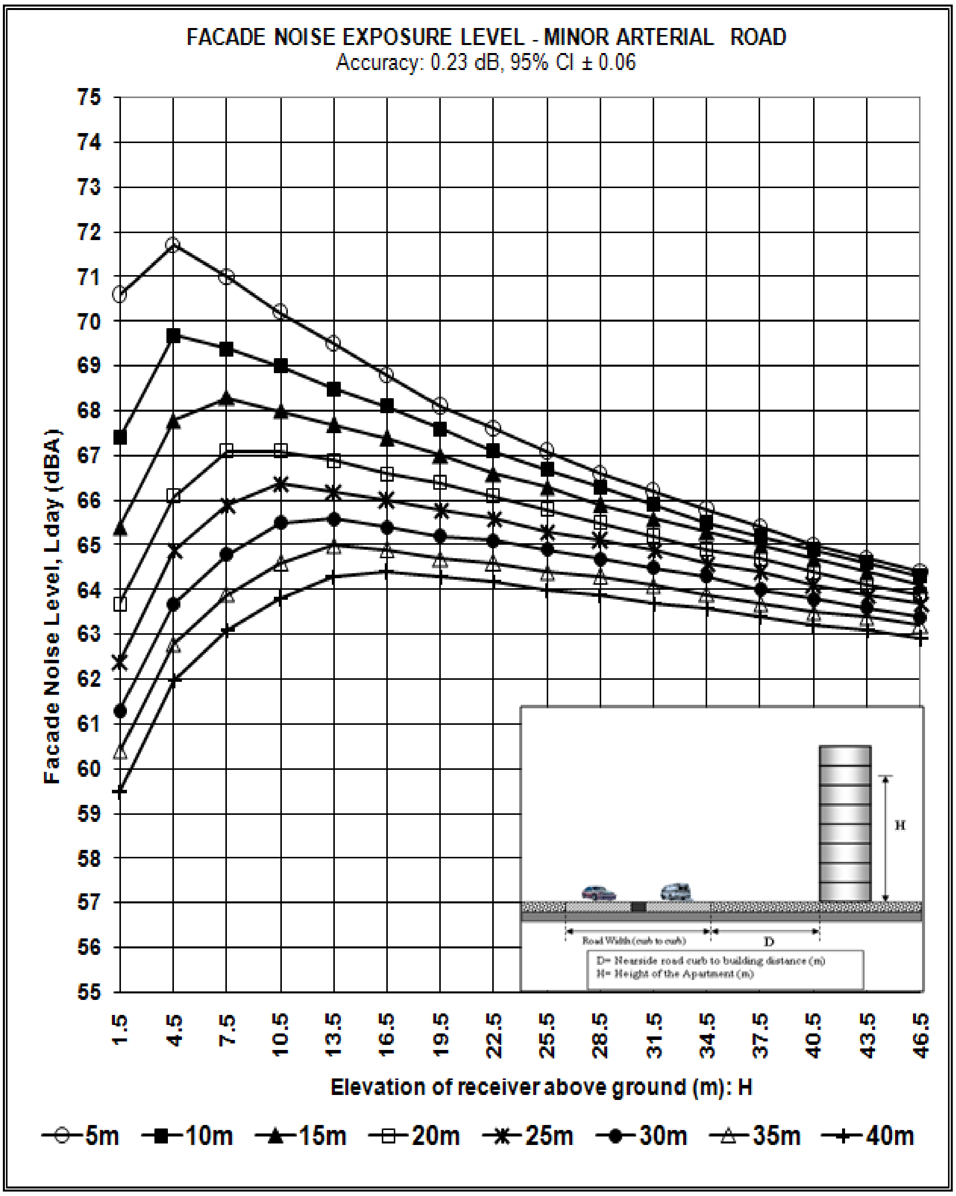


Figure 4-9: Noise profile of high-rise apartments subjected to Minor Arterial Road Noise

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

The maximum mean difference for the same in model with traffic flow was found to be 1.41 dB with a 95% confidence interval of ±0.08. The predicted façade noise levels by emission level modelling input are therefore found to be in very good agreement with the measured noise level from the Minor Arterial road.

Noise profile charts were established and presented in Figure 4-9 to predict the façade noise levels of high-rise apartments for varying road (minor arterial road) to building distances. According to the building design guideline (URA, 2011), a buffer distance of 10m is required for buildings near a minor arterial road. It is noted from Figure 4-9 that the facade noise levels of building located at this distance (assuming similar road traffic flow condition) ranges between A-weighted noise level of 65 dB and 70 dB. *As a result, buildings located next to minor arterial roads are exposed to considerable high level of noise (as compared to the acceptable outdoor A-weighted noise level of 55 dB) due to the provision of open window for natural ventilation.*

4.4.4 Building Facade Subjected to Primary Access Road Traffic Noise

Evaluation of façade noise levels subjected to a primary access road was carried out at Punggol residential estate along the Punggol Field road. Punggol is a new public housing estate where a number of high-rise residential buildings are located next to the road. Traffic information and measured road noise emission level for this study is presented in Appendix B. Measured and predicted facade noise levels at different receiver locations at the study site are presented in Figure 4-10. The maximum mean difference between measured and predicted noise levels with the noise emission model was found to be 0.89 dB with a 95% confidence interval of ±0.07.

On the other hand the maximum mean difference between measured and predicted levels in the model with traffic flow was 0.63 dB with a 95% confidence interval of ±0.09. The predicted noise levels by the emission level modelling input were therefore found to be in very good agreement with the measured noise level from the Primary Access road.

Noise profile charts were established and presented in Figure 4-11 to predict the façade noise levels of high-rise apartments for varying road (primary access road) to building distances. According to the building design guideline (URA, 2011), a buffer distance of 7.5m is required for buildings near a primary access road.

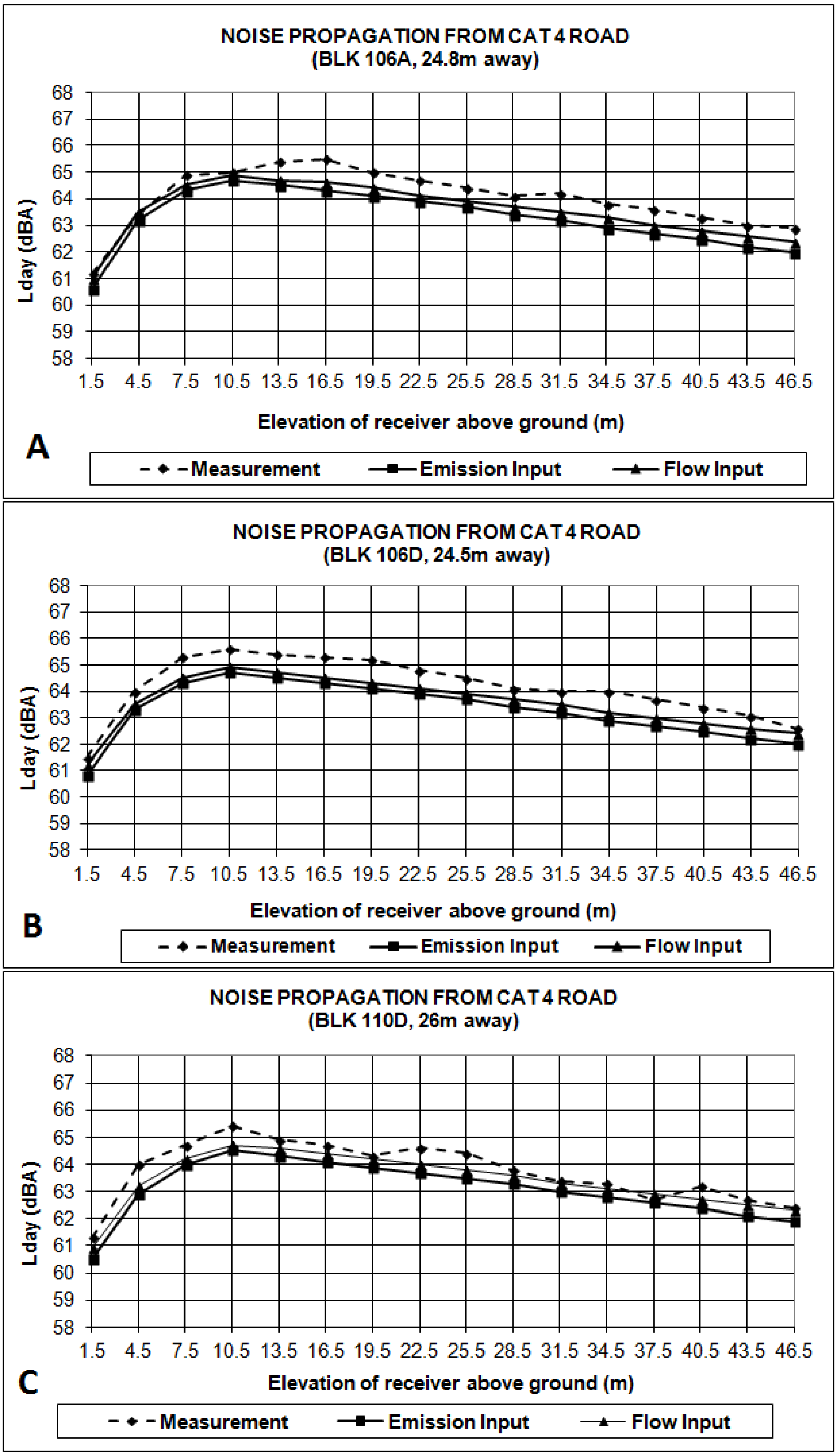


Figure 4-10: Predicted and measured façade noise levels for Primary Access Road

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

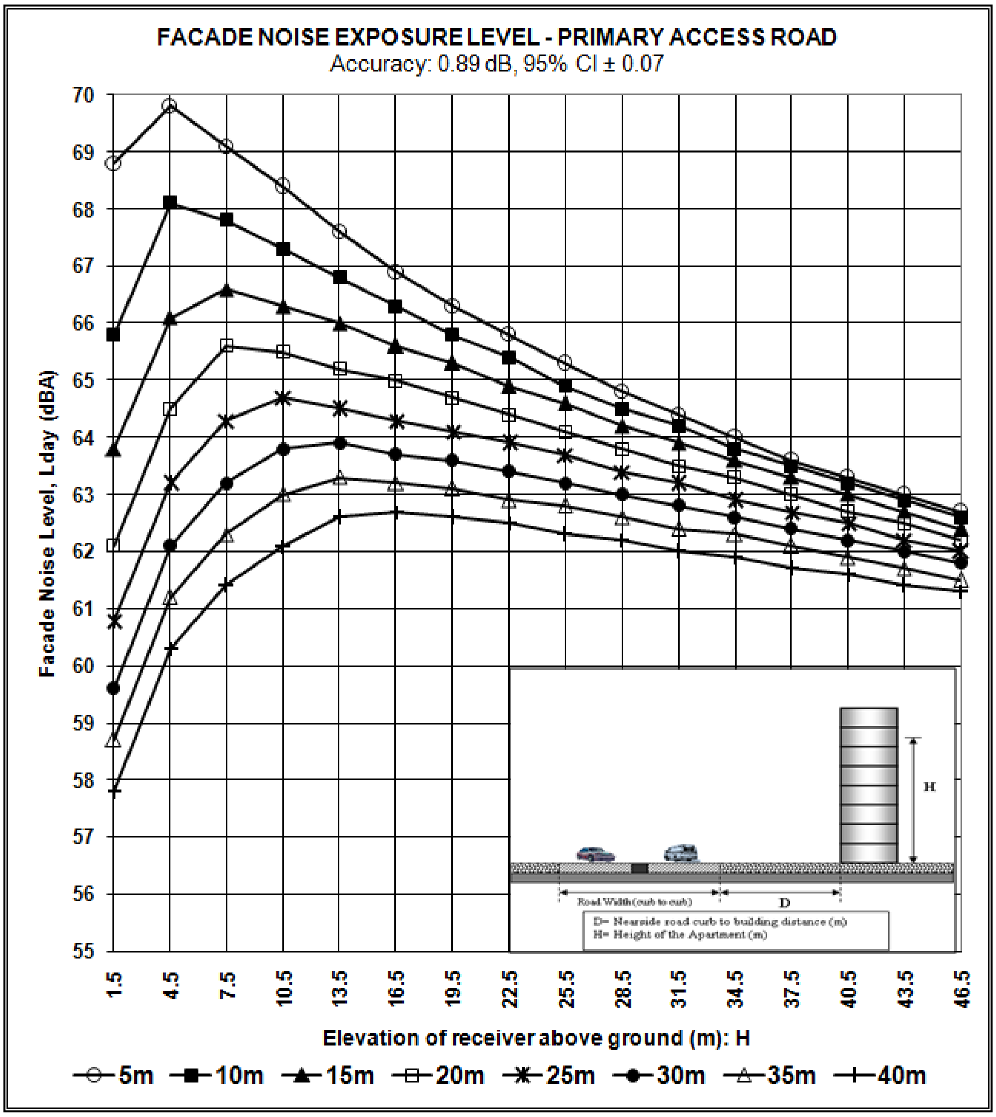


Figure 4-11: Noise profile of high-rise apartments subjected to a Primary Access Road

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

From Figure 4-11 it is seen that the facade noise levels of a building located at this distance (assuming similar road traffic flow condition) ranges between A-weighted noise level of 64 dB and 69 dB. *As a result, buildings located next to primary access roads are exposed to considerably high levels of noise (as compared to the acceptable outdoor A-weighted noise level of 55 dB) due to the provision of open window for natural ventilation.*

4.4.5 Building Facade Subjected to Local Road Traffic Noise

This study was carried out at Jurong West residential estate along Jurong West St 64. Jurong West is a new public housing estate where a number of high-rise residential buildings are located next to the road. Traffic information and measured road noise emission level are presented in Appendix B. Measured and predicted facade noise levels at different receiver locations at the study site are presented in Figure 4-12.

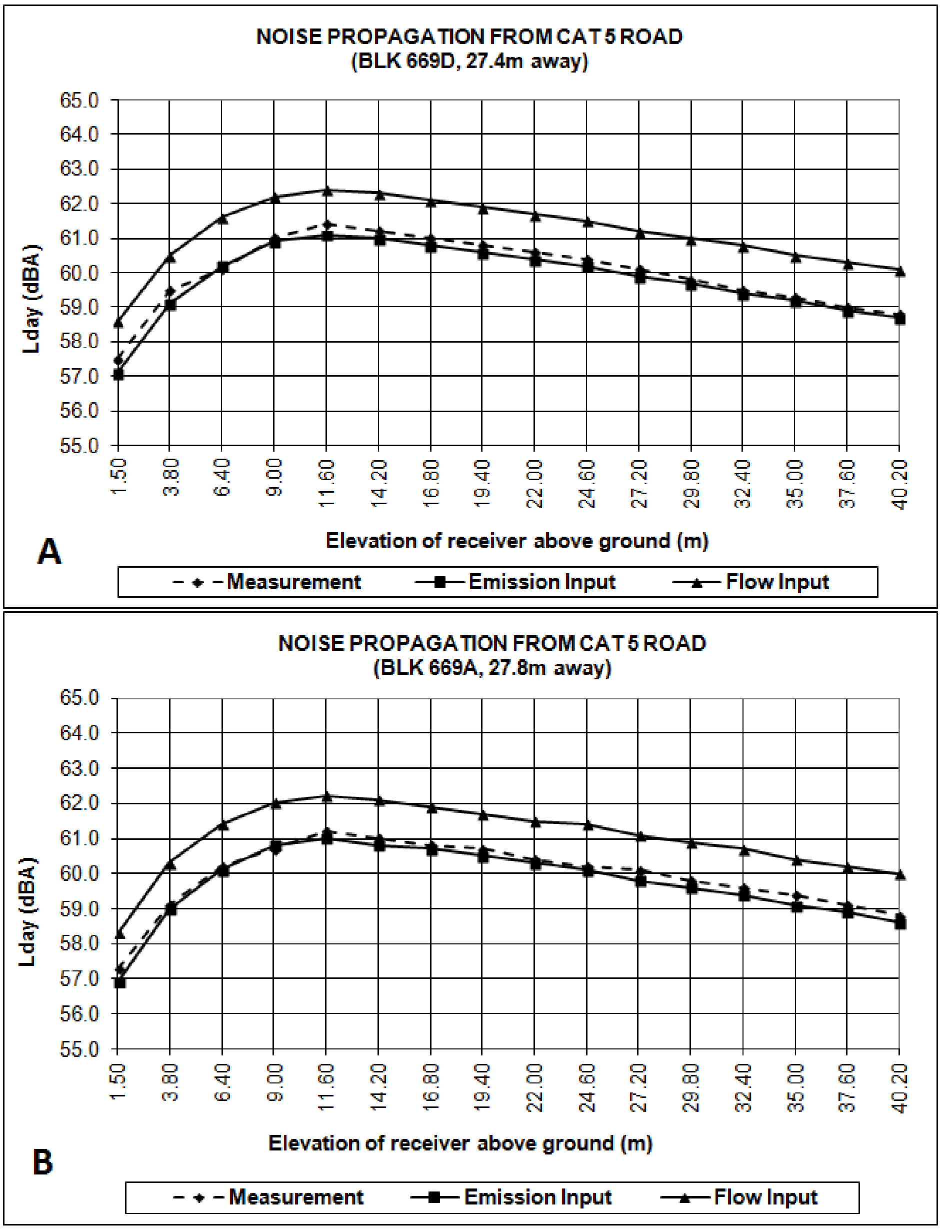


Figure 4-12: Predicted and measured façade noise levels for Local Road

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Statistical analysis showed that the maximum mean difference between measured and predicted noise levels in the model with noise emission were found to be 0.18 dB with a 95% confidence interval of ±0.06. The maximum mean difference between measured and predicted levels in the model with traffic flow was found to be 1.17 dB with a 95% confidence interval of ±0.07. The predicted noise levels by the noise emission model were therefore found to be in very good agreement with the measured noise level from the Local road.

Noise profile charts were established and presented in Figure 4-13 to predict the façade noise levels of high-rise apartments for varying road (local road) to building distances. According to the building design guideline (URA, 2011), a buffer distance of 7.5m is required for buildings near local road.

From Figure 4-13 it is seen that the facade noise levels of a building located at this distance (assuming similar road traffic flow condition) ranges between A-weighted noise levels of 60 dB and 66 dB. *As a result, buildings located next to local roads are exposed to elevated levels of noise (as compared to the acceptable outdoor A-weighted noise level of 55 dB) due to the provision of open window for natural ventilation.*

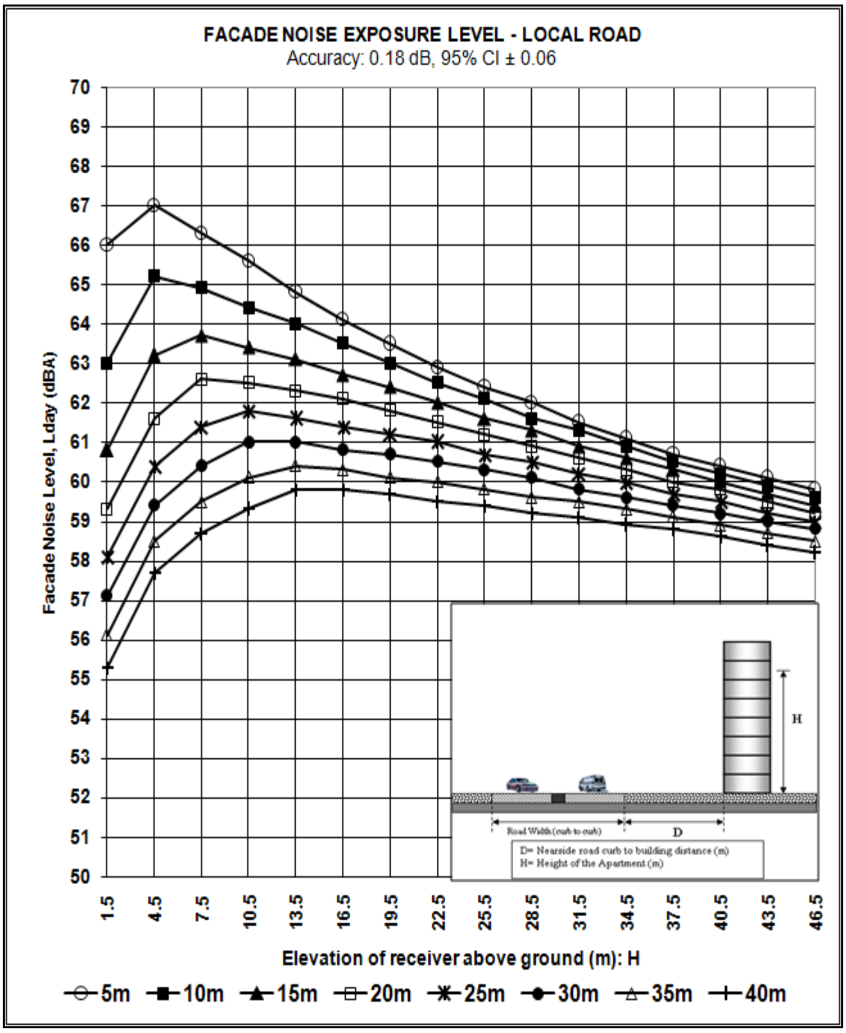


Figure 4-13: Noise profile of high-rise apartments subjected to Local Road Noise

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

4.4.6 Discrepancies Between Predicted Façade Noise Levels in the Model with Traffic Flow Data and Measured Data

It is observed throughout the road noise study that the predicted facade noise levels when modelled with road traffic flow input method were generally high as compared to the measured facade noise exposure levels. This is obvious for cases with relatively high road traffic volume, in particular for an expressway. The analysis showed that the computed noise emission level (as per the CRTN standard) was higher when compared to the measured noise emission levels on site (refer to Figure 4-14). This implies that the UK CRTN road traffic noise emission level does not hold true for

Singapore roads. This is probably due to different road traffic composition in two countries. It is important to note that the Noise Emission Levels predicted by UK CRTN standard is established based on the road traffic composition and speed in their context. This could be resolved by establishing a regression model based on the measured road noise emission level for different road traffic volume (with different composition of traffic) and speed information in Singapore.

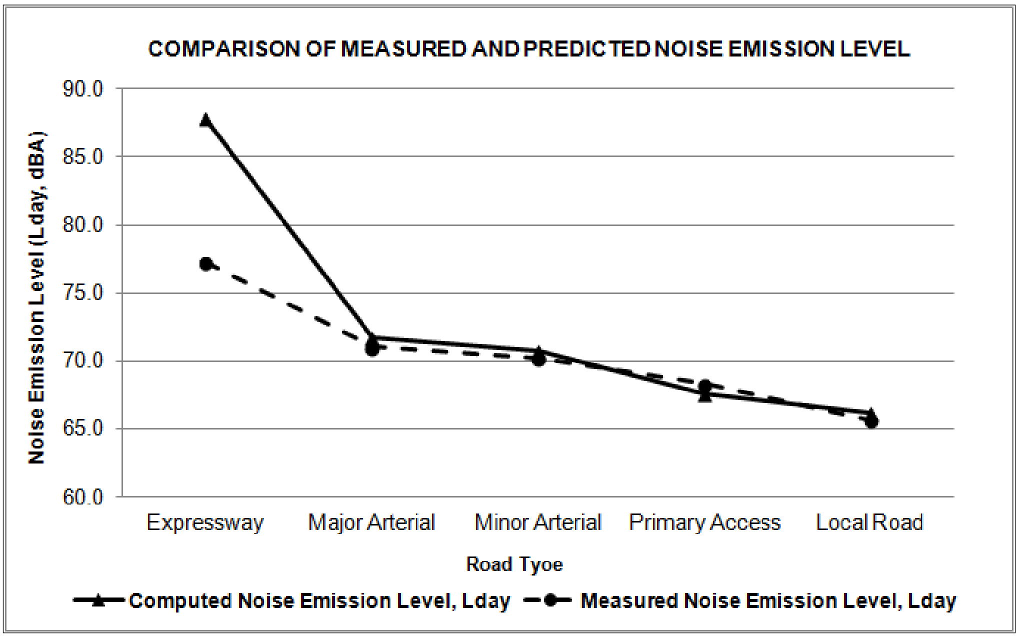


Figure 4-14: Computed (as per CRTN) and measured noise emission levels for different categories of roads

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

4.5 EVALUATION OF FACADE NOISE LEVELS SUBJECTED TO MRT TRAIN NOISE

The evaluation of facades noise evaluation subjected to MRT train noise was carried out along Commonwealth Avenue West (after Clementi Station). The track for which the noise emission was measured is part of the East West Line. Photograph of the location, measured train noise emission level, measured noise level at the reference locations are presented in Appendix B. Predicted and measured façade noise levels are shown in Figure 4-15.

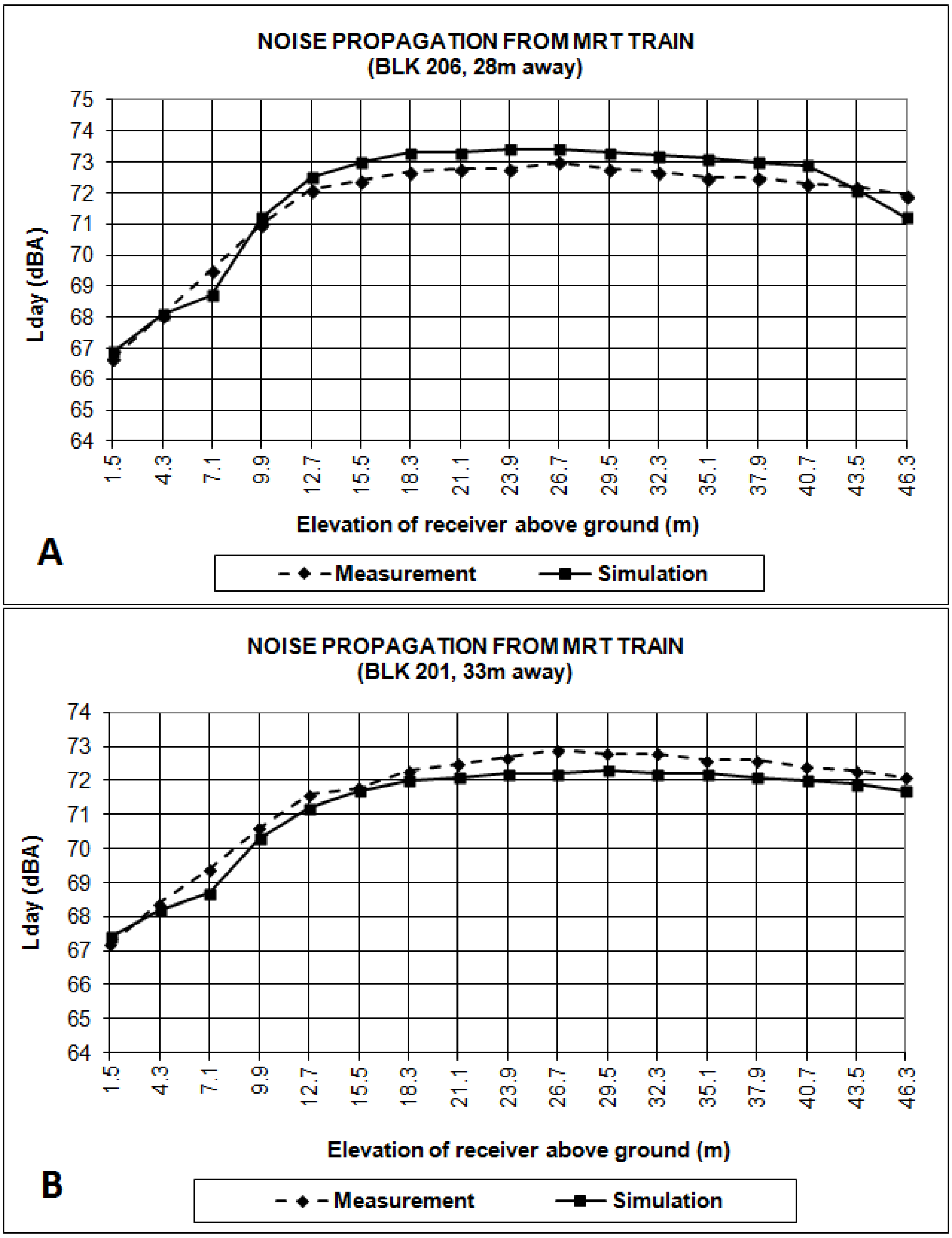


Figure 4-15: Predicted and measured façade noise levels for the MRT Train

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

The study was carried out at two residential buildings along the Commonwealth Avenue West which are approximately parallel to and facing the MRT track.

Measured noise emission level of the MRT train was found to be 72.5 dB with a confidence interval of ±0.4. Basic information about the MRT train, obtained from Singapore Mass Rapid Transport (SMRT) authority, is presented below:

- Running speed of train = 41 km/hr
- Maximum speed = 80 km/hr
- No. of Cars in a train : 6
- Length of each car = 23.65m
- Height of Train = 3.69m

Reference sound level meters were placed at the ground floor of the buildings under study to measure the average daily noise exposure due to the MRT train. $L_{Aeq,20s}$ was measured for each of the fifteen train runs and the average of these was considered to be the daily average MRT noise level at 1.5m above the ground. Measured A-weighted noise levels of 66.7 dB and 67.2 dB were established as the daily average noise levels at a distances of 33m and 28m away from the centre of the nearside rail track respectively. The measured and predicted facade noise exposure levels of apartments at different height of the buildings are graphically presented in Figure 4-15. It can be observed that noise level generally increase with the increase in building elevation. The increase in noise level is maximum, with respect to the reference noise level at ground floor (at a 1.5m height), at a height of 26.7m. The maximum increases of noise level with height at 28m and 33m away from the nearside MRT track centre are 6.3 dB and 5.7 dB respectively. The test statistics for the mean difference between the measured and predicted facade noise levels show that the maximum mean difference between measured and predicted facade noise levels is 0.39 dB with a 95% confidence interval of ±0.11. Therefore, it is found that the predicted facade noise levels are in very good agreement with the measured facade noise levels from MRT train noise.

Further modelling was carried out using CadnaA to evaluate the noise exposure levels of facades subjected to MRT Train noise for different track to building distances. The predicted results are plotted in Figure 4-16. According to the local building design norm, a buffer distance of 30-35m is required for buildings near MRT Track. From Figure 4-16 it is noted that the facade noise levels of a building located at this distance ranges between A-weighted noise levels of 67 dB and 72 dB. *As a result, buildings located next to MRT tracks are exposed to elevated level of noise (as compared to the acceptable outdoor A-weighted noise level of 55 dB) due to the provision of open window for natural ventilation.*

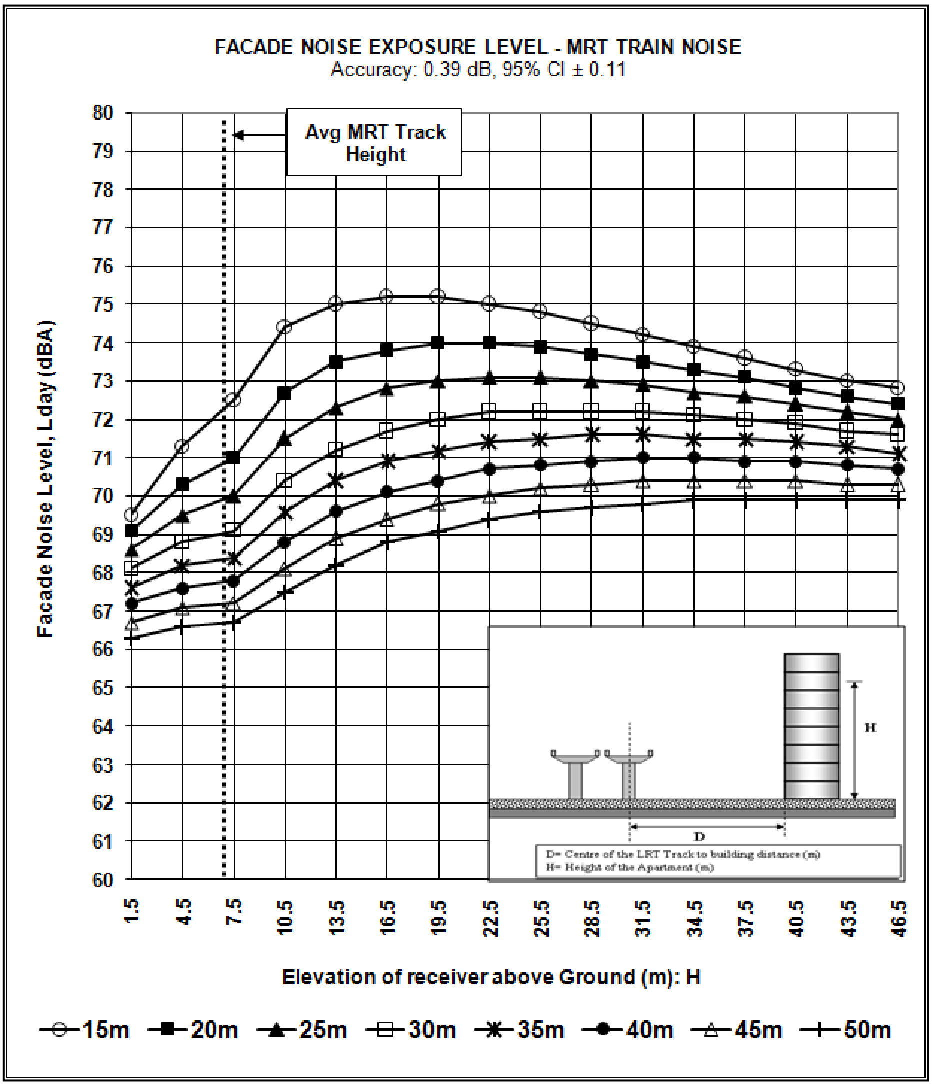


Figure 4-16: Noise profile of high-rise apartments subjected to MRT train Noise

(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

4.6 SOUND TRANSMISSION LOSS PERFORMANCES OF FACADE, PARTY WALLS AND FLOORS

In this section acoustical performances of several building façades, party walls and floors commonly used in the public housing apartments in Singapore are presented. The data presented in this section are extracted from *Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore*

4.6.1 Acoustical Performance of Facades

Measured (in the field condition) sound insulation performances of different types of façades are presented in Figure 4-17.

Acoustical performances of façades were tested with all windows closed and also with the opening of a single window panel. The measurements were carried out in this manner in order to examine the degree of sound insulation provided with a minimum opening of a window as well as the sound insulation of façade when all windows are closed. The decision to open one window at the façade was the result of the noise survey (discussed in Chapter 3) which showed that over 90% of the respondents opened at least one window in their room, for natural ventilation, during their stay at home. It can be observed from Figure 4-17 that the provision of natural ventilation, i.e. by opening one window panel, drastically reduces the insulation performance of the facade. The facade reaches its poorest acoustical performance when all the windows in the room are opened to accommodate full natural ventilation.

The lowest sound insulation performance, of all facades types tested, was observed for the half height window with metal and glass louver (Noise Isolation Class, NIC 18 dB). This type of facade is generally used in the old residential developments and are generally no longer used in newer buildings. Opening the top part of this type of window reduce its performance at least by half. Of the full height glass façades used in recent days, full height (3 Panels) window at living room (6mm thickness) shows a better performance (NIC 31 dB) than the average (NIC 25~26 dB) provided by other facades. This may be due to the continuity of the glass along the full height of the apartment resulting in fewer openings between the window frames when compared to the general casement windows.

However, an average Noise Isolation Class (NIC) of 25 to 26 dB is achieved by other glass facade elements used in recent times (windows closed). Interestingly it is noted that with the opening of one window panel, the resulting sound insulation performance of the facade is very poor and ranges between NIC of 9 dB and 14 dB. It is clear that the opening of all or most of the windows within the space would further reduce the sound insulation of the facade and thus allow the free flow of outdoor noise into the indoor environment. In general, it can be concluded that the sound insulation performance of a facade with a window open is approximately NIC 11 dB. It is noted that the measure of NIC will not provide an accurate assessment of the true facade performance. However, in this case, the ascertained value is to use to analysis a subjective assessment of indoor aural comfort. Hence, the use of NIC which relates close to the actual sound level heard and perceived is deemed sufficient for this purpose.

4.6.2 Airborne Sound Transmission Loss Performance of Party Walls

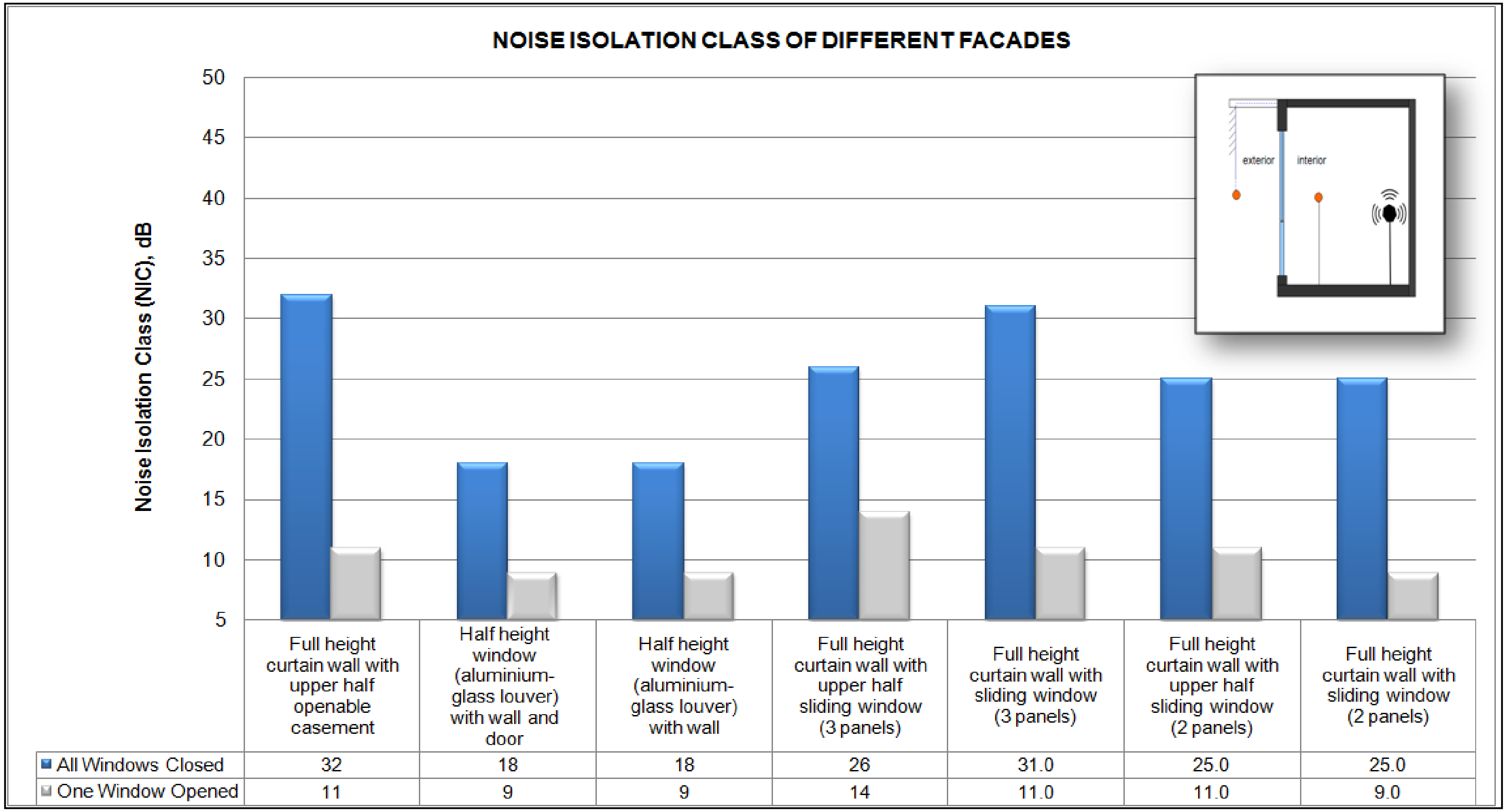
The airborne sound transmission loss performance of party walls between dwelling units were measured in several new and old residential buildings. A total of 9 different types of walls were tested in the field condition. The acoustical rating of different types of walls are presented in Figure 4-18.

Reinforced Concrete (RC) walls of 100mm thickness are generally used in modern public housing apartments and RC walls of 150mm and 200mm thickness and brick walls of 230mm thickness are commonly used in newer private housing apartments. The airborne sound transmission loss rating of different types of party walls are used in conjunction with the subjective responses of the respondents (from the noise survey discussed in Chapter 5) to investigate the influence of neighbour noise on aural comfort.

4.6.3 Impact Sound Transmission Loss Performance of Floors

A total of 15 different types of floors were tested in the field condition for examination of impact sound transmission loss performance. Acoustical rating of different types of floor are presented in Figure 4-19.

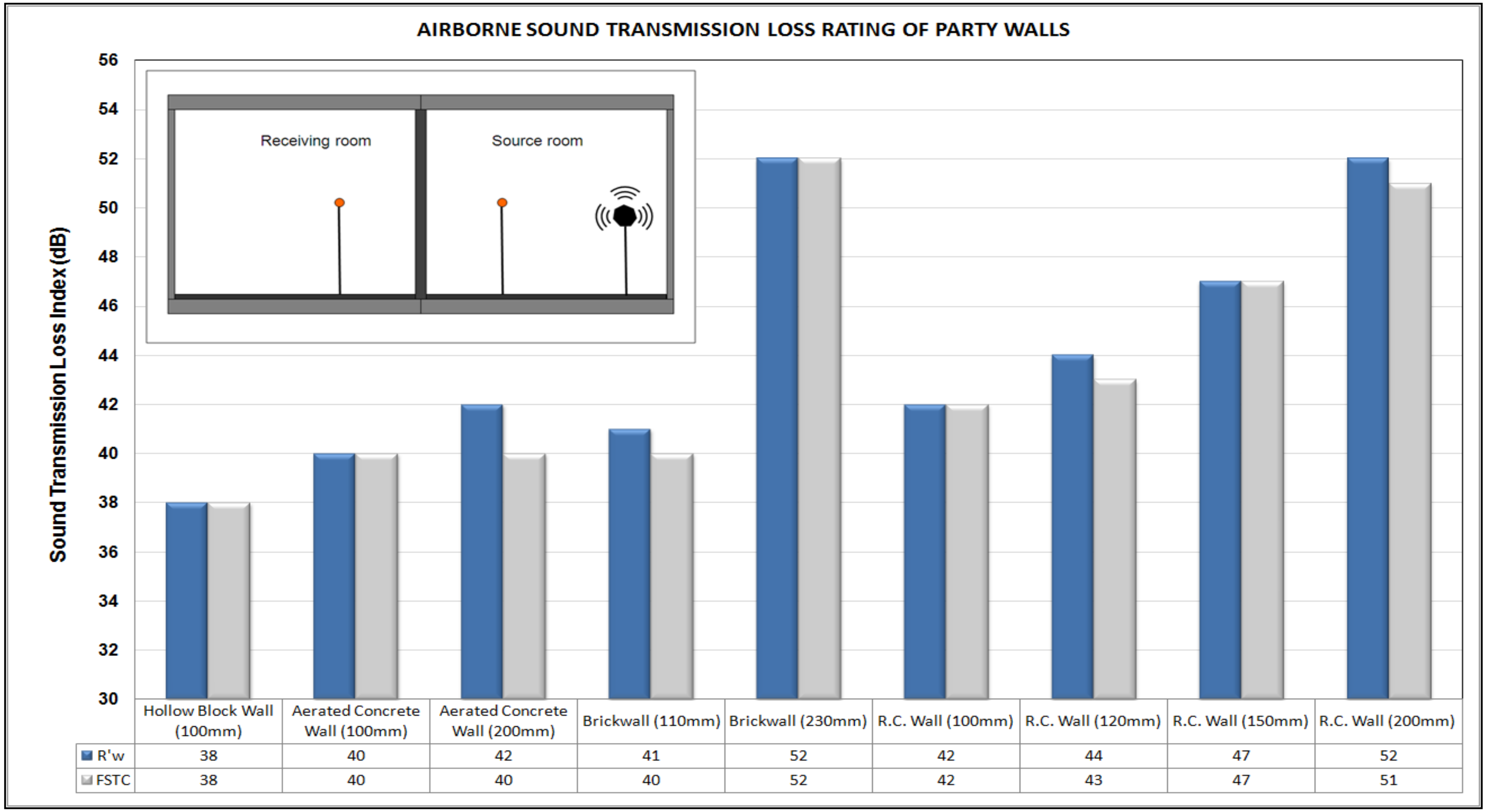
RC floor of thickness 150mm (bare concrete floors) are generally used in public housing apartments. The impact sound transmission ratings of different floors are used in conjunction with the subjective responses of the respondents (survey discussed in Chapter 5) to examine the influence of neighbour noise on aural comfort.



	Full height curtain wall with upper half openable casement	Half height window (aluminium-glass louver) with wall and door	Half height window (aluminium-glass louver) with wall	Full height curtain wall with upper half sliding window (3 panels)	Full height curtain wall with sliding window (3 panels)	Full height curtain wall with upper half sliding window (2 panels)	Full height curtain wall with sliding window (2 panels)
🟦 All Windows Closed	32	18	18	26	31.0	25.0	25.0
⬜ One Window Opened	11	9	9	14	11.0	11.0	9.0

Figure 4-17: Measured acoustical performances of different types of facades

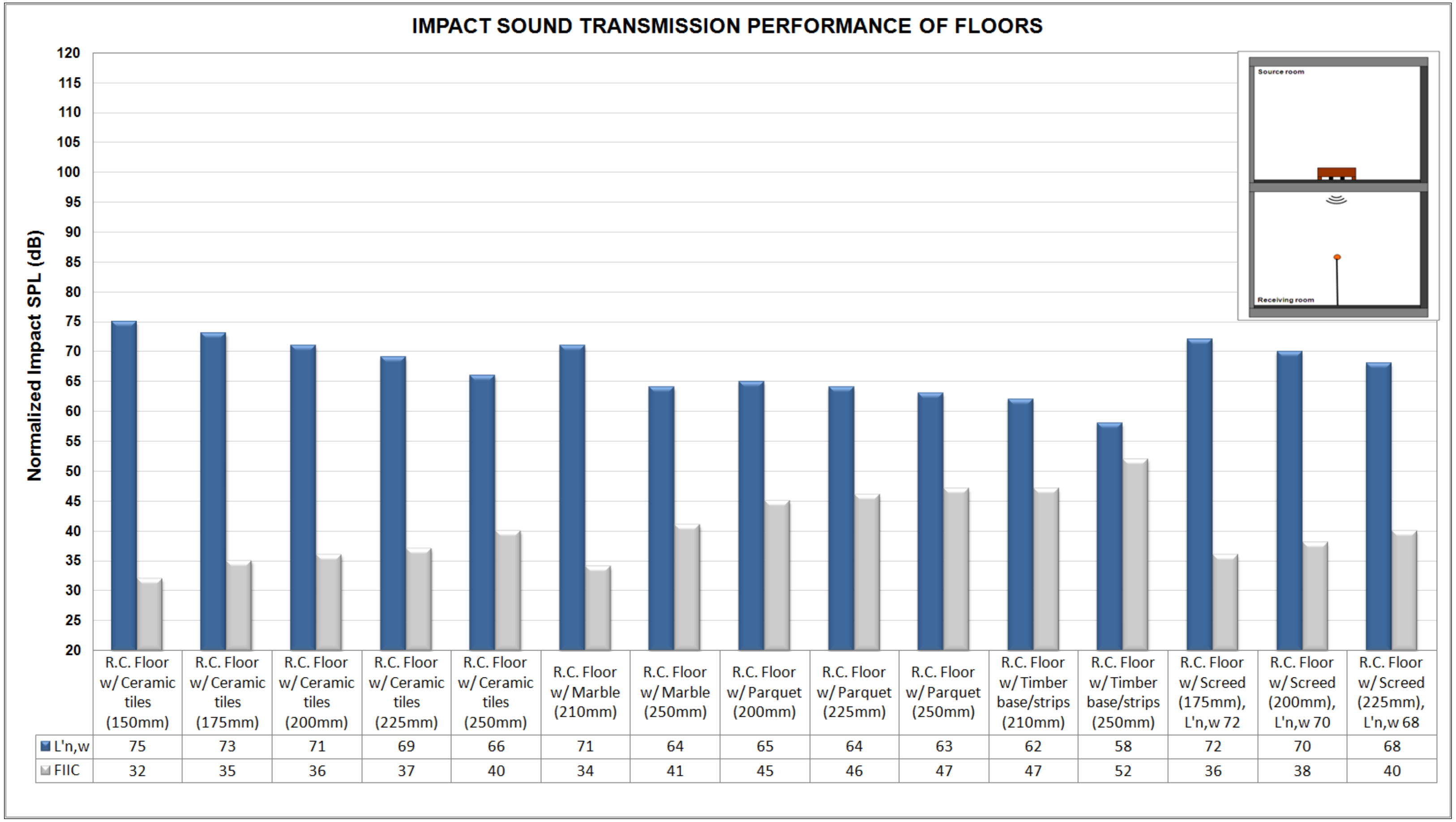
(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)



	Hollow Block Wall (100mm)	Aerated Concrete Wall (100mm)	Aerated Concrete Wall (200mm)	Brickwall (110mm)	Brickwall (230mm)	R.C. Wall (100mm)	R.C. Wall (120mm)	R.C. Wall (150mm)	R.C. Wall (200mm)
■ R'w	38	40	42	41	52	42	44	47	52
▨ FSTC	38	40	40	40	52	42	43	47	51

Figure 4-18: Airborne sound transmission loss rating of party walls

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)



	R.C. Floor w/ Ceramic tiles (150mm)	R.C. Floor w/ Ceramic tiles (175mm)	R.C. Floor w/ Ceramic tiles (200mm)	R.C. Floor w/ Ceramic tiles (225mm)	R.C. Floor w/ Ceramic tiles (250mm)	R.C. Floor w/ Marble (210mm)	R.C. Floor w/ Marble (250mm)	R.C. Floor w/ Parquet (200mm)	R.C. Floor w/ Parquet (225mm)	R.C. Floor w/ Parquet (250mm)	R.C. Floor w/ Timber base/strips (210mm)	R.C. Floor w/ Timber base/strips (250mm)	R.C. Floor w/ Screed (175mm), L'n,w 72	R.C. Floor w/ Screed (200mm), L'n,w 70	R.C. Floor w/ Screed (225mm), L'n,w 68
■ L'n,w	75	73	71	69	66	71	64	65	64	63	62	58	72	70	68
■ FIIC	32	35	36	37	40	34	41	45	46	47	47	52	36	38	40

Figure 4-19: Impact sound transmission rating of floors

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

4.7 SUMMARY

Propagation characteristics of road traffic noise, train noise and facade noise levels subjected to these sources are discussed in this chapter. As noted in this chapter that high-rise buildings in Singapore are generally located 30m away from the road curb and 50m away from the MRT track. From the establish noise charts for different categories of Roads and MRT Train, mean facade noise exposure levels at different height of a building at these distances are presented in Table 4-2 below.

Table 4-2: Predicted Facade noise levels subjected to Road and MRT Train noise

Elevation of Noise Receiver above Ground	Building to Road Distance 30m					Building to MRT Track Distance 50m
	Cat 1 Rd	Cat 2 Rd	Cat 3 Rd	Cat 4 Rd	Cat 5 Rd	MRT Train Track
	Predicted Mean Facade Noise Exposure Levels of Apartments, dBA					
1.5m - 7.5m	70.4	64.3	63.3	61.6	59.0	66.5
7.5m - 13.5m	72.4	66.2	65.3	63.6	60.8	67.5
13.5m - 19.5m	72.4	66.3	65.4	63.7	60.8	68.7
19.5m - 25.5m	72.1	65.9	65.1	63.4	60.5	69.4
25.5m - 31.5m	71.7	65.5	64.7	63.0	60.1	69.7
31.5m - 37.5m	71.2	65.1	64.3	62.6	59.6	69.9
37.5m - 43.5m	70.8	64.6	63.8	62.2	59.2	69.9

It has been established from the preliminary noise survey that an outdoor measured noise level of 55 dBA is considered as an acceptable level to 95% of the sampled population. A comparison of this acceptable level with the predicted mean facade noise levels in Table 4-2 shows that the noise exposure levels are significantly higher than the acceptable noise level.

Test results for Facade showed that approximately 11 dB noise reduction is achieved with an window open condition. This provides an understanding of the indoor noise level as summarised below.

Table 4-3: Predicted Indoor noise levels subjected to Road and MRT Train noise

Elevation of Noise Receiver above Ground	Building to Road Distance 30m					Building to MRT Track Distance 50m
	Cat 1 Rd	Cat 2 Rd	Cat 3 Rd	Cat 4 Rd	Cat 5 Rd	MRT Train Track
	Predicted Mean Indoor Noise Levels of Apartments, dBA					
1.5m - 7.5m	59.4	53.3	52.3	50.6	48	55.5
7.5m - 13.5m	61.4	55.2	54.3	52.6	49.8	56.5
13.5m - 19.5m	61.4	55.3	54.4	52.7	49.8	57.7
19.5m - 25.5m	61.1	54.9	54.1	52.4	49.5	58.4
25.5m - 31.5m	60.7	54.5	53.7	52	49.1	58.7
31.5m - 37.5m	60.2	54.1	53.3	51.6	48.6	58.9
37.5m - 43.5m	59.8	53.6	52.8	51.2	48.2	58.9

Subjective noise survey carried out in next chapter establishes the acceptable indoor noise level which will give an understanding of the indoor aural comfort in high-rise residential dwellings (comparing the levels established in Table 4-3) .

CHAPTER 5: SUBJECTIVE ASSESSMENT AND DEVELOPMENT OF THE AURAL COMFORT MODEL (ACM)

5.1 INTRODUCTION

This chapter presents the details and findings of the noise survey (stratified sampled population) carried out for the research projects "Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore (Project Ref. R-296-000-121-490)" by Building and Construction Authority (BCA), Housing and Development Board (HDB) and Department of Building, National University of Singapore.

This chapter focuses on the analysis of major environmental noise exposure (road traffic and train noise) on the residents of high rise apartments through their subjective responses. This is achieved by adopting a stratified sample of residents living in the vicinity of these noise sources. With the categorization of the samples according to noise source type, the noise survey aimed to determine residents' subjective responses about neighbour noise and the factors that influence it. Indoor noise exposure levels of the individual apartments surveyed were computed from the noise profile charts established from objective assessments (Chapter 4) and the measured mean noise insulation performance of facades. The computed indoor noise exposure levels of the apartments were then correlated with the subjective responses of the respondents with respect to environmental and neighbour noise. Refer to Chapter 4 for detailed survey methodology. The subjective responses on aural comfort then underwent regression analysis for the development of an Aural Comfort Model (ACM). Relationships between subjective responses to neighbour noise and objective indoor noise levels and sound transmission performances of party walls are also investigated in this chapter.

5.2 STRATIFIED SAMPLED NOISE SURVEY RESULTS

A total of 604 public households were surveyed in 20 locations in Singapore. Noise measurements for short period (30 sec) were carried out inside the residential apartments at the end of each survey to establish an acceptable day-time indoor noise level. The noise survey was conducted in the month of February 2009 through to March 2009 between Mondays to Saturdays from 10am to 6pm under dry weather conditions. Temperature, relative humidity and wind speed measurements were carried out at each site during the survey. A total of 6 measurements (2 minutes each) for each meteorological parameter were carried out around the building perimeter where the survey was conducted. Figure 5-1 shows the mean values of temperature, RH and wind speed at the survey sites.

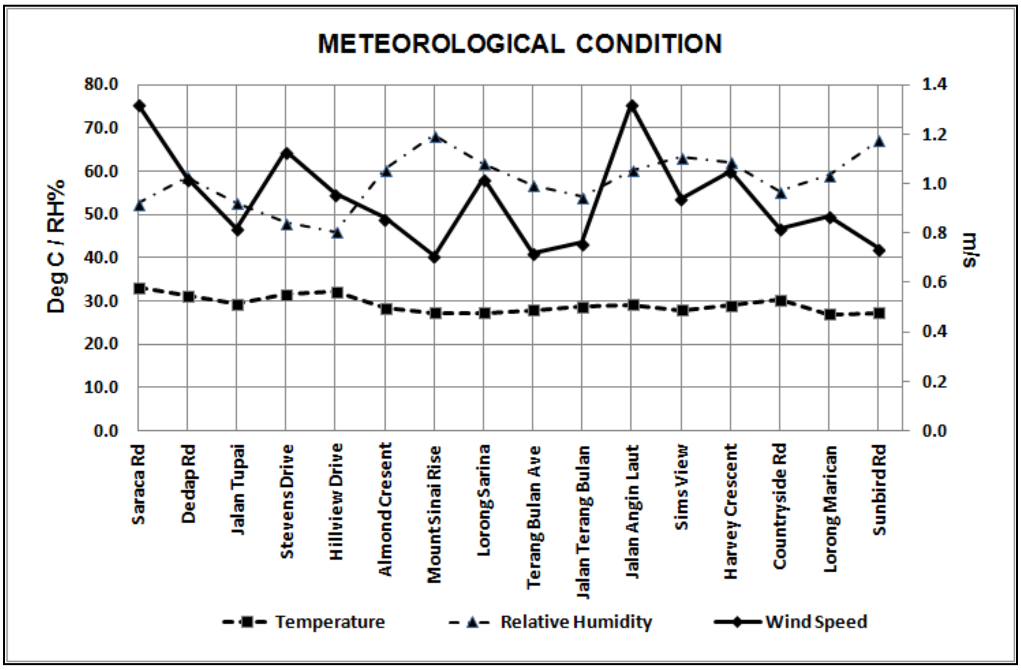


Figure 5-1: Temperature, relative humidity and wind speeds at survey locations

This study was carried out entirely to investigate daytime aural comfort, hence night time noise measurement and relevant comfort studies are excluded from this research. Survey sites were selected such that there were no existing nearby construction sites in the vicinity of the residential development under investigation during the survey. Aircraft noise was probably unavoidable in some housing estates. However, noise annoyance due to these two sources were investigated through the noise survey in this research (refer to survey questionnaire presented in Appendix E of this thesis).

Of the respondents, 42.2% were male and 57.8% were female. 28.6% of the sample size was found to be 'not sensitive' to noise, 40.6% was a 'little sensitive' and 22.7% was 'sensitive' to noise. 11.3% of the sample population identified their working environment as noisy and 46% as not noisy while 42.7% (including students, housewives, retired persons and others) stated that they do not work.

5.2.1 Evaluation of Outdoor Environmental and Community Noise

Rating of noise level in the surrounding general living environment (Figure 5-2) showed that 54.5% of the sample population felt noise level in their environment is in the range of very quiet to acceptable. The remaining 45.6% of the sample population rated the noise level between noisy and very noisy.

An overall rating of the apartment in terms of the noisiness of the indoor noise environment showed a normal distribution. It is observed from Figure 5-3 that 78.3% of the entire sample population rated the overall noisiness of their apartment's indoor environment as very quiet to acceptable while 21.7% felt it was noisy and very noisy.

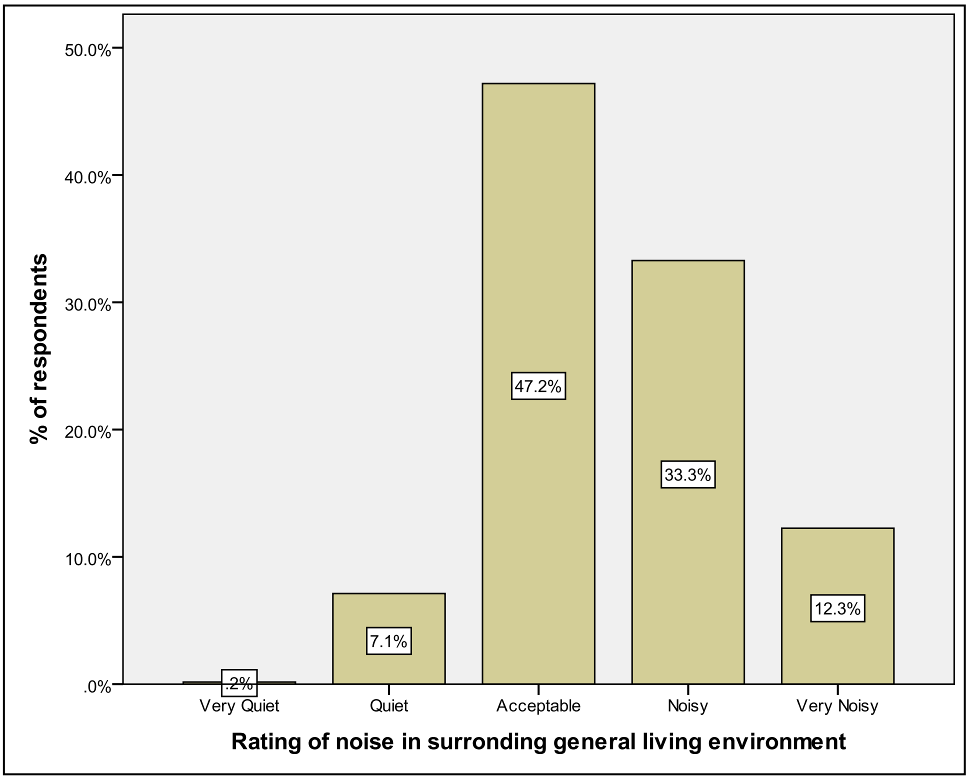


Figure 5-2: Rating of noise level in surrounding general living environment

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

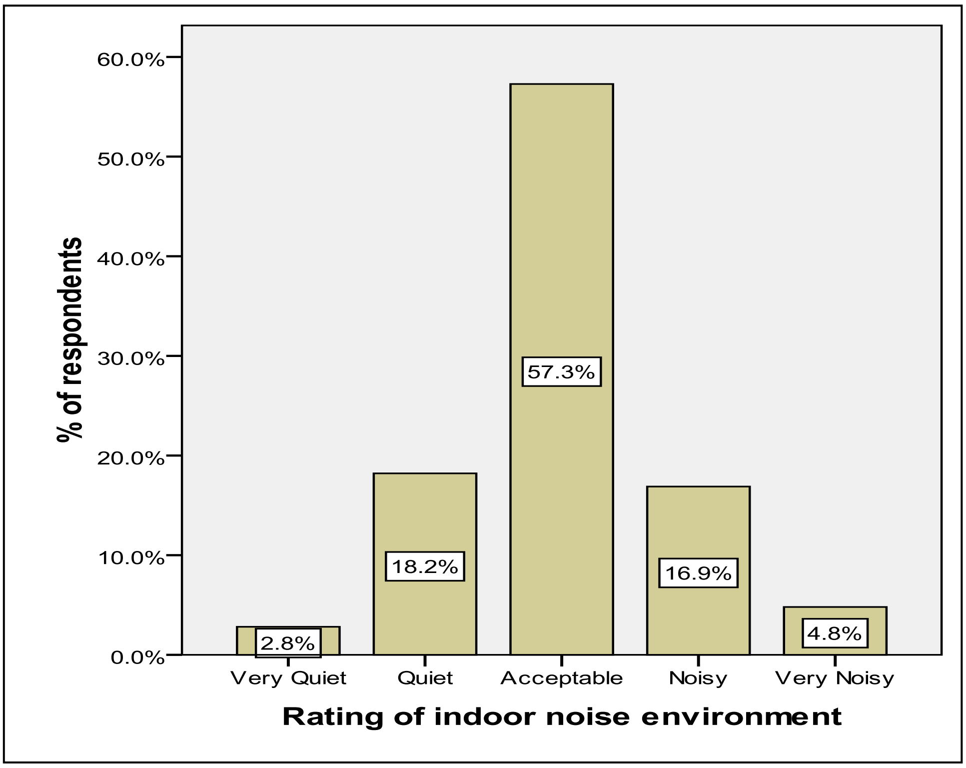


Figure 5-3: Rating of 'noisiness' of indoor noise environment in the apartment

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

To examine the type of outdoor environmental and community noise sources that may cause aural discomfort in an indoor environment, each respondent was asked to rate the level of overall perceived disturbance caused by specific noise sources. Road traffic and MRT train noise were found to be the major sources of disturbance of all the environmental and community noise sources. It is noted from Figure 5-4 that 39.2% of the respondents felt that road traffic noise was disturbing to extremely disturbing while 49.9% felt the same for MRT train noise.

As discussed in Chapter 3, A-weighted noise measurement were carried out for a period of 30 seconds each ($L_{Aeq,30s}$) at the centre of the living room of the apartments after each interview and respondents were asked to rate their overall perception about the noise if the same noise environment persisted in their indoor living environment. As seen from Figure 5-5, the overall noise rating (both for road traffic and MRT train noise) are very close to the subjective ratings given for individual noise sources. *Figure 5-6 shows that 95% of the resident population of high rise HDB feel the indoor noise level is 'acceptable', the expected corresponding measured A-weighted indoor noise level is 52 dB.*

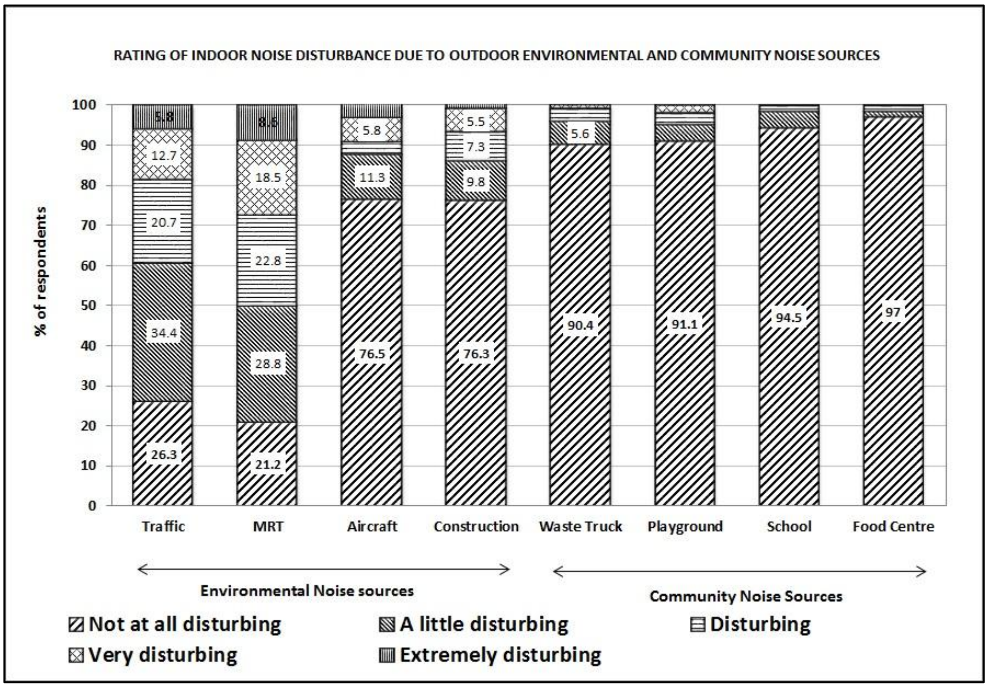
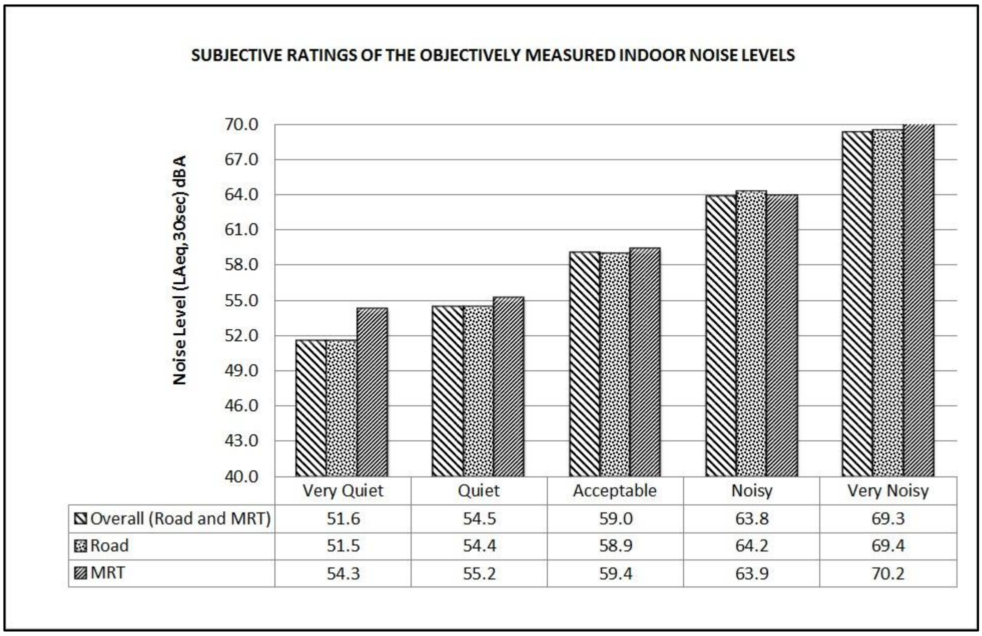


Figure 5-4: Rating of disturbance due to outdoor environmental and community noise sources

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)



	Very Quiet	Quiet	Acceptable	Noisy	Very Noisy
▧ Overall (Road and MRT)	51.6	54.5	59.0	63.8	69.3
▩ Road	51.5	54.4	58.9	64.2	69.4
▨ MRT	54.3	55.2	59.4	63.9	70.2

Figure 5-5: Subjective ratings of the measured indoor noise levels from road traffic and MRT train

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

Through the analysis of indoor aural comfort and rating of overall noisiness of the apartment, some divergence in the responses surfaced. Although 78.3% of the respondents rated the 'noisiness' of their apartments' noise environment as acceptable (Figure 5-3), a relatively smaller proportion of them (60.3% in Figure 5-8) felt acoustically comfortable to very comfortable while the rest (39.7%) felt neither to very uncomfortable. ***Therefore, the 'overall rating of the noisiness of the apartment' is found not to be a sole indicator of aural comfort among high-rise dwellers but it accounts for the significant proportion of the 'aural comfort' data.***

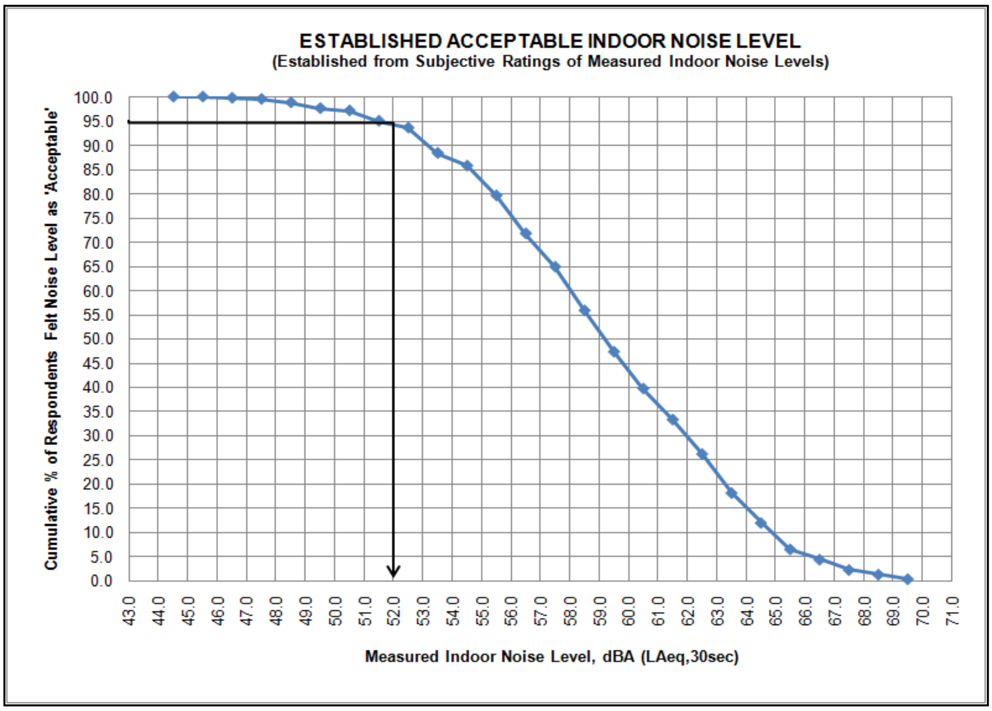


Figure 5-6: Established acceptable indoor noise level

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

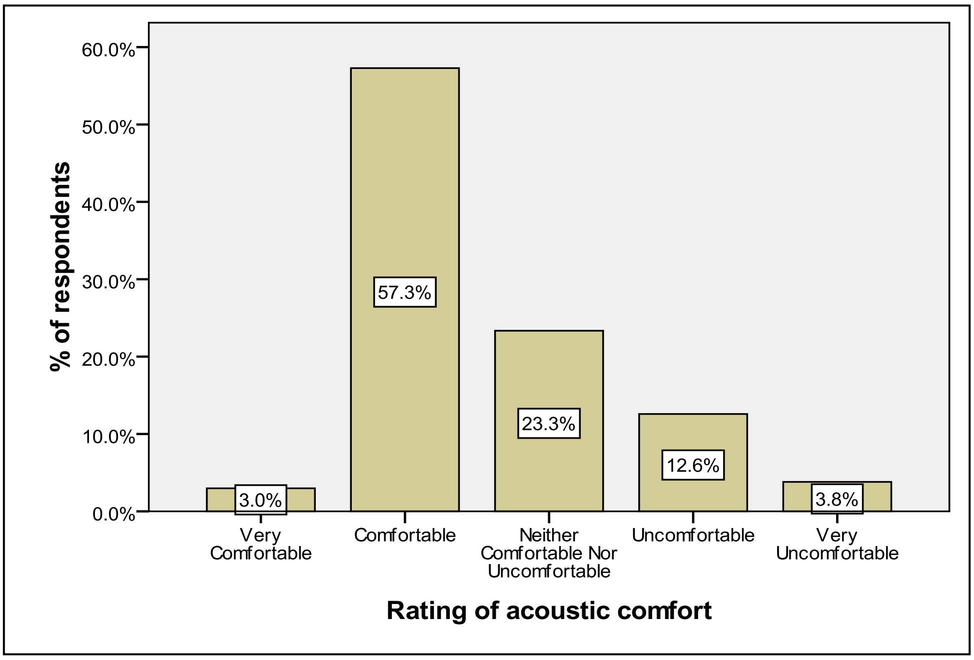


Figure 5-7: Overall rating of aural comfort

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

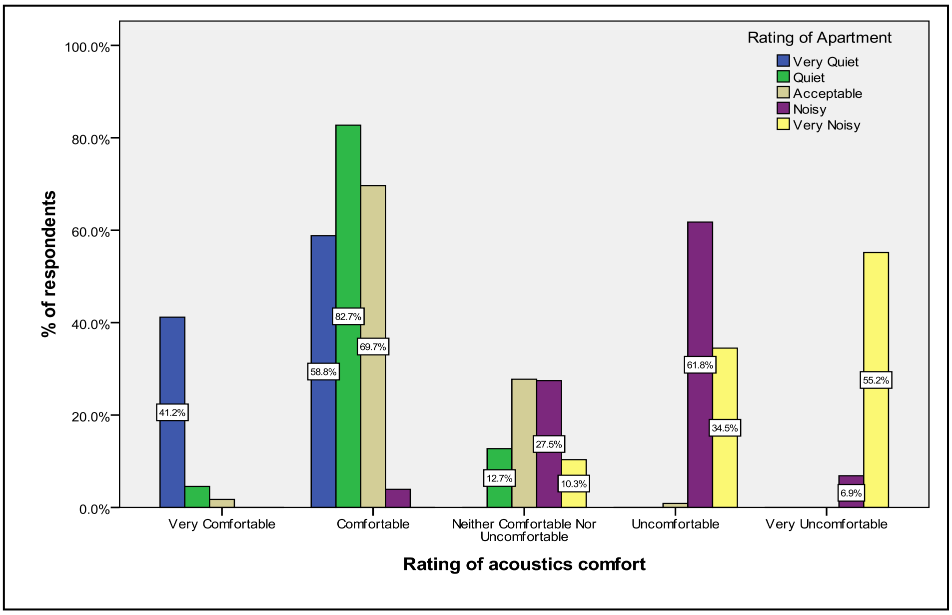


Figure 5-8: Rating of aural comfort vs. rating of rating of noisiness of apartment

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

5.2.1.1 Statistical analysis

Spearman rank correlation tests were carried out to further investigate the relationship between the rating of overall noisiness of the apartment and other acoustical and non-acoustical factors. Among the different factors considered in the survey, factors presented in Table 5-1 are found well correlated to the rating of apartments' overall noisiness. The correlation coefficients and their level of significance are also listed in Table 5-1.

Table 5-1: Correlations between rating of apartments' overall noisiness and other factors

Type of Factor	**Factors**	**Correlation Coefficient**	**Level of Significance**
Acoustical	***Rating of noise in general surrounding living environment***	***0.543***	***0.01***
Non-Acoustical	Sensitivity to noise	0.183	0.01
Non-Acoustical	Consideration of noise as an important aspect in general environment	0.188	0.01
Acoustical	***Rating of disturbance by road traffic noise***	***0.358***	***0.01***
Acoustical	***Rating of disturbance by MRT train noise***	***0.249***	***0.01***
Adaptive Behaviour	Likelihood of closing window	0.201	0.01
	Likelihood of closing door	0.192	0.01
	Likelihood of playing music	0.183	0.01
	Likelihood of watching TV/Video	0.181	0.01
	Likelihood of feeling helpless	0.233	0.01
Acoustical	Lday (MRT) Indoor, dBA	0.132	0.05
Acoustical	Lday (Road) Indoor, dBA	0.145	0.01

It is noted from Table 5-1 that the overall rating of the noisiness of the apartments are well correlated with the rating of noise in surrounding general living environment, rating of disturbance due to road traffic and MRT train noise as well. On the other hand, the overall rating of the noisiness of the apartment is weakly related (but significantly) to the individual’s sensitivity to noise, consideration of noise as an important aspect in general environment, the adaptive behaviours in terms of achieving aural comfort and the daily indoor noise exposure levels due to road traffic and MRT train. Principal component analysis was carried out (using oblique rotation) to further analyse the relationship between the rating of the apartments' overall noisiness and other correlated factors.

It is noted that Principal Component Analysis (PCA) is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The number of principal components is less than or equal to the number of original variables. This transformation is defined in such a way that the first principal component has the largest possible variance (that is, it accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible to the preceding components. PCA is used to find optimal ways of combining variables into a small number of subsets. This approaches is particularly useful in situations where the dimensionality of data and its structural composition are not well known.

In order to make the interpretation of the factors that are considered relevant, the first selection step is generally followed by a rotation of the factors that were retained. Two main types of rotation are generally used: Orthogonal (when the new axes are also orthogonal to each other), and Oblique (when the new axes are not required to be orthogonal to each other). The exact choice of rotation will depend on the assumption that the underlying factors should be related. If there are theoretical grounds to assume that the factors might correlate, oblique rotations (direct oblimin or promax). technique is chosen. As such, an oblique rotation is used in this study. The output of the PCA is Factor Pattern Matrix which is used to identify the sub-groups of the factors that explains the highest variance of the data in the particular component (with a loading generally greater than 0.4).

From the Principal Component Analysis (PCA), four components were extracted. From the patter matrix in Table 5-2, it is observed that the most important factors related to the *1st Component* are: Rating of noise in general surrounding living environment, Noise sensitivity, Consideration of noise as an important aspect in the living environment, Rating of disturbance by road traffic noise, Rating of disturbance by MRT train noise and Likeliness of feeling helpless. It is found that the factors related to the first component are the subjective perception about the noise environment and an individual’s sensitivity to noise and his/her emotions about noise. The *2nd Component* is related to regulation of emotion such as playing/listening music and watching television. The *3rd Component* is mostly related to noise management and coping resources such as closing doors and closing window. The *4th Component* is related to objective noise exposure levels (road traffic and train noise) and also the consideration of noise as an important aspect in the surrounding living environment. All the four components extracted from PCA together explains approximately 63% of the total variance in all of the variables.

Table 5-2: PCA analysis – rating of apartments' overall noisiness

Pattern Matrix[a]				
	Component			
	1	2	3	4
Rating of noise in general surrounding living environment	**.741**	.037	-.111	.309
Noise Sensitivity	**.605**	.055	-.010	-.301
Consideration of noise as an important aspect in general environment	**.445**	.014	-.057	**-.403**
Rating of disturbance by road traffic noise	**.721**	.049	-.108	.160
Rating of disturbance by MRT train noise	**.775**	-.067	-.092	.222
Likeliness of Closing Window	-.014	.025	**.917**	.010
Likeliness of Closing Door	.000	.074	**.925**	.043
Likeliness of Playing Music	.080	**.924**	.038	.027
Likeliness of Watching TV/Video	-.063	**.877**	.055	-.022
Likeliness of Feeling Helpless	**-.586**	.184	-.118	.052
Lday (MRT) Indoor	.183	-.053	.130	**.685**
Lday (Road) Indoor	-.012	.075	-.120	**.643**
Cumulative % of variance explained	**29.5**	**42.3**	**53**	**63**
Extraction Method: Principal Component Analysis. Rotation Method: Oblimin with Kaiser Normalization.				
a. Rotation converged in 7 iterations.				

Table 5-3: Influence of different factors on the overall rating of noisiness of the apartments

Type of Factor	Factors	Test Statistics	Significance
Acoustical	Level of apartment in the building	$F = 0.903$	$p > 0.05$
Non-Acoustical	Age	$F = 1.504$	$p > 0.05$
Non-Acoustical	Length of residence	$F = 0.949$	$p > 0.05$
Non-Acoustical	Level of education	$F = 1.556$	$p > 0.05$
Non-Acoustical	***Noise Sensitivity***	$\boldsymbol{F = 6.557}$	$\boldsymbol{p} < 0.05$
Non-Acoustical	Gender	$F = 2.103$	$p > 0.05$
Acoustical	***Type of noise source exposure***	$\boldsymbol{F = 9.209}$	$\boldsymbol{p} < 0.05$
Non-Acoustical	Type of apartment	$F = 0.518$	$p > 0.05$

One way Anova tests were carried out for several factors to observe the difference in rating of noisiness of the apartments by different groups of respondents. From Table 5-3 it is observed that the mean rating of an apartment's noisiness is generally equal across different groups of respondents. It is noted that the rating of apartments' noisiness is unequal ($p<0.05$) between respondents with different noise sensitivity. Rating of the noisiness of apartment is also found unequal ($p<0.05$) between respondents living near roads or near MRT trains. This is likely due to the fact that the mean noise exposure levels of the residents living nearby MRT track are higher than that of the residents living near roads. This required further investigations through the psycho-acoustical test in the laboratory environment. However, from the noise exposure data it is observed that the mean daily noise exposure level for the respondents living near roads is an A-weighted noise level of 58.7 dB (95% C.I. 0.4) and for the respondents living near MRT train lives is an A-weighted noise level of 59.2 dB (and 95% C.I. 0.2).

5.2.2 Evaluation of Neighbour Noise

Analysis of the survey data showed that 23.2% of the entire sample size was disturbed by neighbour noise from immediately adjacent apartments and the remaining 76.8% of the respondents were not disturbed.

In a broader view, regardless of disturbance, from Figure 5-9 it is observed that 38% of the sampled population felt that the sound coming from immediately adjacent neighbours' apartments was a little loud to very loud. Among these respondents, 18% of the respondents felt that the sound was a little loud, 13.2% loud and about 6.8% felt it to be very loud.

With regards to the location from where the sound was heard, the survey data showed that 29.3% of the sample population heard sound coming from the apartment directly above. About 4.6% of them heard sound coming from the apartment directly below and 4.1% from the immediately adjacent right or left apartment. It was also noted that neighbour sound was mostly heard in the living room area of the apartment (13.7% of respondents) and 8.6% of the respondents heard the sound mostly from their master bedroom.

The survey data also reveals that neighbour noise was heard more frequently during evening and night periods as shown in Figure 5-10. 11.7% of the respondents heard sound between 6am and 6pm whereas 19.5% of them heard sound between 6pm to 6am. From this data, it may be logical at the outset to relate the night time periods during which neighbour noise was heard by more dwellers to the likely location in the bedroom area where most of them are possibly resting or sleeping as opposed to actual findings which stated the living room area instead. A plausible explanation for this phenomenon may be attributed to the fact that these residents heard the neighbour noise in the living room area from 10pm onwards to around 12am (within the range of 10pm – 6am) during which they may still have been be awake.

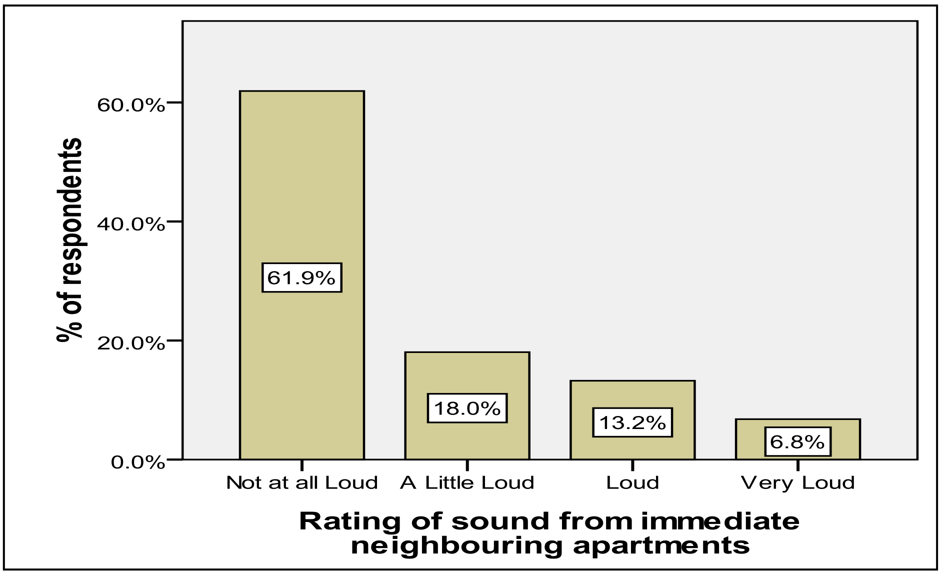


Figure 5-9: Rating of loudness of the immediately adjacent neighbour sound

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

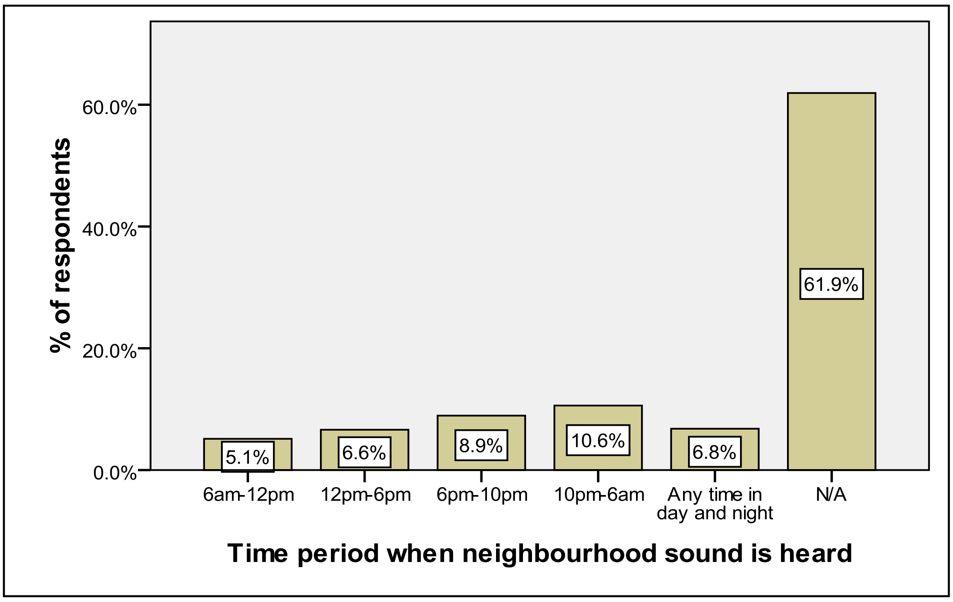


Figure 5-10: Time period when the neighbour sound is heard most frequently

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

To examine the type of neighbour noise sources, survey data revealed that 10.6% of the sample population heard dropping objects followed by 8.4% who heard furniture dragging and 5.8% heard neighbours’ speech from the neighbours' apartments immediately adjacent.

5.2.2.1 Statistical analysis

In studying the correlations between neighbour noise disturbance and other factors, Spearman rank correlation tests were carried out using SPSS Software. The correlation coefficients and their level of significance are listed in Table 5-4.

Table 5-4: Correlations between disturbance by neighbour noise and other factors

Type of Factor	Factors	Correlation Coefficient	Level of Significance
Acoustical	Rating of noise in surrounding general environment	-0.115	0.01
Non-Acoustical	Age	0.131	0.01
Non-Acoustical	Sensitivity to noise	-0.143	0.01
Acoustical	***Location of neighbours' apartment from where noise was heard***	***0.689***	***0.01***
Acoustical	***Rating of loudness of neighbour noise***	***0.751***	***0.01***
Acoustical	***Area within the apartment where neighbour noise was mostly heard***	***0.699***	***0.01***
Non-Acoustical	***Time period when neighbour noise was mostly heard***	***0.634***	***0.01***
Acoustical	***Type of neighbour noise***	***0.680***	***0.01***
Non-Acoustical	***Personal activities disturbed by neighbour noise***	***0.99***	***0.01***

From Table 5-4, it is observed that disturbance due to neighbour noise is strongly and significantly correlated with the following factors: Area in apartment and Location of neighbour apartment from where noise was mostly heard, Rating of subjective loudness of neighbour noise, Time period in which noise was most frequently heard, Types of noise and the Activities disturbed by the noise. It is observed that the disturbance by neighbour noise is dependent on the disturbance of the personal activities (i.e. the task he/she engaged in - sleeping, watching television, reading books, etc.) of the noise recipient and thus is highly correlated. This is an obvious cause-effect relationship whereby neighbour noise is the cause and disturbance of personal activity is the effect. As such, a high regression coefficient is found from the analysis. Rating of neighbour noise disturbance is found loosely related to the rating of noise in the surrounding general environment, sensitivity to noise and age of the respondents.

Table 5-5: PCA analysis – Neighbour noise in apartment

Pattern Matrix[a]			
	Component		
	1	**2**	**3**
Rating of noise in surrounding general environment	-.021	**.807**	.276
Age	.026	.005	**.937**
Sensitivity to noise	.016	**.765**	-.304
Location of neighbours' apartment from where noise was heard	**.942**	.008	-.027
Rating of loudness of neighbour noise	**-.901**	.044	.044
Area within the apartment where neighbour noise was mostly heard	**.896**	-.006	.057
Time period when neighbour noise was mostly heard	**.930**	.047	.014
Type of neighbour noise	**.909**	.010	-.002
Cumulative % of variance explained	**52.7**	**68**	**81**
Extraction Method: Principal Component Analysis. Rotation Method: Oblimin with Kaiser Normalization.			
a. Rotation converged in 5 iterations.			

From the Principal Component Analysis (PCA) using Oblique rotation, three components were extracted. From the patter matrix in Table 5-5, it is observed that the most important factors related to the *1st Component* are: Location of neighbours' apartment from where noise was heard, Rating of loudness of neighbour noise, Area within the apartment where neighbour noise was mostly heard, Time period when neighbour noise was mostly heard, Type of neighbour noise. It is noted that the factors related to the first component mostly describes the nature of neighbour noise causing disturbance. The *2nd Component* is related to the rating of noise in surrounding living environment and noise sensitivity of the resident which are mostly related to psychological (emotional) aspect of the receiver. The *3rd Component* is mostly related to the age of the receiver. All the three components extracted from PCA together explains approximately 81% of the total variance in all of the variables.

Table 5-6: Influences of factors on overall rating of neighbour transmitted noise

Type of Factor	**Factors**	**Test Statistics**	**Significance**
Acoustical	Level of apartment in the building	$F = 1.238$	$p > 0.05$
Non-Acoustical	***Age***	$\boldsymbol{F = 2.358}$	$\boldsymbol{p} < 0.05$
Non-Acoustical	Length of residence	$F = 1.175$	$p > 0.05$
Non-Acoustical	Level of education	$F = 1.349$	$p > 0.05$
Non-Acoustical	***Noise Sensitivity***	$\boldsymbol{F = 3.183}$	$\boldsymbol{p} < 0.05$
Non-Acoustical	Gender	$F = 0.136$	$p > 0.05$
Acoustical	Type of noise source exposed to	$F = 0.334$	$p > 0.05$
Non-Acoustical	Type of apartment	$F = 0.300$	$p > 0.05$

One way Anova tests were carried out on several factors to examine the differences in rating of the neighbour noise disturbance by different groups of respondents. The results are presented in Table 5-6. On the whole, rating of disturbance due to neighbour noise is generally equal across different groups of respondents. However, it is noted that groups with different noise sensitivity and age had rated unequally ($p<0.05$). These are the common factors in noise annoyance evaluation and is published in many literature related to noise annoyance.

It is thought to be interesting to investigate the relationships between age of the resident, noise sensitivity and rating of loudness of neighbour noise. Figure 5-11 presents the relationships among these variables. It illustrates that with the increase in age after 45 years, noise sensitivity decrease and consequently subjective rating of neighbour noise is reduced (towards lower level of subjective loudness).

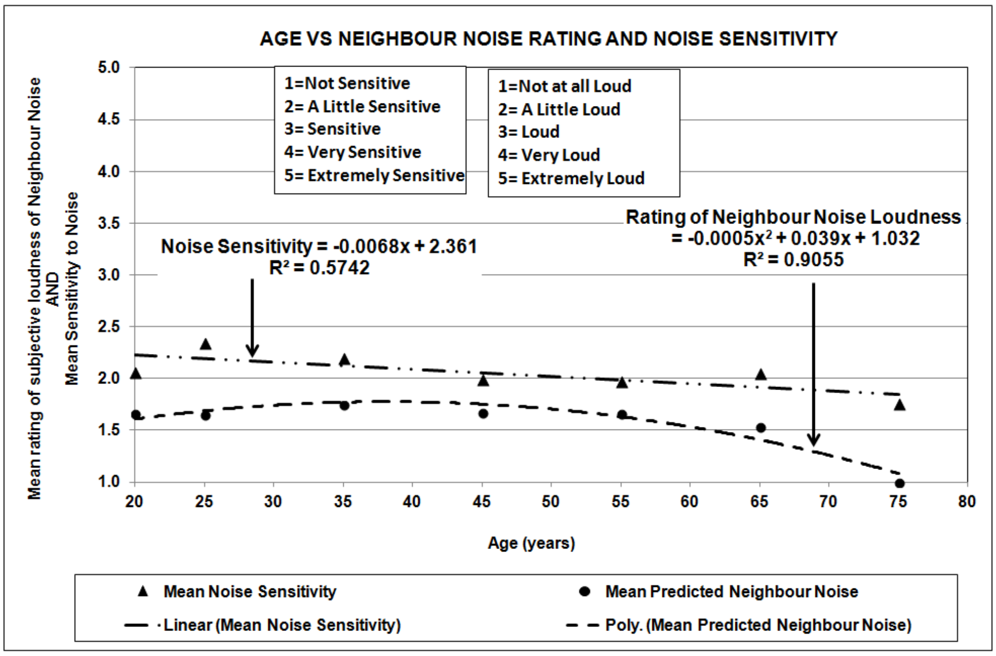


Figure 5-11: Relationship between age and noise sensitivity and rating of subjective loudness of neighbour noise

A general multi-linear regression model is established to predict rating of loudness of neighbour noise relating it with age and noise sensitivity of the resident as follows:

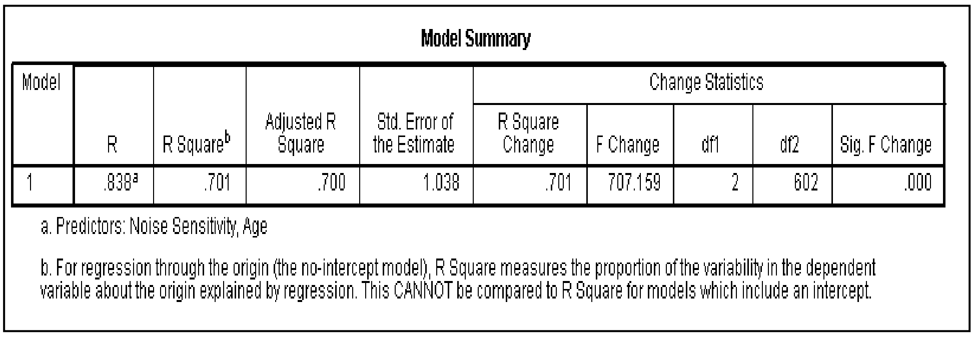
$$Rating\ of\ Loudness\ of\ Neighbour\ Noise$$

$$= 0.017 * Age + 0.406 * Noise\ Sensitivity$$

.... [Eq. 5-1]

The model summary is given in Table 5-7 below.

Table 5-7: Model summary for the Neighbour noise regression model



Model Summary

Model	R	R Square[b]	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.838[a]	.701	.700	1.038	.701	707.159	2	602	.000

a. Predictors: Noise Sensitivity, Age

b. For regression through the origin (the no-intercept model), R Square measures the proportion of the variability in the dependent variable about the origin explained by regression. This CANNOT be compared to R Square for models which include an intercept.

5.3 ASSESSMENT OF INDOOR AURAL COMFORT

5.3.1 Aural comfort and Environmental Noise

A simple linear regression is plotted in Figure 5-12 to demonstrate the relationship between the noise disturbance and the distances between the residential building and the road.

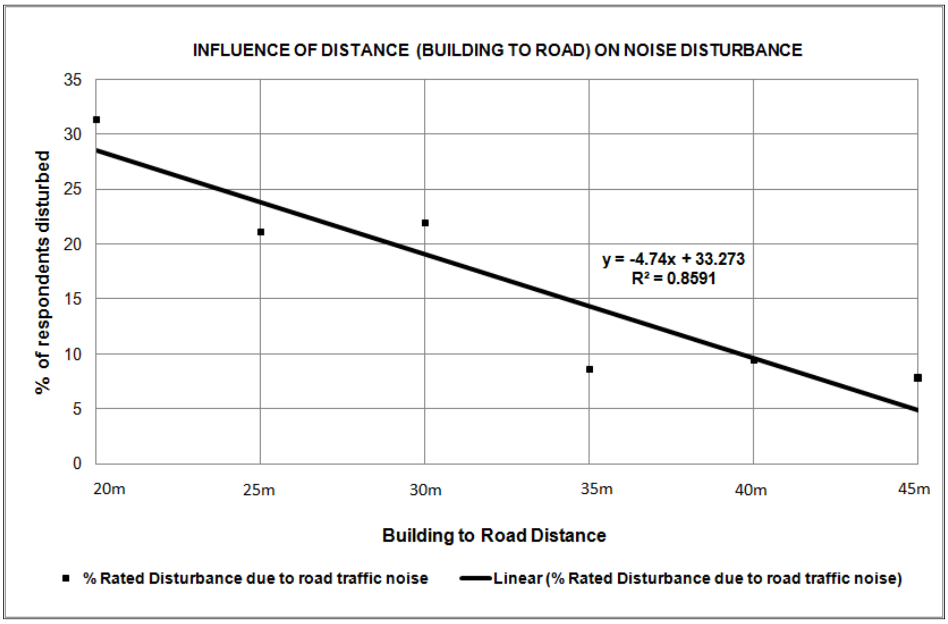


Figure 5-12: Noise disturbance due to road traffic for different source to building distances

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

It is seen from Figure 5-12 that noise disturbance among high-rise public housing dwellers reduces significantly when the buildings are further away from the road.

This simply implies that the noise exposure levels of the dwellers in the naturally ventilated high-rise dwellings are much lower for those respondents who live further away from the roads (this is demonstrated in Chapter 5 of this thesis) and thus noise disturbance is reduced.

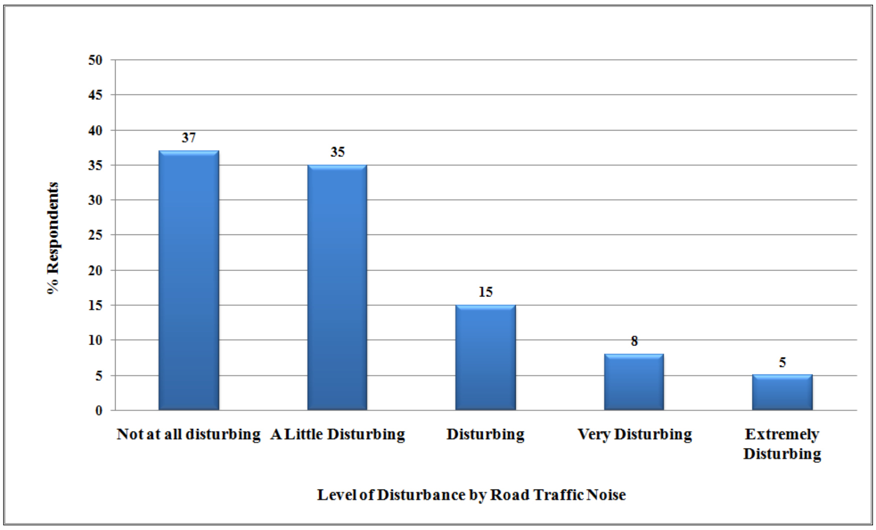


Figure 5-13: Aural comfort vs. noise disturbance due to road traffic

On the other hand, it is noted from Figure 5-13 that among the respondents who felt aurally comfortable, about 37% of them are not at all disturbed and 35% are a little disturbed due to road traffic noise. Interestingly, about 28% of the population who felt acoustically comfortable within their apartment, still felt disturbed due to road traffic noise. This is probably due to the influence of different non-acoustical factors such as noise sensitivity, belief of noise as an important aspect in the living environment, etc. The qualitative aspects of the road traffic noise in terms of loudness, sharpness, and roughness and fluctuation strength might also be responsible for such noise disturbance. This is investigated in depth in Chapter 6 of this thesis.

Similar to road traffic noise, a linear regression is plotted in Figure 5-14 to demonstrate the relationship between the noise disturbance and the distances between the residential buildings and the MRT track. It is noted from Figure 5-14 that noise disturbance among the high-rise public housing dwellers reduces significantly when the buildings are further away from the MRT track. This, again, implies that the noise exposure levels of the dwellers in the naturally ventilated high-rise dwellings are much lower for those respondents who live further away from the MRT tracks (this is demonstrated in Chapter 4 of this thesis) and thus the noise disturbance is reduced.

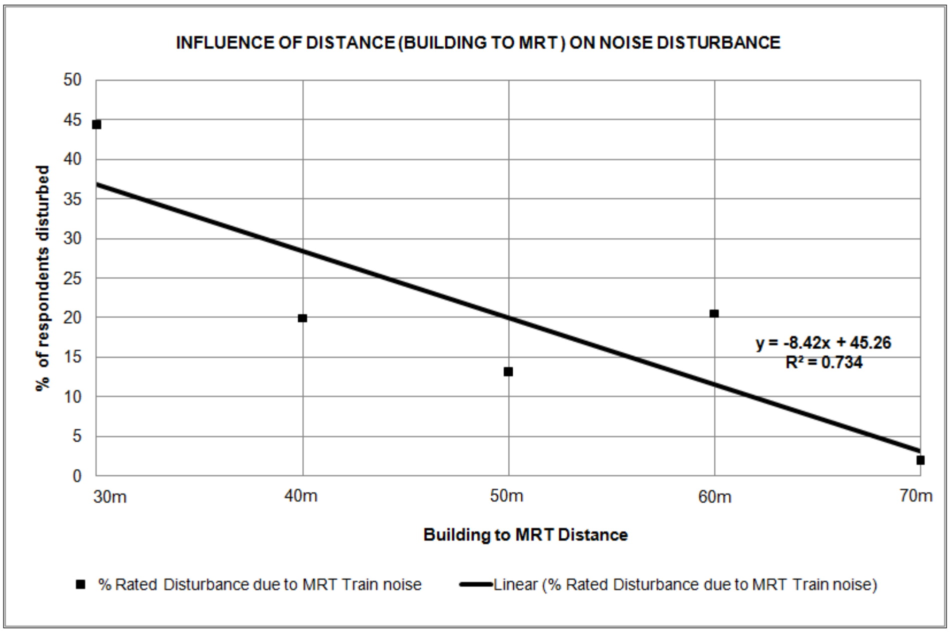


Figure 5-14: Noise disturbance due to MRT train for different source to building distances

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

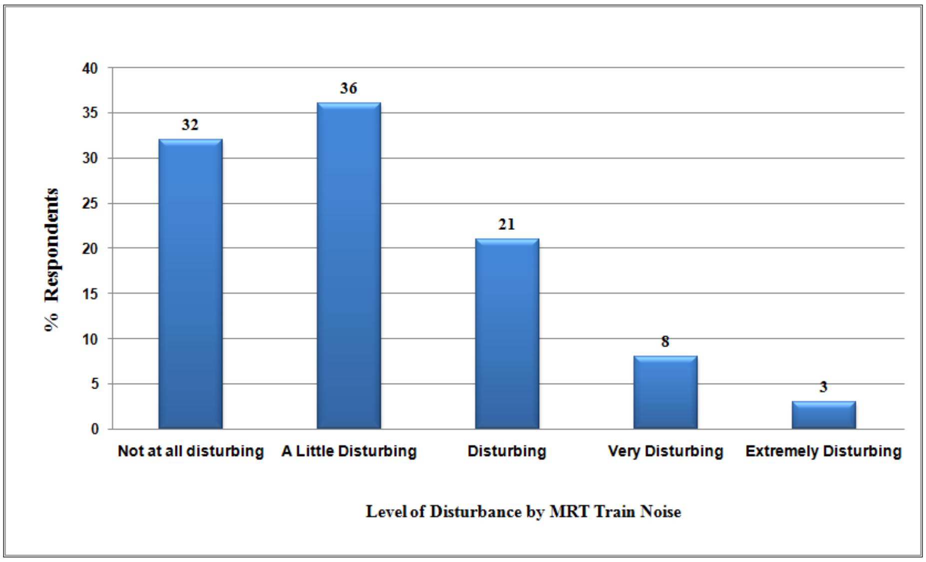


Figure 5-15: Aural comfort vs. noise disturbance due to MRT train

Figure 5-15 reveals that among the respondents who felt acoustically comfortable, about 32% of them are not at all disturbed and 36% are a little disturbed by the MRT train noise. Interestingly, as with the road traffic noise, about 32% of the respondents who felt acoustically comfortable within their apartment, still felt disturbed due to MRT train noise. This is probably due to the influence of different non-acoustical factors such as noise sensitivity, belief of noise as an important aspect in living environment, etc. The qualitative aspects of the MRT train noise in terms of loudness, sharpness, and roughness and fluctuation strength might also be responsible for such noise disturbance. This is investigated in depth in Chapter 6 of this thesis.

5.3.2 Aural comfort and Neighbour Noise

As neighbour noise is one of the main causes of noise annoyance in the high-rise residential environment, party walls and floors of adequate acoustical performance must be provided to ensure that the majority of the population is not affected considerably by the noise. Analysis was based on the rating of loudness by top 1% of the sample most affected by neighbour noise. It has been common in practice to choose the top one-percentile noise level for the development of community noise criteria, especially for aircraft noise annoyance (Schultz, 1982), and hence the same criteria have been used for analysis of neighbour noise.

5.3.2.1 Airborne transmitted neighbours' noise

The buildings in which the noise survey was conducted (in the stratified sampling method) consisted of three main types of party wall constructions. These include the 100mm hollow brick wall, 100mm RC wall and 200mm RC wall. Hollow brick walls were generally used in the older buildings (> 25 years) while the precast concrete walls are used in newer developments. Field measurements were carried out to test the sound transmission performances of these walls (presented in Chapter 4). The measured sound transmission performance of these walls are then correlated with the subjective responses of the corresponding group dwellers (604 households). As well as the sound transmission measurement of walls, indoor noise exposure levels of the apartments involved in the survey were also computed through the predicted façade noise exposure of the buildings and average sound insulation performance of the façades. Analysis was then carried out on the rating of 'subjective loudness' of the neighbour noise with the indoor masking noise levels. It is noted that for each of the three different types of party walls and indoor noise levels, cumulative rating of subjective neighbour noise (total sample size 604) was plotted from where the rating for top 1% sample population mostly affected by neighbour noise was determined for establishment of Figure 5-16 and Figure 5-17.

Figure 5-16 demonstrates that the perception rating of the 'subjective loudness' of the neighbour noise is higher when the sound transmission loss performance of the wall is lower and vice versa. On the other hand, Figure 5-17 demonstrates that when the indoor background noise level is lower, the rating of the 'subjective loudness' of the neighbour noise is higher and vice versa.

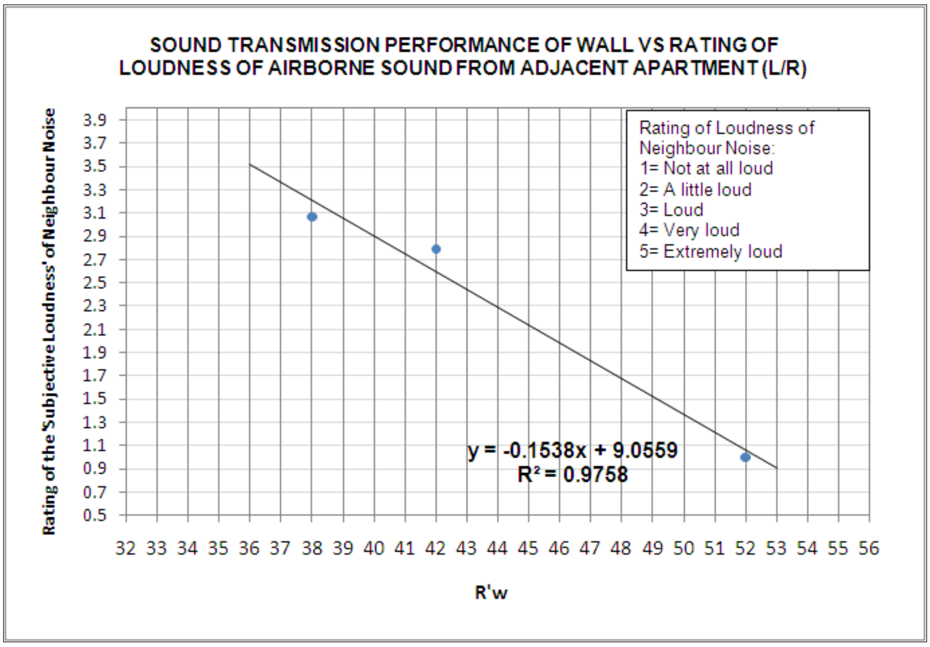


Figure 5-16: Neighbour noise loudness vs sound transmission loss of party wall (plotted for top 1% of the sample population mostly affect by neighbour noise)

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

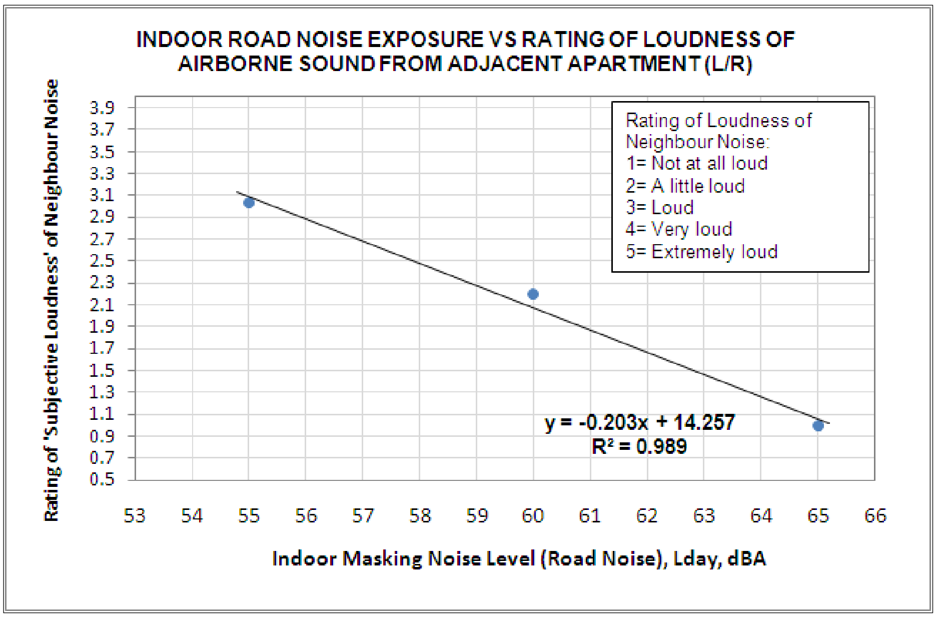


Figure 5-17: Neighbour noise loudness vs indoor noise level (plotted for top 1% of the sample population mostly affect by neighbour noise)

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

5.3.2.2 Impact transmitted neighbour noise

The buildings where the noise survey was conducted consist of five main types of floor constructions. These included RC floors thickness 150mm, 175mm, 200mm, 225mm and 250mm with ceramic tiles. Field measurements were carried out to test the impact sound transmission performance of these floors (presented in Chapter 4). The measured impact sound transmission performance of these floors was then correlated with the subjective responses of the dwellers and the results are presented in Figure 5-18. The graph illustrates that the perception rating of the 'subjective loudness' of the neighbour impact noise is higher when the impact sound transmission performance of the floors is lower and vice versa. Analysis was then carried out on the rating of 'subjective loudness' of the neighbour impact transmitted noise with the indoor masking noise levels.

As with the situation for inter-apartments walls, it is seen from Figure 5-19 that when the indoor background noise level is lower, the perception rating of the 'subjective loudness' of the neighbour impact transmitted noise is higher and vice versa.

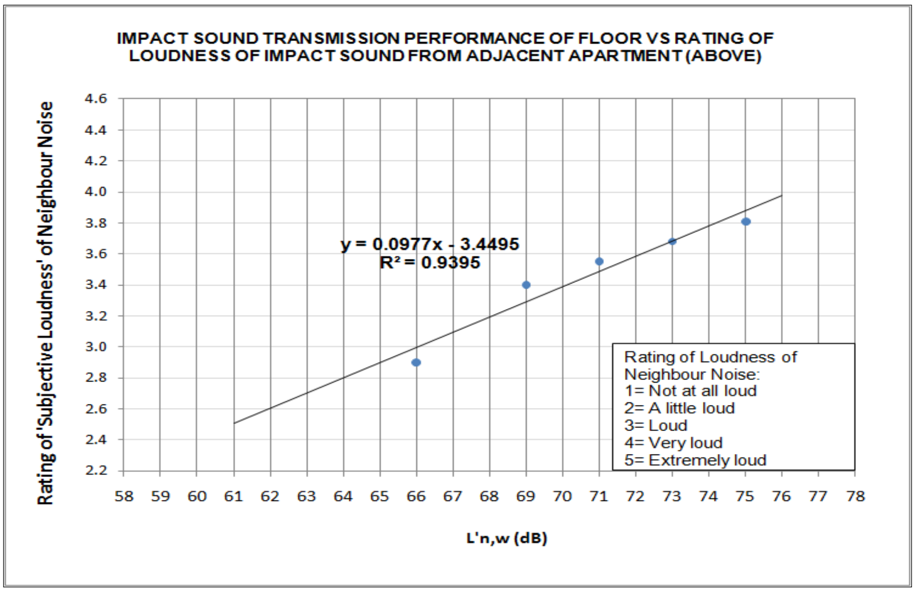


Figure 5-18: Subjective loudness of neighbour impact sound vs. impact sound transmission performance of floors (plotted for top 1% of the sample population mostly affect by neighbour noise)

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

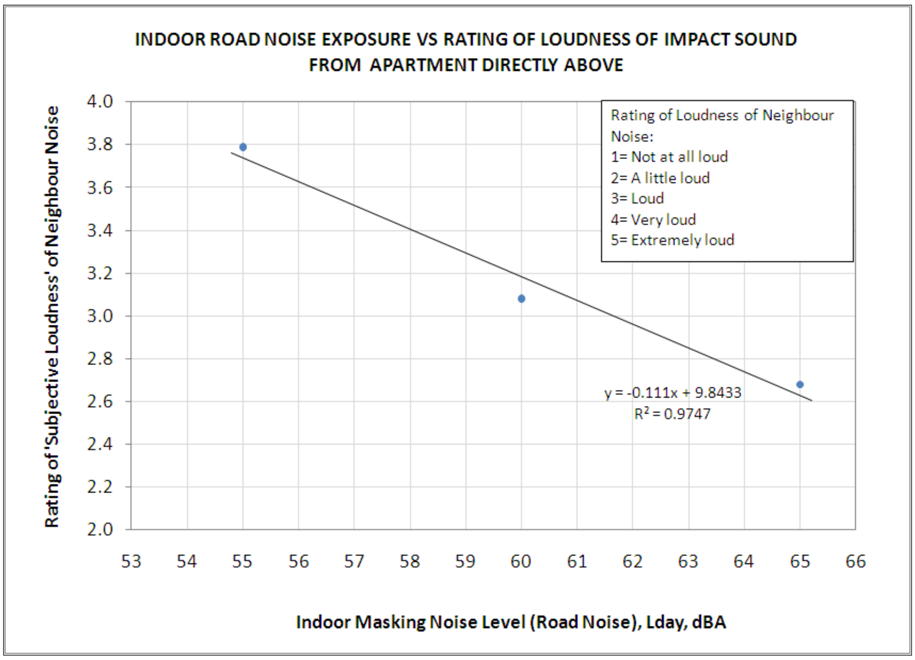


Figure 5-19: Indoor noise level vs. subjective loudness of neighbour impact sound (plotted for top 1% of the sample population mostly affect by neighbour noise)

(Source: Report on the Impact and Airborne Sound Insulation Performance of Party Walls and Floors in Singapore, 2008-2011, Singapore)

5.3.3 Adaptive Behaviours to Achieve Aural comfort

This research took an insight into the adaptive behaviours that residents would consider to achieve aural comfort while living in the naturally ventilated public housing residential buildings. Figure 5-20 illustrates some of these adaptive behaviours (perceived control) that residents would likely to exhibit in order to achieve aural comfort.

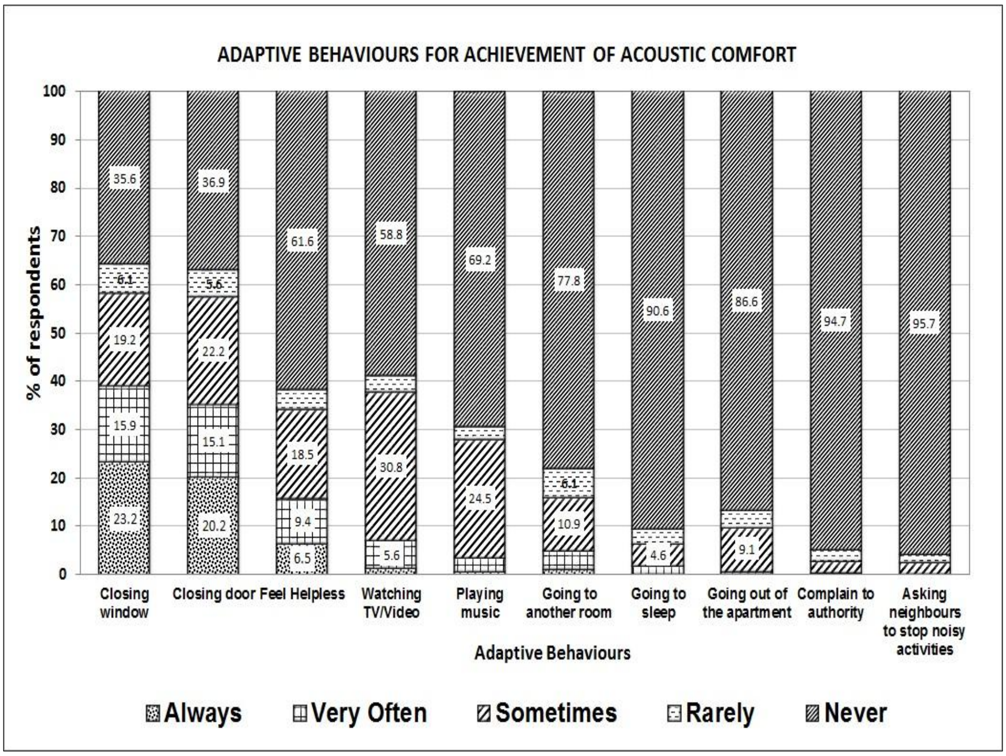


Figure 5-20: Adaptive behaviour for achieving aural comfort

Investigation into the adaptive behaviours of the residents showed that approximately 40% of the entire sample population size prefers to close the windows 'very often' and 'always' when they want to achieve aural comfort. On the other hand about 35% of the entire sample size prefer to close doors 'always' and 'very often' for achievement of aural comfort. About 34% of the entire sample size felt helpless 'always' and 'very often' while 18.5% of the entire cohort felt helpless 'sometimes' with regards to control of noise for the achievement of aural comfort. These adaptive behaviours generally represent the management of the cause of stress (reducing noise annoyance and achieve aural comfort) as shown in the proposed aural comfort framework in Chapter 3 of this thesis. On the other hand, approximately 31% of the entire sample population prefer TV and about 25% prefer music 'sometimes' to achieve aural comfort in the indoor environment which is categorized as regulation of emotion (as presented in the proposed aural comfort assessment framework).

5.3.4 Statistical Analysis

Table 5-8 lists the relationships between overall indoor acoustical comfort and several acoustical and non-acoustical factors. It is noted from Table 5-8 that the rating of the ***overall aural comfort in the apartment is strongly and significantly correlated to three factors, namely: rating of the overall noisiness of the apartment, rating of disturbance by Road traffic noise and the rating of disturbance by MRT train noise.***

Table 5-8: Correlations between overall aural comfort and other factors

Type of Factor	Factors	Correlation Coefficient	Level of Significance
Acoustical	***Rating of overall noisiness of the apartment***	***.673***	***0.01***
Non-Acoustical	Sensitivity to noise	.178	0.01
Non-Acoustical	Consideration of noise as an important aspect in living environment	.175	0.01
Acoustical	Disturbance by neighbour noise	.129	0.01
Non-Acoustical	Personal activities disturbed by neighbour noise	.134	0.01
Acoustical	***Rating of disturbance by road traffic noise***	***.414***	***0.01***
Acoustical	***Rating of disturbance by MRT train noise***	***.244***	***0.01***
Adaptive Behaviours	Likelihood of closing window	.174	0.01
	Likelihood of closing door	.150	0.01
	Likelihood of playing music	.165	0.01
	Likelihood of watching TV/Video	.139	0.01
Acoustical	Calculated indoor noise exposure level, Lday (dBA)	.154	0.01

Other factors that are also significantly related to aural comfort (but the relationship is not strong) includes sensitivity to noise, consideration of noise as an important aspect in the general surrounding living environment, neighbour noise disturbance, activities disturbed by neighbour noise and the predicted apartment's daily indoor noise exposure levels (L_{day}) when subjected to both road traffic and MRT train noise. Adaptive behaviours like management of the cause of stress (closing doors and windows) and regulation of emotions (watching TV and playing music) are also found significantly correlated to the overall aural comfort.

Table 5-9: PCA analysis – aural comfort in apartment

Pattern Matrix[a]					
	Component				
	1	**2**	**3**	**4**	**5**
Rating of overall noisiness of the apartment	-.377	-.014	-.193	**.501**	.146
Sensitivity to noise	.190	-.067	.005	**.705**	-.089
Consideration of noise as an important aspect in living environment	.106	-.011	.093	**.722**	-.048
Disturbance by neighbour noise	.018	**.994**	.005	.015	-.020
Personal activities disturbed by neighbour noise	.023	**.992**	-.006	.007	-.009
Rating of disturbance by road traffic noise	-.175	.067	-.010	**.649**	.004
Rating of disturbance by MRT train noise	**-.821**	.001	.007	.060	-.086
Likelihood of closing window	.072	.004	-.022	-.042	**.905**
Likelihood of closing door	.031	-.027	.062	.010	**.903**
Likelihood of playing music	-.070	-.008	**.918**	.061	.037
Likelihood of watching TV/Video	-.038	.009	**.913**	.024	.003
Calculated indoor noise exposure level, Lday (dBA)	**-.876**	-.034	.083	-.133	-.062
Cumulative % variance explained	**24.6**	**40.7**	**53.4**	**64.3**	**73.5**

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

Pattern Matrix[a]					
	Component				
	1	2	3	4	5
a. Rotation converged in 9 iterations.					

A Principal Component Analysis (PCA) was carried out (using Oblique rotation) on all these factors in SPSS. Five components were extracted from PCA which explains approximately 74% of the total variance. From the Pattern Matrix in Table 5-9, it can be observed that the most important factors related to the *1st* C*omponent* are rating of disturbance by MRT train noise and the computed indoor noise exposure level. The *2nd* C*omponent* is found mostly related to disturbance by neighbour noise and related personal activities disturbed by the receiver. Regulation of emotion, for example, listening to music and watching TV falls under the *3rd Component* in the PCA analysis. *The 4th Component* mostly related to subjective noise perception (overall noisiness of apartment, sensitivity to noise, consideration of noise as an important aspect in living environment) and subjective assessment of road traffic noise. The *5th Component* is found related to management of the cause of stress (reduce noise annoyance to achieve aural comfort) like closing doors and windows.

Table 5-10: Influences of factors on overall aural comfort

Type of Factor	Factors	Test Statistics	Significance
Acoustical	Level of apartment in the building	$F = 0.629$	$p > 0.05$
Non-Acoustical	Age	$F = 0.951$	$p > 0.05$
Non-Acoustical	Length of residence	$F = 0.657$	$p > 0.05$
Non-Acoustical	Level of education	$F = 1.437$	$p > 0.05$
Non-Acoustical	***Noise Sensitivity***	$\boldsymbol{F = 6.394}$	$\boldsymbol{p} < 0.05$
Non-Acoustical	Gender	$F = 0.005$	$p > 0.05$
Acoustical	Type of noise source exposed to	$F = 3.051$	$p > 0.05$

Type of Factor	Factors	Test Statistics	Significance
Non-Acoustical	Type of apartment	$F = 0.665$	$p > 0.05$

One way Anova tests were carried out on several factors in order to observe the differences in rating of the aural comfort by different groups of respondents. From Table 5-10 it is observed that the *mean rating of indoor aural comfort was equal across the different groups except for the respondents with different noise sensitivity*.

5.4 DEVELOPMENT OF AN AURAL COMFORT MODEL (ACM)

As discussed in Chapter 3 (refer to Figure 3-8), experience of indoor aural comfort (hereby referred as Aural Comfort Model) is planned to be established through the integration of objective and subjective assessment of indoor aural environment. Objective assessment of the indoor aural environment is essentially the assessment of indoor noise levels at different high-rise apartments which is carried out through prediction of facade noise level and measurement of facade sound insulation performances. This is discussed in Chapter 4 in greater detail. The noise profile charts established in Chapter 4 for different Road/MRT to residential building distances are used along with the relevant facade sound insulation to predict the indoor noise levels for the apartments in which subjective noise evaluations are carried out through clustered sampled noise survey (refer to Section 5.2 of this chapter).

Dwellers' perceived experiences of the indoor aural environment is developed based on the statistical relationship (or integration) between the perceived aural comfort response from the clustered sampled noise survey (non-acoustical factors that were found significantly related to aural comfort) and the objective noise exposure data (from objective assessment). This statistical model is named as Aural Comfort Model (ACM).

Multinomial Logistic Regression (MLR) is used for the development of the aural comfort model. A multinomial logistic regression model determines the probabilities of the different possible outcomes of a categorically distributed dependent variable., given a set of independent variables (which may be real-valued, binary-valued, categorical-valued, etc.). Multinomial logistic model is used to predict categorical data. MLR assumes that the dependent variable (aural comfort) cannot be perfectly predicted from the independent variables for any case and from this, a probability is predicted for each categories. Since the acoustic comfort of residents is evaluated on a category scale, MLR is the appropriate regression model that can be used to develop aural comfort model.

Based on the analysis of subjective assessment of indoor aural environment (refer to section 5.2), twelve factors were identified that were found significantly correlated with the overall rating of aural comfort. In the following sections, these factors are used together with the predicted indoor noise exposure levels for the development of an 'aural comfort' model.

5.4.1 Model Specification

Since the dependent variable - aural comfort - used in the noise survey is ordered category scale with five distinct categories (i.e. very comfortable, comfortable, neither comfortable or uncomfortable, uncomfortable, very uncomfortable), it is inappropriate to use a simple linear/multiple regression model for its specification. Therefore, ***Multinomial Logistic Regression*** (MLR) is considered appropriate for the development of an aural comfort model.

Multinomial Logistic Regression is a regression model that is used to develop statistical models that determine the probabilities of the different possible outcomes of a categorically distributed dependent variable. Multinomial logistic regression uses the maximum likelihood estimation rather than the least squares estimation used in traditional multiple regression (Chatterjee and Ali, 2006). The multinomial logistic regression model assumes that data are case specific. It also assumes that the dependent variable cannot be perfectly predicted from the independent variables for any case. Multinomial logistic regression does not make any assumptions in regards to normality, linearity, and homogeneity of variance for the independent variables. As with other types of regression, there is no need for the independent variables to be statistically independent from each other, co linearity is assumed to be relatively low, as it becomes difficult to differentiate between the impact of several variables if they are highly correlated (Multinomial Logistic Regression Model, Wikipedia, 2011).

The general form of the Multinomial Logistic Regression Model is given by (Chatterjee and Ali, 2006):

$$\log\left(\frac{\Pr(y_i = j)}{\Pr(y_i = k)}\right) = \beta_{0j} + \beta_{1j}x_{1i} + \beta_{2j}x_{2i} + \cdots + +\beta_{pj}x_{pi}\ , \quad j = 1,2,\ldots,k-1$$

....[Eq. 5-2]

Here, for the i-th individual or groups, y_i is the dependent variable with k categories, x_i represents the p independent variables and β_{ij} represents the regression parameters which can be estimated by the Maximum Likelihood method.

As the probability is equal to one, Eq. 5-2 reduces to the form

$$\Pr(y_i = j) = \frac{\exp(\beta_{0j}+\beta_{1j}x_{1i}+\beta_{2j}x_{2i}+\cdots++\beta_{pj}x_{pi})}{1+\sum_{j=1}^{k-1}\exp(\beta_{0j}+\beta_{1j}x_{1i}+\beta_{2j}x_{2i}+\cdots++\beta_{pj}x_{pi})}$$

..........................[Eq. 5-3]

As the dependent variable, Aural comfort, is chosen to have a total of five categories, Multinomial Logistic Regression (MLR) requires specification of a set of four equations to quantify the dependent variable (aural comfort). Therefore, the set of equations (relating aural comfort with the twelve factors that are correlated with it) for defining aural comfort can be specified as follows:

$$\Pr(y_i = 1) = \frac{\exp\,(\beta_{11}x_{1i} + \beta_{21}x_{2i} + \cdots + \beta_{12\,1}x_{12i}\ )}{1 + \sum_{j=1}^{4} \exp\,(\beta_{1j}x_{1i} + \beta_{2j}x_{2i} + \cdots + \beta_{12j}x_{12i}\ )}$$

$$\Pr(y_i = 2) = \frac{\exp\,(\beta_{12}x_{1i} + \beta_{22}x_{2i} + \cdots + \beta_{12\,2}x_{12i}\ )}{1 + \sum_{j=1}^{4} \exp\,(\beta_{1j}x_{1i} + \beta_{2j}x_{2i} + \cdots + \beta_{12j}x_{12i}\ )}$$

$$\Pr(y_i = 3) = \frac{\exp\,(\beta_{13}x_{1i} + \beta_{23}x_{2i} + \cdots + \beta_{12\,3}x_{12i}\ )}{1 + \sum_{j=1}^{4} \exp\,(\beta_{1j}x_{1i} + \beta_{2j}x_{2i} + \cdots + \beta_{12j}x_{12i}\ )}$$

$$\Pr(y_i = 4) = \frac{\exp\,(\beta_{14}x_{1i} + \beta_{24}x_{2i} + \cdots + \beta_{12\,4}x_{12i}\ )}{1 + \sum_{j=1}^{4} \exp\,(\beta_{1j}x_{1i} + \beta_{2j}x_{2i} + \cdots + \beta_{12j}x_{12i}\ )}$$

....[Eq. 5-4]

Where,

y_i *is the Rating of overall Acoustic Comfort,*

x_1 *is the Indoor Noise Exposure Level,*

x_2 *is the Rating of Noisiness of the Apartment*

x_3 *is the Rating of Noise Sensitivity of the Respondent*

x_4 *is the Rating of Consideration of Noise as an Important Aspect*

x_5 *is the Rating of Disturbance by Neighbour Noise*

x_6 *is the Personal Activities Disturbed by Neighbour Noise*

x_7 *is the Rating of Disturbance due to Road Traffic Noise*

x_8 *is the Rating of Disturbance due to MRT Train Noise*

x_9 *is the Rating of Likelihood of Closing Door for Achieving Acoustic Comfort*

x_{10} *is the Rating of Likelihood of Closing Window for Achieving Acoustic Comfort*

x_{11} *is the Rating of Likelihood of Listening Music for Achieving Acoustic Comfort*

x_{12} *is the Rating of Likelihood of Watching TV for Achieving Acoustic Comfort*

β_{pj} represents the regression parameters;

$p\ is\ the\ variable\ number\ such\ as\ 1,2,\cdots,12.$

It is noted that the $\Pr(y_i = 5) = 1 - \sum_{j=1}^{4} \Pr(y_i = j)$.

5.4.2 Regression Output and Model Refinement

Based on the above model specification, Multinomial logistic regression was carried out in SPSS software. The Cox and Snell Pseudo R-square value computed from SPSS was 0.831 and the Nagelkerke Pseudo R-square value was computed as 0.866 which are both much higher than the recommended value of 0.5 and thus demonstrates the good fit of the model.

However, the likelihood ratio test result shows that, among the twelve factors used for the model development, only four factors are significant in developing a relationship with the dependent variable, aural comfort. From Table 5-11, it is noted that these factors are: 1) Indoor Noise Exposure Level, 2) Rating of the Noisiness of the apartment, 3) Rating of Disturbance due to Road Traffic Noise and 4) Rating of Disturbance due to MRT Train Noise. As a result, the model needs to be refined and the regression needs to be carried out with these four factors.

The likelihood ratio test results of the second regression analysis (Table 5-12) show that all four factors are significantly related to aural comfort in the multinomial regression model. The Cox and Snell Pseudo R-square value computed from SPSS was 0.817 and the Nagelkerke Pseudo R-square value was computed as 0.851 which demonstrates the good fit of the model.

Table 5-11: Likelihood ratio test result of the first regression

Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Indoor noise exposure level	***984.040***	***114.236***	***4***	***.000***
Rating of noisiness of the apartment	***1.164E3***	***294.041***	***4***	***.000***
Rating of noise sensitivity of the respondents	870.670	.866	4	.929
Rating of consideration of noise as an important aspect	872.404	2.601	4	.627
Rating of disturbance due to Neighbour Noise	870.627	.823	4	.935
Personal Activities Disturbed by Neighbourhood Noise	870.282	.478	4	.976
Rating of disturbance due to Road Traffic noise	***899.815***	***30.012***	***4***	***.000***
Rating of disturbance due to MRT Train noise	***905.751***	***35.948***	***4***	***.000***
Rating of likelihood of closing door	871.820	2.016	4	.733
Rating of likelihood of closing window	874.210	4.407	4	.354
Rating of likelihood of listening to music	878.469	8.666	4	.070
Rating of likelihood of watching TV/Video	877.181	7.378	4	.117

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

Table 5-12: Likelihood ratio test result of the second regression

Likelihood Ratio Tests						
Effect	**Model Fitting Criteria**			**Likelihood Ratio Tests**		
	AIC of Reduced Model	**BIC of Reduced Model**	**-2 Log Likelihood of Reduced Model**	**Chi-Square**	**df**	**Sig.**
Indoor noise exposure level	1470.802	1523.645	1446.802	578.395	4	.000
Rating of noisiness of the apartment	1199.494	1252.336	1175.494	307.086	4	.000
Rating of disturbance due to Road Traffic noise	920.085	972.927	896.085	27.677	4	.000
Rating of disturbance due to MRT Train noise	948.523	1001.366	924.523	56.115	4	.000
AIC= Akaike's information criterion BIC= Bayesian Information Criterion						
The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.						

Bayesian Information Criterion (BIC), has been proposed by Raftery (1995) as a way of assessing the independent variables in a logistic regression equation. BIC in the context of logistic regression should be greater than 0 to support retaining the variable in the model. As a rule of thumb, BIC of 0-2 is weak, 2 - 6 is moderate, 6 - 10 is strong, and over 10 is very strong. Table 5-12 shows that all the four variables have BIC greater than 10 and as such cannot be made redundant from the model.

Therefore, the set of equations representing the ***aural comfort model*** can be written as:

$$\Pr(y_i = Very\ Comfortable) = \frac{\exp\,(x_{1i}\beta_{11} + x_{2i}\beta_{12} + x_{3i}\beta_{13} + \ x_{4i}\beta_{14})}{1 + \sum_{j=1}^{4} \exp\,(x_{1i}\beta_{j1} + x_{2i}\beta_{j2} + x_{3i}\beta_{j3} + x_{4i}\beta_{j4})}$$

$$\Pr(y_i = Comfortable) = \frac{\exp\,(x_{1i}\beta_{21} + x_{2i}\beta_{22} + x_{3i}\beta_{23} + x_{4i}\beta_{24})}{1 + \sum_{j=1}^{4} \exp\,(x_{1i}\beta_{j1} + x_{2i}\beta_{j2} + x_{3i}\beta_{j3} + x_{4i}\beta_{j4})}$$

$$\Pr(y_i = Neither) = \frac{\exp\,(x_{1i}\beta_{31} + x_{2i}\beta_{32} + x_{3i}\beta_{33} + x_{4i}\beta_{34})}{1 + \sum_{j=1}^{4} \exp\,(x_{1i}\beta_{j1} + x_{2i}\beta_{j2} + x_{3i}\beta_{j3} + x_{4i}\beta_{j4})}$$

$$\Pr(y_i = Uncomfortable) = \frac{\exp\,(x_{1i}\beta_{41} + x_{2i}\beta_{42} + x_{3i}\beta_{43} + x_{4i}\beta_{44})}{1 + \sum_{j=1}^{4} \exp\,(x_{1i}\beta_{j1} + x_{2i}\beta_{j2} + x_{3i}\beta_{j3} + x_{4i}\beta_{j4})}$$

....[Eq. 5-5]

Where,

$y_i = Rating\ of\ Acoustic\ Comfort\ for\ the\ i-th\ subject,$

$x_{1i} = Indoor\ Noise\ Exposure\ Level\ for\ the\ i-th\ subject$

$x_{2i} = Rating\ of\ the\ Noisiness\ of\ the\ Apartment\ for\ the\ i-th\ subject$

$x_{3i} = Rating\ of\ Disturbance\ due\ to\ Traffic\ Noise\ for\ the\ i-th\ subject$

$x_{4i} = Rating\ of\ Disturbance\ due\ to\ MRT\ Train\ Noise\ for\ the\ i-th\ subject$

$\beta_{pj} = Regression\ parameters$

$p = Comfort\ rating\ category\ 1\ to\ 4$

Note that $\Pr(y_i = 5) = 1 - \sum_{j=1}^{4} \Pr(y_i = j)$.

Table 5-13: Case processing summary of the final regression model

		N	Marginal Percentage
Rating of Acoustic Comfort	Very Comfortable	18	3.00%
	Comfortable	346	57.30%
	Neither Comfortable Nor Uncomfortable	141	23.30%
	Uncomfortable	76	12.60%
	Very Uncomfortable	23	3.80%
Valid		604	100.00%
Missing		0	
Total		604	
Subpopulation		502	

The classification accuracy rate for the multinomial logistic regression (MLR) model, was found to be 67.9%. For a good fit multinomial logistic regression model, this classification accuracy rate is required to be greater than or equal to the 'proportional by chance' accuracy criteria (Priyantha and Dilum, 2009). For the aural comfort model, the calculated proportion by chance criteria is 52.6% which is lower than the classification accuracy criteria and therefore, the criteria for classification accuracy is satisfied. For reference, the 'proportional by chance' accuracy rate for the aural comfort model is computed by squaring and summing the proportion of cases (Table 5-13) in each group and then taking an extra of 25% [$(0.03^2 + 0.573^2 + 0.233^2 + 0.126^2 + 0.083^2)$x1.25% = 52.6%)].

Table 5-14: Parameter estimates of the final regression model

Parameter Estimates									
Rating of Acoustic Comfort[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
Very Comfortable	Indoor noise exposure level	.608	.064	90.259	1	.000	1.836	1.620	2.081
	Rating of noisiness of the apartment	-8.37	.830	101.737	1	.000	.000	4.5E-5	.001
	Rating of disturbance due to road traffic noise	-1.24	.408	9.300	1	.002	.288	.130	.641
	Rating of Disturbance due to MRT Train Noise	-1.29	.300	18.768	1	.000	.273	.152	.491
Comfortable	Indoor noise exposure level	.592	.062	91.572	1	.000	1.808	1.602	2.041
	Rating of noisiness of the apartment	-6.81	.750	82.679	1	.000	.001	.000	.005
	Rating of disturbance due to road traffic noise	-1.21	.338	12.914	1	.000	.297	.153	.576
	Rating of Disturbance due to MRT Train Noise	-1.20	.202	35.579	1	.000	.300	.202	.445
Neither Comfortable Nor Uncomfortable	Indoor noise exposure level	.478	.061	61.522	1	.000	1.613	1.431	1.818
	Rating of noisiness of the apartment	-5.35	.730	53.738	1	.000	.005	.001	.020
	Rating of disturbance due to road traffic noise	-.814	.332	6.019	1	.014	.443	.231	.849
	Rating of Disturbance due to MRT Train Noise	-.879	.195	20.375	1	.000	.415	.283	.608
Uncomfortable	Indoor noise exposure level	.258	.054	23.024	1	.000	1.295	1.165	1.439
	Rating of noisiness of the apartment	-2.46	.614	16.098	1	.000	.085	.026	.284
	Rating of disturbance due to road traffic noise	-.466	.299	2.426	1	.119	.628	.349	1.128
	Rating of Disturbance due to MRT Train Noise	-.519	.169	9.481	1	.002	.595	.428	.828

a. The reference category is: Very Uncomfortable.

Other than satisfying the 'goodness' of fit criteria and the classification accuracy criteria, another important aspect that needs to be examined for MLR is the multi collinearity. Based on the parameter estimates for the MLR model, as shown in Table 5-14, none of the standard errors ($Std.Error$) of the regression coefficient (B) was found larger than a value of 2 and therefore (Sheskin, 2007; Priyantha and Dilum, 2009) it can be concluded that the multicollinearity is not present in the developed aural comfort model.

Table 5-14 also presents the computed values of the regression coefficients ($B\ or\ \beta$) from the MLR regression analysis by SPSS. Substituting the estimated values of the regression coefficients in [Eq. 5-5], the final form of the Aural Comfort Model (ACM) is as follows:

$$\widehat{\mathbf{Pr}}(\boldsymbol{y_i} = \boldsymbol{Very\ Comfortable})$$

$$= \frac{\exp\left(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}\right)}{\begin{gathered}1 + [\exp(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}) + \exp(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}) \\ + \exp(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}) + \exp(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i})]\end{gathered}}$$

$$\widehat{\mathbf{Pr}}(\boldsymbol{y_i} = \boldsymbol{Comfortable})$$

$$= \frac{\exp\left(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}\right)}{\begin{gathered}1 + [\exp(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}) + \exp(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}) \\ + \exp(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}) + \exp(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i})]\end{gathered}}$$

$$\widehat{\mathbf{Pr}}(\boldsymbol{y_i} = \boldsymbol{Neither\ Comfortable\ nor\ Uncomfortable})$$

$$= \frac{\exp\left(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}\right)}{\begin{gathered}1 + [\exp(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}) + \exp(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}) \\ + \exp(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}) + \exp(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i})]\end{gathered}}$$

$$\widehat{\mathbf{Pr}}(\boldsymbol{y_i} = \boldsymbol{Uncomfortable})$$

$$= \frac{\exp\left(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i}\right)}{\begin{gathered}1 + [\exp(0.608x_{1i} - 8.377x_{2i} - 1.244x_{3i} - 1.299x_{4i}) + \exp(0.592x_{1i} - 6.819x_{2i} - 1.215x_{3i} - 1.205x_{4i}) \\ + \exp(0.478x_{1i} - 5.351x_{2i} - 0.814x_{3i} - 0.879x_{4i}) + \exp(0.258x_{1i} - 2.463x_{2i} - 0.466x_{3i} - 0.519x_{4i})]\end{gathered}}$$

....[Eq. 5-6]

Where,

$y_i = Rating\ of\ Acoustic\ Comfort\ for\ the\ i - th\ subject,$

$x_{1i} = Indoor\ Noise\ Exposure\ Level\ for\ the\ i - th\ subject$

$x_{2i} = Rating\ of\ the\ Noisiness\ of\ the\ Apartment\ for\ the\ i - th\ subject$

$x_{3i} = Rating\ of\ Disturbance\ due\ to\ Traffic\ Noise\ for\ the\ i - th\ subject$

$x_{4i} = Rating\ of\ Disturbance\ due\ to\ MRT\ Train\ Noise\ for\ the\ i - th\ subject$

$$\begin{aligned}\widehat{Pr}(y_i &= Very\ Uncomfortable)\\ &= 1 - \widehat{Pr}(y_i = Very\ Comfortable)\\ &- \widehat{Pr}(y_i = Comfortable)\\ &- \widehat{Pr}(y_i = Neither\ Comfortable\ nor\ Unconfortable)\\ &- \widehat{Pr}(y_i = Uncomfortable)\end{aligned}$$

The developed aural comfort model has clearly demonstrated that as well as the day average indoor noise exposure level, aural comfort is dependent on the 'noisiness of the apartment' and 'noise disturbance' due to Road traffic and MRT train noise. The relationships of these variables with the overall daytime aural comfort are found statistically significant and shown in Table 5-12. ***As a result, the hypothesis of this research, 'Daytime subjective aural comfort in high-rise naturally ventilated residential dwellings can be defined as a function of the daily average indoor noise exposure level, the perception of the overall noisiness at the apartment and the noise disturbance due to road traffic and Mass Rapid Transit (MRT) train noise', cannot be rejected.***

5.5 SUMMARY

Assessment of aural comfort was carried out through a noise survey in a stratified sampling technique. A total of twelve factors were found correlated with the overall rating of aural comfort in this chapter. Principal Component Analysis revealed that all these factors explain approximately 74% of the total variation. The spearman rank correlation test showed that aural comfort is strongly and significantly related to four factors - indoor noise exposure level, rating of noisiness of the apartment, rating of noise disturbance due to road traffic noise and rating of disturbance due to MRT train noise. There were no significant rating differences found for rating of aural comfort by all the factors investigated except the individuals' sensitivity to noise. These factors were then used for the development of the aural comfort model through a multinomial logistic regression analysis. Multi-collinearity is one of the important issue in Multinomial Logistic Regression (MLR) model. From the Parameter Estimates of the established MLR Comfort Model, it is noted that none of the standard errors ($Std. Error$) of the regression coefficient (B) was found larger than a value of 2 and therefore (Priyantha and Dilum, 2009) it is concluded that the multi-collinearity is not present in the developed aural comfort model.

In the following chapter, validation of the developed aural comfort model is carried out through a psychoacoustic experiment.

CHAPTER 6: PSYCHOACOUSTICS EXPERIMENT AND PARAMETRIC STUDY

6.1 INTRODUCTION

For many decades, research in cognitive psychology mostly involved conducting experiments on human subjects in laboratory conditions. Such research experiments were generally conducted in controlled laboratory environments and were scientific in nature. The findings from these subjective experiments played a major role in the development and subsequent testing of many theories in cognitive psychology (Eysenck et al., 2000). Psychoacoustic testing is such a cognitive experiment where subjective judgments are gathered from evaluations of auditory stimuli in a controlled laboratory environment.

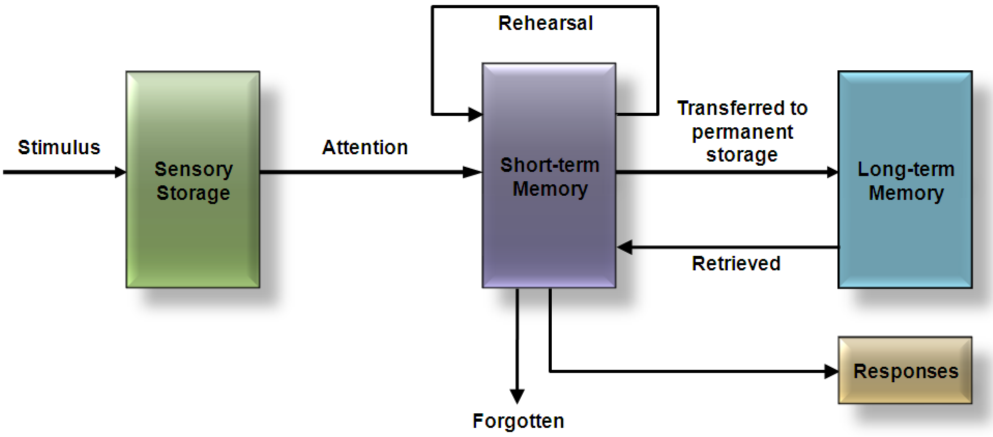


Figure 6-1: Cognitive model of Waugh and Norman (1965)

Several theories about sensory reception were developed in the area of cognitive psychology. Eysenck and Keane (2000) noted that the underlying the concept of these theories is that observations are developed by comparing incoming information to ‘inner models’ (within the memory) and so creating an image of the outside world. This process takes place in the ‘short-term’ and ‘long-term’ memory.

The cognitive model of Waugh and Norman (1965) is presented in Figure 6-1. Akira and Priti (1999) noted that the traditional view of human memory (Waugh & Norman, 1965) offers an elegant account of the basic mechanisms (encoding, maintenance, and retrieval) and representations in working memory or, rather, STM. According to this view, there are a number of structurally separate components or stores through which information is transferred. A sub-set of the information in the sensory registers is chosen for later processing via selective attentionand is transferred into a short-term store (STS) (encoding). The information in the STS is considered fragile and decays quickly, so rehearsal is necessary to keep it within the STS (maintenance) and to transfer it to a more durable long-term store (LTS). The information in the STS is assumed to be accessible relatively quickly and effortlessly (retrieval), but there may be a slight slowdown of retrieval speed as a function of the number of items within the STS. Once lost from the STS, information cannot be retrieved unless it is encoded in the LTS. Retrieval from the LTS, however, is generally considered a slower and more effortful process than that from the STS.

As for the representation issue, the traditional view emphasizes speech-based codes (i.e., acoustic, phonological, or verbal) as the predominant memory code in STM, as reflected in the fact that most of the STM experiments in the 1960s and 1970s were done using verbal materials, despite the fact that Atkinson and Shiffrin (1968) themselves explicitly acknowledged the possibility of other STM codes (e.g., visual, spatial). The emphasis on speech-based codes in STM is contrasted with meaning-based (semantic) codes considered dominant in LTM (Miyake and Priti, 1999).

Subjective assessment of a stimulus in a controlled laboratory environment attempts to retrieve the information from the long-term memory and compare the same with the auditory event in the short-term memory using ‘inner models’.

In this chapter, the developed aural comfort model is validated through a laboratory psychoacoustical experiment in which subjects were exposed to binaurally recorded road traffic and train noise and their subjective assessment of aural comfort was recorded. It was also the intention of the experiment to collect sufficient data for the examination of the relationships between noisiness, disturbance and different psychoacoustical quantities for parametric studies. The research design for the laboratory experiment is already discussed in Chapter 3 of this thesis.

6.2 PSYCHOACOUSTICS EXPERIMENT

The developed Acoustic Comfort Model (ACM) is founded on the subjective factors correlated to indoor aural comfort (collected from cluster sampled noise survey) and the objective indoor noise levels, deduced from the predicted facade noise levels and sound insulation of building facades for the relevant apartments at which noise survey was carried out. These noise levels are basically the indoor noise exposure levels due to Road Traffic and MRT Train in the vicinity of the residential buildings in noise survey area.

The indoor aural environment in a high-rise apartment is generally complex. This aural space is influenced by both indoor noise sources (such as, television, radio, vacuum machine, speech, washing machine, fan, air-con etc.) and outdoor noise sources (road traffic, train noise, playground noise, people's speech from other apartments, outdoor community functions etc.). Since the ACM has excluded the influence of all other noise sources on aural comfort except Road Traffic and MRT Train noise, assessing the characteristics of these noise sources in such a complex noise environment will be biased unless the other influencing noise could be totally eliminated. This is a challenging task to exercise with sufficient accuracy. As such, it is thought to be best to evaluate these noise characteristics (Road Traffic and MRT Train) in isolation and relate their qualitative aspects with the ACM. This is done through binaural recording of Road Traffic and MRT Train noise on survey sites and getting them evaluated in a controlled laboratory environment by the residents living in such high-rise public housing apartments.

In order to simulate a 'homely' environment for the evaluation of Road Traffic and MRT Train noise, psychoacoustics tests were carried out in a conducive environment (university staff lounge) where subjects were in comfortable level with regards to Thermal Comfort, Visual Comfort and Spatial Comfort. The provision of such comfort is expected to reduce bias in assessing aural comfort in comparison to subject's own home environment. In addition, earlier research (Poulsen, 1990) demonstrated that the duration of a listening session does not influence the evaluation of noise environment if the evaluation question refers to the home situation. As such, all the questions for laboratory psychoacoustics experiments were structured such that the subjects evaluate the noise as if they were in their own home environment.

In addition to the above, it is noted that the stimuli evaluated in the laboratory environment are binaurally recorded at the noise survey sites. As a results, the characteristics of the noise sources tested in the laboratory are not different from that on noise survey site. It is, however, the subjects who are different in the laboratory setup. It is important to take note that the indoor thermal comfort condition in the residential settings was assumed to be comfortable which is not investigated in greater detail in this thesis. The indoor aural environment in the laboratory has been chosen such that it representative of the 'homely' condition. The overall laboratory setup thus represents the on-site noise condition with a different set of subject group.

6.3 ETHICAL APPROVAL

Prior to the psychoacoustic research investigations, an ethical approval was received from the National University of Singapore Institutional Review Board (NUS-IRB) to conduct the study (Approval number: NUS 1118). The certificate of approval is presented in Appendix C of this thesis.

6.3.1 Test Room for the Psychoacoustic Studies

The study of aural comfort requires a conducive environment to carry out the psychoacoustic research experiment. Based on the experimental design, criteria for such an environment include a signal-to-noise ratio of 10 dB and thermal, visual and spatial comfort. Due to the lack of funding to build such an environment, the 'Staff Lounge' (which is generally used for the resting of the academic staff) of the School of Design and Environment was considered suitable for the study, since it meets all the required criteria. Although not usual, permission was received from the Dean's office to use the 'Staff Lounge' for a month for the research.

Figure 6-2: Photograph of the staff lounge

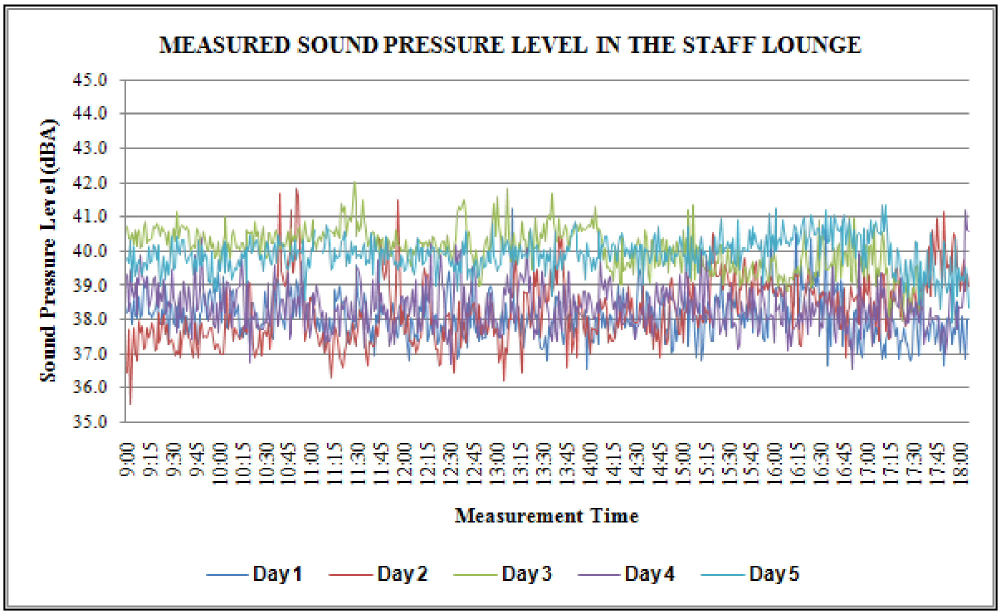


Figure 6-3: Measured sound pressure level in the test room

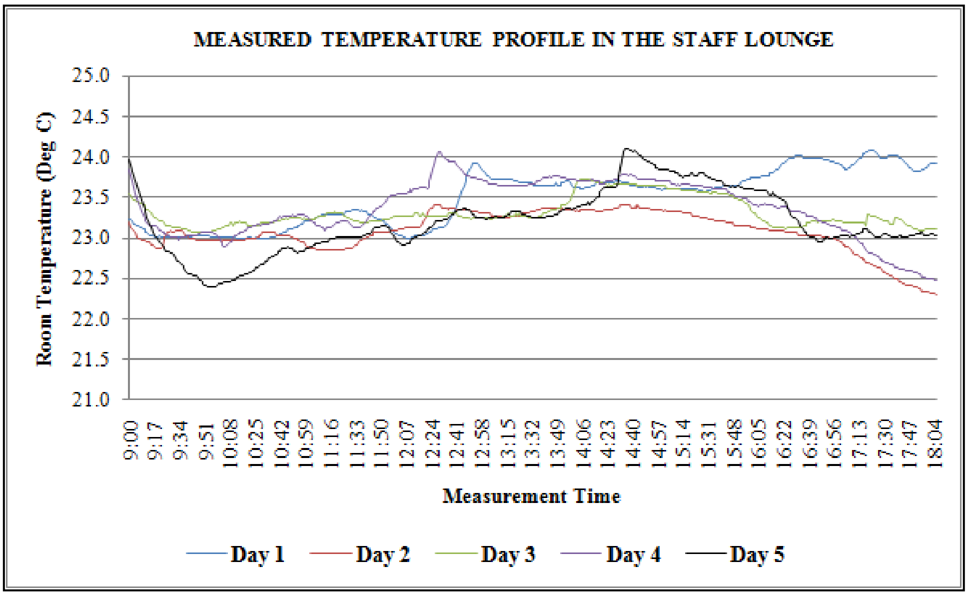


Figure 6-4: Measured temperature profile in the test room

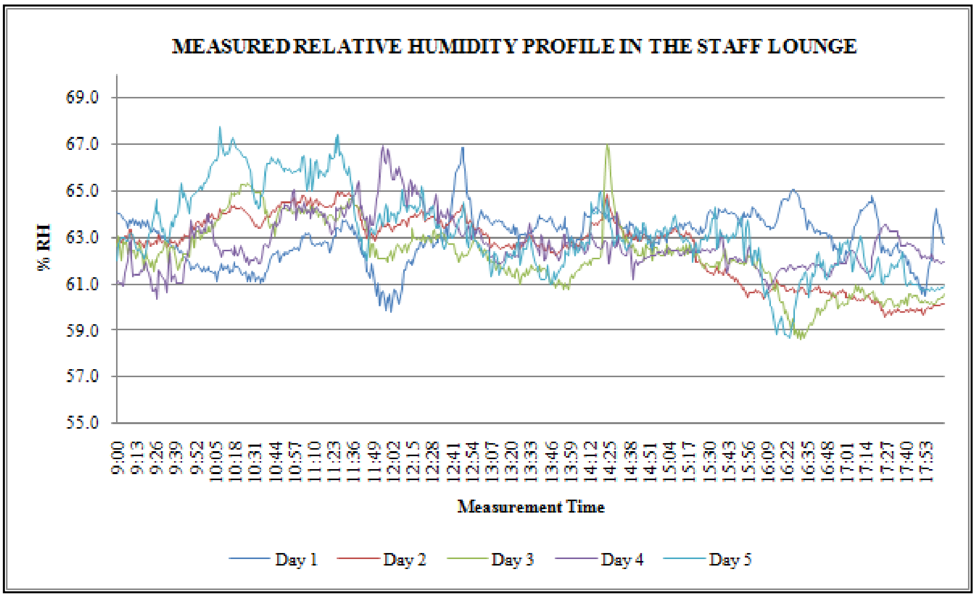


Figure 6-5: Measured relative humidity profile in the test room

A photograph of the staff lounge is shown in Figure 6-2. Sound pressure level, temperature and relative humidity measurements were carried out for a period of five days (from 9am to 6pm) in the staff lounge and the profiles are shown in Figure 6-3 to Figure 6-5. It is found that the indoor sound pressure level ranged between 36 dBA and 41 dBA which is considered a low background noise level for the experiment. It is noted that the lowest sound exposure level from the test stimuli was 51 dBA and therefore the test room provided a good signal to noise ratio. In general the temperature ranged between 22.5^{0}C to 24^{0}C. Relative humidity ranged between 60% and 67%. It is noted that the noise measurements were carried out using B&K 2250 Sound Level Meter (s/n 428334) and Temperature and Relative humidity were measured using HOBO data logger (s/n 2434460, 2434431) all duly calibrated prior to the measurements.

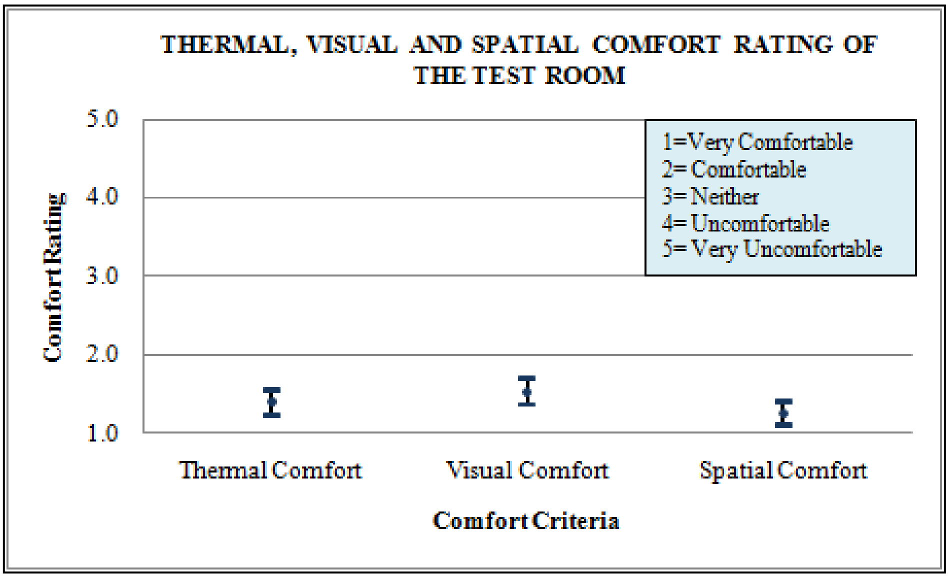


Figure 6-6: Subjective comfort rating of the test room

From this point onward, the 'staff lounge' is referred as the 'test room' or 'Laboratory Environment' in this thesis. The test room was evaluated (on a rating scale of 1 to 5 with '1' being very comfortable, '2' being comfortable, '3' being neither, '4' being uncomfortable and '5' being very uncomfortable) by all the subjects who completed all the experiments (total 36 subjects) and their evaluation in terms of thermal, visual and spatial comfort are shown in Figure 6-6 which shows that the test room environment was evaluated to be comfortable and very comfortable by the subjects.

6.3.2 Selection of Subjects

As there were no funds available to pay the subjects for the experiment, initiative was taken to get subjects who were willing to volunteer for the experiment at no payment. A total of 50 subjects were willing to voluntarily take part in the research experiments. They were generally students and staff from different departments of the university. All the fifty subjects went through the audiometric hearing test, conducted in the audiometric test booth located in the Acoustic Laboratory of the Building Department by qualified professionals who are authorized by the Ministry of Manpower (MOM) to carry out such test in Singapore. This part of the research experiment (payment to the Audiologist) was supported by a private organization - Sound and Vibration Pte. Ltd. We acknowledge their unconditional support for the research. A photograph of the audiometric hearing test taking place is shown in Figure 6-7.

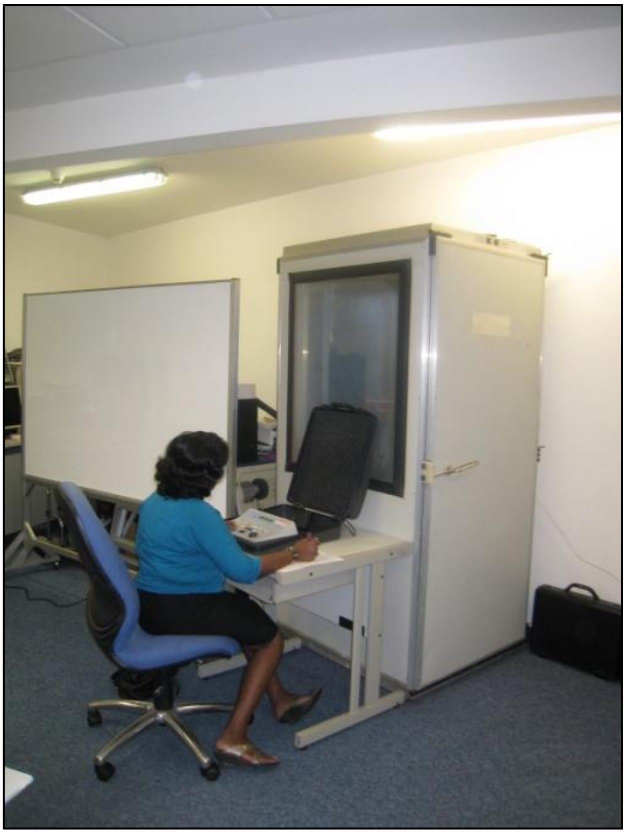


Figure 6-7: Audiometric hearing test for subjects

Figure 6-8 shows the hearing thresholds of all the 36 subjects who were qualified for the research experiment, through the audiometric hearing test, and finally took part in all the experiments. The criterion for computation of hearing threshold is illustrated in Chapter 3.

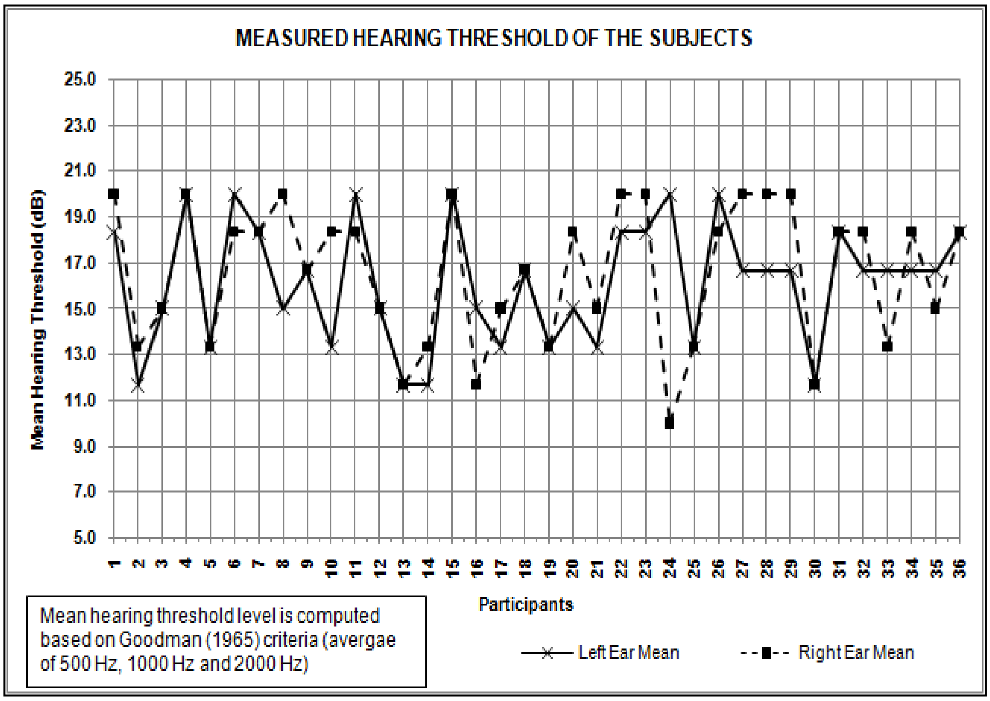


Figure 6-8: Audiometric hearing test results of the subjects

There were 16 female and 20 male subjects who took part in the experiments. 6 subjects aged between 20 years and 25 years, 25 subjects were aged between 26 years and 30 years and the remaining 5 subjects were aged between 30 years and 40 years. A total of 22 subjects were Singaporean and Singapore Permanent Resident while the remaining 14 subjects were nationals of different Asian countries. Prior to the experiments, subjects were asked to rate their noise sensitivity on a scale of 1 to 5 where 1 refers to not sensitive at all, 2 refers to a little sensitive, 3 refers to moderately sensitive, 4 refers to very sensitive and 5 refers to extremely sensitive to noise. It was found that among all the subjects, 2 were a little sensitive to noise, 25 of them were moderately sensitive to noise and the remaining 9 of them were very sensitive to noise.

6.3.3 Experimental Schedule and Procedure

The research experiment started on the 18th of October, 2010 and ended on the 11th November, 2010. There were a total of 75 sessions programmed in the Jury Listening

Software for evaluation. As discussed earlier, each experimental session generally took about 2.5 minutes (on the average). In a day, a subject was allowed to take part in the 'Experimental Block' only once which comprised of 12 experimental session at the most and lasted up to 30 minutes at the most. Based on these criteria, each subject was required to visit the 'test room' to take part in the experiment a total of 6 times during the entire experimental period. Each visit by the subjects was separated by 2-4 days. The schedule of the experiment was communicated with the subjects and finalized prior to the experiment.

The experimental setup is shown in Figure 6-9. Sound signals were sent from the Jury Listening Software (on a laptop computer) to the Sennheiser HD650 Binaural Headphones through a 24 bit Professional Sound Card. Subjects were required to listen to the sounds through the binaural headset and evaluate them on a rating scale shown on the Jury Listening Software interface. The Jury Listening Software plays the sound signals within a session in random order. The detailed methods of evaluations of the stimuli are discussed in Chapter 3.

Figure 6-9: Experimental setup in the test room

6.3.4 Analysis of the Recorded Sound Signals

As discussed in Chapter 3, Road traffic noise from 5 different categories of roads were recorded and evaluated. Similar to road traffic noise, MRT train sounds were studied for 5 different distances between the track and the residential buildings. Binaural sounds were recorded at two different sites for each category of the roads and train. Afterwards, equalization and calibration was carried out on each sound signal (using dBSonic software) which were then referred as 'Ref + 0 dB' or simply '+ 0 dB'. Additional sound signals were generated for +3 dB, -3dB and -6 dB in relation to the reference sound ('+0 dB'). A brief summary of the acoustical indices such as overall level, mean loudness, mean sharpness, mean fluctuation strength and mean roughness for recorded road traffic and train noise are summarized in Table 6-1 and Table 6-2 respectively. Detailed psychoacoustical indices related to all the road and train sound signals are presented in Appendix D of this thesis. It is noted from Table 6-1 that the reference noise levels for Category 1 to Category 5 roads are approximately 71 dBA, 66 dBA, 65 dBA, 63 dBA and 58 dBA respectively. Mean loudness of the reference sounds of these road traffic noise varied between 12 Sone to 25 Sone. Mean sharpness for these traffic noises ranged between 1.2 acum to 1.3 acum. Fluctuation strength (slow modulation up to 15Hz) was found to be between 1.8 centi Vacil and 9.6 centi Vacil while the Roughness (rapid modulation between 15 and 300 Hz) ranged between 26 centi Asper and 33 centi Asper.

It is noted from Table 6-2 that the reference noise levels for MRT trains located between 30m and 70m (at 10m intervals) are approximately 70 dBA, 67 dBA, 64 dBA, 60 dBA and 56 dBA respectively. Mean loudness of the reference sounds of these train noise categories varied between 11 Sone to 25 Sone. Mean sharpness for these train noises varied between 1.2 acum to 1.5 acum. Fluctuation strength (slow modulation up to 15Hz) was found to be between 3.3 centi Vacil and 12.7 centi Vacil while the Roughness (rapid modulation between 15 and 300 Hz) ranged between 26 centi Asper and 36 centi Asper.

Table 6-1: Psychoacoustical indices for different road traffic noise categories

	Cat-1 Kranji				**Cat-1-Tampines**			
Category 1 Road	+3 dB	Ref 0 dB	-3 dB	- 6 dB	+3 dB	Ref 0 dB	-3 dB	- 6 dB
Lmean, dBA	73.4	70.4	67.4	64.4	74.3	71.3	68.3	65.3
Nmean (sone)	30.6	25.4	21.0	17.3	33.0	27.3	22.5	18.5
Smean (acum)	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1
Fmean (cVacil)	3.8	3.3	3.1	2.8	10.5	9.6	8.8	8.1
Rmean (cAsper)	33.3	31.4	29.5	28.0	34.4	32.7	31.2	29.8
Category 2 Road	**Cat 2 - Woodlands Ave 2**				**Cat - 2 - Punggol Rd**			
Lmean, dBA	69.1	66.1	63.2	60.2	68.8	65.8	62.8	59.8
Nmean (sone)	26.0	21.5	17.7	14.5	24.2	20.0	16.5	13.4
Smean (acum)	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2
Fmean (cVacil)	2.5	2.3	2.1	1.9	4.7	4.3	4.1	3.8
Rmean (cAsper)	32.0	30.1	28.6	27.5	31.0	29.3	27.9	26.9
Category 3 Road	**Cat - 3 - Bedok North Rd**				**Cat - 3 - Yishun Ave 1**			
Lmean, dBA	68.6	65.6	62.6	59.6	68.0	65.0	62.0	59.0
Nmean (sone)	26.8	22.2	18.3	15.0	23.0	19.0	15.6	12.8
Smean (acum)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Fmean (cVacil)	3.2	3.0	2.8	2.5	2.8	2.7	2.5	2.3
Rmean (cAsper)	31.7	30.0	28.5	27.6	31.1	29.4	28.1	27.0
Category 4 Road	**Cat-4-Sembawang Dr**				**Cat 4 - Clementi Ave 5**			
Lmean, dBA	66.5	63.5	60.5	57.5	66.0	63.0	60.0	57.0
Nmean (sone)	22.0	18.2	14.9	12.1	22.0	18.2	14.9	12.2
Smean (acum)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Fmean (cVacil)	3.5	3.3	3.1	2.9	4.8	4.4	4.2	4.0
Rmean (cAsper)	30.8	29.3	28.0	27.0	29.8	28.3	27.5	26.5
Category 5 Road	**Cat - 5 - Tampines St 81**				**Cat - 5- Jurong West St 65**			
Lmean, dBA	60.8	57.8	54.8	51.8	61.0	58.0	55.0	52.0
Nmean (sone)	15.6	12.7	10.4	8.4	15.8	12.9	10.5	8.5
Smean (acum)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Fmean (cVacil)	2.1	1.9	1.8	1.6	1.9	1.8	1.6	1.5
Rmean (cAsper)	27.5	26.5	25.0	23.6	27.2	26.2	24.9	23.4

Table 6-2: Psychoacoustical indices for different train noise categories

	MRT - 30M Holland Rise				MRT - 30M Woodlands Dr 42			
	+3 dB	Ref 0 dB	-3 dB	- 6 dB	+3 dB	Ref 0 dB	-3 dB	- 6 dB
Lmean, dBA	72.7	69.7	66.7	63.7	72.3	69.3	66.3	63.3
Nmean (sone)	28.7	23.7	19.6	16.1	30.3	25.1	20.8	17.1
Smean (acum)	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5
Fmean (cVacil)	6.4	5.9	5.6	5.4	13.3	12.7	12.0	11.3
Fperc (cVacil)	8.6	8.0	7.6	7.3	18.4	17.3	16.3	15.5
Rmean (cAsper)	35.0	32.8	31.0	29.4	38.2	35.7	33.7	31.9
	MRT - 40M Clementi Ave 2				MRT - 40M Toh Guan Rd			
Lmean, dBA	69.4	66.4	63.4	60.4	70.4	67.4	64.4	61.4
Nmean (sone)	23.3	19.3	15.9	12.9	24.4	20.2	16.5	13.6
Smean (acum)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Fmean (cVacil)	6.7	6.1	5.7	5.6	6.9	6.4	6.0	5.8
Fperc (cVacil)	9.3	8.5	8.3	8.2	7.9	7.3	6.8	6.6
Rmean (cAsper)	33.8	32.0	30.2	28.5	37.0	34.9	32.8	31.0
	MRT - 50M Bedok Central				MRT - 50M Bedok South Ave 2			
Lmean, dBA	66.5	63.5	60.5	57.5	67.2	64.2	61.2	58.3
Nmean (sone)	19.8	16.3	13.3	10.9	19.3	15.9	12.9	10.6
Smean (acum)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Fmean (cVacil)	4.9	4.7	4.4	4.3	7.7	7.4	7.3	7.0
Fperc (cVacil)	5.4	5.1	4.9	4.7	11.4	10.9	10.6	10.3
Rmean (cAsper)	32.2	30.5	28.7	27.2	31.7	30.0	28.4	26.9
	MRT - 60M Choa Chu Kang Crescent				MRT - 60M Yishun St 20			
Lmean, dBA	62.7	59.7	56.7	53.7	63.3	60.3	57.3	54.3
Nmean (sone)	15.0	12.2	9.9	8.1	14.0	11.4	9.3	7.5
Smean (acum)	1.2	1.2	1.2	1.2	1.3	1.2	1.2	1.2
Fmean (cVacil)	4.8	4.4	4.2	3.8	6.8	6.4	6.1	5.7
Fperc (cVacil)	6.1	5.7	5.4	4.9	8.0	7.5	7.2	6.8
Rmean (cAsper)	29.9	28.0	26.3	24.8	31.5	29.5	27.7	25.8
	MRT - 70M Jurong East St 21				MRT - 70M Woodlands St 32			
Lmean, dBA	61.6	58.6	55.6	52.6	59.4	56.4	53.4	50.4
Nmean (sone)	14.0	11.4	9.3	7.5	13.0	10.5	8.5	6.9
Smean (acum)	1.2	1.2	1.2	1.2	1.4	1.4	1.4	1.4
Fmean (cVacil)	3.6	3.3	3.1	2.9	8.2	7.8	7.7	7.7
Fperc (cVacil)	4.1	3.8	3.5	3.3	12.8	12.4	12.1	12.1
Rmean (cAsper)	28.7	27.3	25.7	23.8	28.6	27.2	25.6	23.5

6.4 PARAMETRIC STUDY

The only quantitative acoustical parameter that was involved in the developed aural comfort model (Eq. 5-6) is the A-weighted indoor noise exposure level. Examinations of psychoacoustical quantities and their inclusion in the overall aural comfort model were beyond the scope. This was due to the fact that it was not possible to examine the different qualitative acoustical quantities of individual noise sources in a complex noise environment and hence the influence of the specific noise source on overall aural comfort could not be established. However, the developed aural comfort model distinctly demonstrated that aural comfort is influenced by the perceived responses (noisiness and disturbance) related to Road Traffic and MRT Train noise in a naturally ventilated public housing residential environment. As such, it is of utmost importance to look into the psychoacoustical aspects of these noise sources and integrate the associated quantitative parameters into the model so as to realize a comprehensive aural comfort assessment.

In this Chapter, the two key parameters of the aural comfort model: 'noisiness' and 'disturbance' are investigated for their relationship with different acoustical and psychoacoustical quantities in relation to road traffic and train noise.

6.4.1 Perceived Noisiness and Disturbance due to Road Traffic Noise

The different acoustical quantities of the road traffic noise were correlated with the subjective perceptions of 'apartment's noisiness' and 'noise disturbance' due to road traffic noise. The spearman rank correlation test statistics are presented in Table 6-3.

Table 6-3: Correlations between noisiness, disturbance and acoustical quantities of road traffic noise

Acoustical Quantities	**Correlation Coefficient**		
	Noisiness Rating	Disturbance Rating	N
Mean Level, L_{mean} (dBA)	**.736****	**.737****	1440
Mean Level, L_{mean} (dB)	**.679****	**.674****	1440
Maximum Loudness, N_{max} (Sone)	**.731****	**.731****	1440

Acoustical Quantities	**Correlation Coefficient**		
	Noisiness Rating	Disturbance Rating	N
Mean Loudness, N_{mean} (Sone)	**.745****	**.743****	1440
Zwicker Loudness, $N_{ISO532B}$	**.740****	**.738****	1440
Five Percentile Loudness N_5 (Sone)	**.730****	**.729****	1440
Maximum Sharpness, S_{max} (Acum)	0.002	0.007	1440
Mean Sharpness S_{mean} (Acum)	-0.008	-0.016	1440
Five Percentile Sharpness, S_5 (Acum)	0.029	0.029	1440
Maximum Fluctuation Strength, Fmax (Centi Vacil)	**.417****	**.433****	1440
Mean Fluctuation Strength, Fmean (Centi Vacil)	**.472****	**.486****	1440
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	**.427****	**.443****	1440
Maximum Roughness, R_{max} (Centi Asper)	**.716****	**.710****	1440
Mean Roughness, R_{mean} (Centi Asper)	**.744****	**.742****	1440
Five Percentile Roughness, R_5 (Centi Asper)	**.732****	**.726****	1440
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	.379**	.377**	1440
Maximum Tone to Noise Ratio, TNR	.292**	.282**	1440
The Frequency of the Maximum Prominence, F_{PR} (Hz)	-.246**	-.239**	1440
Maximum Prominance, PR_{max} (dB)	.216**	.222**	1440
Mean Prominance, PR_{mean} (dB)	.216**	.222**	1440
Global Prominance, PR (dB)	.216**	.222**	1440

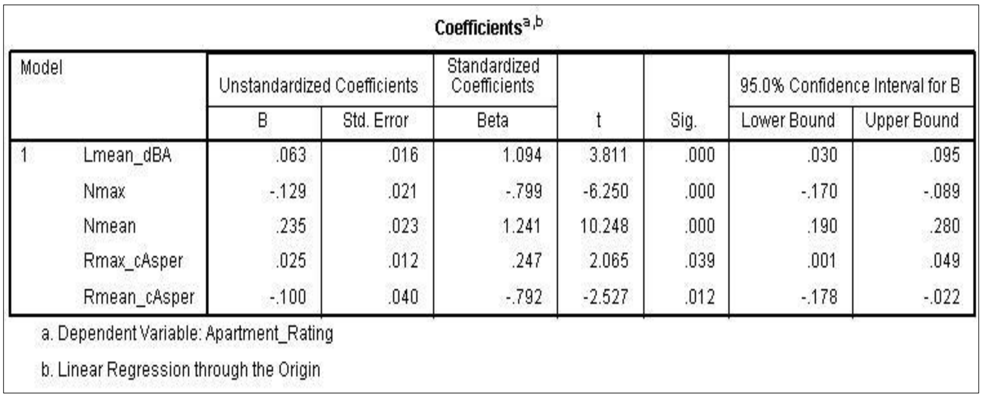
**. Spearman's rho Correlation is significant at the 0.01 level (1-tailed).

6.4.1.1 Rating of noisiness of the apartment (road traffic noise)

It is noted from Table 6-3 that 'rating of noisiness of the apartment' is significantly correlated (at 0.01 significance level) to the overall noise level and to Loudness (Mean loudness, Maximum loudness, Zwicker loudness and Five percentile loudness), Fluctuation Strength (Maximum, Mean and Five percentile fluctuation strength) and Roughness (Maximum roughness, Mean roughness and Five percentile roughness). Noisiness of the apartment is found not to be correlated with Sharpness.

Noisiness rating is found weakly (but significantly) correlated with tonality and prominence ratio.

Table 6-4: Variables and the regression coefficients of the final model



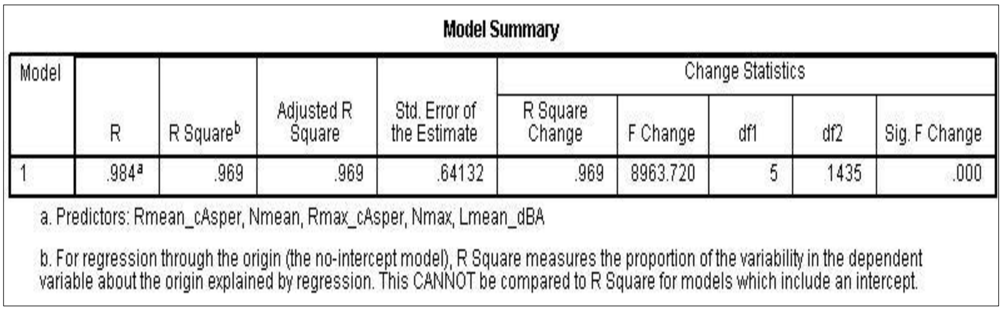
Coefficients^{a,b}

Model		Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B	
		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
1	Lmean_dBA	.063	.016	1.094	3.811	.000	.030	.095
	Nmax	-.129	.021	-.799	-6.250	.000	-.170	-.089
	Nmean	.235	.023	1.241	10.248	.000	.190	.280
	Rmax_cAsper	.025	.012	.247	2.065	.039	.001	.049
	Rmean_cAsper	-.100	.040	-.792	-2.527	.012	-.178	-.022

a. Dependent Variable: Apartment_Rating

b. Linear Regression through the Origin

Table 6-5: Test statistics showing 'goodness of fit' of the model



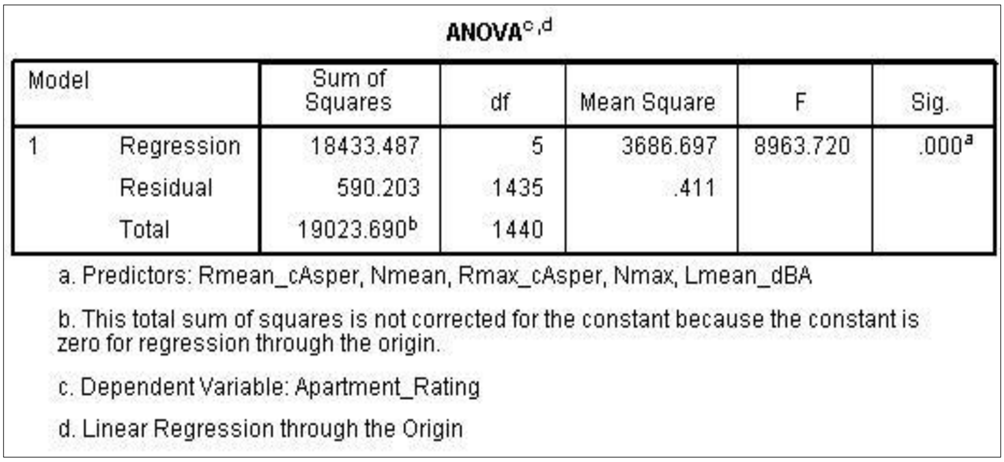
Model Summary

Model					Change Statistics				
	R	R Square^b	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.984^a	.969	.969	.64132	.969	8963.720	5	1435	.000

a. Predictors: Rmean_cAsper, Nmean, Rmax_cAsper, Nmax, Lmean_dBA

b. For regression through the origin (the no-intercept model), R Square measures the proportion of the variability in the dependent variable about the origin explained by regression. This CANNOT be compared to R Square for models which include an intercept.

Table 6-6: ANOVA test results showing the statistical significance of the model



ANOVA^{c,d}

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	18433.487	5	3686.697	8963.720	.000^a
	Residual	590.203	1435	.411		
	Total	19023.690^b	1440			

a. Predictors: Rmean_cAsper, Nmean, Rmax_cAsper, Nmax, Lmean_dBA

b. This total sum of squares is not corrected for the constant because the constant is zero for regression through the origin.

c. Dependent Variable: Apartment_Rating

d. Linear Regression through the Origin

Linear regression in the least square method was carried out to develop a statistical model relating rating of noisiness of the apartment with different correlated psychoacoustical quantities as shown in Table 6-3. The psychoacoustical quantities that are found significantly correlated with the 'rating of noisiness of apartment due to road traffic noise' in development of a statistical model are shown in Table 6-4.

The 'goodness of fit' test statistics of the model is presented in Table 6-5. They illustrate that the established model is a good fit model (R^2=0.969). The $adjusted\ R^2$ value also illustrates that the model accounts for 96.9% of the variance in defining noisiness of the apartment due to road traffic noise. The ANOVA test statistics, presented in Table 6-6, confirm that the model is statistically significant ($p < 0.05$).

Based on the regression coefficients, presented in Table 6-4, the established model can be written as:

$$\boldsymbol{Rating\ of\ Noisiness\ of\ Apartment}\ (\boldsymbol{Subjected\ to\ Road\ Traffic\ noise}) \\ = 0.063 * L_{mean}\ (dBA) - 0.129 * N_{max}\ (Sone) + 0.235 \\ * N_{mean}(Sone) + 0.025 * R_{max}(cAsper) - 0.1 * R_{mean}\ (cAsper)$$

....[Eq. 6-1]

Where,

$L_{mean}\ (dBA)\ is\ the\ A-weighted\ overall\ noise\ exposure\ level$

$N_{max}\ (Sone)\ is\ the\ maximum\ Loudness\ in\ Sone$

$N_{mean}\ (Sone)\ is\ the\ mean\ Loudness\ in\ Sone$

$R_{max}\ (cAsper)\ is\ the\ maximum\ Roughness\ in\ Centi\ Asper$

$R_{mean}\ (cAsper)\ is\ the\ mean\ Roughness\ in\ Centi\ Asper$

To examine the influence of each of these factors (in Eq. 6-1), overall rating of noisiness due to road traffic is plotted against these factors in Figure 6-10 to Figure 6-12. Subjective perception of noisiness of apartment is measured on a continuous scale of 1 to 5 where 1 refer to 'very quiet', 2 refers to 'quiet', 3 refers to 'acceptable', 4 refers to 'noisy' and 5 refers to 'very noisy'.

Figure 6-10 illustrates that the noisiness of an apartment is perceived 'acceptable' with a mean A-weighted noise exposure level of about 60 dB while it is perceived as 'quiet' with a mean A-weighted noise exposure level of 53 dB. It is noted from Figure 6-11 that the noisiness of an apartment is perceived as 'acceptable' with a mean Loudness level of 15 sone and maximum loudness level of 17 sone. On the other hand, noisiness of an apartment is perceived as 'quiet' with a mean Loudness level of 7 Sone and maximum Loudness level of 9 sone. Noisiness of an apartment was found as 'acceptable' (Figure 6-12) with a mean Roughness level of 27 centi-Asper and maximum Roughness level of 34 centi-Asper. On the other hand, noisiness of an apartment was felt 'quiet' with a mean Roughness level of 24 centi-Asper and maximum Roughness level of 27 centi-Asper.

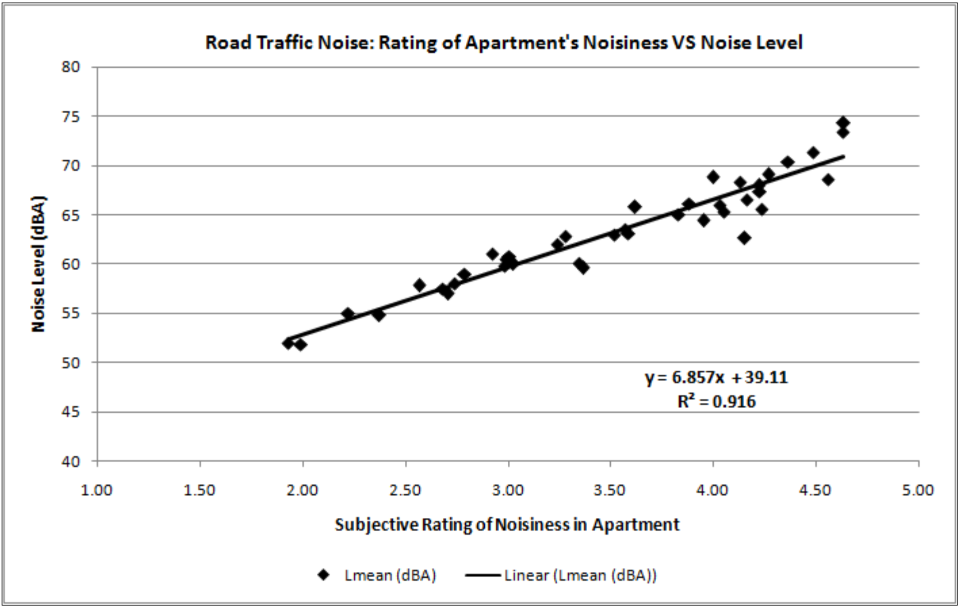


Figure 6-10: Rating of apartment's noisiness for different noise exposure levels

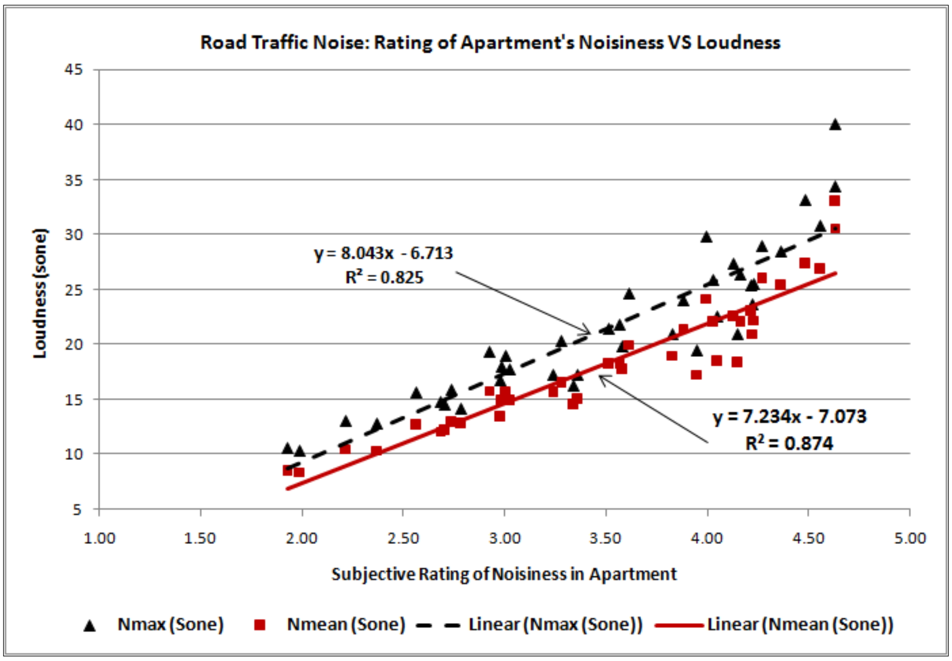


Figure 6-11: Rating of apartment's noisiness for different Loudness levels

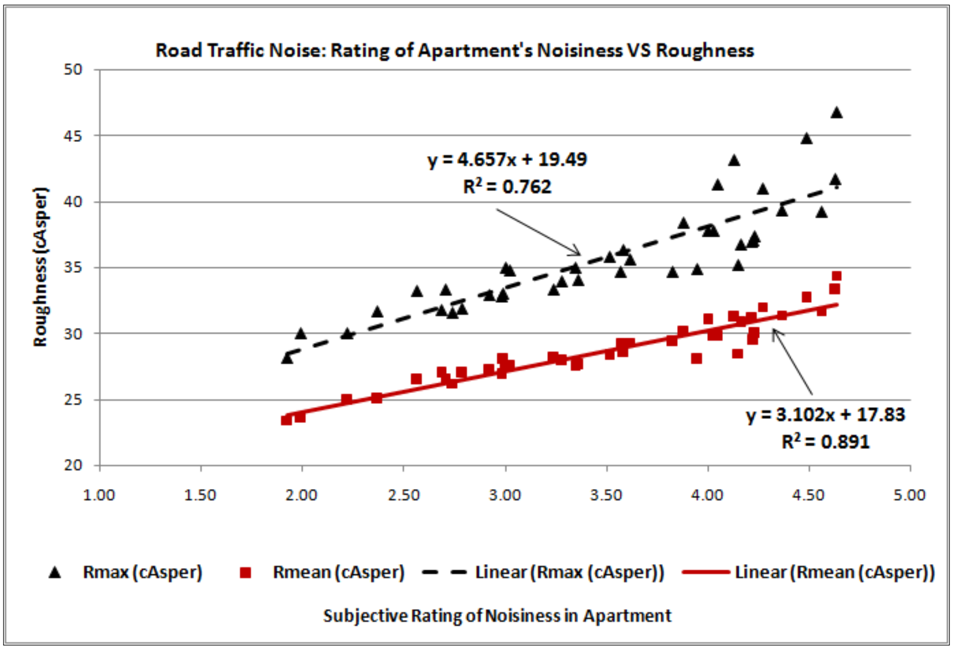


Figure 6-12: Rating of apartment's noisiness for different Roughness levels

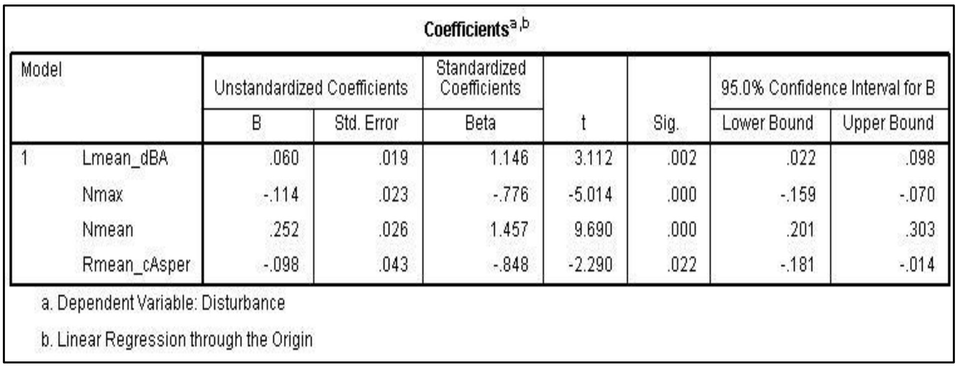
6.4.1.2 Rating of noise disturbance (road traffic noise)

Like noisiness perception, 'rating of noise disturbance of the apartment due to road traffic' was found (Table 6-3) significantly correlated (at 0.01 significance level) to the overall noise level, Loudness (Mean Loudness, Maximum Loudness, Zwicker

Loudness and Five percentile Loudness), Fluctuation Strength (Maximum, Mean and Five percentile Fluctuation Strength) and Roughness (Maximum Roughness, Mean Roughness and Five percentile Roughness). Noise disturbance due to road traffic was found not correlated with Sharpness. Noise disturbance was found weakly (but significantly) correlated with tonality and prominence ratio.

Linear regression in the least square method was carried out to establish a statistical model relating noise disturbance with different correlated psychoacoustical quantities as shown in Table 6-3. The psychoacoustical quantities that were found significantly correlated with the 'noise disturbance due to road traffic noise' in development of a statistical model are shown in Table 6-7.

Table 6-7: Variables and the regression coefficients of the final model



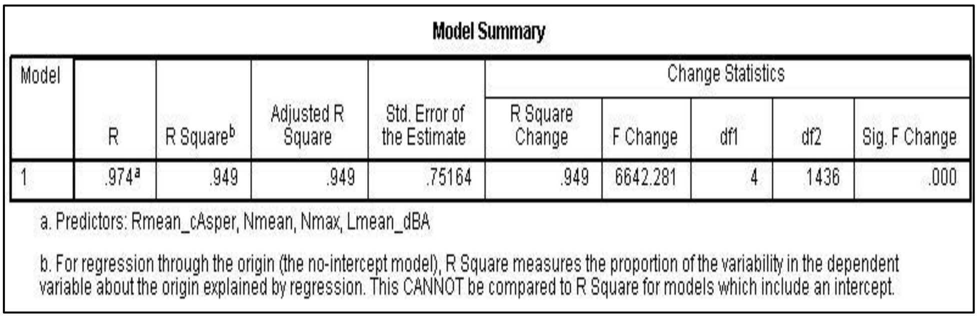
Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	Lmean_dBA	.060	.019	1.146	3.112	.002	.022	.098
	Nmax	-.114	.023	-.776	-5.014	.000	-.159	-.070
	Nmean	.252	.026	1.457	9.690	.000	.201	.303
	Rmean_cAsper	-.098	.043	-.848	-2.290	.022	-.181	-.014

a. Dependent Variable: Disturbance

b. Linear Regression through the Origin

Table 6-8: Test statistics showing 'goodness of fit' of the model



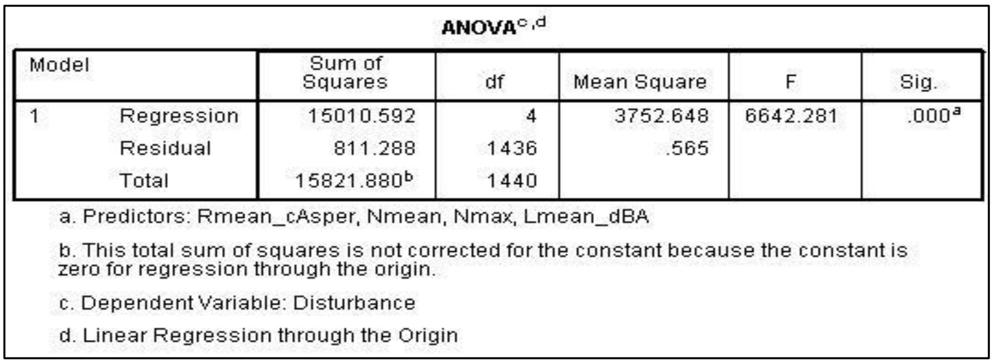
Model Summary

Model	R	R Square[b]	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.974[a]	.949	.949	.75164	.949	6642.281	4	1436	.000

a. Predictors: Rmean_cAsper, Nmean, Nmax, Lmean_dBA

b. For regression through the origin (the no-intercept model), R Square measures the proportion of the variability in the dependent variable about the origin explained by regression. This CANNOT be compared to R Square for models which include an intercept.

Table 6-9: ANOVA test results showing statistical significance of the model



ANOVA[c,d]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15010.592	4	3752.648	6642.281	.000[a]
	Residual	811.288	1436	.565		
	Total	15821.880[b]	1440			

a. Predictors: Rmean_cAsper, Nmean, Nmax, Lmean_dBA

b. This total sum of squares is not corrected for the constant because the constant is zero for regression through the origin.

c. Dependent Variable: Disturbance

d. Linear Regression through the Origin

The 'goodness of fit' test statistics of the model presented in Table 6-8 illustrates that the established model is a good fit model (R^2=0.949). The $adjusted\ R^2$value also illustrates that the model accounts for 94.9% of the variance in defining noisiness of the apartment due to road traffic noise. The ANOVA test statistics, presented in Table 6-9, confirm that the model is statistically significant ($p < 0.05$). Based on the regression coefficients, presented in Table 6-7, the established model can be written as:

$$\boldsymbol{Rating\ of\ Disturbance\ due\ to\ Road\ Traffic\ Noise}$$
$$= 0.06 * L_{mean}\ (dBA) - 0.114 * N_{max}\ (Sone) + 0.252 * N_{mean}(Sone)\ - 0.098 * R_{mean}(cAsper)$$

..............................[Eq. 6-2]

Where,

$L_{mean}\ (dBA)\ is\ the\ A - weighted\ overall\ noise\ exposure\ level$

$N_{max}\ (Sone)\ is\ the\ maximum\ Loudness\ in\ Sone$

$N_{mean}\ (Sone)\ is\ the\ mean\ Loudness\ in\ Sone$

$R_{mean}\ (cAsper)\ is\ the\ mean\ Roughness\ in\ Centi\ Asper$

To examine the influence of each of these factors (in Eq. 6-2), the overall rating of noise disturbance due to road traffic is plotted against these factors in Figure 6-13 to Figure 6-15. Subjective rating of noise disturbance due to road traffic is measured on a continuous scale of 1 to 5 where 1 refer to 'not at all disturbed', 2 refers to 'a little disturbed', 3 refers to 'disturbed', 4 refers to 'very disturbed' and 5 refers to 'extremely disturbed'.

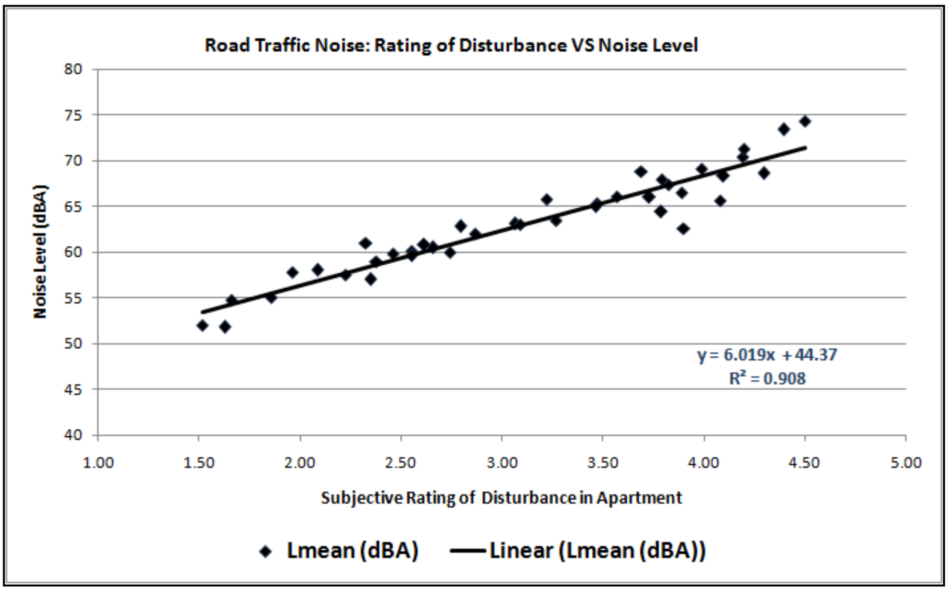


Figure 6-13: Rating of noise disturbance for different noise exposure levels

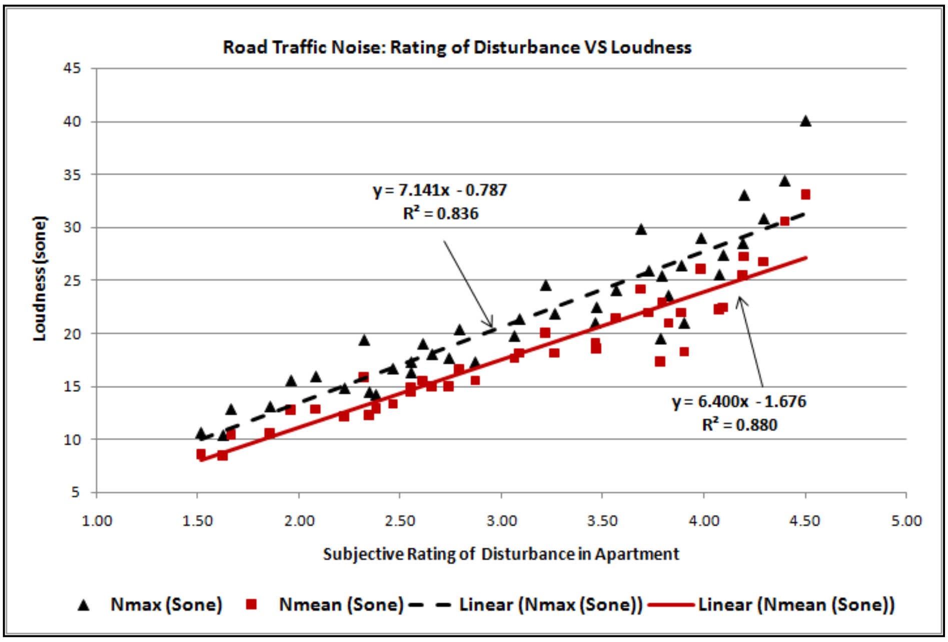


Figure 6-14: Rating of noise disturbance for different Loudness levels

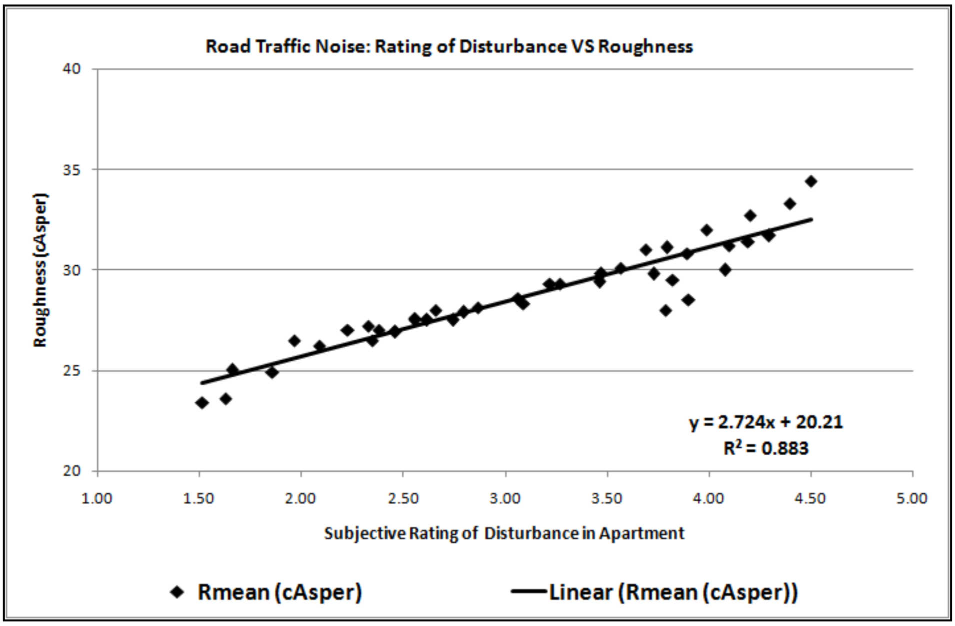


Figure 6-15: Rating of noise disturbance for different Roughness levels

Figure 6-13 illustrates that the noise disturbance due to road traffic is perceived as 'a little disturbing' with a mean A-weighted noise exposure level of about 57 dB. Figure 6-14 illustrates that the noise disturbance is felt to be 'a little disturbing' with a mean Loudness level of 11 sone and maximum Loudness level of 13 sone. Noise disturbance is perceived as 'a little disturbing' with a mean Roughness of 26 centi-Asper (Figure 6-15).

6.4.2 Perceived Noisiness and Disturbance due to MRT Train Noise

The different psychoacoustical quantities of the MRT train noise are correlated with the subjective perceptions of 'apartment's noisiness' and 'noise disturbance'. Spearman rank correlation tests were carried out to examine the correlations between these factors and their significance and the test statistics are presented in Table 6-10.

Table 6-10: Correlations between noisiness, disturbance and acoustical quantities of train noise

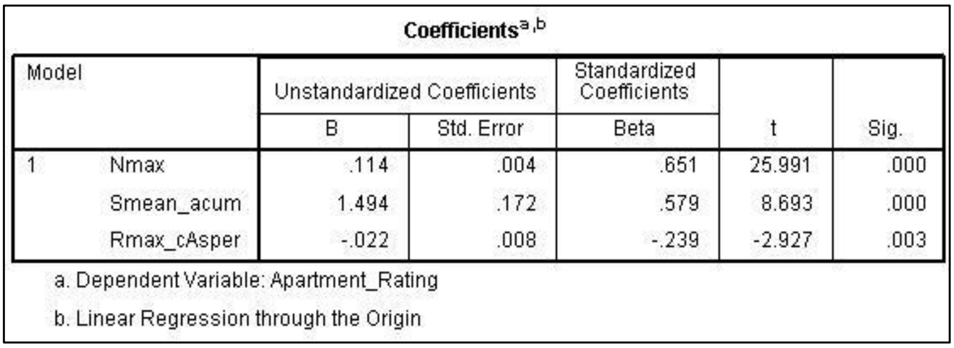
Acoustical Quantities	**Correlation Coefficient**		
	Noisiness Rating	**Disturbance Rating**	**N**
Mean Level, L_{mean} (dBA)	**.759****	**.782****	1440
Mean Level, L_{mean} (dB)	**.756****	**.768****	1440
Maximum Loudness, N_{max} (Sone)	**.771****	**.794****	1440
Mean Loudness, N_{mean} (Sone)	**.769****	**.786****	1440
Zwicker Loudness, $N_{ISO532B}$	**.772****	**.788****	1440
Five Percentile Loudness N_5 (Sone)	**.776****	**.795****	1440
Maximum Sharpness, S_{max} (Acum)	**.424****	**.428****	1440
Mean Sharpness S_{mean} (Acum)	**.587****	**.606****	1440
Five Percentile Sharpness, S_5 (Acum)	**.485****	**.495****	1440
Maximum Fluctuation Strength, Fmax (Centi Vacil)	**.339****	**.342****	1440
Mean Fluctuation Strength, Fmean (Centi Vacil)	**.305****	**.320****	1440
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	**.330****	**.332****	1440
Maximum Roughness, R_{max} (Centi Asper)	**.677****	**.705****	1440
Mean Roughness, R_{mean} (Centi Asper)	**.741****	**.763****	1440
Five Percentile Roughness, R_5 (Centi Asper)	**.715****	**.735****	1440
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	.230**	.273**	1440
Maximum Tone to Noise Ratio, TNR	.261**	.302**	1440
The Frequency of the Maximum Prominence, F_{PR} (Hz)	-.201**	-.171**	1440
Maximum Prominance, PR_{max} (dB)	.097**	.141**	1440
Mean Prominance, PR_{mean} (dB)	.097**	.141**	1440
Global Prominance, PR (dB)	.097**	.141**	1440
**. Spearman's rho Correlation is significant at the 0.01 level (1-tailed).			

6.4.2.1 Rating of noisiness of apartment (MRT train noise)

It is noted from Table 6-10 that 'rating of noisiness of apartment' is significantly correlated (to 0.01 significance level) with the overall noise level and Loudness (mean Loudness, maximum Loudness, Zwicker Loudness and Five percentile Loudness), Sharpness (Maximum, Mean and Five percentile Sharpness), Fluctuation Strength (Maximum, Mean and Five percentile Fluctuation Strength) and Roughness (Maximum Roughness, Mean Roughness and Five percentile Roughness). Noisiness rating was found weakly (but significantly) correlated with tonality and prominence ratio.

Linear regression in the least square method was carried out to develop a statistical model relating rating of noisiness of the apartment with different correlated psychoacoustical quantities as shown in Table 6-10. The psychoacoustical quantities that were found significantly correlated with the 'rating of noisiness of apartment due to MRT train noise' in development of a statistical model are shown in Table 6-11.

Table 6-11: Variables and the regression coefficients of the final model



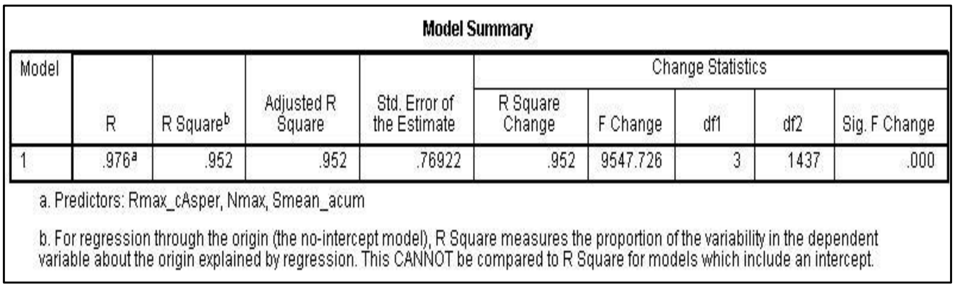
Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	Nmax	.114	.004	.651	25.991	.000
	Smean_acum	1.494	.172	.579	8.693	.000
	Rmax_cAsper	-.022	.008	-.239	-2.927	.003

a. Dependent Variable: Apartment_Rating

b. Linear Regression through the Origin

Table 6-12: Test statistics showing 'goodness of fit' of the model



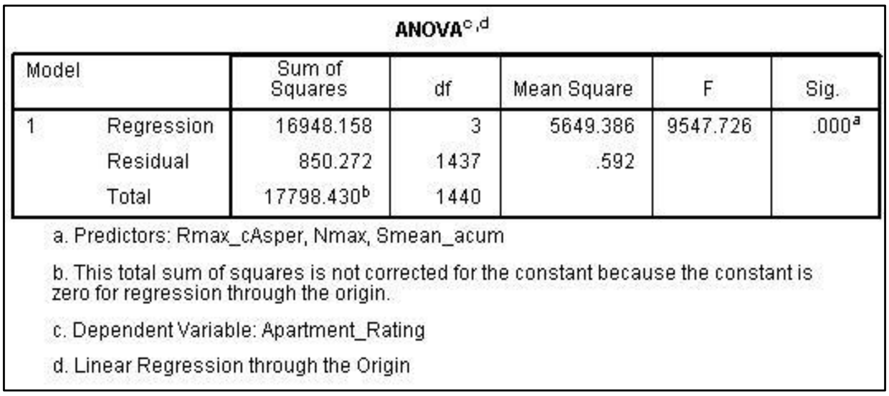
Model Summary

Model	R	R Square[b]	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.976[a]	.952	.952	.76922	.952	9547.726	3	1437	.000

a. Predictors: Rmax_cAsper, Nmax, Smean_acum

b. For regression through the origin (the no-intercept model), R Square measures the proportion of the variability in the dependent variable about the origin explained by regression. This CANNOT be compared to R Square for models which include an intercept.

Table 6-13: ANOVA test results showing statistical significance of the model



ANOVA[c,d]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	16948.158	3	5649.386	9547.726	.000[a]
	Residual	850.272	1437	.592		
	Total	17798.430[b]	1440			

a. Predictors: Rmax_cAsper, Nmax, Smean_acum

b. This total sum of squares is not corrected for the constant because the constant is zero for regression through the origin.

c. Dependent Variable: Apartment_Rating

d. Linear Regression through the Origin

The 'goodness of fit' test statistics of the model presented in Table 6-12 illustrate that the established model is a 'good fit' model (R^2=0.976). The $adjusted\ R^2$value also illustrates that the model accounts for 95.2% of the variance in defining noisiness of the apartment due to MRT train noise. The ANOVA test statistics, presented in Table 6-13, confirms that the model is statistically significant ($p < 0.05$).

Based on the regression coefficients, presented in Table 6-11, the established model can be written as:

$$\boldsymbol{Rating\ of\ Noisiness\ of\ Apartment}\ (\boldsymbol{Subjected\ to\ MRT\ Train\ noise}) \\ = 0.114 * N_{max}\ (Sone) + 1.494 * S_{mean}(Acum) - 0.022 \\ * R_{max}\ (cAsper)$$

..............................[Eq. 6-3]

Where,

$N_{max}\ (Sone)\ is\ the\ maximum\ Loudness\ in\ Sone$

$S_{mean}\ (Acum)\ is\ the\ mean\ Sharpness\ in\ Acum$

$R_{max}\ (cAsper)\ is\ the\ maximum\ Roughness\ in\ Centi\ Asper$

To examine the influence of each of these factors (in Eq. 6-3), overall rating of noisiness due to MRT train is plotted against these factors in Figure 6-16 to Figure 6-18. Subjective perception of noisiness of apartment is measured on a continuous scale of 1 to 5 where 1 refer to 'very quiet', 2 refers to 'quiet', 3 refers to 'acceptable', 4 refers to 'noisy' and 5 refers to 'very noisy'.

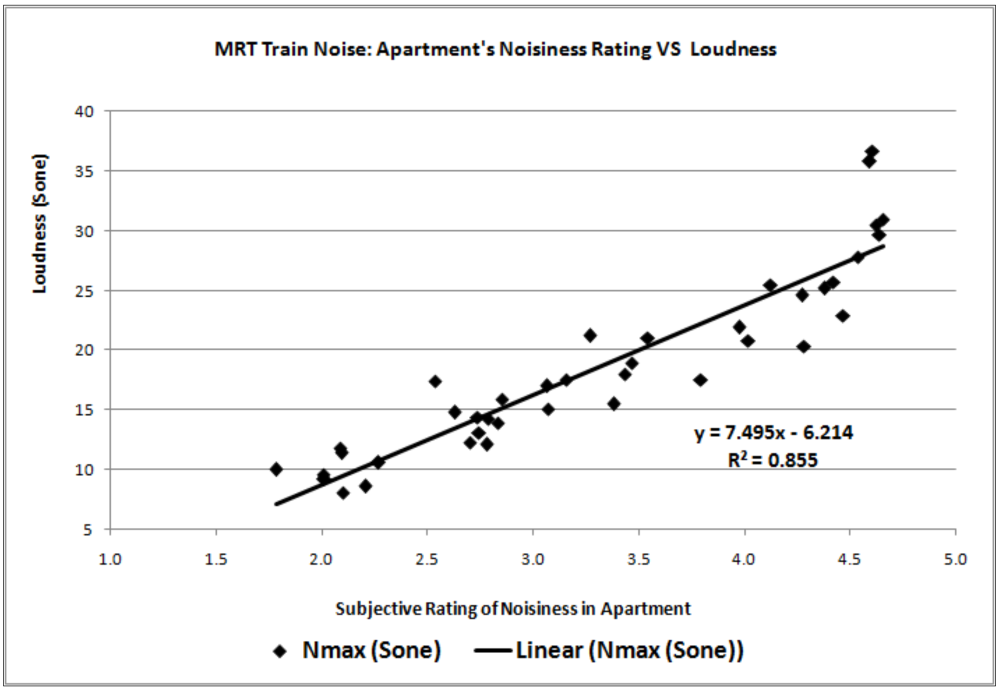


Figure 6-16: Rating of noisiness for different Loudness levels

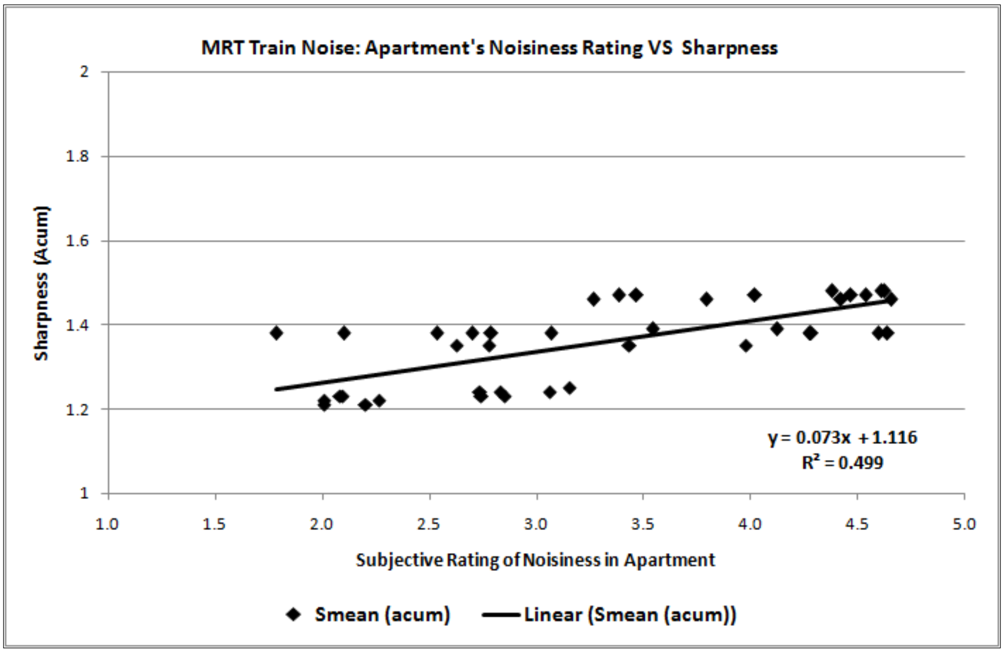


Figure 6-17: Rating of noisiness for different Sharpness levels

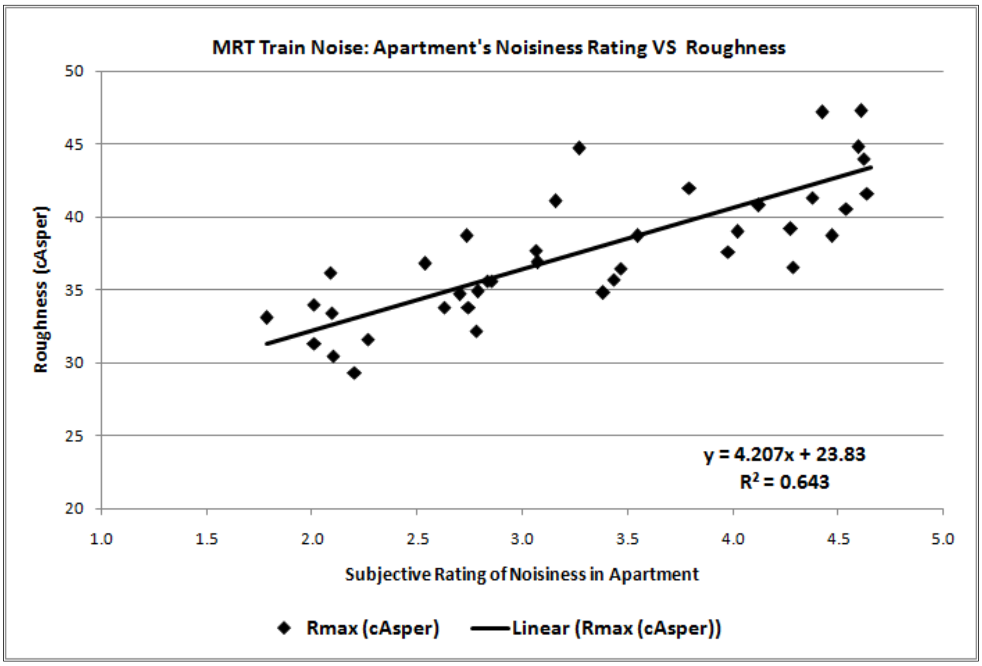


Figure 6-18: Rating of noisiness for different Roughness levels

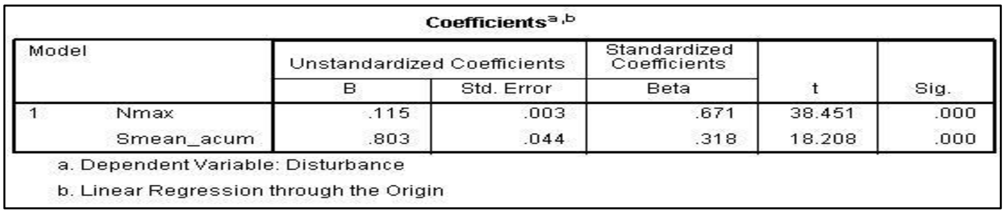
Figure 6-16 illustrates that the noisiness of an apartment is perceived as 'acceptable' with a maximum Loudness level of 17 sone while the noisiness of the apartment is perceived as 'quiet' with a maximum Loudness level of 8 Sone. It is noted from Figure 6-17 that the noisiness of an apartment is felt 'acceptable' with a mean Sharpness level of 1.35 acum while the noisiness of the apartment is perceived as 'quiet' with a mean sharpness level of 1.22 acum. Noisiness of an apartment is found as 'acceptable' (Figure 6-18) with a maximum Roughness level of 37 centi-Asper and is felt 'quiet' with a maximum Roughness level of 33 centi-Asper.

6.4.2.2 Rating of noise disturbance (MRT train)

It is noted from Table 6-10 that 'rating of disturbance due to MRT train noise' is significantly correlated (to 0.01 significance level) with the overall noise level and Loudness (mean Loudness, maximum Loudness, Zwicker Loudness and Five percentile Loudness), Sharpness (Maximum, Mean and Five percentile Sharpness), Fluctuation Strength (Maximum, Mean and Five percentile Fluctuation Strength) and

Roughness (Maximum roughness, Mean roughness and Five percentile roughness). Noisiness rating is found weakly (but significantly) correlated with tonality and prominence ratio. Linear regression in the least square method was carried out to develop a statistical model relating rating of noise disturbance with different correlated psychoacoustical quantities as shown in Table 6-10. The psychoacoustical quantities that were found significantly correlated with the 'rating of noise disturbance due to MRT train' in the development of a statistical model are shown in Table 6-14.

Table 6-14: Variables and the regression coefficients of the final model



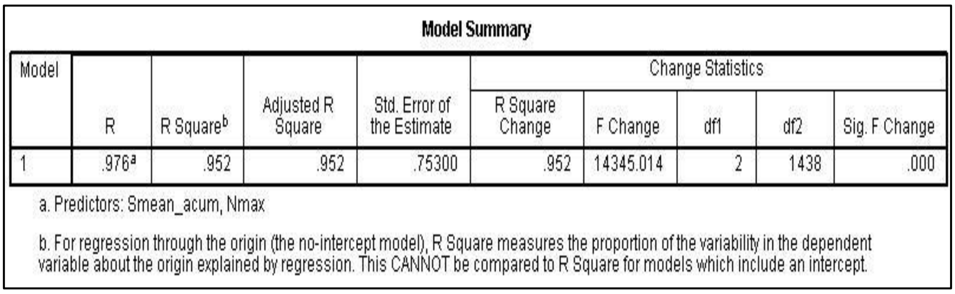
Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	Nmax	.115	.003	.671	38.451	.000
	Smean_acum	.803	.044	.318	18.208	.000

a. Dependent Variable: Disturbance

b. Linear Regression through the Origin

Table 6-15: Test statistics showing 'goodness of fit' of the model



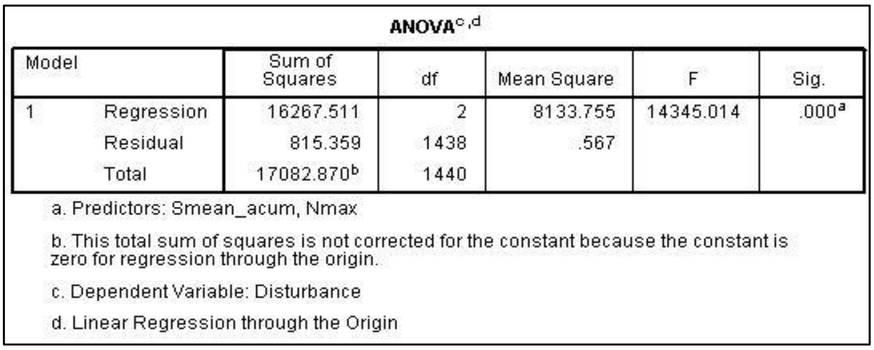
Model Summary

Model	R	R Square[b]	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.976[a]	.952	.952	.75300	.952	14345.014	2	1438	.000

a. Predictors: Smean_acum, Nmax

b. For regression through the origin (the no-intercept model), R Square measures the proportion of the variability in the dependent variable about the origin explained by regression. This CANNOT be compared to R Square for models which include an intercept.

Table 6-16: ANOVA test results showing statistical significance of the model



ANOVA[c,d]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	16267.511	2	8133.755	14345.014	.000[a]
	Residual	815.359	1438	.567		
	Total	17082.870[b]	1440			

a. Predictors: Smean_acum, Nmax

b. This total sum of squares is not corrected for the constant because the constant is zero for regression through the origin.

c. Dependent Variable: Disturbance

d. Linear Regression through the Origin

The 'goodness of fit' test statistics of the model presented in Table 6-15 illustrate that the established model is a 'good fit' model (R^2=0.952). The $adjusted\ R^2$value illustrates that the model accounts for 95.2% of the variance in defining noisiness of the apartment due to road traffic noise. The ANOVA test statistics, presented in Table 6-16, confirm that the model is statistically significant ($p < 0.05$). Based on the regression coefficients, presented in Table 6-7, the established model can be written as follows:

$$\boldsymbol{Rating\ of\ Disturbance\ due\ to\ MRT\ Train\ Noise} = 0.115 * N_{max}(Sone) + 0.803 * S_{mean}(Acum)$$

....[Eq. 6-4]

To examine the influence of each of these factors (in Eq. 6-4), the overall rating of noise disturbance due to MRT train is plotted against these factors in Figure 6-19 to Figure 6-20. Subjective rating of noise disturbance due to MRT train is measured on a continuous scale of 1 to 5 where 1 refers to 'not at all disturbed', 2 refers to 'a little disturbed', 3 refers to 'disturbed', 4 refers to 'very disturbed' and 5 refers to 'extremely disturbed'. Figure 6-19 illustrates that the noise disturbance was perceived as 'a little disturbing' with a maximum loudness level of 10 sone. On the other hand, noise disturbance was perceived as 'a little disturbing' with a mean Sharpness of 1.3 acum (Figure 6-20).

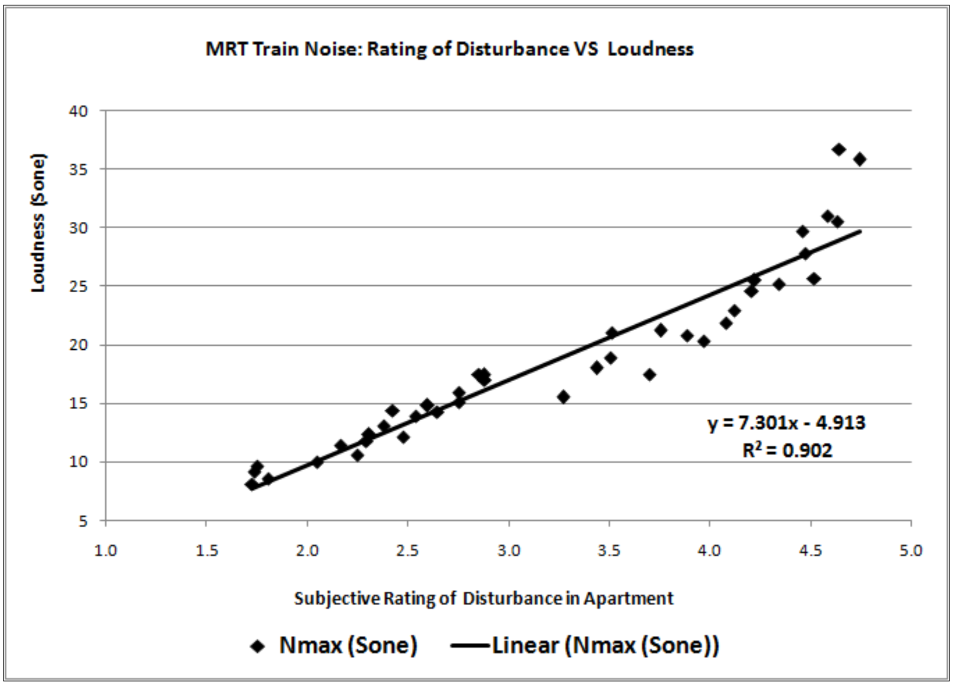


Figure 6-19: Rating of noise disturbance for different Loudness levels

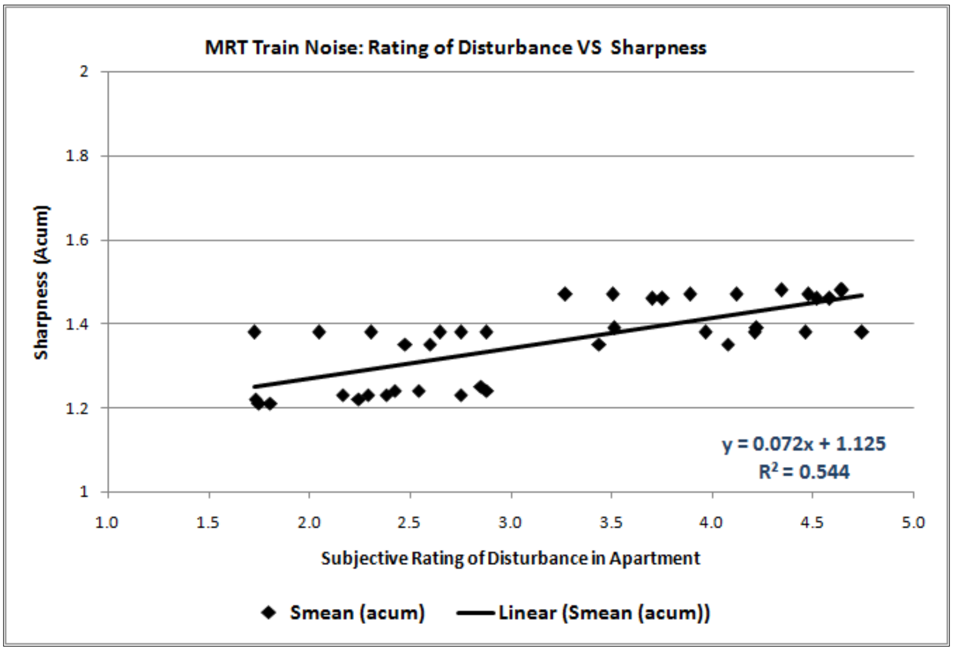


Figure 6-20: Rating of noise disturbance for different Sharpness levels

6.5 SUMMARY

In this chapter, the details of the psychoacoustic experiment is presented. Subjective response data in terms of indoor aural comfort, noisiness and disturbance were measured for different road traffic and MRT train noise levels. These are used for validation of the Aural Comfort Model (ACM) in Chapter 7.

A parametric study is carried out in this chapter on the two factors of the developed aural comfort model - noisiness of apartment and disturbance due to road and train noise. Statistical analysis was carried out to establish relationships (statistical models) between these factors and different psychoacoustical acoustical indices. The sensitivity of these factors with related psychoacoustical factors is also analysed and presented in this chapter.

CHAPTER 7: MODEL VALIDATION AND MULTIDIMENSIONAL ASSESSMENT OF THE ROAD TRAFFIC AND TRAIN NOISE

7.1 INTRODUCTION

Test data from the psychoacoustic experiment, described in Chapter 6, is used for the validation of the established aural comfort model in this chapter. In addition, multidimensional evaluation of the binaurally recorded road traffic and train noises are carried out and their relationships with different psychoacoustical indices have been discussed and presented in this chapter.

7.2 EXPERIMENTAL RESULTS AND VALIDATION OF THE AURAL COMFORT MODEL

The aural comfort model (Eq. 5-6) was validated for different levels of noise exposure due to road traffic and MRT train noise. During the psychoacoustical experiments in an absolute evaluation approach, subjects were asked how would they rate the 'aural comfort', 'noisiness of the apartment' and the 'noise disturbance' due to road traffic and MRT train noise they listened to considering their home environment during the day. The aural comfort ratings by all the 36 subjects for all 80 different stimuli in the experiments were then used to validate the primary aural comfort model. The predicted aural comfort ratings were computed (using Eq. 5-6) by taking into account the subjective responses on the 'noisiness of the apartment' and 'noise disturbance' due to road traffic and train noise from the experiment.

Since perception of aural comfort is subjective in nature, the data are generally disperse for a given stimulus (noise level) and use of the mean comfort rating value do not account for aural comfort for the majority of the population. As such, predicted and experimental comfort ratings were analysed for a cumulative percentage of respondents. As the first variable of the primary aural comfort model is the A-weighted noise exposure level, both predicted and experimental comfort ratings are plotted against the A-weighted noise exposure level. It is noted that the experimental and predicted regression lines on the plots are the best fitted regression lines to visualize experimental and predicted comfort ratings.

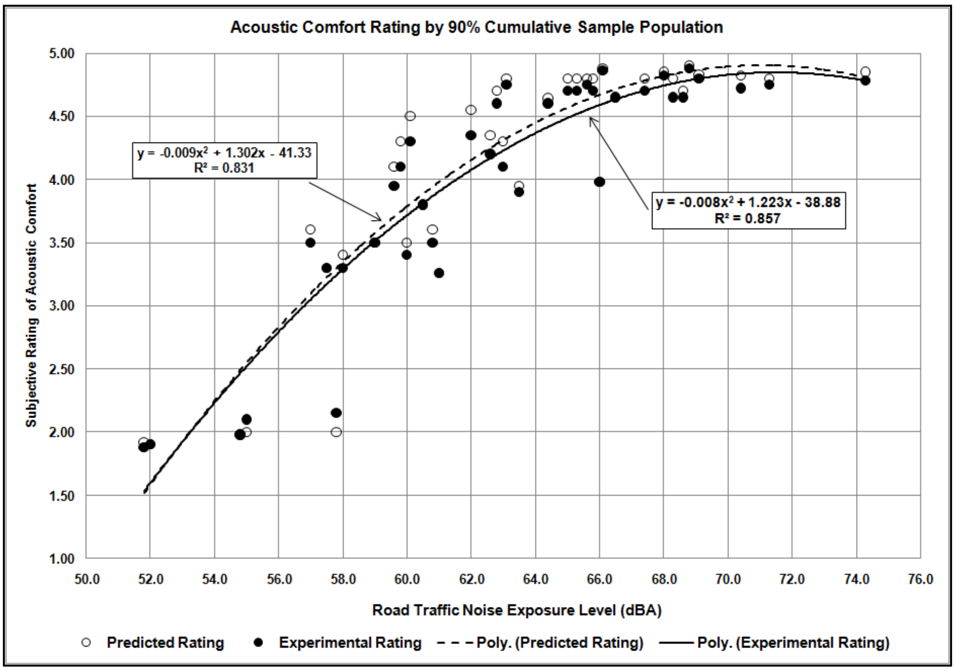


Figure 7-1: Comparison of predicted and experimental aural comfort ratings for different road traffic noise exposure levels (90% Cumulative sample population)

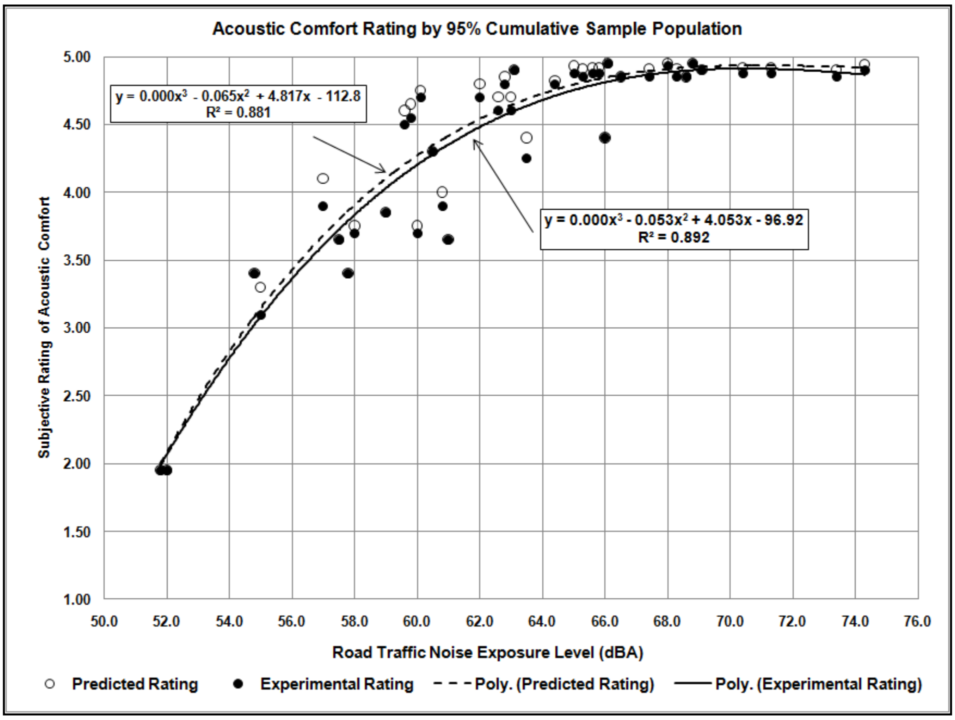


Figure 7-2: Comparison of predicted and experimental aural comfort ratings for different road traffic noise exposure levels (95% Cumulative sample population)

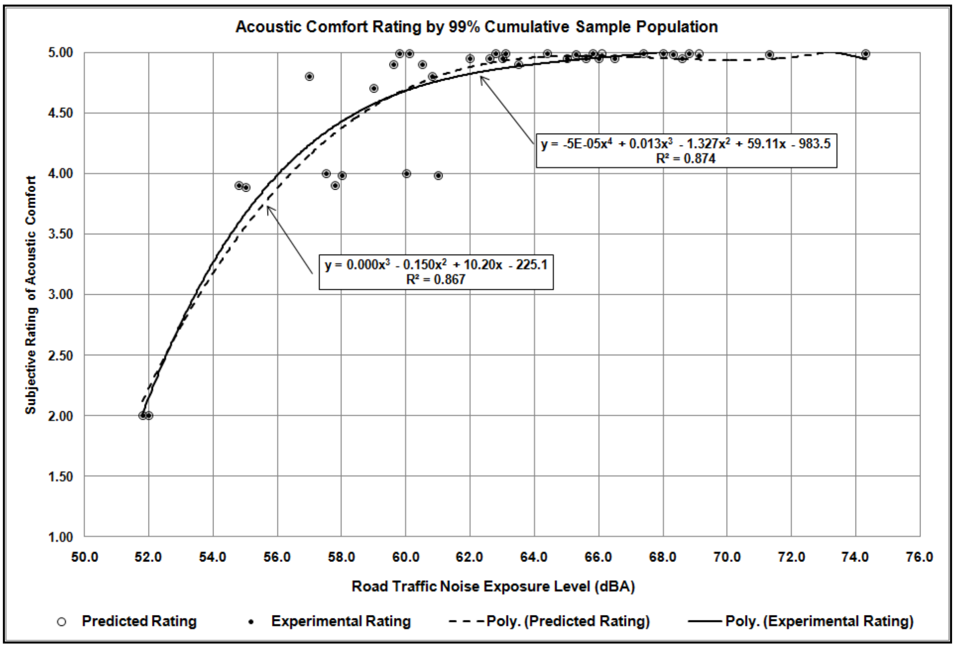


Figure 7-3: Comparison of predicted and experimental aural comfort ratings for different road traffic noise exposure levels (99% Cumulative sample population)

The predicted and experimental aural comfort ratings for different *road noise exposure levels* are plotted in Figure 7-1 to Figure 7-3 for different cumulative percentages of respondents. In general, the predicted results (using Eq 5-6) are in very good agreement with the experimental results.

Paired sample t-tests were carried out for the predicted and experimental results for different cumulative population exposure and presented in Table 7-1. Paired sample t-test statistics in Table 7-1 show that for all the cases (Figure 7-1 to Figure 7-3) the mean differences for the pairs were small (0.001 to 0.065). The standard deviations of the mean difference were between 0.004 and 0.1. In addition, the test statistics show that the correlation between the predicted and experimental results is strong and significant (correlation coefficient is 1, $p<0.001$). *The above analysis demonstrates that proposed aural comfort model accurately predicts the aural comfort in relation to road traffic noise.*

Table 7-1: Paired sample t-test statistics for aural comfort related to road traffic noise

Description of the Pairs		**Paired Mean Differences**					**Correla -tion**	**Sig.**
		Mean Diff.	**Std. Dev.**	**Std. Error Mean**	**95% Confidence Interval of the Difference**			
					Lower	**Upper**		
Pair 01	90% Cumulative Sample - **Predicted**	.0650	.07582	.0119	.04075	.0892	0.997	0.000
	90% Cumulative Sample - **Experimental**							
Pair 02	95% Cumulative Sample - **Predicted**	.0467	.05303	.0083	.02979	.0637	0.998	0.000
	95% Cumulative Sample - **Experimental**							
Pair 03	99% Cumulative Sample - **Predicted**	.0010	.00441	.0007	-.0004	.0024	1.000	0.000
	99% Cumulative Sample - **Experimental**							

Similar to road traffic noise, the predicted and experimental aural comfort ratings for different *train noise exposure levels* are plotted in Figure 7-4 to Figure 7-6 for different cumulative percentages of respondents. In general, the predicted results (using Eq 5-6) are in very good agreement with the experimental results.

Paired sample t-tests were carried out for the predicted and experimental results for different cumulative percentages of population exposure levels and are presented in Table 7-2. Paired sample t-test statistics show that for all the cases (Figure 7-4 to Table 7-6) the mean differences for the pairs were small (0.009 to 0.05). The standard deviations of the mean difference were between 0.05 and 0.13. The test statistics also show that the correlation between the predicted and experimental results is strong and significant (correlation coefficient is 1, p<0.001). *The above analysis demonstrates that the proposed aural comfort model accurately predicts the aural comfort in relation to MRT train noise.*

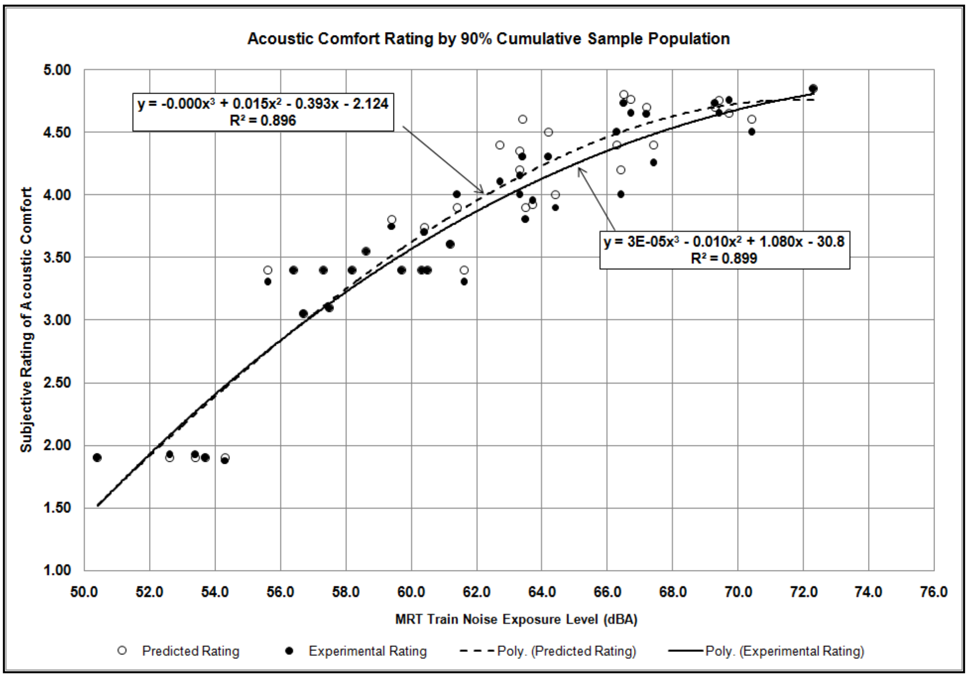


Figure 7-4: Comparison of predicted and experimental aural comfort ratings for different MRT train noise exposure levels (90% Cumulative sample population)

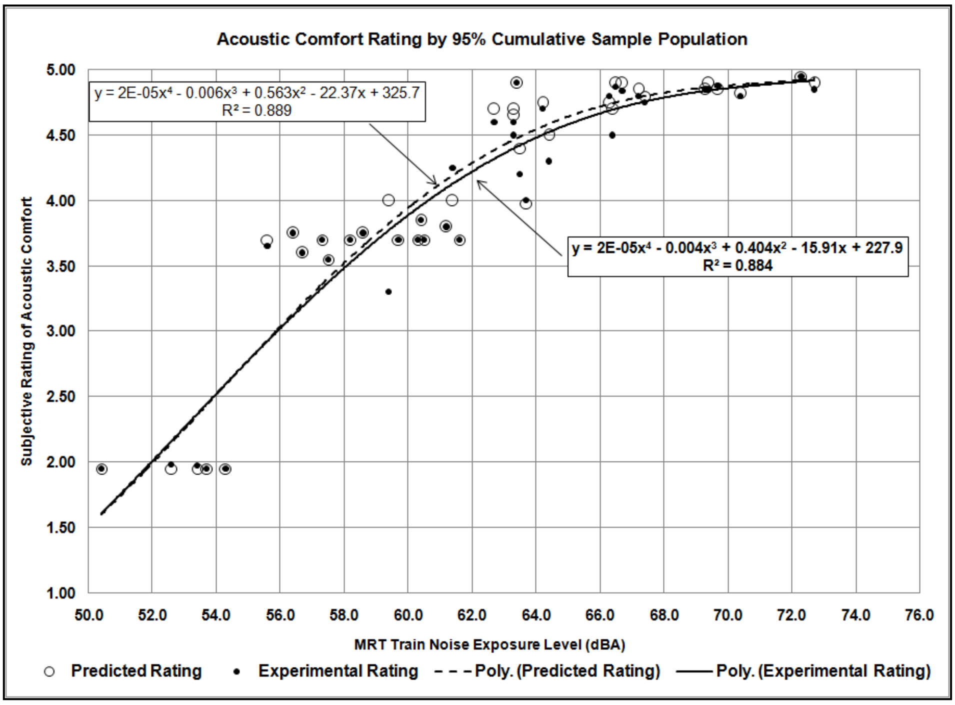


Figure 7-5: Comparison of predicted and experimental aural comfort ratings for different MRT train noise exposure levels (95% Cumulative sample population)

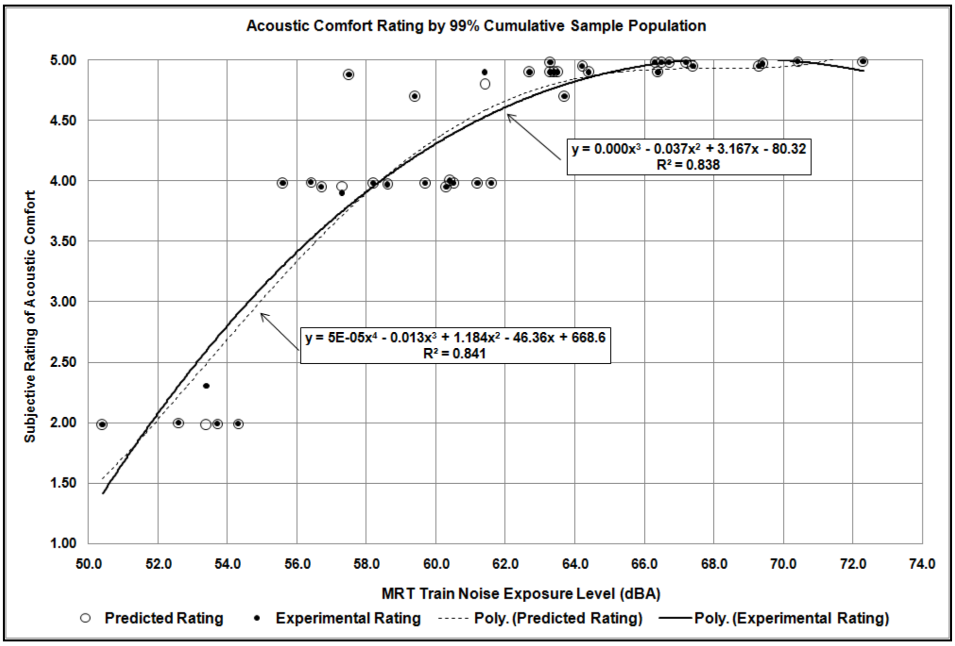


Figure 7-6: Comparison of predicted and experimental aural comfort ratings for different MRT train noise exposure levels (99% Cumulative sample population)

Table 7-2: Paired sample t-test statistics for aural comfort related to MRT train noise

Description of the Pairs		**Paired Mean Differences**					**Correlation**	**Sig.**
		Mean Diff.	**Std. Dev.**	**Std. Error Mean**	**95% Confidence Interval of the Difference**			
					Lower	**Upper**		
Pair 01	95% Cumulative Sample - **Predicted**	.04150	.13118	.0207	-.0004	.08345	0.990	0.000
	95% Cumulative Sample - **Experimental**							
Pair 02	90% Cumulative Sample - **Predicted**	.05300	.09717	.0153	.02192	.08408	0.994	0.000
	90% Cumulative Sample - **Experimental**							
Pair 03	99% Cumulative Sample - **Predicted**	-.0090	.05377	.0085	-.0262	.00820	0.999	0.000
	99% Cumulative Sample - **Experimental**							

Based on the above discussion and analysis, it can be concluded that the developed aural comfort model is validated with experimental data. The developed aural comfort model is able to predict the level of aural comfort among the high-rise residential dwellers in tropical Singapore with very good accuracy.

7.3 PAIRED COMPARISON ANALYSIS OF ROAD TRAFFIC AND MRT TRAIN SOUNDS

Paired comparison of five different types of road traffic and MRT train noise was carried out during the psychoacoustic experiment through a mixed evaluation approach. Five pairs of sounds were examined through this study. The first pair comprised of Expressway road traffic noise and MRT train noise (MRT track 30m away from residential building), both having the same A-weighted equivalent noise exposure level (L_{Aeq}) of 71 dB. The second pair comprised of Major Arterial road traffic noise and MRT train noise (MRT track 40m away from residential building), both having the same A-weighted equivalent noise exposure level (L_{Aeq}) of 67 dB. The third pair consisted of Minor Arterial road traffic noise and MRT train noise (MRT track 50m away from residential building), both having the same A-weighted equivalent noise exposure level (L_{Aeq}) of 65 dB. The fourth pair comprised of Primary Access road traffic noise and MRT train noise (MRT track 60m away from residential building), both having the same A-weighted equivalent noise exposure level (L_{Aeq}) of 63 dB. The last pair comprised of Local road traffic noise and MRT train noise (MRT track 70m away from residential building), both having the same A-weighted equivalent noise exposure level (L_{Aeq}) of 58 dB. It is very important to note that all these sounds were binaurally recorded at the sites where the noise survey was carried out for the development of the aural comfort model. The noise exposure levels under evaluation are approximately the reference noise levels which mean that they represent the actual noise exposure levels at the residential dwellings located near the roads or MRT train tracks.

The paired sounds were evaluated with respect to aural comfort, rating of noisiness of apartment and the noise disturbance by the noise sources. Figure 7-7 illustrates that *the test subjects were more uncomfortable with the MRT train sounds when compared with the sounds of the same level (*L_{Aeq}*) from Expressway, Major Arterial and Minor Arterial Road*. A paired sample t-test (refer to Table 7-3) confirms this observation and shows that the mean difference between the subjective perceptions for the paired stimuli are significant. *Aural comfort (or discomfort) due to MRT train noise was not found to be significantly different from Primary Access and Local road traffic noise of same level. Similar observations were made for Road Traffic noise and MRT Train when apartments' noisiness and noise disturbance were evaluated* (refer to Figure 7-8, Figure 7-9 and Table 7-3 to Table 7-5).

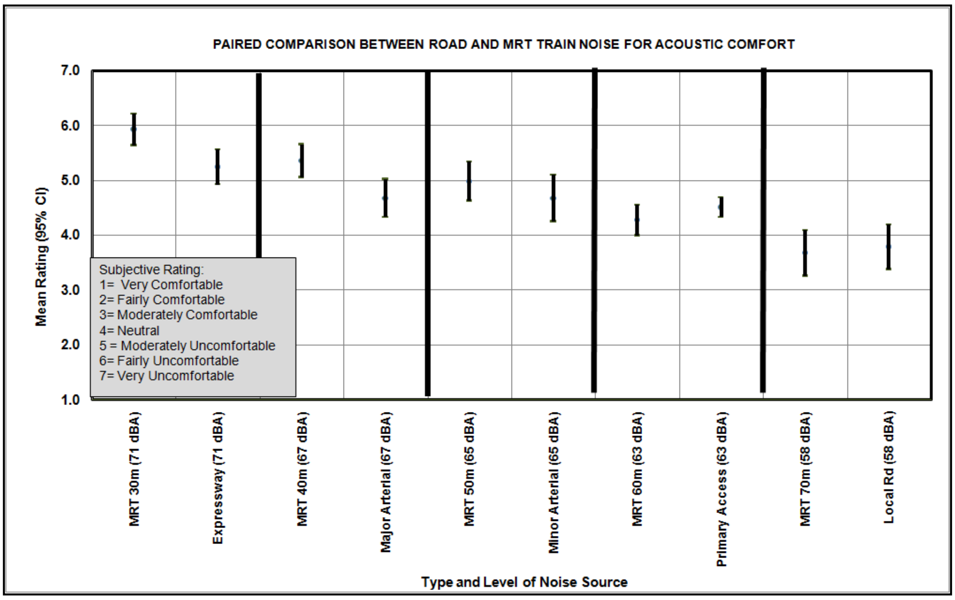


Figure 7-7: Paired comparison of Road Traffic and MRT Train noise for aural comfort

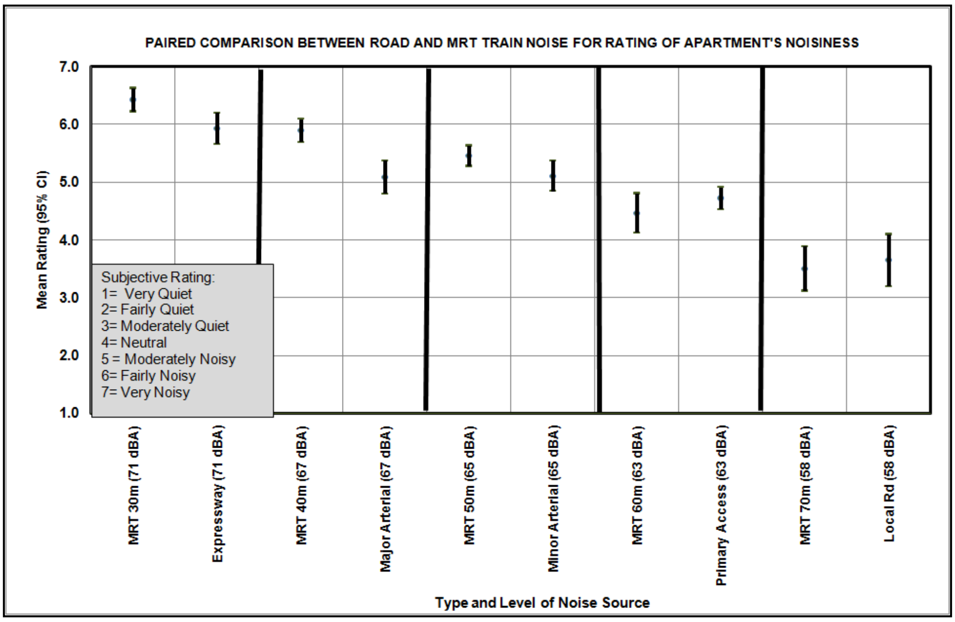


Figure 7-8: Paired comparison of Road Traffic and MRT train noise for noisiness of apartment

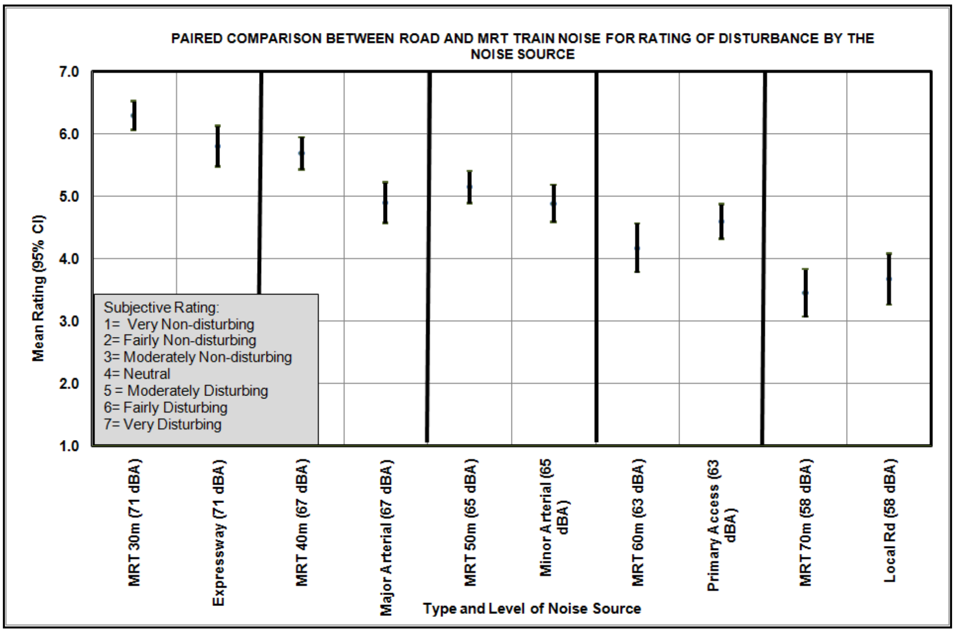


Figure 7-9: Paired comparison of Road Traffic and MRT train noise for noise disturbance

Table 7-3: Test statistics of Paired Sample t-test for Comfort Analysis

Description of the Pairs		**Noise Level**	**Paired Mean Differences**					**t**	**df**	**Sig.**
			Mean Diff.	**Std. Dev.**	**Std. Error Mean**	**95% Confidence Interval of the Difference**				
						Lower	**Upper**			
Pair 1	MRT (30m) and Expressway	71 dBA	.7111	.85081	.1418	.42324	.99898	5.015	35	**.000**
Pair 2	MRT (40m) and Major Arterial Rd	67 dBA	.6916	.64692	.1078	.47278	.91055	6.415	35	**.000**
Pair 3	MRT (50m) and Minor Arterial Rd	65 dBA	.2472	.71093	.1184	.00668	.48777	2.086	35	**.044**
Pair 4	MRT (60m) and Primary Access Rd	63 dBA	-.2333	1.06422	.1773	-.59341	.12675	-1.316	35	.197
Pair 5	MRT (70m) and Local Rd	58 dBA	-.1222	.71198	.1186	-.36312	.11868	-1.030	35	.310

Table 7-4: Test statistics of Paired Sample t-test for rating of Apartment's Noisiness Analysis

Description of the Pairs		**Noise level**	**Paired Mean Differences**					**t**	**df**	**Sig.**
			Mean Diff.	**Std. Dev**	**Std. Error Mean**	**95% Confidence Interval of the Difference**				
						Lower	**Upper**			
Pair 1	MRT (30m) and Expressway	71 dBA	.48889	.44771	.07462	.33741	.64037	6.552	35	**.000**
Pair 2	MRT (40m) and Major Arterial Rd	67 dBA	.80556	.67058	.11176	.57866	1.03245	7.208	35	**.000**
Pair 3	MRT (50m) and Minor Arterial Rd	65 dBA	.35000	.66569	.11095	.12476	.57524	3.155	35	**.003**
Pair 4	MRT (60m) and Primary Access Rd	63 dBA	-.26667	1.17571	.19595	-.66447	.13114	-1.361	35	.182
Pair 5	MRT (70m) and Local Rd	58 dBA	-.14722	.64873	.10812	-.36672	.07228	-1.362	35	.182

Table 7-5: Test statistics of Paired Sample t-test for Disturbance due to Noise Source Analysis

Description of the Pairs		**Noise Level**	**Paired Mean Differences**					**t**	**df**	**Sig.**
			Mean Diff.	**Std. Dev**	**Std. Error Mean**	**95% Confidence Interval of the Difference**				
						Low	**Upper**			
Pair 1	MRT (30m) and Expressway	71 dBA	.486	.64194	.1069	.2689	.70331	4.54	35	**.000**
Pair 2	MRT (40m) and Major Arterial Rd	67 dBA	.800	.91652	.1527	.4899	1.11010	5.23	35	**.000**
Pair 3	MRT (50m) and Minor Arterial Rd	65 dBA	.266	.73017	.1216	.0196	.51372	2.19	35	**.035**

Description of the Pairs		**Noise Level**	**Paired Mean Differences**					**t**	**df**	**Sig.**
			Mean Diff.	**Std. Dev**	**Std. Error Mean**	**95% Confidence Interval of the Difference**				
						Low	**Upper**			
Pair 4	MRT (60m) and Primary Access Rd	63 dBA	-.4222	1.4014	.2335	-.8964	.0519	-1.8	35	.079
Pair 5	MRT (70m) and Local Rd	58 dBA	-.2333	.71952	.1199	-.4767	.0101	-1.9	35	.060

7.4 MULTIDIMENSIONAL EVALUATION OF ROAD TRAFFIC AND MRT TRAIN SOUND

In Chapter 6, statistical regression models have been developed for 'noisiness of apartment' and 'noise disturbance' due to Road Traffic and MRT Train noise relating them to several psychoacoustical quantities. However, as generally practiced in soundscape research, it is also important to investigate the qualitative aspects of these noises and quantify them in terms of psychoacoustical quantities. This will result in a comprehensive evaluation of the noise sources under investigation.

Semantic differential technique by Osgood (1957) has been used for years to evaluate emotional meaning of sounds. Osgood (1957) illustrated that the factor analyses of different adjectives used for affective evaluation typically return three dimensions: evaluation, potency, and activity. Here 'evaluation' is concerned with the subjects' preferences (e.g. pleasant-unpleasant, relaxing-stressful) about the attitude object (for example, noise). 'Potency' is the perception of the subjects about the strength of the attitude object (e.g. soft-loud, weak-strong). 'Activity' is concerned with whether the attitude object is perceived as active or passive (e.g. quiet-busy, ignoring-distracting). Through the evaluation of these three dimensions, as suggested by Osgood, the connotative meaning of the different types of sounds (road traffic and MRT train) were expected to be established in this research investigation.

In addition to the above, it is also the aim of the Multidimensional evaluation to establish a set of charts in semantic space to assess the different types of road traffic and train noises and later relating them to different psychoacoustical quantities. This will help establishing the characteristics of noise sources that influence the aural comfort and extracting the corresponding psychoacoustical indices (and also their magnitudes) for use in the ACM to predict the 'noisiness' and 'disturbance'.

Multidimensional evaluation of road traffic and MRT train sound was carried out during the psychoacoustics experiment through a mixed evaluation approach. Multidimensional evaluations were measured on a 7 point semantic differential scale with 12 adjective pairs. The pairs of adjectives evaluated are: Pleasant-Unpleasant, Relaxing-Stressful, Bearable-Unbearable, Peaceful-Violent, Soft-Loud, Weak-Strong, Dull-Sharp, Mild-Tense, Quiet-Busy, Ignoring-Distracting, Smooth-Rough and Calm-Exciting.

7.4.1 Multidimensional Evaluation of Road Traffic Sound

Subjective perceptions about road traffic sounds from different classes of roads and their varying levels (0 dB, -3 dB and -6 dB) were measured in the psychoacoustical experiment on a semantic differential scale having 12 different adjective pairs. In Figure 7-10 to Figure 7-12, semantic differential profiles are established for different classes of roads with varying levels at +0 dB, -3 dB and -6 dB. The semantic profiles were found generally flat in nature.

It is also noted from these figures that, among all classes of roads, the semantic profile of the expressway (at all levels) is distinct and always perceived towards 'fairly' unfavourable semantic adjective pairs. Interestingly the semantic profiles of the Major Arterial Roads, Minor Arterial Roads and Primary Access roads lie very closely to each other and are perceived towards 'moderately' unfavourable semantic adjective pairs. The perception of the Local road is very distinct in all varying levels and is towards 'moderately' favourable semantic adjective pairs.

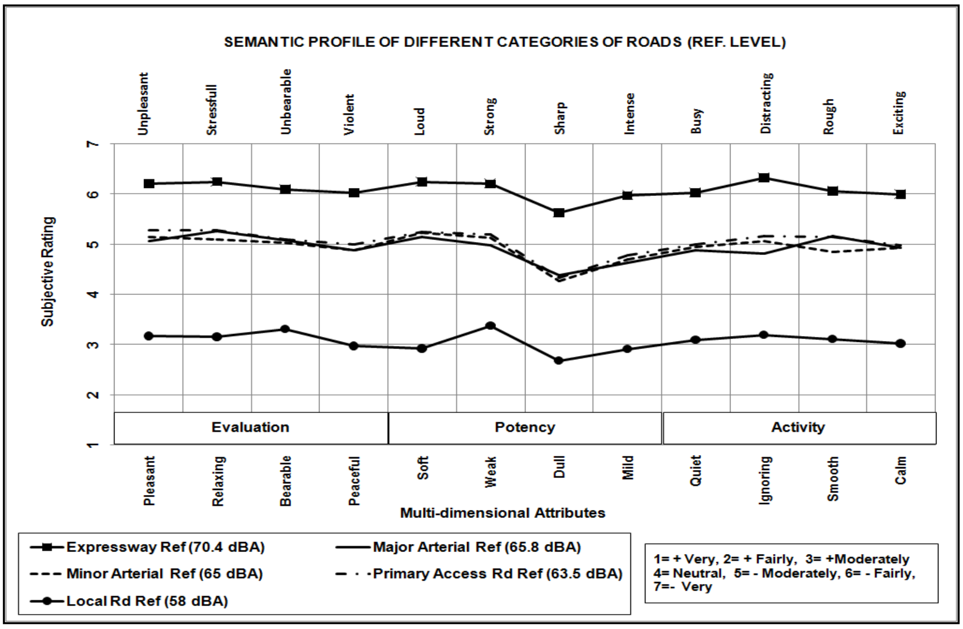


Figure 7-10: Comparison of semantic profiles of different classes road traffic noise (Ref. Level)

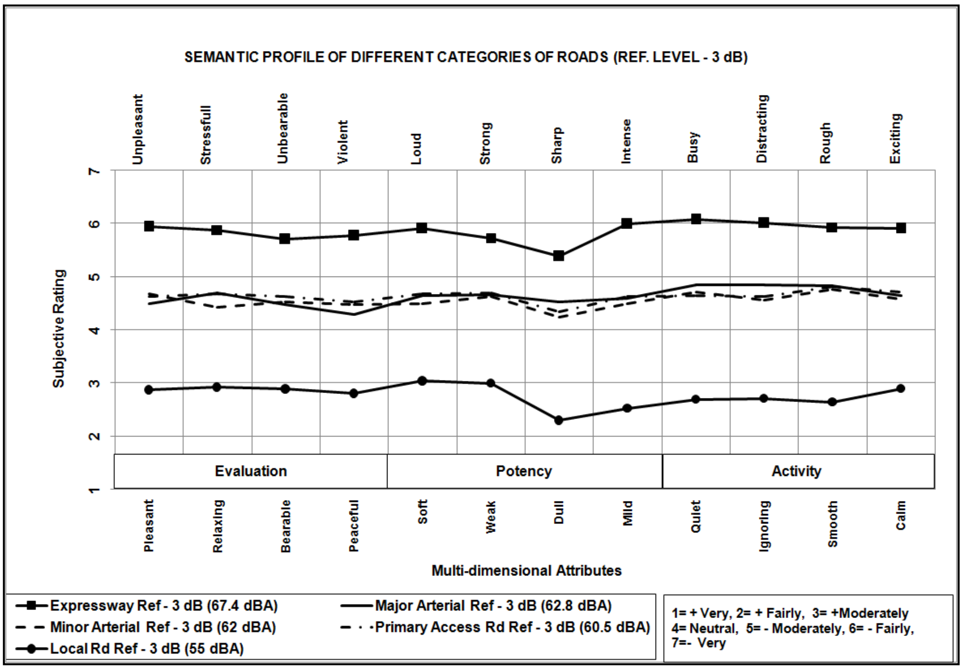


Figure 7-11: Comparison of semantic profiles of different classes road traffic noise (Ref. Level - 3dB)

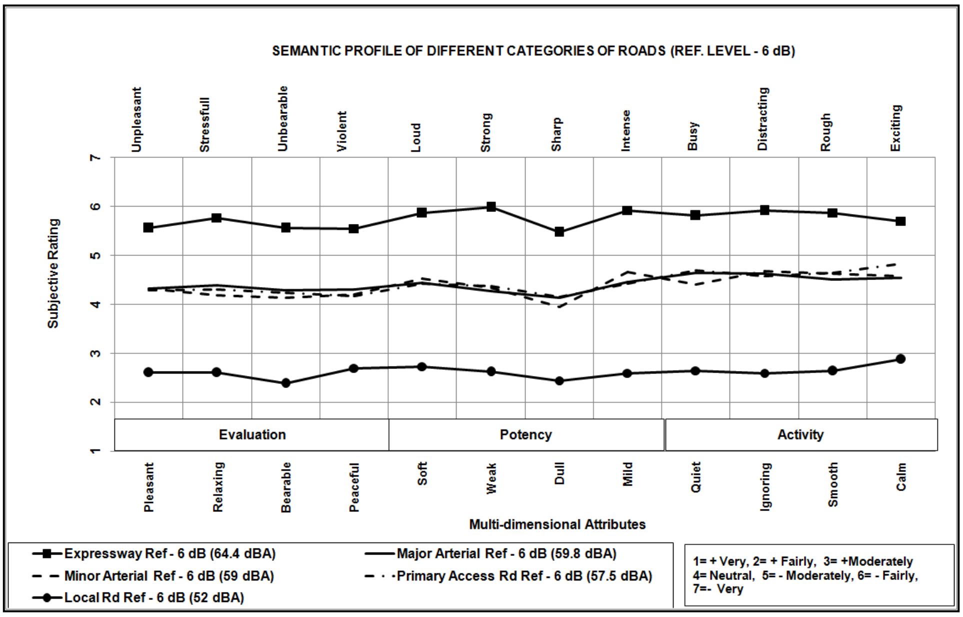


Figure 7-12: Comparison of semantic profiles of different classes road traffic noise (Ref. Level - 6dB)

7.4.1.1 Relationships between subjective qualities in semantic space and psychoacoustical quantities (Road traffic noise)

The correlations between semantic space (12 adjective pairs) and several psychoacoustic quantities are shown in Table 7-6 and in Table 7-7. The spearman rho coefficients illustrate that 'aural comfort' is strongly and significantly correlated with the 12 adjective pairs ($p < 0.05$). It is also observed from Table 7-6 and Table 7-7 that all 12 perception dimensions are strongly and significantly correlated with the overall noise levels, loudness and roughness quantities of the road traffic sounds. The perception dimensions of road traffic sound are found weakly correlated with sharpness, fluctuation strength, tonality and prominence ratios.

Table 7-6: Correlations between semantic space and psychoacoustic quantities related to road traffic noise (First six pairs of the SD)

FACTORS	**Pleasant-Unpleasant**	**Relaxing-Stressful**	**Bearable-Unbearable**	**Peaceful-Violent**	**Soft-Loud**	**Weak-Strong**
Acoustic Comfort	**.630****	**.635****	**.592****	**.614****	**.625****	**.580****
Mean Level, L_{mean} (dBA)	**.621****	**.642****	**.599****	**.609****	**.638****	**.642****
Mean Level, L_{mean} (dB)	.482**	**.508****	.477**	.455**	.472**	.487**
Maximum Loudness, N_{max} (Sone)	**.579****	**.607****	**.562****	**.564****	**.589****	**.588****
Mean Loudness, N_{mean} (Sone)	**.603****	**.623****	**.579****	**.590****	**.615****	**.614****
Zwicker Loudness, $N_{ISO532B}$	**.607****	**.629****	**.585****	**.594****	**.620****	**.619****
Five Percentile Loudness N_5 (Sone)	**.589****	**.617****	**.571****	**.575****	**.602****	**.599****
Maximum Sharpness, S_{max} (Acum)	.091*	.087*	.088*	.072*	.098*	.077*
Mean Sharpness S_{mean} (Acum)	-.110**	-.142**	-.108**	-.144**	-.133**	-.136**
Five Percentile Sharpness, S_5 (Acum)	.107**	.110**	.104**	.089*	.113**	.093*
Maximum Fluctuation Strength, Fmax (Centi Vacil)	.351**	.379**	.344**	.340**	.374**	.350**
Mean Fluctuation Strength, Fmean (Centi Vacil)	.422**	.467**	.419**	.417**	.453**	.426**
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	.378**	.406**	.369**	.367**	.402**	.378**
Maximum Roughness (Centi Asper), R_{max}	**.623****	**.645****	**.602****	**.614****	**.640****	**.640****
Mean Roughness (Centi Asper), R_{mean}	**.621****	**.634****	**.599****	**.602****	**.633****	**.631****
Five Percentile Roughness (Centi Asper), R_5	**.630****	**.646****	**.606****	**.617****	**.643****	**.644****
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	.341**	.396**	.342**	.361**	.381**	.364**
Maximum Tone to Noise Ratio, TNR	.172**	.225**	.186**	.182**	.202**	.178**
The Frequency of the Maximum Prominence, F_{PR} (Hz)	0.057	0.047	0.05	0.045	0.055	0.052
Maximum Prominance, PR_{max} (dB)	.172**	.226**	.186**	.184**	.202**	.181**
Mean Prominance, PR_{mean} (dB)	.172**	.226**	.186**	.184**	.202**	.181**
Global Prominance, PR (dB)	.172**	.226**	.186**	.184**	.202**	.181**
N	540	540	540	540	540	540
****. Pearson Correlation is significant at the 0.01 level (1-tailed).**						
***. Pearson Correlation is significant at the 0.05 level (1-tailed).**						

Table 7-7: Correlations between semantic space and psychoacoustic quantities related to road traffic noise (Second six pairs of the SD)

FACTORS	**Dull-Sharp**	**Mild-Intense**	**Quiet-Busy**	**Ignoring-Distracting**	**Smooth-Rough**	**Calm-Exciting**
Acoustic Comfort	**.557****	**.583****	**.583****	**.598****	**.605****	**.556****
Mean Level, L_{mean} (dBA)	**.590****	**.582****	**.614****	**.609****	**.604****	**.581****
Mean Level, L_{mean} (dB)	.406**	.384**	.433**	.435**	.432**	.400**
Maximum Loudness, N_{max} (Sone)	**.532****	**.515****	**.555****	**.553****	**.549****	**.526****
Mean Loudness, N_{mean} (Sone)	**.555****	**.546****	**.579****	**.579****	**.571****	**.551****
Zwicker Loudness, $N_{ISO532B}$	**.560****	**.551****	**.586****	**.585****	**.578****	**.558****
Five Percentile Loudness N_5 (Sone)	**.544****	**.528****	**.567****	**.565****	**.562****	**.540****
Maximum Sharpness, S_{max} (Acum)	.091*	.086*	.115**	.097*	.136**	.128**
Mean Sharpness S_{mean} (Acum)	-.160**	-.152**	-.135**	-.134**	-.103**	-.115**
Five Percentile Sharpness, S_5 (Acum)	.109**	.096*	.130**	.110**	.149**	.142**
Maximum Fluctuation Strength, Fmax (Centi Vacil)	.362**	.339**	.383**	.357**	.396**	.378**
Mean Fluctuation Strength, Fmean (Centi Vacil)	.452**	.416**	.465**	.438**	.466**	.437**
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	.389**	.366**	.410**	.385**	.421**	.404**
Maximum Roughness (Centi Asper), R_{max}	**.594****	**.588****	**.618****	**.616****	**.606****	**.588****
Mean Roughness (Centi Asper), R_{mean}	**.573****	**.570****	**.607****	**.604****	**.603****	**.581****
Five Percentile Roughness (Centi Asper), R_5	**.588****	**.586****	**.617****	**.615****	**.608****	**.590****
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	.410**	.378**	.398**	.379**	.379**	.361**
Maximum Tone to Noise Ratio, TNR	.236**	.194**	.225**	.202**	.218**	.192**
The Frequency of the Maximum Prominence, F_{PR} (Hz)	0.039	0.044	0.058	0.049	.074*	.084*
Maximum Prominence, PR_{max} (dB)	.237**	.195**	.223**	.203**	.214**	.189**
Mean Prominence, PR_{mean} (dB)	.237**	.195**	.223**	.203**	.214**	.189**
Global Prominence, PR (dB)	.237**	.195**	.223**	.203**	.214**	.189**
N	540	540	540	539	539	540

****. Pearson Correlation is significant at the 0.01 level (1-tailed).**

***. Pearson Correlation is significant at the 0.05 level (1-tailed).**

The relationship between the Pleasantness-Unpleasantness and the psychoacoustical quantities that are strongly and significantly correlated (found in Table 7-6 and Table 7-7) to this dimension are graphically presented in Figure 7-13 to Figure 7-15. Relationships for the remaining 11 semantic dimensions with the correlated psychoacoustical quantities are presented in Appendix F of this thesis.

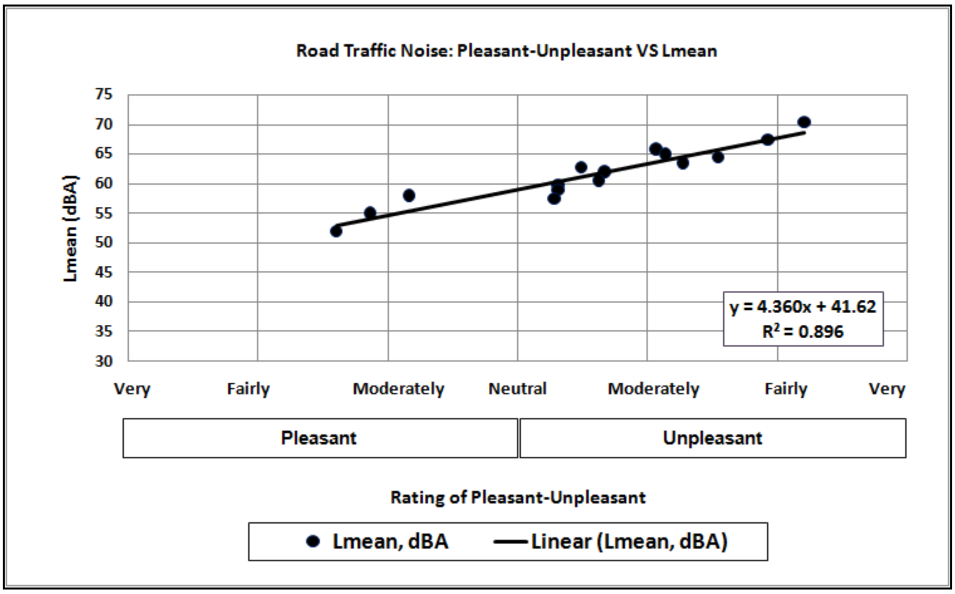


Figure 7-13: Relationship between pleasant-unpleasant and mean noise level (Lmean, dBA)

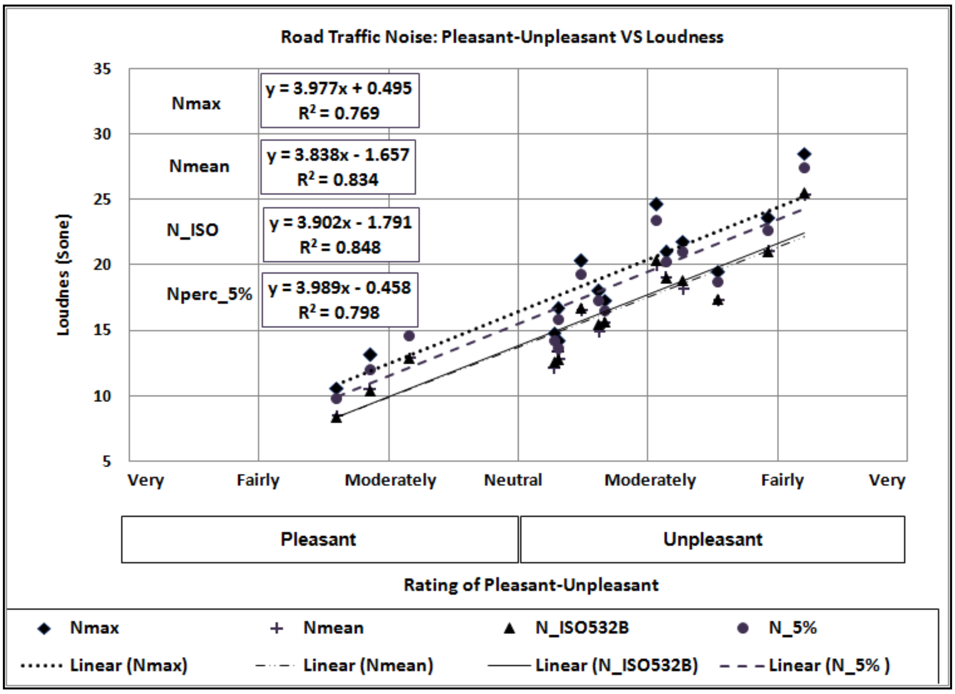


Figure 7-14: Relationships between pleasant-unpleasant and Loudness

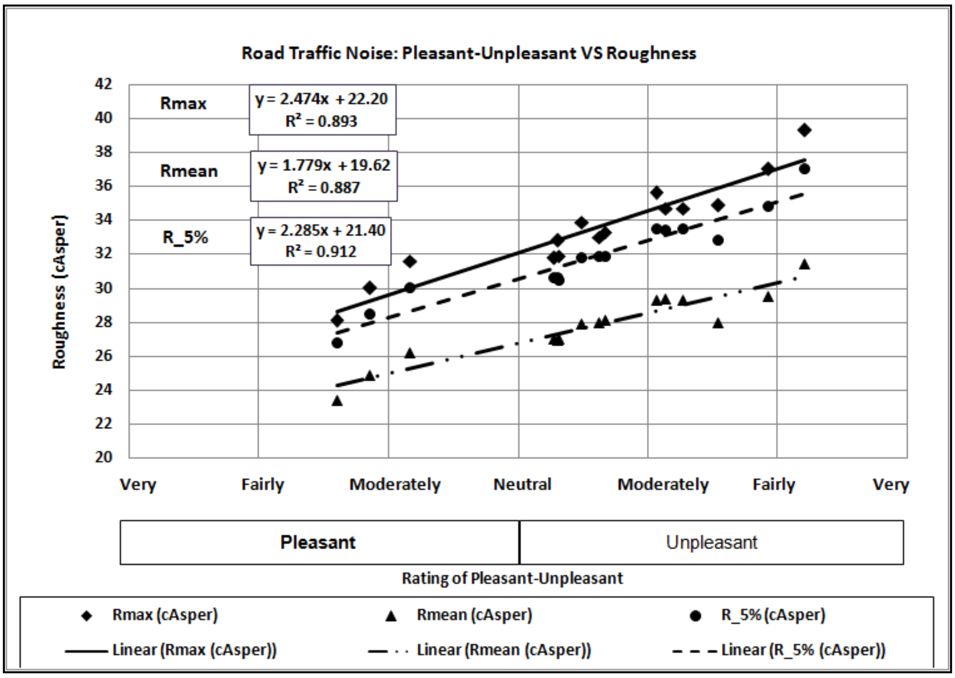


Figure 7-15: Relationships between pleasant-unpleasant and Roughness

Analysis of the data (refer to Appendix F) shows that all the twelve semantic adjective pairs (Pleasant-Unpleasant, Relaxing-Stressful, Bearable-Unbearable, Peaceful-Violent, Soft-Loud, Weak-Strong, Dull-Sharp, Mild-Tense, Quiet-Busy, Ignoring-Distracting, Smooth-Rough and Calm-Exciting) are strongly correlated with the mean noise level $L_{Aeq}(dBA)$. *In general, it is observed that at an A-weighted equivalent noise level ($L_{Aeq}(dBA)$) of 55 dB, a moderately favourable subjective perceptions (i.e. moderately pleasant, moderately bearable, etc.) are observed across the twelve semantic adjective pairs.*

Among the different psychoacoustical quantities relating to loudness (N_{max}, N_{mean} , $N_{ISO\ 532B}$ and *and* $N_{perc,5\%}$) the mean loudness (N_{mean}) is observed to have the strongest relationship with all the twelve semantic differential adjective pairs. *It is observed that at about 10 Sone N_{mean} a moderately favourable subjective perception (i.e. moderately pleasant, moderately bearable etc.) is observed across the twelve semantic adjective pairs.*

It is also noted that among all the different psychoacoustical quantities relating to roughness (R_{max}, R_{mean}, $R_{perc,5\%}$), the five percentile roughness ($R_{perc,5\%}$) has the strongest relationship with all the twelve semantic differential adjective pairs. *At 28 centi-asper $R_{perc,5\%}$, a moderately favourable subjective perception (i.e. moderately pleasant, moderately bearable, etc.) are observed across the twelve semantic objective pairs.*

7.4.2 Multidimensional Evaluation of MRT Train Sound

As with the road traffic noise evaluation, subjective perceptions of MRT train sounds of varying levels (0 dB, -3 dB and -6 dB) were measured in the psychoacoustical experiment. In Figure 7-16 to Figure 7-18, semantic profiles of MRT train sounds of different track to building distances are compared for varying levels. It is noted from these figures that the subjective perceptions of the MRT train sounds for 30m and 40m distances are nearly equal for all varying levels (0 dB, -3 dB and - 6 dB) and they range between moderately and fairly unfavourable on the semantic scale of all the unfavourable semantic adjective pairs. For MRT trains located at 50m distances, at all varying levels (0 dB, -3 dB and - 6 dB) the subjective perception ranges between neutral and fairly on the semantic scale for all the unfavourable semantic adjective pairs. Again, the subjective perception of the MRT train sounds for 60m and 70m distances are nearly equal for all varying levels (0 dB, -3 dB and - 6 dB) and they range between moderately and fairly favourable on the semantic scale of all the favourable semantic adjective pairs (for example fairly pleasant etc).

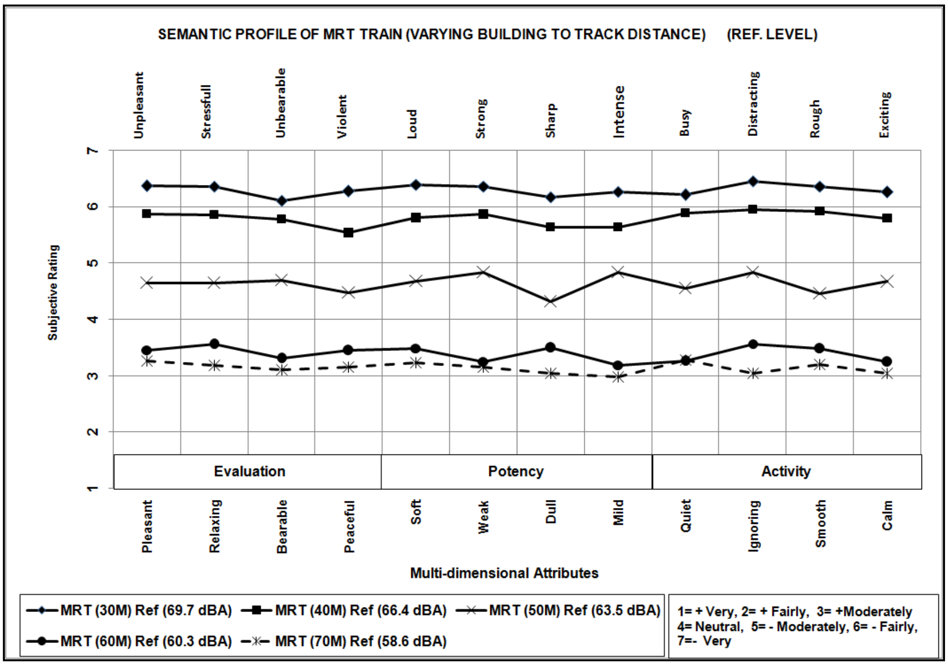


Figure 7-16: Comparison of semantic profiles of MRT train noise at different distances from residential buildings (Ref. Level)

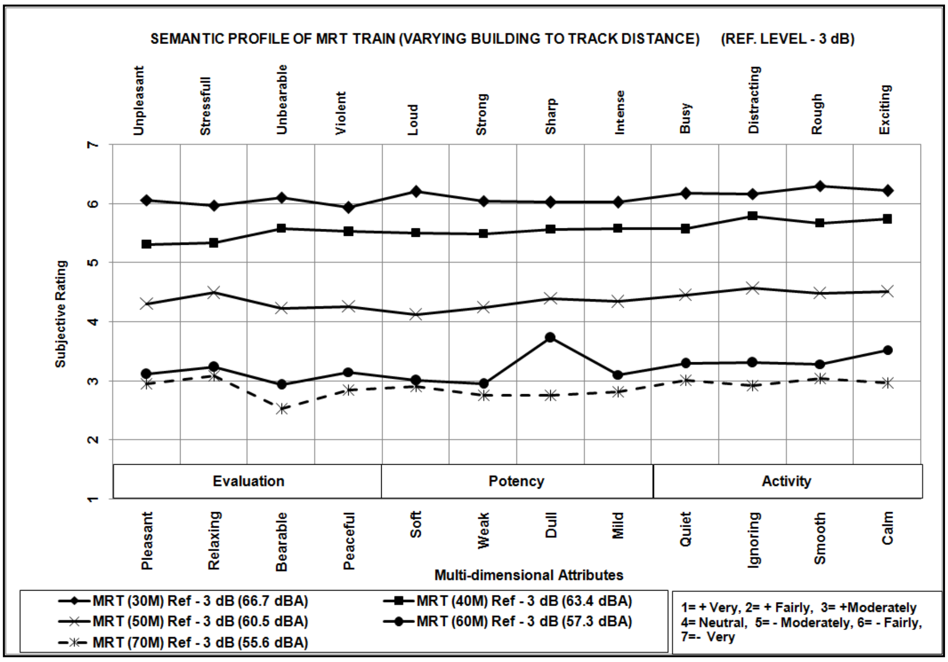


Figure 7-17: Comparison of semantic profiles of MRT train noise at different distances from residential buildings (Ref. Level -3 dB)

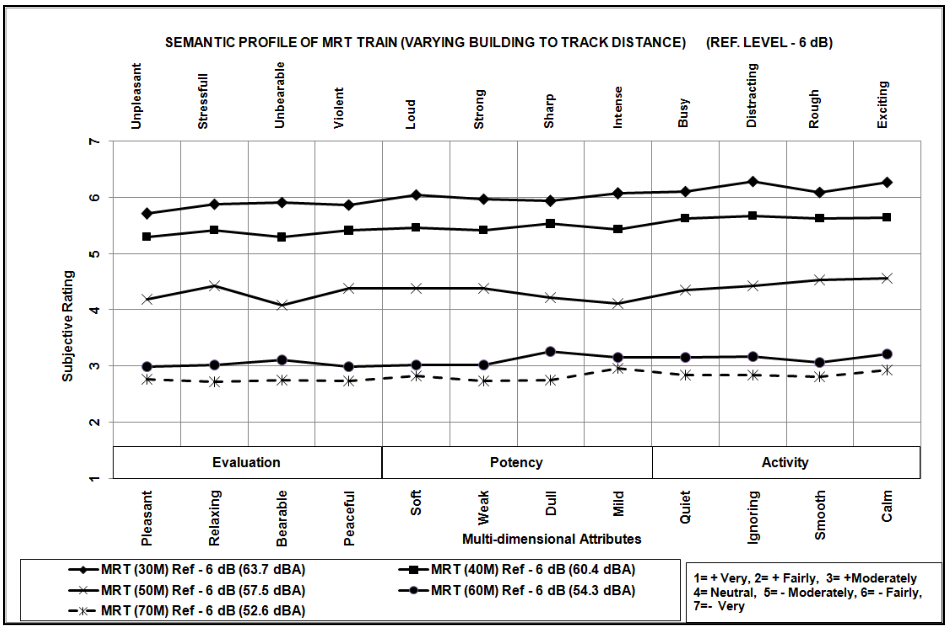


Figure 7-18: Comparison of semantic profiles of MRT train noise at different distances from residential buildings (Ref. Level -6 dB)

7.4.2.1 Relationships between subjective qualities in semantic space and psychoacoustical quantities (MRT train noise)

For analysis of the MRT train noise in the semantic differential space, the correlations between the twelve semantic adjective pairs and several psychoacoustic quantities are shown in Table 7-8 and in Table 7-9. The spearman rho coefficients in the table illustrate that 'aural comfort' is strongly and significantly correlated with all the 12 adjective pairs ($p < 0.05$). It is also observed that *all the 12 perception dimensions are strongly and significantly correlated with the overall noise levels, loudness, sharpness, fluctuation strength and roughness quantities of the MRT train sounds*. The perception dimensions of MRT train sound are found weakly correlated with tonality and prominence ratios.

Table 7-8: Correlations between semantic space and psychoacoustic quantities related to MRT train noise (First six pairs of the SD)

FACTORS	**Pleasant-Unpleasant**	**Relaxing-Stressful**	**Bearable-Unbearable**	**Peaceful-Violent**	**Soft-Loud**	**Weak-Strong**
Acoustic Comfort	**.640****	**.662****	**.667****	**.647****	**.681****	**.659****
Mean Level, L_{mean} (dBA)	**.680****	**.688****	**.678****	**.684****	**.704****	**.723****
Mean Level, L_{mean} (dB)	**.667****	**.675****	**.661****	**.668****	**.689****	**.713****
Maximum Loudness, N_{max} (Sone)	**.682****	**.686****	**.677****	**.686****	**.709****	**.724****
Mean Loudness, N_{mean} (Sone)	**.685****	**.689****	**.679****	**.686****	**.709****	**.730****
Zwicker Loudness, $N_{ISO532B}$	**.686****	**.690****	**.680****	**.688****	**.710****	**.730****
Five Percentile Loudness N_5 (Sone)	**.686****	**.690****	**.681****	**.689****	**.711****	**.729****
Maximum Sharpness, S_{max} (Acum)	**.707****	**.729****	**.734****	**.747****	**.755****	**.777****
Mean Sharpness S_{mean} (Acum)	**.651****	**.675****	**.676****	**.687****	**.691****	**.722****
Five Percentile Sharpness, S_5 (Acum)	**.697****	**.722****	**.724****	**.736****	**.742****	**.769****
Maximum Fluctuation Strength, Fmax (Centi Vacil)	**.520****	**.534****	**.544****	**.551****	**.551****	**.555****
Mean Fluctuation Strength, Fmean (Centi Vacil)	.376**	.392**	.396**	.399**	.394**	.397**
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	.494**	**.507****	**.519****	**.525****	**.524****	**.527****
Maximum Roughness (Centi Asper), R_{max}	**.527****	**.529****	**.519****	**.527****	**.540****	**.542****
Mean Roughness (Centi Asper), R_{mean}	**.634****	**.644****	**.631****	**.636****	**.651****	**.672****
Five Percentile Roughness (Centi Asper), R_5	**.554****	**.556****	**.546****	**.554****	**.571****	**.573****
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	.322**	.327**	.345**	.342**	.339**	.354**
Maximum Tone to Noise Ratio, TNR	.322**	.327**	.345**	.342**	.339**	.354**
The Frequency of the Maximum Prominence, F_{PR} (Hz)	-.360**	-.343**	-.357**	-.365**	-.392**	-.378**
Maximum Prominance, PR_{max} (dB)	0.051	0.061	0.071	0.06	0.044	0.068
Mean Prominance, PR_{mean} (dB)	0.051	0.061	0.071	0.06	0.044	0.068
Global Prominance, PR (dB)	0.051	0.061	0.071	0.06	0.044	0.068
N	540	540	540	540	540	540
****. Pearson Correlation is significant at the 0.01 level (1-tailed).**						
***. Pearson Correlation is significant at the 0.05 level (1-tailed).**						

Table 7-9: Correlations between semantic space and psychoacoustic quantities related to MRT train noise (Second six pairs of the SD)

FACTORS	**Dull-Sharp**	**Mild-Intense**	**Quiet-Busy**	**Ignoring-Distracting**	**Smooth-Rough**	**Calm-Exciting**
Acoustic Comfort	**.622****	**.632****	**.654****	**.643****	**.626****	**.633****
Mean Level, L_{mean} (dBA)	**.675****	**.674****	**.684****	**.695****	**.689****	**.678****
Mean Level, L_{mean} (dB)	**.643****	**.660****	**.668****	**.677****	**.672****	**.660****
Maximum Loudness, N_{max} (Sone)	**.677****	**.679****	**.686****	**.693****	**.692****	**.681****
Mean Loudness, N_{mean} (Sone)	**.668****	**.681****	**.687****	**.694****	**.691****	**.680****
Zwicker Loudness, $N_{ISO532B}$	**.672****	**.682****	**.689****	**.696****	**.693****	**.682****
Five Percentile Loudness N_5 (Sone)	**.680****	**.682****	**.690****	**.698****	**.695****	**.684****
Maximum Sharpness, S_{max} (Acum)	**.755****	**.741****	**.763****	**.765****	**.762****	**.772****
Mean Sharpness S_{mean} (Acum)	**.683****	**.681****	**.705****	**.706****	**.702****	**.710****
Five Percentile Sharpness, S_5 (Acum)	**.744****	**.731****	**.751****	**.757****	**.750****	**.762****
Maximum Fluctuation Strength, Fmax (Centi Vacil)	**.605****	**.536****	**.552****	**.570****	**.560****	**.564****
Mean Fluctuation Strength, Fmean (Centi Vacil)	.464**	.382**	.389**	.420**	.402**	.409**
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	**.582****	**.509****	**.526****	**.543****	**.534****	**.537****
Maximum Roughness (Centi Asper), R_{max}	**.551****	**.504****	**.512****	**.534****	**.528****	**.509****
Mean Roughness (Centi Asper), R_{mean}	**.636****	**.621****	**.630****	**.650****	**.639****	**.626****
Five Percentile Roughness (Centi Asper), R_5	**.572****	**.534****	**.541****	**.561****	**.556****	**.536****
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	.357**	.336**	.365**	.355**	.359**	.353**
Maximum Tone to Noise Ratio, TNR	.357**	.336**	.365**	.355**	.359**	.353**
The Frequency of the Maximum Prominence, F_{PR} (Hz)	-.341**	-.366**	-.393**	-.352**	-.383**	-.364**
Maximum Prominance, PR_{max} (dB)	0.07	0.057	.074*	.078*	0.069	0.069
Mean Prominance, PR_{mean} (dB)	0.07	0.057	.074*	.078*	0.069	0.069
Global Prominance, PR (dB)	0.07	0.057	.074*	.078*	0.069	0.069
	540	540	540	539	539	540

****. Pearson Correlation is significant at the 0.01 level (1-tailed).**

***. Pearson Correlation is significant at the 0.05 level (1-tailed).**

The relationship between the Pleasantness-Unpleasantness and the psychoacoustical quantities that are strongly and significantly correlated (found in Table 7-8 and in Table 7-9) with this dimension are graphically presented in Figure 7-19 to Figure 7-23. Relationships for the remaining 11 semantic dimensions with the correlated psychoacoustical quantities are presented in Appendix of this thesis.

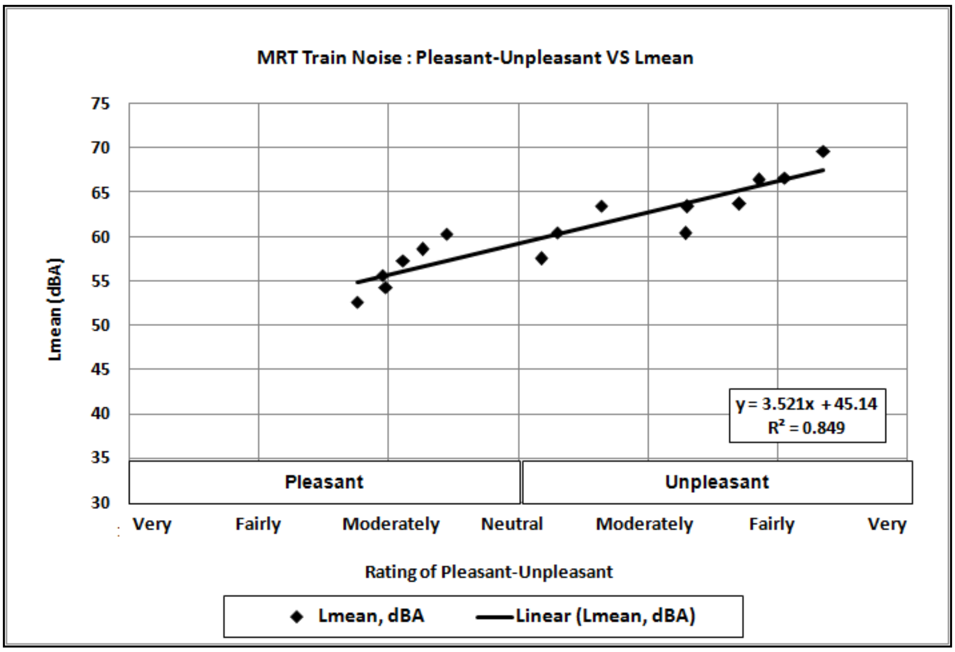


Figure 7-19: Relationships between pleasant-unpleasant and mean noise level

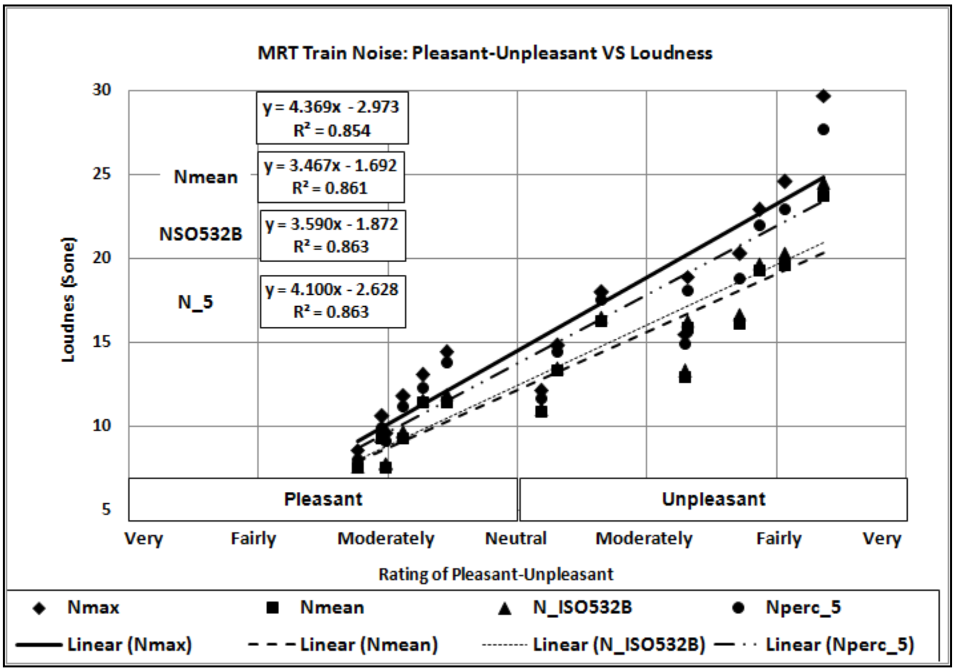


Figure 7-20: Relationships between pleasant-unpleasant and Loudness

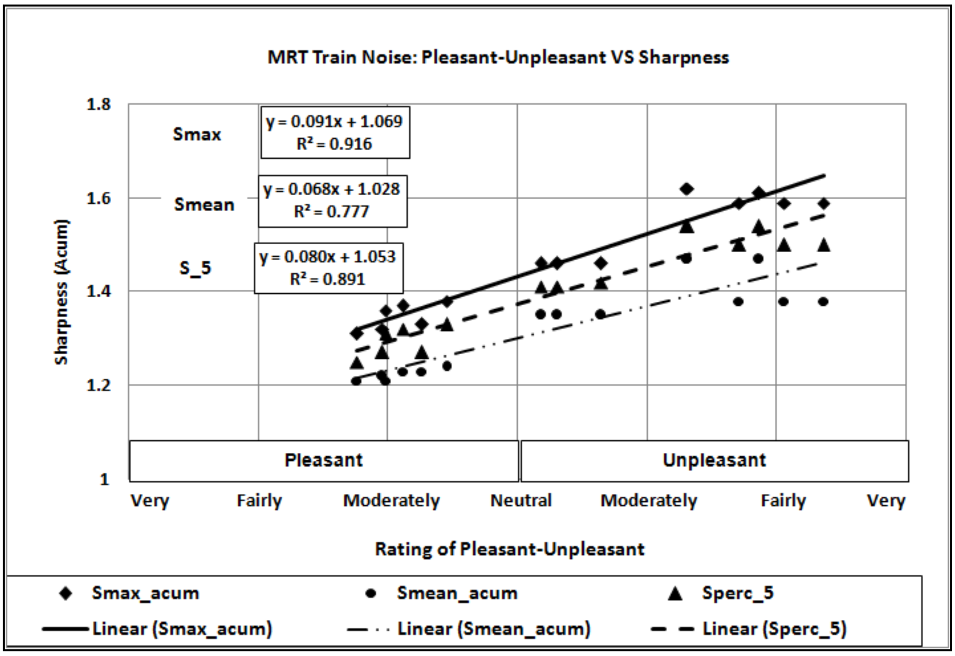


Figure 7-21: Relationships between pleasant-unpleasant and Sharpness

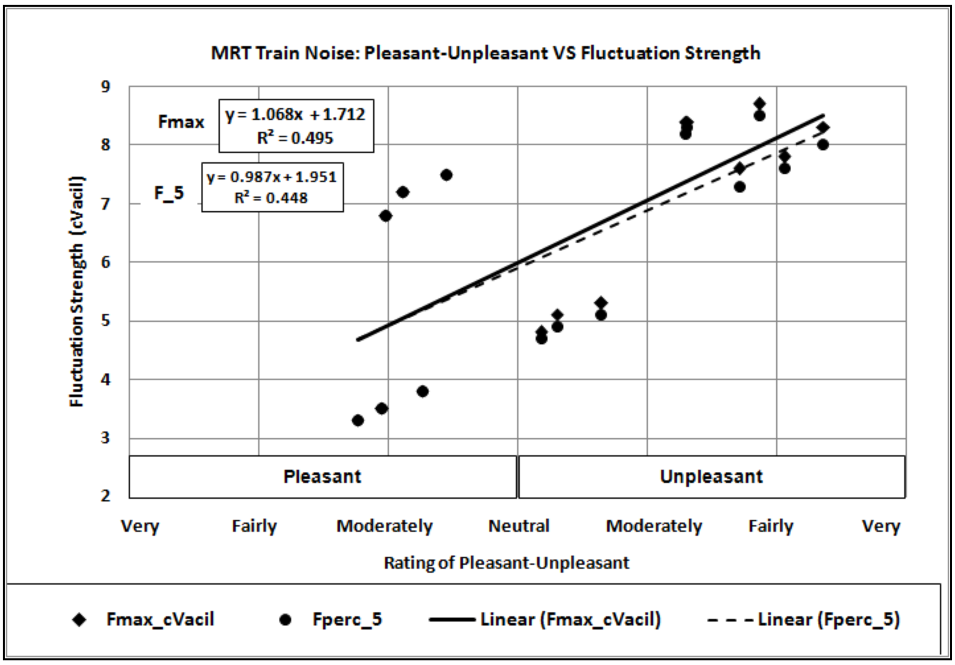


Figure 7-22: Relationships between pleasant-unpleasant and Fluctuation Strength

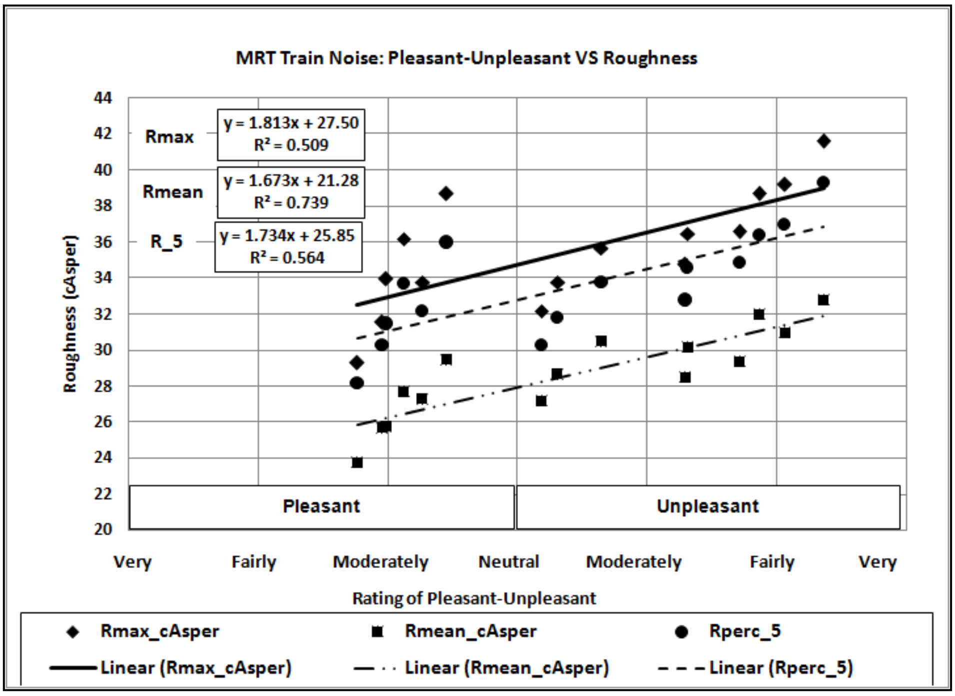


Figure 7-23: Relationships between pleasant-unpleasant and Roughness

As with road traffic noise, the analysis of all the relationships (refer to Appendix F) demonstrates that that the subjective perceptions of all twelve semantic differential adjective pairs are strongly correlated with the mean noise level $L_{Aeq}(dBA)$. *In general, it is observed that at an A-weighted equivalent noise level ($L_{Aeq}(dBA)$) of 56 dB moderately favourable subjective perceptions (i.e. moderately pleasant, moderately bearable etc.) are observed across the twelve semantic adjective pairs.*

Among the different psychoacoustical quantities relating to Loudness (N_{max}, N_{mean}, $N_{ISO\ 532B}$ and *and* $N_{perc,5\%}$) the five percentile Loudness ($N_{perc,5\%}$) is observed to have the strongest relationship with all the twelve semantic differential adjective pairs. *It is observed that at about 10 Sone $N_{perc,5\%}$ a moderate favourable subjective perceptions (i.e. moderately pleasant, moderately bearable etc.) are observed across the twelve semantic objective pairs.*

Among the different psychoacoustical quantities relating to Sharpness (S_{max} , S_{mean} , and $S_{perc,5\%}$) the Five percentile Sharpness ($S_{perc,5\%}$) is observed to have the strongest relationship with all the twelve semantic differential adjective pairs. *It is* *observed that at about 1.35 acum* $S_{perc,5\%}$ *moderately favourable subjective perceptions (i.e. moderately pleasant, moderately bearable, etc.) are observed across the twelve semantic objective pairs.*

For relationship between Fluctuation Strength (F_{max} and $F_{perc,5\%}$) and the twelve semantic differential adjective pairs are not strong (R^2 is about 0.4). *However, at about 5 cenit-vacil, (ether* F_{max} *or* $F_{perc,5\%}$*) moderately favourable subjective perceptions (i.e. moderately pleasant, moderately bearable, etc.) are observed across the twelve semantic objective pairs.*

It is also noted that among all the different psychoacoustical quantities relating to Roughness (R_{max}, R_{mean}, $R_{perc,5\%}$), the mean Roughness (R_{mean}) has the strongest relationship with all the twelve semantic differential adjective pairs. *At about 26 centi-asper* R_{mean} *moderately favourable subjective perceptions (i.e. moderately pleasant, moderately bearable, etc.) are observed across the twelve semantic objective pairs.*

7.4.3 Comparison of Semantic Profiles of Road Traffic and MRT Train Sound

A comparative examination of the semantic profiles of all different categories of roads and different distance categories of MRT trains was made for varying sound levels (i.e. reference level +0 dB, -3 dB and -6 dB). It is observed from Figure 7-24 to Figure 7-26 that there exists a very distinct categorization among the different types of noises.

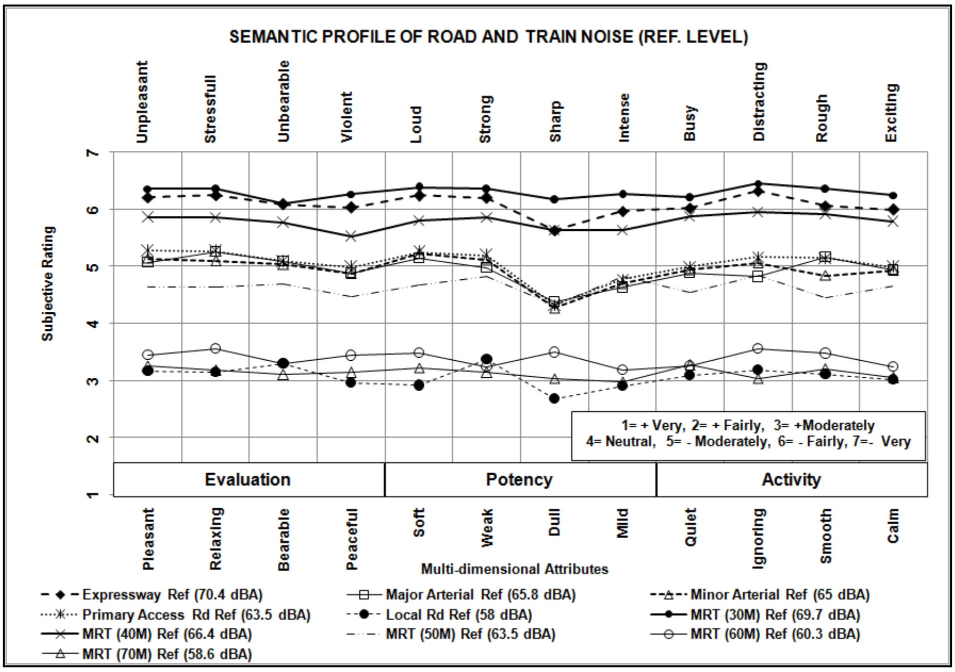


Figure 7-24: Comparison of semantic profiles of Road Traffic and MRT train noise (Ref. Level)

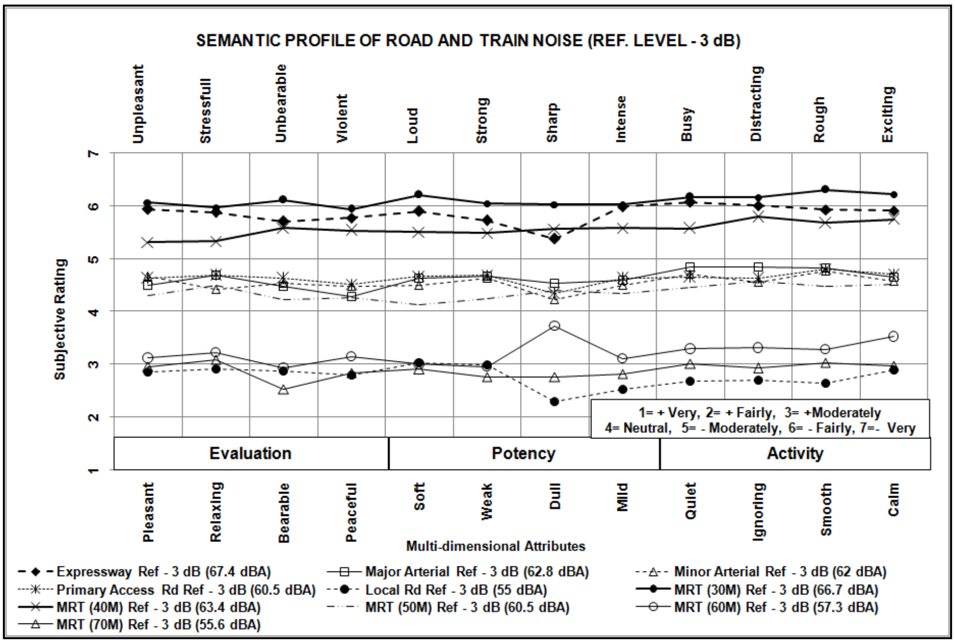


Figure 7-25: Comparison of semantic profiles of Road Traffic and MRT train noise (Ref. Level -3 dB)

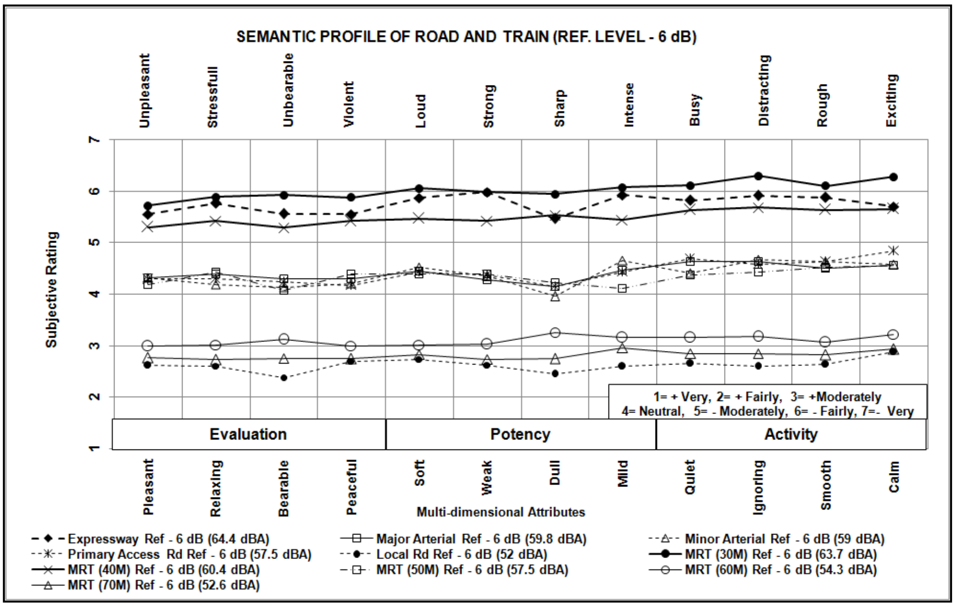


Figure 7-26: Comparison of semantic profiles of Road Traffic and MRT train noise (Ref. Level -6 dB)

A total of 3 distinct categories are observed. In the first category, road traffic sounds from expressways are approximately equally perceived as the MRT train sounds for building to track distances of 30m and 40m. The A-weighted noise levels, for which such perceptions were made, ranged between 60 dB and 70 dB. The subjective perceptions of all these sounds tend towards the 'fairly' unfavourable semantic adjective pairs (for example, fairly unpleasant, fairly stressful, etc).

In the second category, the semantic profiles show that the road traffic sounds from Major Arterial, Minor Arterial and Primary Access roads are approximately equally perceived as the MRT train sounds for a building to track distance of 50m. The A-weighted noise levels, for which such perceptions were made ranged between 57 dB and 66 dB. The subjective perceptions of all these sounds varied between 'neutral' and 'moderately' unfavourable semantic adjective pairs (for example, moderately unpleasant, moderately stressful, etc).

In the third and last category, the semantic profiles show that the road traffic sounds from Local roads are approximately equally perceived as the MRT train sounds for a building to track distance of 60m and 70m. The A-weighted noise levels, for which such perceptions were made, varied between 52 dB and 60 dB. *The subjective perceptions of all these sounds are towards 'moderately' favourable semantic adjective pairs (for example, fairly pleasant, fairly relaxing, etc).*

7.5 SUMMARY

In this chapter, the Aural Comfort Model (ACM) is validated using the subjective responses collected from the psychoacoustics experiments in the laboratory. Predicted aural comfort levels are, in general, good agreement with the experimental aural comfort responses.

A paired comparison study is also made in this chapter to examine the pair wise evaluation of the road traffic and train noise. It was noted that the MRT train sounds were more uncomfortable when compared with the sounds of the same level (L_{Aeq}) from Expressway, Major Arterial and Minor Arterial Road. In addition, aural comfort (or discomfort) due to MRT train noise was found to be not significantly different to that due to from the Primary Access and Local road traffic noise of same level. Similar observations were made for MRT train and road traffic noise when apartments' noisiness and noise disturbance were evaluated.

A semantic differential study is also made in this chapter to evaluate the subjective perceptions of road traffic and train noise in twelve bipolar adjective pairs. The adjective pairs that formed the semantic space comprise of Pleasant-Unpleasant, Relaxing-Stressful, Bearable-Unbearable, Peaceful-Violent, Soft-Loud, Weak-Strong, Dull-Sharp, Mild-Tense, Quiet-Busy, Ignoring-Distracting, Smooth-Rough and Calm-Exciting. Aural comfort was found strongly and significantly correlated with all these semantic dimensions. A comparison of road traffic and train noise in the semantic space showed three distinct categories where the road traffic and train noises were perceived equally. It was observed that in the first category, road traffic sounds from expressways were about as equally perceived as the MRT train sounds for building to track distances of 30m and 40m. These sounds were generally perceived as 'fairly' unfavourable semantic adjective pairs (for example, fairly unpleasant, fairly stressful etc). In the second category, the road traffic sounds from Major Arterial, Minor Arterial and Primary Access roads were found to be about equally perceived as the MRT train sounds for a building to track distance of 50m. These sounds were generally perceived between 'neutral' and 'moderately' unfavourable semantic adjective pairs. In the third category, road traffic sounds from local roads were found to be almost equally perceived as the MRT train sounds for building to track distance of 60m and 70m. The subjective perceptions of these sounds were towards 'moderately' favourable semantic adjective pairs (for example, fairly pleasant, fairly relaxing, etc).

The adjective pairs in the semantic space were correlated with psychoacoustic quantities of the road traffic and train sounds.

For road traffic sounds, it was found that at A-weighted equivalent noise level ($\mathrm{L_{Aeq}(dBA)}$) of 55 dB, 'moderately' favourable subjective perceptions were observed across the twelve semantic adjective pairs. A 10 Sone (N_{mean}) 'moderately' favourable perceptions were also observed. In relation to roughness, at 28 centi-asper ($\mathrm{R_{5\%}}$), 'moderately' favourable perceptions were also observed.

For MRT train sounds, the analysis showed that that moderately favourable subjective perceptions were observed across the twelve semantic adjective pairs at an A-weighted equivalent noise level ($\mathrm{L_{Aeq}(dBA)}$) of 56 dB. At 10 Sone ($\mathrm{N_{5\%}}$), 'moderately' favourable perceptions were also observed. Even though subjective perceptions of road traffic sounds were found not strongly correlated with sharpness, MRT train sounds were correlated with Sharpness. The analysis showed that at 1.35 acum ($\mathrm{S_{5\%}}$), moderately favourable perceptions were observed. In 26 centi-asper ($\mathrm{R_{mean}}$), 'moderately' favourable perceptions were also observed.

CHAPTER 8: CONCLUSION

8.1 INTRODUCTION

This research study endeavours to assess the daytime 'Aural comfort' of high-rise apartment dwellers in tropical Singapore. In this thesis, the term 'aural comfort' is defined as the condition of mind which articulates satisfaction (or dissatisfaction) with the surrounding aural environment. Aural comfort does not depend on the physical noise level alone, but on the inter-relations between the factors that contribute to a person's satisfaction with his/her surrounding aural environment. In the past, noise annoyance was evaluated extensively which is generally towards the unfavourable (negative) evaluation of sounds. There was little study in the past on the positive evaluation of the noise, i.e. aural comfort, in urban residential environments (Marquis et al., 2005). A comprehensive study on aural comfort of high-rise dwellers in tropical climatic environment is totally missing in literature. With this in mind, the key objective of this research was to develop an aural comfort model. *In the following, a summary of the key research contributions and their importance is presented.*

8.2 ASSESSMENT OF AURAL COMFORT OF HIGH RISE DWELLERS IN THE TROPICS

As previously stated, assessment of aural comfort of high-rise apartment dwellers in a tropical environment is missing in literature. In temperate countries, windows and doors are kept closed and well sealed for much of the year to prevent heat loss. This results in the effective use of openings in facades and separating walls for sound insulation. Contrary, in the tropical environment windows at the facades are left open for natural ventilation. This results in direct exposure to outdoor environmental noise and airborne flanking noises from immediate neighbours' apartments. Due to limited land space in countries like Singapore and Hong Kong, high-rise residential buildings are developed to meet housing shortage requirements and the transport networks are brought closer to the residential buildings. As a result, the context of indoor aural environment in high-rise tropical areas is significantly different to that of temperate countries. It is therefore important to investigate the factors related to the aural comfort of high-rise dwellers in the context of a tropical environment. Based on the literature review and preliminary findings from noise survey in Singapore, it was inductively hypothesized that *'Daytime subjective aural comfort in high-rise naturally ventilated residential dwellings can be defined as a function of the daily average indoor noise exposure level, the perception of the overall noisiness at the apartment and the noise disturbance caused by road traffic and Mass Rapid Transit (MRT) train noise'***.**

In this thesis, aural comfort of high-rise residential dwellers (in public housing) in tropical Singapore is assessed. Given the extensive high-rise living and tropical environment in Singapore, the findings of an aural comfort assessment stands to offer important implications on aural comfort in cities considering high-rise housing. Based on the author's knowledge, this research investigation is probably the pioneering study to address the subject.

8.3 DEVELOPMENT OF AN AURAL COMFORT ASSESSMENT FRAMEWORK

The evaluation of noise annoyance has been limited to either subjective or objective assessment of outdoor transportation noise or to neighbour noise in isolation. Reasonably, Jin (2010) commented that suitability of the established noise annoyance models for the evaluation of the indoor noise environment of residential premises is in question. A holistic framework based on the integration of subjective and objective assessment is therefore missing in literature.

In this thesis, a novel framework is proposed for the assessment of aural comfort among high-rise dwellers in the tropics. The proposed aural comfort assessment framework is rooted in Stallen’s (1999) theory of noise annoyance and is based on the theory of Evaluation Response Model (ERM) (Eagly and Chaiken, 1993). The evaluation framework illustrates that noise in an indoor environment, considered as 'perceived disturbance' or an 'attitude object', impinges on the 'human interface' which is surrounded by its relevant physical and environmental conditions. The 'human interface' refers to the residential dwellings of the individuals and the 'attitude' of the individuals towards the noise exposure in their dwellings. In such a residential setting, the indoor noise is attributed to outdoor environmental, community noise sources and neighbour noise.

The assessment of the physical environment for overall evaluation of aural comfort is defined as the 'Objective assessment' in this proposed framework. The 'Subjective assessment' of the aural comfort is fundamentally the evaluation of the 'attitude' response of the individuals towards the aural environment they are exposed to in their dwellings. According to Eagly and Chaiken (1993), an individual’s attitude towards this noise environment is an evaluative process which is founded on several psychological and physiological variables that determine the individual's state of aural comfort. As illustrated in the Evaluation Response Model (ERM), the fundamental components of an individual’s attitude towards the noise environment include cognitive responses (thoughts - importance of noise in the living environment) to noise, affective responses (feeling - noisiness of the apartment, noisiest time of the day, noise sensitivity, perceived disturbance due to noise) to noise and behavioural responses (adaptive behaviours - likeliness of closing doors, windows) to noise.

Through objective and subjective assessment of aural comfort comprehensively, the 'experience' of the dweller's aural comfort condition can be established. Examination of the dominant outdoor noise source characteristics, as well as their exposure levels, sound transmission performances of facades, party walls and floors was carried out in objective assessment. Subjective assessment was carried out through the evaluation of 'attitude' of the residents with respect to the noise environment in their dwelling. Once such 'acoustical experience' is defined through acoustical and non-acoustical factors, an aural comfort assessment model can be developed.

The data collected from the objective and subjective assessment were integrated through statistical modelling to establish the long term daytime aural comfort model. *To the author's knowledge, the use of such a theoretical framework for holistic assessment of aural comfort (or discomfort) has never before been studied in the tropics.*

8.4 DEVELOPMENT OF AN AURAL COMFORT MODEL

In objective assessment of aural comfort, propagation characteristics of road traffic and train noise along elevation of building were investigated to predict the noise exposure at different floor levels. Indoor noise exposure levels at different individual dwellings were predicted based on the facade noise levels and measured sound insulation performances of facade (considering an window opened). The decision to open one window at the façade was the result of the noise survey which showed that over 90% of the respondents opened at least one window in their room, for natural ventilation, during their stay at home. In addition, airborne sound insulation performances of party walls and impact sound insulation performances of floors were also evaluated. The computed indoor noise exposure levels were then used with the subjective comfort responses of the residents (through stratified sampled noise survey) to establish an aural comfort model.

Subjective assessment of aural comfort was carried out through a noise survey in a stratified sampling technique. A total of twelve factors were found correlated with the overall rating of aural comfort. They are: Rating of noisiness of an apartment, Sensitivity to noise, Consideration of noise as an important aspect in living environment, Disturbance by neighbour noise, Type of personal activities disturbed by neighbour noise, Rating of disturbance by Road traffic and Train noise, and Likelihood of closing Door, Windows, Playing music and Watching television to cope with the noise annoyance and finally the Indoor noise level. Factor analysis showed that all these factors explain 74% of the total variation. There were no significant rating differences found for rating of aural comfort by all the factors investigated except the individuals' sensitivity to noise.

Findings from subjective assessment and its integration with objective noise evaluation revealed some interesting findings. It was found that noise disturbance of residents of high-rise naturally ventilated buildings reduces significantly when the buildings are located further away from Road traffic or MRT train track (thus reducing noise exposure level). Among the respondents who felt acoustically comfortable, a significant portion of them were either not disturbed or a little disturbed due to road traffic or MRT train noise.

For neighbour noise, the rating of the ‘subjective loudness’ of the neighbour noise was found higher when the sound insulation performance of the party wall was lower. Interesting, the analysis revealed that when the indoor background noise level was lower, the rating of the ‘subjective loudness’ of the neighbour noise was found higher. It is evident from the noise survey that among the respondents who were acoustically comfortable, about 97% of them rated the loudness of the airborne transmitted noise as not at all loud to a little loud.

For neighbour's floor impact noise, the perception rating of the ‘subjective loudness’ of the neighbour impact noise was found higher when the impact sound insulation of the floors was lower. Interesting, the analysis revealed that when the indoor background noise level was lower, the rating of the ‘subjective loudness’ of the neighbour impact noise was found higher and vice versa. However, the influence of neighbour noise on the overall aural comfort was found weak and therefore excluded from the final model.

All the twelve factors identified through noise survey were then used for the development of an aural comfort model through a multinomial logistic regression analysis. Regression analysis concluded that four factors namely, Indoor noise exposure level, Rating of noisiness of the apartment, Rating of disturbance due to Road Traffic noise and Rating of disturbance due to MRT Train noise, are significantly correlated to the overall aural comfort and thus formed the aural comfort model.

The developed aural comfort model confirmed the research hypothesis that aural comfort is dependent on the noise exposure level, the subjective perceptions of the noisiness of the apartments due to the noise exposure, the level of disturbances due to road traffic noise and also the perceived noise disturbances due to MRT train noise. The aural comfort model was validated using subjective comfort responses collected from the psychoacoustics experiments in a laboratory condition. The predicted aural comfort responses were in good agreement with the measured subjective responses from the experiment.

8.5 ESTABLISHMENT OF THE RELATIONSHIPS BETWEEN NOISINESS, NOISE DISTURBANCE AND PSYCHOACOUSTICAL QUANTITIES

The subjective perception of 'noisiness of apartment' and 'noise disturbance due to road traffic and MRT train components of the aural comfort model are integrated with psychoacoustical quantities of the road traffic and MRT train sounds in this thesis.

Established statistical models for the *road traffic noise* show that *noisiness of an apartment* is dependent on the noise exposure level, mean and maximum Loudness and also on the mean and maximum Roughness (rapid modulation between 15 and 300 Hz) of the road traffic noise. Similarly, *noise disturbance due to road traffic* is dependent on the noise exposure level, mean and maximum loudness and also on the mean Roughness.

Established statistical models for the *MRT Train* noise show that *noisiness of an apartment* is best described by the maximum loudness, maximum roughness and also the mean Sharpness of the MRT train noise. On the other hand, *noise disturbance due to MRT Train* is found dependent on the maximum Loudness and mean Sharpness.

Analysis of the data has shown that the noisiness of an apartment subjected to Road Traffic noise was perceived as 'quiet' at a mean A-weighted noise exposure level of about 53 dB; also at a mean Loudness level of 7 sone and maximum Loudness level of 9 sone and at a mean Roughness level of 24 centi-Asper and maximum Roughness level of 27 centi-Asper. Noise disturbance due to road traffic was perceived as 'a little disturbing' at a mean A-weighted noise exposure level of about 57 dB , a mean Loudness level of 11 sone and at maximum Loudness level of 13 sone and at a mean Roughness of 26 centi-Asper. On the other hand, analysis of the data shows that noisiness of an apartment subjected to MRT train noise was perceived as 'quiet' at a maximum Loudness level of 8 Sone and at a mean Sharpness level of 1.22 acum and at a maximum Roughness level of 33 centi-Asper whereas noise disturbance due to MRT train noise was perceived as 'a little disturbing' with a maximum Loudness level of 10 sone and at a mean Sharpness of 1.3 acum. Statistical models have been established for 'noisiness of apartment' and 'disturbance due to road traffic and train noises' relating different psychoacoustical quantities.

8.6 PAIR-WISE EVALUATION OF THE ROAD TRAFFIC AND MRT TRAIN SOUNDS

A paired comparison study is also made in this thesis to examine the pair-wise evaluation of the road traffic and train noise. It was observed that the MRT train sounds were more uncomfortable when compared with the sounds of the same level (L_{Aeq}) from Expressway, Major Arterial and Minor Arterial Road. In addition, aural comfort (or discomfort) due to MRT train noise was found to be not significantly different to that due to from the Primary Access and Local road traffic noise of same level. Similar observations were made for MRT train and road traffic noise when apartments' noisiness and noise disturbance were evaluated.

8.7 CHARACTERIZATION OF ROAD TRAFFIC AND TRAIN NOISE IN A SEMANTIC DIFFERENTIAL SPACE

Road traffic and MRT train noises have been evaluated in a semantic differential space comprising of twelve bipolar adjective pairs namely Pleasant-Unpleasant, Relaxing-Stressful, Bearable-Unbearable, Peaceful-Violent, Soft-Loud, Weak-Strong, Dull-Sharp, Mild-Tense, Quiet-Busy, Ignoring-Distracting, Smooth-Rough and Calm-Exciting. Aural comfort has been found strongly and significantly correlated with all of these semantic dimensions.

A comparative evaluation of the semantic profiles of all different categories of roads and MRT trains was made for varying sound levels (i.e. reference level +0 dB, -3 dB and -6 dB). A total of 3 distinct categories were observed. In the *first category*, road traffic sounds from expressways were approximately equally perceived as the MRT train sounds for building to track distances of 30m and 40m. The A-weighted noise levels, for which such perceptions were made, ranged between 60 dB and 70 dB. The subjective perceptions of all these sounds tend towards the 'fairly' unfavourable semantic adjective pairs (for example, fairly unpleasant, fairly stressful, etc). In the *second category*, the semantic profiles showed that the road traffic sounds from Major Arterial, Minor Arterial and Primary Access roads are approximately equally perceived as the MRT train sounds for a building to track distance of 50m. The A-weighted noise levels, for which such perceptions were made ranged between 57 dB and 66 dB. The subjective perceptions of all these sounds varied between 'neutral' and 'moderately' unfavourable semantic adjective pairs (for example, moderately unpleasant, moderately stressful, etc). In the *third and last category*, the semantic profiles show that the road traffic sounds from Local roads are approximately equally perceived as the MRT train sounds for a building to track distance of 60m and 70m. The A-weighted noise levels, for which such perceptions were made, varied between 52 dB and 60 dB. The subjective perceptions of all these sounds were towards 'moderately' favourable semantic adjective pairs (for example, fairly pleasant, fairly relaxing, etc).

Table 8-1: Magnitude of psychoacoustical indices providing aural comfort in semantic dimensions

Acoustical Indices	**Moderately favourable subjective perception**	
	Magnitude of Acoustical Indices for Road Traffic Noise	**Magnitude of Acoustical Indices for MRT Train Noise**
$\boldsymbol{N_{mean}(Sone)}$	10	-
$\boldsymbol{N_{5\%}(Sone)}$	-	10
$\boldsymbol{R_{5\%}\ (cAsper)}$	28	26
$\boldsymbol{S_{5\%}(Acum)}$	-	1.35

While assessing aural comfort with respect to *Road traffic sounds*, the analysis showed that at an A-weighted equivalent noise level ($\mathrm{L_{Aeq}}$(dBA)) of 55 dB, 'moderately' favourable subjective perceptions were observed across the twelve semantic adjective pairs. In addition, in relation to psychoacoustical quantities (refer to Table 8-1), at a mean Loudness of 10 Sone 'moderately' favourable perceptions were also observed. In relation to Roughness, at Five percentile Roughness value of 28 centi-asper, 'moderately' favourable perceptions were observed.

Similarly, while assessing aural comfort with respect to *MRT train sounds*, moderately favourable perceptions were observed at an A-weighted noise level (L_{Aeq}(dBA)) of 56 dB. The analysis also showed that a Five percentile Loudness value of 10 Sone and Five percentile Sharpness of 1.35 acum 'moderately' favourable subjective perceptions were observed. At a mean Roughness of 26 centi-asper, 'moderately' favourable perceptions were also observed.

8.8 AURAL COMFORT MODEL AND ITS IMPLICATION ON THE HIGH RISE DWELLINGS IN THE TROPICS

The Aural Comfort Model (ACM) developed in this thesis is based on the subjective noise perception of the residents living in high-rise naturally ventilated residential apartments in tropical Singapore and relates their day-time indoor aural comfort to the dominant noise sources: Road Traffic and MRT Train. Four factors are identified influencing aural comfort in this thesis. These are noise level in the apartment, noisiness of the apartment, disturbance due to Road traffic noise and disturbance due to MRT train noise.

High-rise apartments subjected to Road Traffic and MRT Train noise sources are often exposed to higher noise levels (compared to the noise at the lower floors) due to vertical propagation of noise. In order to achieve a higher thermal comfort and reduce energy dependency in building design in the tropics, provision of natural ventilation is a key design strategy. As a result, with the windows left open at the facade, air-borne noise from nearby sources find their way to indoor environment and thus affect aural comfort. Due to limited research on aural comfort in high-rise tropical environment, key factors influencing aural comfort are not identified in greater detail and their influences on comfort are left unknown. As a result, the noise management policies often lack theses information in order to provide a better indoor aural environment.

ACM reveals that at A-weighted noise level of 52 dB or below during the daytime, dwellers will be aurally comfortable in high-rise naturally ventilated apartments. However, since overall A-weighted noise level is not a sole indicator for aural comfort, a reduced level does not necessarily increase the level of aural comfort. Aural comfort is dependent on subjective 'noisiness of apartment' and 'disturbance' due to road traffic and MRT train noise which in turn related to several psychoacoustical quantities.

Table 8-2: Magnitude of psychoacoustical in relation to 'noisiness' and 'disturbance'

Acoustical Indices	**Magnitude of Acoustical Indices for Road Traffic Noise**		**Magnitude of Acoustical Indices for MRT Train Noise**	
	Noisiness (Quiet)	**Disturbance (A Little)**	**Noisiness (Quiet)**	**Disturbance (A Little)**
$\boldsymbol{N_{max}}\ (\boldsymbol{Sone})$	9	13	8	10
$\boldsymbol{N_{mean}}(\boldsymbol{Sone})$	7	11	-	-
$\boldsymbol{R_{max}}(\boldsymbol{cAsper})$	27	-	33	-
$\boldsymbol{R_{mean}}\ (\boldsymbol{cAsper})$	24	26	-	-
$\boldsymbol{S_{mean}}(\boldsymbol{Acum})$	-	-	1.22	1.3

Established regression models reveal that Maximum Loudness (N_{max}) and Maximum Roughness (R_{max}) are the key factors influencing subjective 'noisiness' perception related to both road traffic and MRT train noise. However, it is the Sharpness (S_{mean}) which influence the 'noisiness' perception related to MRT train noise only. In addition, 'disturbance' due to road traffic noise is influenced by Maximum Loudness ($\mathrm{N_{max}}$) and Mean Roughness ($\mathrm{R_{mean}}$) which for train noise is influenced by Maximum Loudness ($\mathrm{N_{max}}$) and Mean Sharpness ($\mathrm{S_{mean}}$). The subjective perceptions at different varying levels of these factors are investigated in greater detail in this thesis. The magnitudes at which these psychoacoustical quantities provide quietness and reduce noise disturbance in achievement of daytime aural comfort are presented in Table 8-2.

The current Code of Practice for Environmental Sustainability of Buildings (BCA, 2008) in Singapore specifies an indoor noise requirement in terms of A-weighted noise level 55 dB. A-weighted noise level is commonly used is in many countries as the criteria for building design, environmental noise control and noise annoyance management policy. Since the dependency on this indicator does not take care of the aural comfort entirely, the inclusion of the factors discussed earlier in this section, specially $\mathrm{N_{max}}$, $\mathrm{R_{max}}$ and $\mathrm{S_{mean}}$ and their corresponding magnitude for achievement of aural comfort, in the environmental noise management policy will be able to increase the level of indoor aural comfort in high-rise naturally ventilated apartments. As noted from Table 8-2 above, Loudness and Roughness are the key indicators for aural comfort with regards to Road Traffic Noise whereas the control of Loudness and Sharpness relating to MRT train noise are vital in delivering aural comfort to the high-rise residential dwellers in the tropics.

In addition to the above, semantic profile analysis discussed in this thesis would be able to give an understanding of the emotional aspect of the noise sources (road traffic and MRT train) in relation to aural comfort. This would be useful as a guide for planning new towns and estates and in the design of high rise residential buildings for provision of indoor aural comfort.

8.9 LIMITATION OF THE RESEARCH AND RECOMMENDATIONS FOR FURTHER STUDIES

Limitations of this research study and recommendations for further studies are as follows:

- This research examined the daytime aural comfort among high-rise apartment dwellers in the tropics. Aural comfort during the night time was not investigated in this thesis. Future research should be carried out to enhance the model for night-time aural comfort. It is important to note that sleep disturbance is a key issue related to nigh-time aural comfort. In order to address this, care must be taken to establish/predict 'indoor noise level' and 'disturbance' due to road traffic and MRT train noise. Night-time indoor noise level should be measured or predicted such that it is representative of the duration prior to the sleep and during the sleep. In addition to the above, to establish the 'disturbance' due to road traffic noise and MRT train noise, residents should be surveyed for night-time aural comfort which was not carried out in this research. As well, 'sleep study' in laboratory/home condition should be considered for the establishment of 'noise disturbance' during night. However, future research should incorporate subjects' age and noise sensitivity which are related to sleep disturbance and possibly substitute 'noise disturbance' from the ACM model that will reduce the probability of multicollinearity in the comfort model.

- Assessment of indoor aural comfort study is limited to daytime comfort subjected to road traffic and train noise. Noise from indoor environment within the apartment is assumed to have insignificant influence on the overall aural comfort and thus excluded from this research. This study focuses exclusively on the aural comfort subjected to environmental noise.
- The indoor thermal environment was assumed 'comfortable' during the noise survey. Therefore, the influences of different indoor thermal environment on overall aural comfort was not investigate in this thesis. As thermal comfort is one of the key aspects in the design consideration of high-rise naturally ventilated buildings in tropical climatic environment, its subjective perception, its influence on the evaluation of 'noisiness of apartment' and 'noise disturbance due to Road Traffic and MRT train noise' are important

consideration for building design and therefore require further research. In addition, the influence of varied noise levels on thermal comfort and vice versa is still unknown and might play an important role in overall evaluation of the indoor aural environment, as such proposed for future research.

- This research also assumed visual comfort exists in the high-rise naturally ventilated residential buildings in Singapore and hence have insignificant influence on the evaluation of aural comfort. Influence of visual information on the overall aural comfort in tropical context remains unknown which can be considered for future research.
- The established acoustic comfort model (ACM), developed based on a Multinomial Logistic Regression (MLR), comprises of four independent variables including an objective variable (indoor noise level) and three other subjective variables (Noisiness rating of apartment, Rating of disturbance by Road traffic noise and Rating of disturbance by MRT Train noise). As subjective noise perception is dependent on a host of psycho-physiological issues which together influence the evaluation of noise, the reliance of a number of such factors as 'independent variable' is subjected to multicollinearity check. Even though statistical analysis showed that there is no multicollinearity in the ACM (it is detected by the presence of very large Standard Errors for the B coefficients (Sheskin, 2007; Priyantha and Dilum, 2009)), the relationship between 'Noisiness of Apartment' and 'Disturbance' were not further investigated to reduced the dimension of the model.
- Noise sensitivity is one of the important psycho-physiological factors that was found significant influencing the subjective noise perception. In aural comfort studies, subjects with different noise sensitivity were found rating unequally. However, this factor was not qualified through multinomial logistic regression analysis during the development of aural comfort model. It

would be interesting to investigate its influence on aural comfort and future works in development of an aural comfort model with inclusion of this factor.

- The subjective noise survey in this research was carried out at the buildings where residential apartments were directly facing the Road or MRT Track. This methodology aided in the precise prediction of the indoor noise level subjected to these noise sources. As a result, the subjective noise response of the residents living in buildings with different orientation and layout were not captured in this study. However, to take this effect into consideration, psychoacoustic tests in the laboratory were carried out for different noise exposure levels (also corresponding psychoacoustical quantities) of the noise sources.
- The subjects qualified for psychoacoustical test in the laboratory environment aged mostly between 20 to 40 years. A wider age distribution of the subjects would allow a researcher to investigate the psychoacoustic evaluation of noise for different age and noise sensitivity.

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APPENDIX A : CALCULATION ALGORITHM FOR ROUGHNESS AND FLUCTUATION STRENGTH IN DBSONIC SOFTWARE

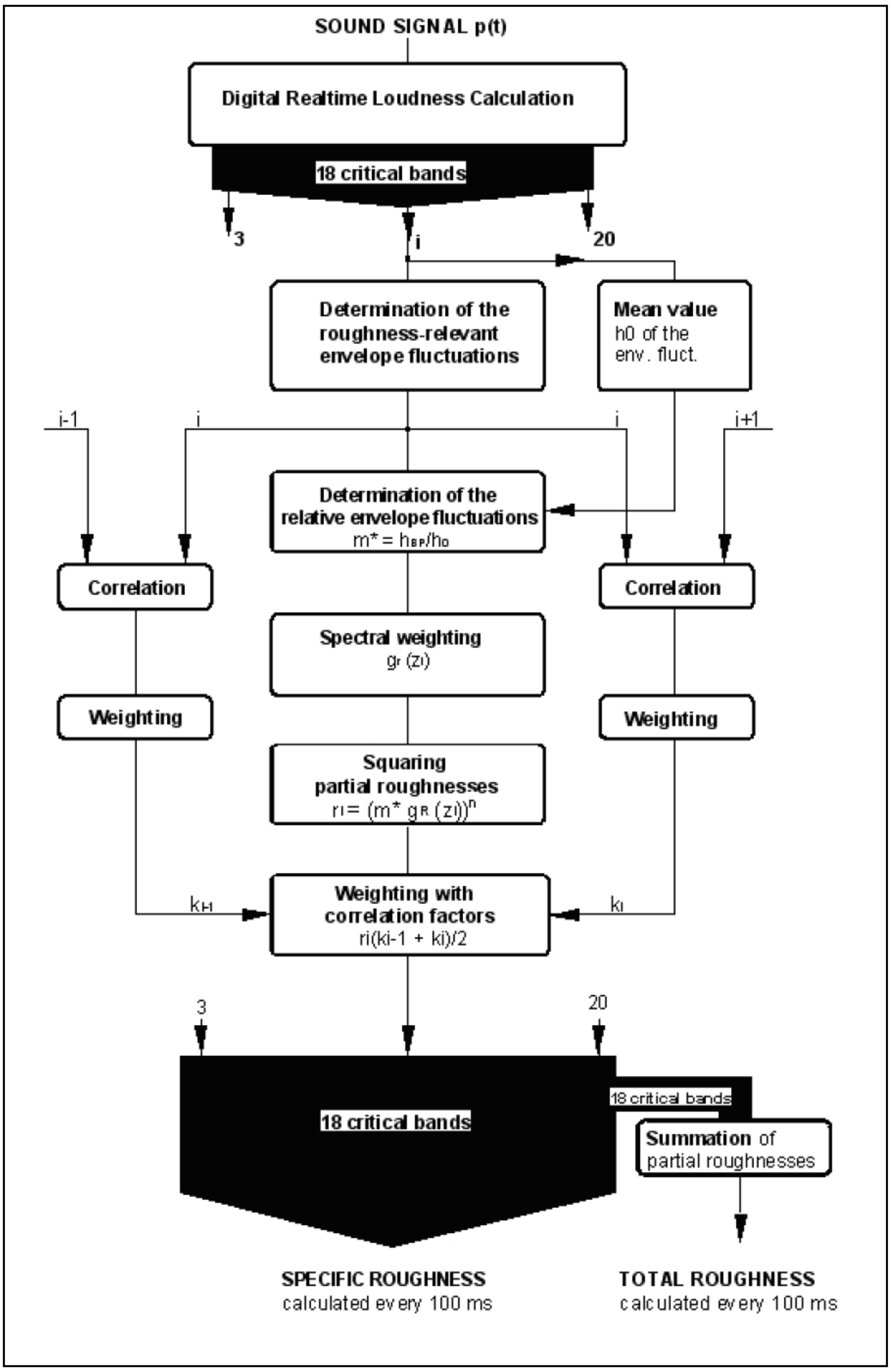


Figure: Computation model for Roughness (Source: dBSonic user manual, 2005)

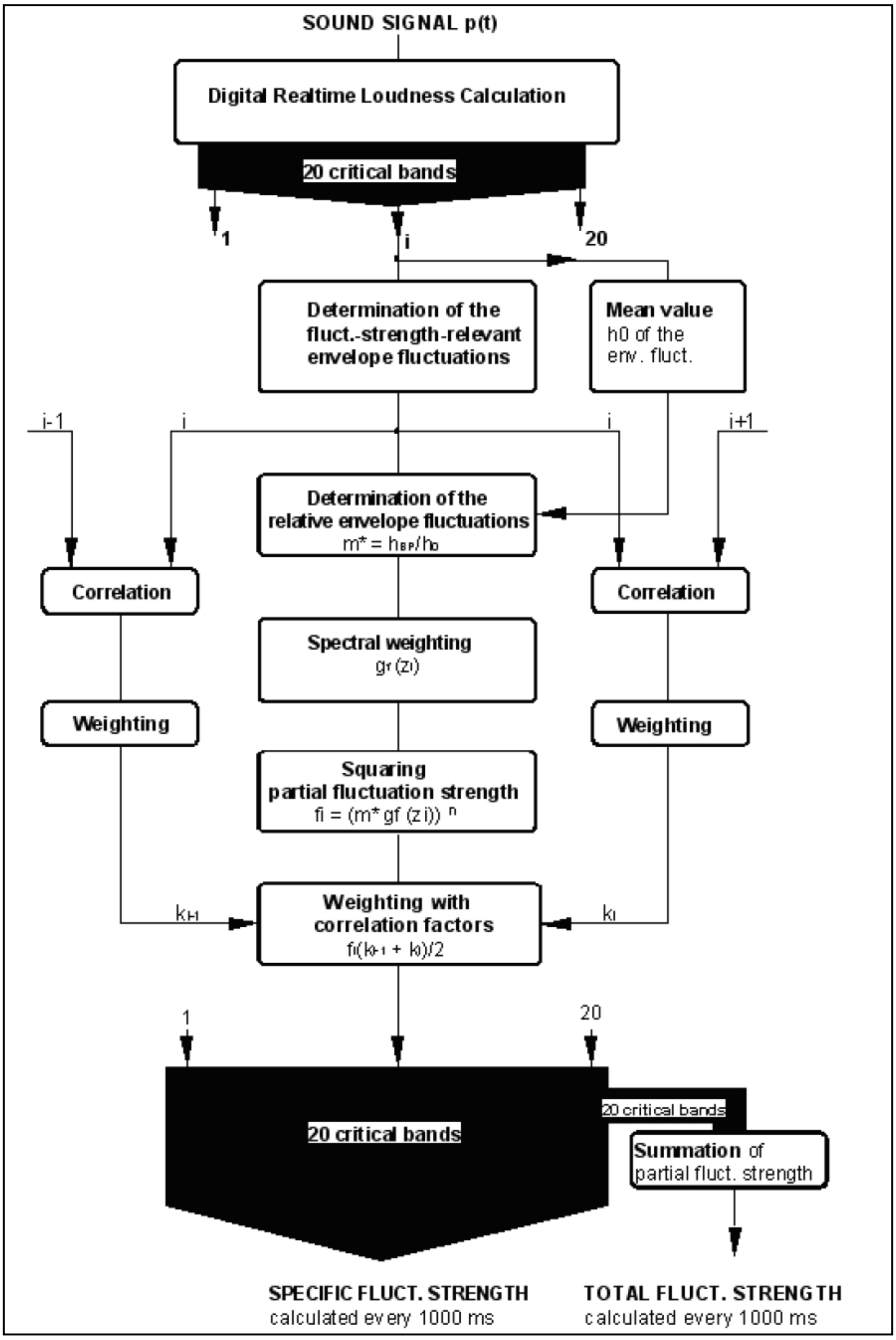
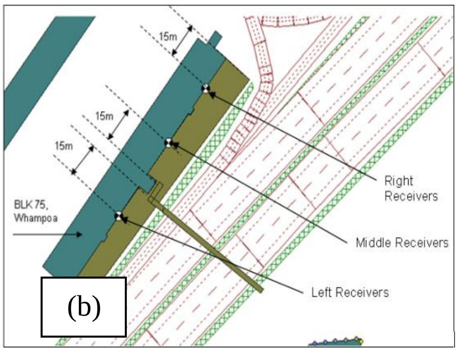


Figure: Computation model for Fluctuation Strength (Source: dBSonic user manual, 2005)

APPENDIX B : NOISE EMISSION AND TRAFFIC FLOW INFORMATION

Building Facade Subjected to Expressway Road Traffic Noise

(a)



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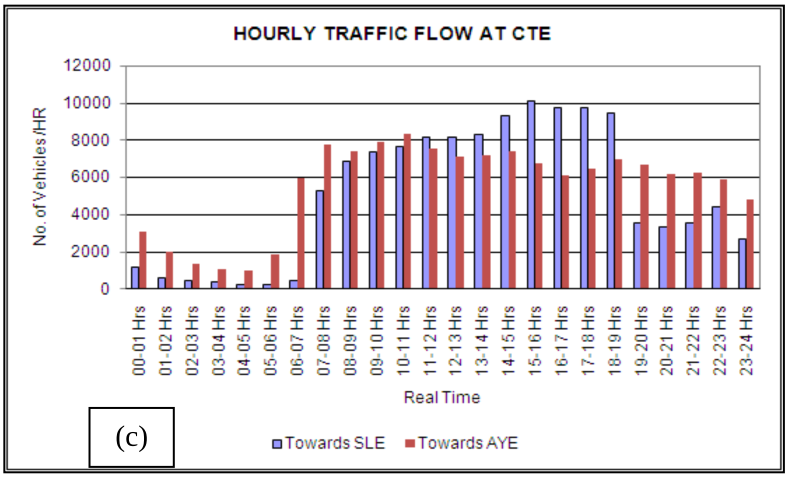

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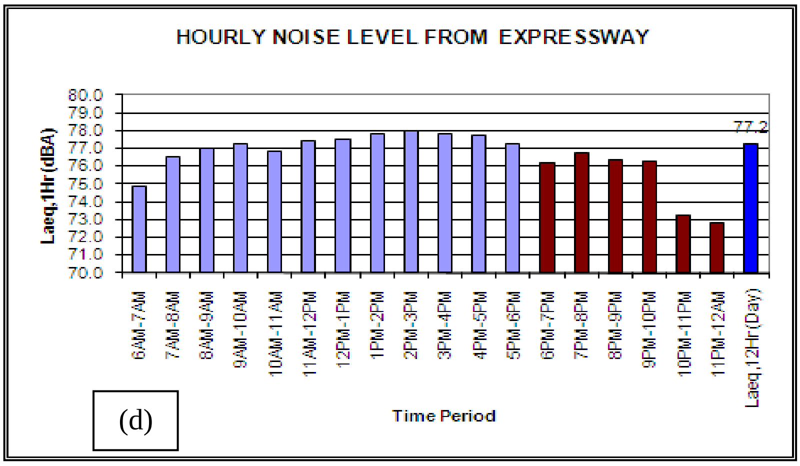
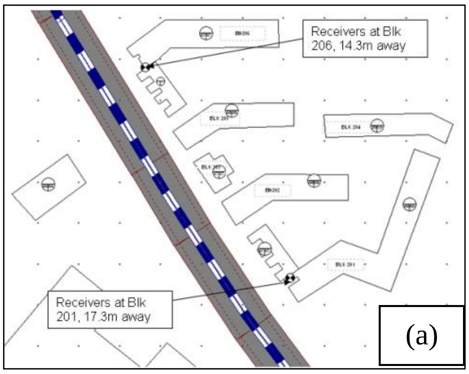
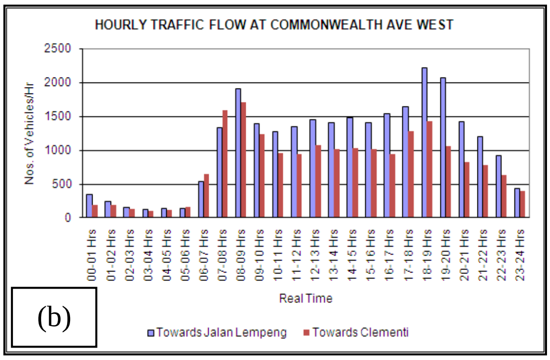


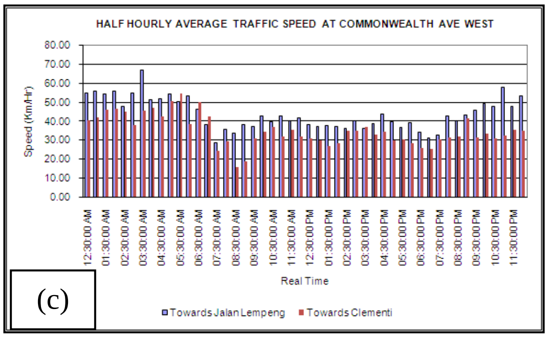
(d)

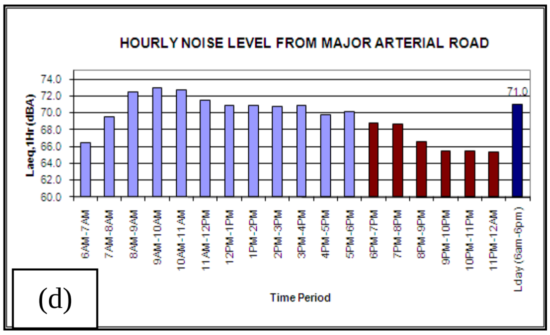
(Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Building Facade Subjected to Major Arterial Road Traffic Noise



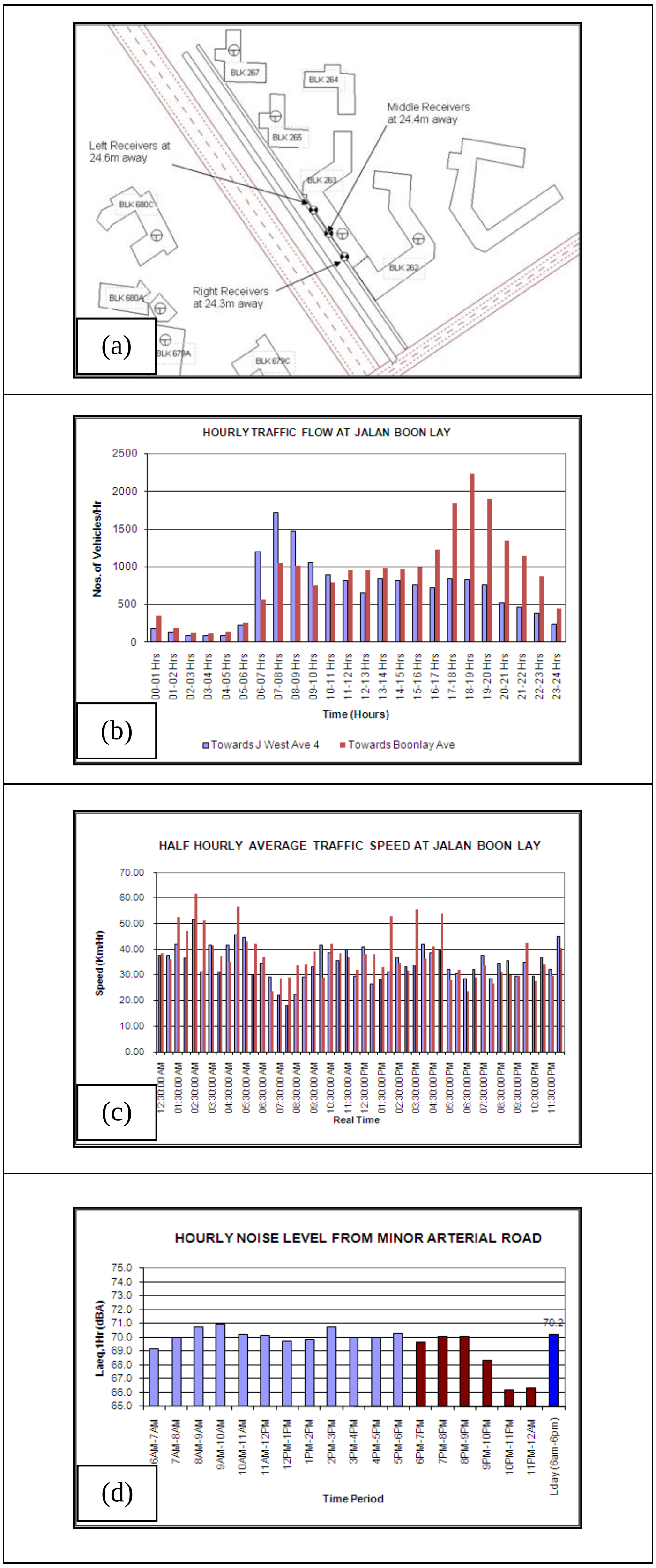






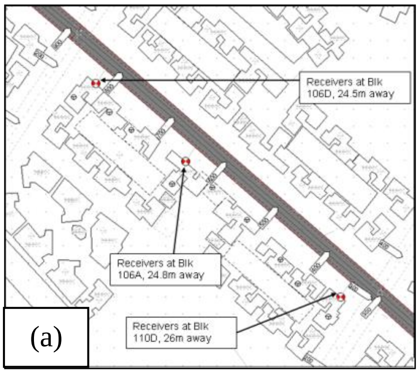
Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Building Facade Subjected to Minor Arterial Road Traffic Noise

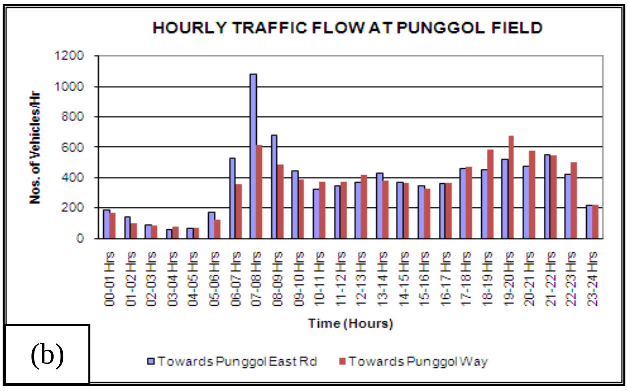


Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Building Facade Subjected to Primary Access Road Traffic Noise



(a)



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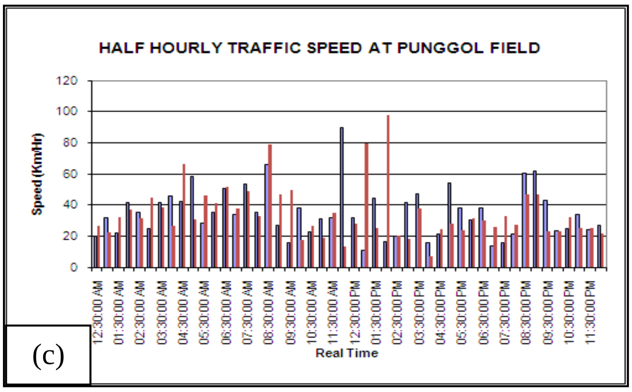

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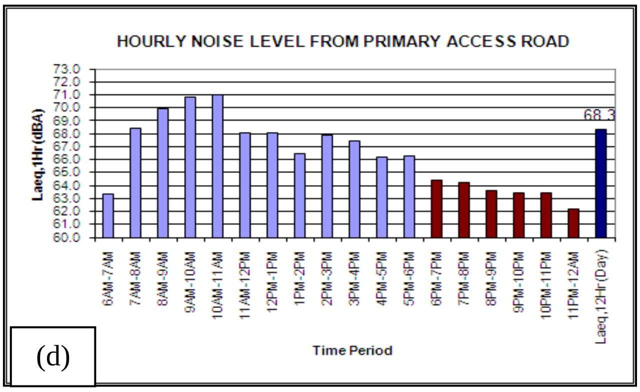
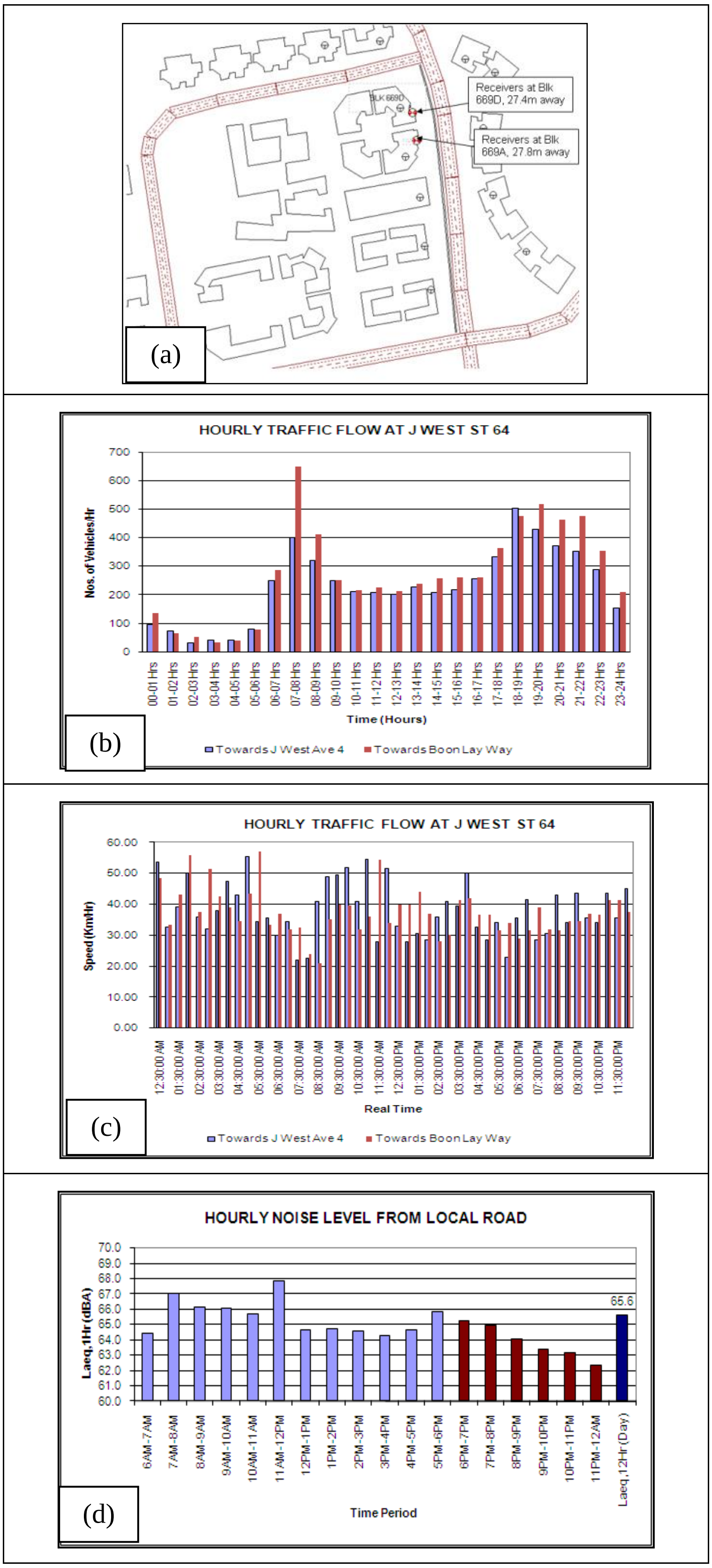


(d)

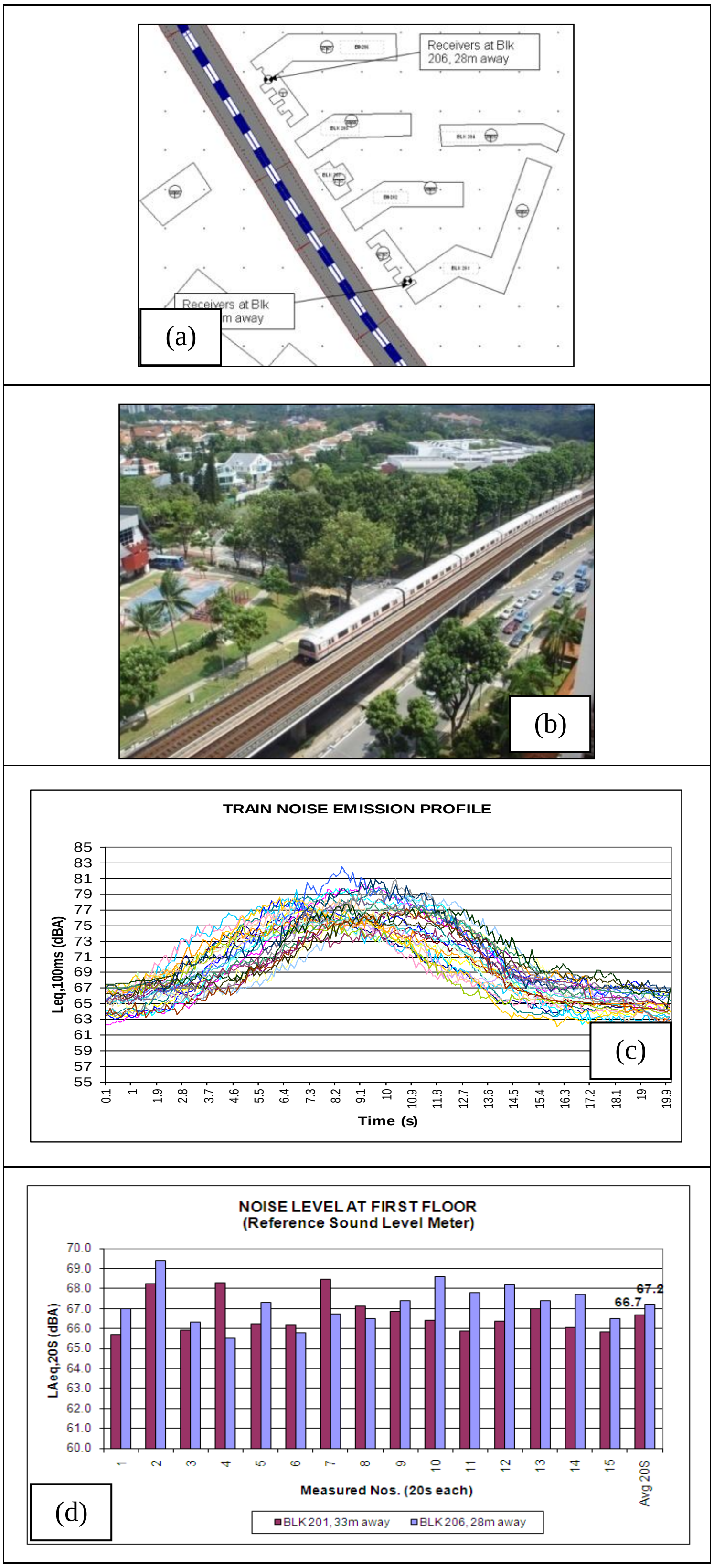
Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Building Facade Subjected to Local Road Traffic Noise



Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

Building Facade Subjected to MRT Train Noise



Source: HDB Report - Development of Environmental Noise Performance Criteria and Evaluation Protocol for the Planning and Design of Residential Developments, 2006-2008, Singapore)

APPENDIX C : APPROVAL BY INSTITUTIONAL REVIEW BOARD (IRB)

NUS
National University of Singapore

Approval Number: NUS 1118

NUS-IRB Reference Code: 10-339

NUS INSTITUTIONAL REVIEW BOARD (IRB) APPROVAL CERTIFICATE

A)

Protocol Title:	Subjective Study on Acoustic Comfort
Principal Investigator:	Mr Sheikh Mahbub Alam (PhD Student)
Department:	Building
Institution:	National University of Singapore
Co-Investigator:	A/Prof Lee Siew Eang
Sponsor (if applicable):	-N.A.-
Research Site:	Dept of Building School of Design & Environment National University of Singapore

B) Documents Reviewed

	Documents	**Document Date**
1.	NUS-IRB Application Form	Version 4, 31 Aug 2010
2.	Research Protocol	Version 4, 31 Aug 2010
3.	Participant Information Sheet	Version 4, 31 Aug 2010
4.	Investigators' Curriculum Vitae	--

C) The above-mentioned documents have been reviewed and have been approved on 1 September 2010. The Board is organized and operated according to GCP guidelines, BAC guidelines and the applicable laws and regulations of Singapore.

D) Please note that:

(1) No subject should be admitted to the trial before MCRC issues the certificate for the trial (applicable for drug trials only).

(2) This approval shall remain valid until the completion of the research or notification of termination of the research, whichever is earlier.

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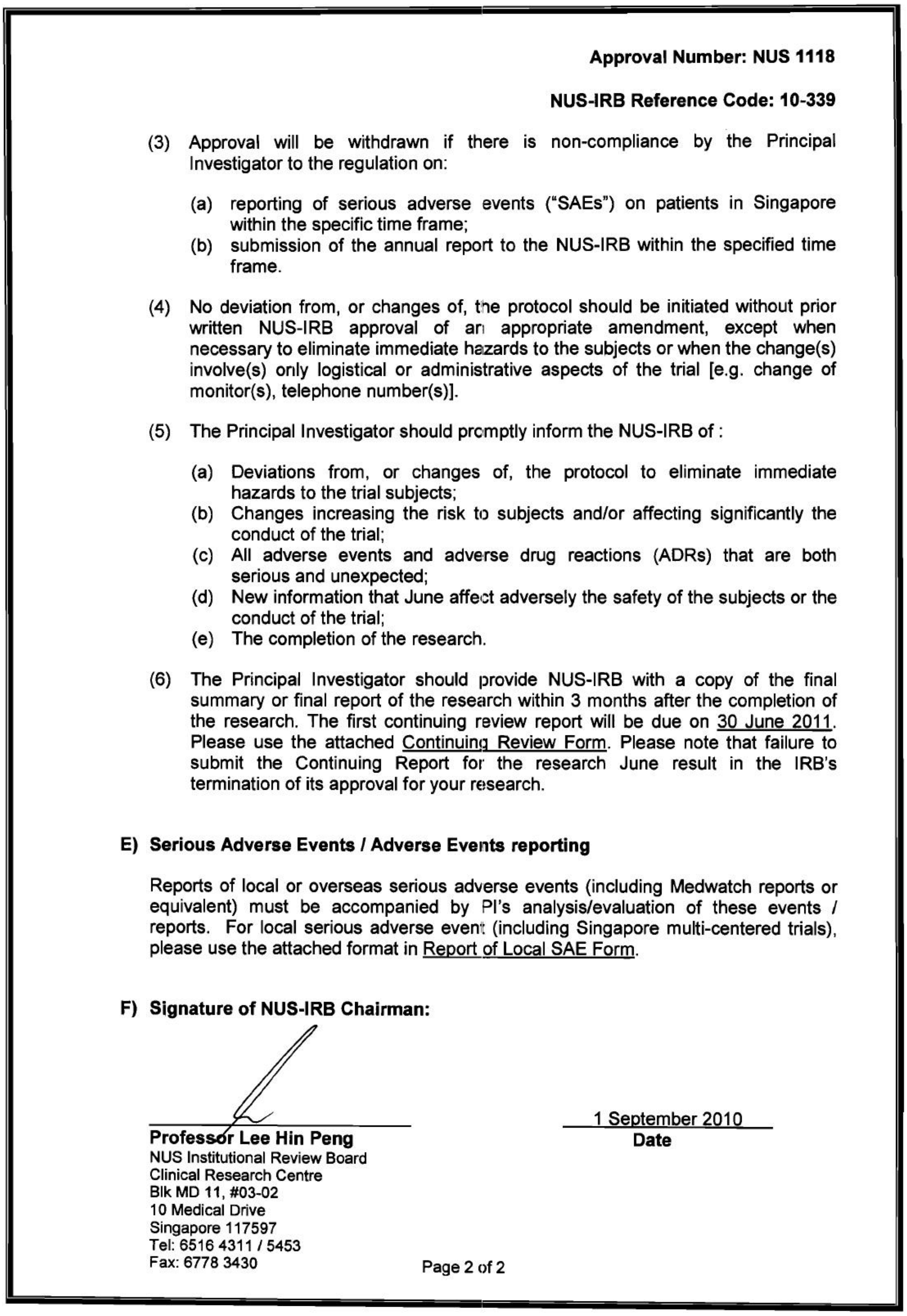

Approval Number: NUS 1118

NUS-IRB Reference Code: 10-339

(3) Approval will be withdrawn if there is non-compliance by the Principal Investigator to the regulation on:

  (a) reporting of serious adverse events ("SAEs") on patients in Singapore within the specific time frame;
  (b) submission of the annual report to the NUS-IRB within the specified time frame.

(4) No deviation from, or changes of, the protocol should be initiated without prior written NUS-IRB approval of an appropriate amendment, except when necessary to eliminate immediate hazards to the subjects or when the change(s) involve(s) only logistical or administrative aspects of the trial [e.g. change of monitor(s), telephone number(s)].

(5) The Principal Investigator should promptly inform the NUS-IRB of :

  (a) Deviations from, or changes of, the protocol to eliminate immediate hazards to the trial subjects;
  (b) Changes increasing the risk to subjects and/or affecting significantly the conduct of the trial;
  (c) All adverse events and adverse drug reactions (ADRs) that are both serious and unexpected;
  (d) New information that June affect adversely the safety of the subjects or the conduct of the trial;
  (e) The completion of the research.

(6) The Principal Investigator should provide NUS-IRB with a copy of the final summary or final report of the research within 3 months after the completion of the research. The first continuing review report will be due on 30 June 2011. Please use the attached Continuing Review Form. Please note that failure to submit the Continuing Report for the research June result in the IRB's termination of its approval for your research.

E) Serious Adverse Events / Adverse Events reporting

Reports of local or overseas serious adverse events (including Medwatch reports or equivalent) must be accompanied by PI's analysis/evaluation of these events / reports. For local serious adverse event (including Singapore multi-centered trials), please use the attached format in Report of Local SAE Form.

F) Signature of NUS-IRB Chairman:

Professor Lee Hin Peng
NUS Institutional Review Board
Clinical Research Centre
Blk MD 11, #03-02
10 Medical Drive
Singapore 117597
Tel: 6516 4311 / 5453
Fax: 6778 3430

1 September 2010
Date

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APPENDIX D : PSYCHOACOUSTICAL TEST DATA

TEST DATA - CATEGORY 1 ROAD (EXPRESSWAY)

Acoustical Indices	Cat-1 Kranji				Cat-1-Tampines			
	+3 dB	Ref	-3 dB	- 6 dB	+3 dB	Ref	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	77.5	74.5	71.5	68.5	81.2	78.2	75.2	72.2
Mean Level, L_{mean} (dB)	73.4	70.4	67.4	64.4	74.3	71.3	68.3	65.3
Maximum Loudness, N_{max} (Sone)	34.4	28.5	23.6	19.5	40.0	33.1	27.4	22.5
Mean Loudness, N_{mean} (Sone)	30.6	25.4	21.0	17.3	33.0	27.3	22.5	18.5
Zwicker Loudness, $N_{ISO532B}$	30.7	25.5	21.0	17.4	33.4	27.6	22.8	18.8
Five Percentile Loudness N_5 (Sone)	33.0	27.4	22.6	18.7	37.2	30.8	25.4	20.9
Maximum Sharpness, S_{max} (Acum)	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2
Mean Sharpness S_{mean} (Acum)	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1
Five Percentile Sharpness, S_5 (Acum)	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2
Maximum Fluctuation Strength, Fmax (Centi Vacil)	5.7	4.9	4.6	4.2	15.4	14.1	13.1	12.0
Mean Fluctuation Strength, Fmean (Centi Vacil)	3.8	3.3	3.1	2.8	10.5	9.6	8.8	8.1
5% Fluctuation Strength, F_5 (Centi Vacil)	5.6	4.8	4.5	4.1	14.8	13.6	12.7	11.7
Maximum Roughness, R_{max} (Centi Asper)	41.7	39.3	37.0	34.9	46.8	44.8	43.1	41.3
Mean Roughness, R_{mean} (Centi Asper)	33.3	31.4	29.5	28.0	34.4	32.7	31.2	29.8
Five Percentile Roughness, R_5 (Centi Asper)	39.4	37.0	34.8	32.8	42.8	40.5	38.5	36.3
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	215.4	215.4	215.4	215.4	256.4	256.4	256.4	256.4
Maximum Tone to Noise Ratio, TNR	-9.6	-9.6	-9.6	-9.6	0.3	0.3	0.3	0.3
The Frequency of the Maximum Prominence, F_{PR} (Hz)	414.5	414.5	414.5	414.5	227.0	227.0	227.0	227.0
Maximum Prominance, PR_{max} (dB)	3.4	3.4	3.4	3.4	6.3	6.3	6.3	6.3
Mean Prominance, PR_{mean} (dB)	3.4	3.4	3.4	3.4	6.3	6.3	6.3	6.3
Global Prominance, PR (dB)	3.4	3.4	3.4	3.4	6.3	6.3	6.3	6.3

TEST DATA - CATEGORY 2 ROAD (MAJOR ARTERIAL)

Acoustical Indices	Cat 2 - Woodlands Ave 2				Cat - 2 - Punggol Rd			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	76.1	73.1	70.1	67.1	76.4	73.4	70.4	67.4
Mean Level, L_{mean} (dB)	69.1	66.1	63.2	60.2	68.8	65.8	62.8	59.8
Maximum Loudness, N_{max} (Sone)	29.0	24.0	19.8	16.3	29.8	24.6	20.3	16.7
Mean Loudness, N_{mean} (Sone)	26.0	21.5	17.7	14.5	24.2	20.0	16.5	13.4
Zwicker Loudness, $N_{ISO532B}$	26.5	21.8	18.0	14.8	24.5	20.3	16.7	13.7
Five Percentile Loudness N_5 (Sone)	28.0	23.1	19.0	15.6	28.3	23.4	19.3	15.8
Maximum Sharpness, S_{max} (Acum)	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Mean Sharpness S_{mean} (Acum)	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2
Five Percentile Sharpness, S_5 (Acum)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Maximum Fluctuation Strength, Fmax (Centi Vacil)	3.3	3.0	2.8	2.7	7.5	6.8	6.3	5.8
Mean Fluctuation Strength, Fmean (Centi Vacil)	2.5	2.3	2.1	1.9	4.7	4.3	4.1	3.8
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	3.2	2.9	2.7	2.6	6.9	6.3	5.9	5.4
Maximum Roughness, R_{max} (Centi Asper)	41.0	38.4	36.3	35.0	37.8	35.6	33.9	32.8
Mean Roughness, R_{mean} (Centi Asper)	32.0	30.1	28.6	27.5	31.0	29.3	27.9	26.9
Five Percentile Roughness, R_5 (Centi Asper)	39.3	36.8	34.7	33.1	35.5	33.5	31.8	30.6
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	159.6	159.6	159.6	159.6	247	247	247	247
Maximum Tone to Noise Ratio, TNR	0.6	0.6	0.6	0.6	7.1	7.1	7.1	7.1
The Frequency of the Maximum Prominence, F_{PR} (Hz)	2616	2616	2616	2616	240	240	240	240
Maximum Prominance, PR_{max} (dB)	1.3	1.3	1.3	1.3	6.1	6.1	6.1	6.1
Mean Prominance, PR_{mean} (dB)	1.3	1.3	1.3	1.3	6.1	6.1	6.1	6.1
Global Prominance, PR (dB)	1.3	1.3	1.3	1.3	6.1	6.1	6.1	6.1

TEST DATA - CATEGORY 3 ROAD (MINOR ARTERIAL)

Acoustical Indices	Cat - 3 - Bedok North Rd				Cat - 3 - Yishun Ave1			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	80.3	77.3	74.3	71.3	74.1	71.1	68.1	65.1
Mean Level, L_{mean} (dB)	68.6	65.6	62.6	59.6	68.0	65.0	62.0	59.0
Maximum Loudness, N_{max} (Sone)	30.8	25.5	21.0	17.3	25.4	21.0	17.3	14.2
Mean Loudness, N_{mean} (Sone)	26.8	22.2	18.3	15.0	23.0	19.0	15.6	12.8
Zwicker Loudness, $N_{ISO532B}$	27.0	22.3	18.4	15.0	23.0	19.0	15.6	12.8
Five Percentile Loudness N_5 (Sone)	29.5	24.4	20.1	16.5	24.4	20.2	16.5	13.6
Maximum Sharpness, S_{max} (Acum)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Mean Sharpness S_{mean} (Acum)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Five Percentile Sharpness, S_5 (Acum)	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3
Maximum Fluctuation Strength, Fmax (Centi Vacil)	4.1	3.9	3.7	3.4	4.6	4.4	4.0	3.8
Mean Fluctuation Strength, Fmean (Centi Vacil)	3.2	3.0	2.8	2.5	2.8	2.7	2.5	2.3
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	4.1	3.8	3.6	3.3	4.4	4.3	3.9	3.6
Maximum Roughness, R_{max} (Centi Asper)	39.2	37.4	35.2	34.0	36.9	34.7	33.3	31.9
Mean Roughness, R_{mean} (Centi Asper)	31.7	30.0	28.5	27.6	31.1	29.4	28.1	27.0
Five Percentile Roughness, R_5 (Centi Asper)	37.1	35.1	33.3	32.2	35.3	33.4	31.9	30.5
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Tone to Noise Ratio, TNR	-18	-18	-18	-18	-18	-18	-18	-18
The Frequency of the Maximum Prominence, F_{PR} (Hz)	612.3	612.3	612.3	612.3	716	716	716	716
Maximum Prominance, PR_{max} (dB)	1.7	1.7	1.7	1.7	1.5	1.5	1.5	1.5
Mean Prominance, PR_{mean} (dB)	1.7	1.7	1.7	1.7	1.5	1.5	1.5	1.5
Global Prominance, PR (dB)	1.7	1.7	1.7	1.7	1.5	1.5	1.5	1.5

TEST DATA - CATEGORY 4 ROAD (PRIMARY ACCESS)

Acoustical Indices	Cat-4-Sembawang Dr				Cat 4 - Clementi Ave 5			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	74.9	71.9	68.9	65.9	75.8	72.8	69.8	66.8
Mean Level, L_{mean} (dB)	66.5	63.5	60.5	57.5	66.0	63.0	60.0	57.0
Maximum Loudness, N_{max} (Sone)	26.4	21.8	18.0	14.8	25.9	21.4	17.7	14.5
Mean Loudness, N_{mean} (Sone)	22.0	18.2	14.9	12.1	22.0	18.2	14.9	12.2
Zwicker Loudness, $N_{ISO532B}$	22.8	18.8	15.4	12.6	22.5	18.5	15.1	12.4
Five Percentile Loudness N_5 (Sone)	25.4	21.0	17.3	14.2	24.9	20.5	16.9	13.9
Maximum Sharpness, S_{max} (Acum)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mean Sharpness S_{mean} (Acum)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Five Percentile Sharpness, S_5 (Acum)	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5
Maximum Fluctuation Strength, Fmax (Centi Vacil)	8.4	8.0	7.6	7.1	7.2	6.8	6.5	6.1
Mean Fluctuation Strength, Fmean (Centi Vacil)	3.5	3.3	3.1	2.9	4.8	4.4	4.2	4.0
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	7.7	7.3	6.9	6.5	7.1	6.6	6.4	6.1
Maximum Roughness, R_{max} (Centi Asper)	36.7	34.7	33.0	31.8	37.8	35.8	34.8	33.3
Mean Roughness, R_{mean} (Centi Asper)	30.8	29.3	28.0	27.0	29.8	28.3	27.5	26.5
Five Percentile Roughness, R_5 (Centi Asper)	35.3	33.5	31.9	30.6	36.3	34.2	32.8	31.6
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Tone to Noise Ratio, TNR	-18	-18	-18	-18	-18	-18	-18	-18
The Frequency of the Maximum Prominence, F_{PR} (Hz)	3027	3027	3027	3027	6061	6061	6061	6061
Maximum Prominance, PR_{max} (dB)	1.3	1.3	1.3	1.3	1.6	1.6	1.6	1.6
Mean Prominance, PR_{mean} (dB)	1.3	1.3	1.3	1.3	1.6	1.6	1.6	1.6
Global Prominance, PR (dB)	1.3	1.3	1.3	1.3	1.6	1.6	1.6	1.6

TEST DATA - CATEGORY 5 ROAD (LOCAL)

Acoustical Indices	Cat - 5 - Tampines St 81				Cat - 5- Jurong West St 65			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	72.4	69.4	66.4	63.4	72.6	69.6	66.6	63.6
Mean Level, L_{mean} (dB)	60.8	57.8	54.8	51.8	61.0	58.0	55.0	52.0
Maximum Loudness, N_{max} (Sone)	19.0	15.6	12.8	10.4	19.4	15.9	13.1	10.6
Mean Loudness, N_{mean} (Sone)	15.6	12.7	10.4	8.4	15.8	12.9	10.5	8.5
Zwicker Loudness, $N_{ISO532B}$	15.8	12.9	10.4	8.4	15.7	12.9	10.4	8.4
Five Percentile Loudness N_5 (Sone)	18.0	14.9	12.1	9.9	17.9	14.6	12.0	9.8
Maximum Sharpness, S_{max} (Acum)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Mean Sharpness S_{mean} (Acum)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Five Percentile Sharpness, S_5 (Acum)	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3
Maximum Fluctuation Strength, Fmax (Centi Vacil)	2.7	2.5	2.3	2.1	2.4	2.3	2.0	1.9
Mean Fluctuation Strength, Fmean (Centi Vacil)	2.1	1.9	1.8	1.6	1.9	1.8	1.6	1.5
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	2.6	2.4	2.3	2.1	2.4	2.2	2.0	1.9
Maximum Roughness, R_{max} (Centi Asper)	35.0	33.2	31.7	30.0	32.9	31.6	30.0	28.1
Mean Roughness, R_{mean} (Centi Asper)	27.5	26.5	25.0	23.6	27.2	26.2	24.9	23.4
Five Percentile Roughness, R_5 (Centi Asper)	31.9	30.5	29.1	27.4	31.1	30.0	28.5	26.8
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Tone to Noise Ratio, TNR	-18	-18	-18	-18	-18	-18	-18	-18
The Frequency of the Maximum Prominence, F_{PR} (Hz)	3102	3102	3102	3102	410	410	410	410
Maximum Prominance, PR_{max} (dB)	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7
Mean Prominance, PR_{mean} (dB)	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7
Global Prominance, PR (dB)	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7

TEST DATA - MRT TRACK 30M AWAY FROM BUILDING

Acoustical Indices	MRT - 30M Holland Rise				MRT - 30M Woodlands Dr 42			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	76.9	73.9	70.9	67.9	76.5	73.5	70.5	67.5
Mean Level, L_{mean} (dB)	72.7	69.7	66.7	63.7	72.3	69.3	66.3	63.3
Maximum Loudness, N_{max} (Sone)	35.8	29.7	24.6	20.3	36.7	30.5	25.2	20.8
Mean Loudness, N_{mean} (Sone)	28.7	23.7	19.6	16.1	30.3	25.1	20.8	17.1
Zwicker Loudness, $N_{ISO532B}$	29.7	24.5	20.3	16.7	32.0	26.5	21.9	18.1
Five Percentile Loudness N_5 (Sone)	33.3	27.7	22.9	18.8	34.8	28.8	23.9	19.7
Maximum Sharpness, S_{max} (Acum)	1.6	1.6	1.6	1.6	1.8	1.8	1.8	1.8
Mean Sharpness S_{mean} (Acum)	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5
Five Percentile Sharpness, S_5 (Acum)	1.5	1.5	1.5	1.5	1.7	1.7	1.7	1.7
Maximum Fluctuation Strength, Fmax (Centi Vacil)	8.9	8.3	7.8	7.6	18.7	17.6	16.7	15.8
Mean Fluctuation Strength, Fmean (Centi Vacil)	6.4	5.9	5.6	5.4	13.3	12.7	12.0	11.3
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	8.6	8.0	7.6	7.3	18.4	17.3	16.3	15.5
Maximum Roughness, R_{max} (Centi Asper)	44.8	41.6	39.2	36.6	47.3	44.0	41.3	39.0
Mean Roughness, R_{mean} (Centi Asper)	35.0	32.8	31.0	29.4	38.2	35.7	33.7	31.9
Five Percentile Roughness, R_5 (Centi Asper)	42.0	39.3	37.0	34.9	44.2	41.5	39.2	37.2
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Tone to Noise Ratio, TNR	-18	-18	-18	-18	-18	-18	-18	-18
The Frequency of the Maximum Prominence, F_{PR} (Hz)	9407	9407	9407	9407	955	955	955	955
Maximum Prominance, PR_{max} (dB)	5.4	5.4	5.4	5.4	3.3	3.3	3.3	3.3
Mean Prominance, PR_{mean} (dB)	5.4	5.4	5.4	5.4	3.3	3.3	3.3	3.3
Global Prominance, PR (dB)	5.4	5.4	5.4	5.4	3.3	3.3	3.3	3.3

TEST DATA - MRT TRACK 40M AWAY FROM BUILDING

Acoustical Indices	MRT - 40M Clementi Ave 2				MRT - 40M Toh Guan Rd			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref 0 dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	73.3	70.3	67.3	64.3	73.8	70.8	67.8	64.8
Mean Level, L_{mean} (dB)	69.4	66.4	63.4	60.4	70.4	67.4	64.4	61.4
Maximum Loudness, N_{max} (Sone)	27.8	22.9	18.9	15.5	31.0	25.7	21.2	17.5
Mean Loudness, N_{mean} (Sone)	23.3	19.3	15.9	12.9	24.4	20.2	16.5	13.6
Zwicker Loudness, $N_{ISO532B}$	23.8	19.7	16.3	13.3	25.1	20.8	17.0	14.1
Five Percentile Loudness N_5 (Sone)	26.5	22.0	18.1	14.9	28.8	23.8	19.6	16.2
Maximum Sharpness, S_{max} (Acum)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Mean Sharpness S_{mean} (Acum)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Five Percentile Sharpness, S_5 (Acum)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Maximum Fluctuation Strength, Fmax (Centi Vacil)	9.6	8.7	8.4	8.4	8.0	7.4	6.9	6.6
Mean Fluctuation Strength, Fmean (Centi Vacil)	6.7	6.1	5.7	5.6	6.9	6.4	6.0	5.8
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	9.3	8.5	8.3	8.2	7.9	7.3	6.8	6.6
Maximum Roughness, R_{max} (Centi Asper)	40.6	38.7	36.5	34.8	50.1	47.2	44.7	42.0
Mean Roughness, R_{mean} (Centi Asper)	33.8	32.0	30.2	28.5	37.0	34.9	32.8	31.0
Five Percentile Roughness, R_5 (Centi Asper)	38.3	36.4	34.6	32.8	44.2	41.3	38.6	36.3
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	12897	12897	12897	12897	4995	4995	4995	4995
Maximum Tone to Noise Ratio, TNR	-5.4	-5.4	-5.4	-5.4	-11.7	-11.7	-11.7	-11.7
The Frequency of the Maximum Prominence, F_{PR} (Hz)	9407	9407	9407	9407	9407	9407	9407	9407
Maximum Prominance, PR_{max} (dB)	8.0	8.0	8.0	8.0	7.3	7.3	7.3	7.3
Mean Prominance, PR_{mean} (dB)	8.0	8.0	8.0	8.0	7.3	7.3	7.3	7.3
Global Prominance, PR (dB)	8.0	8.0	8.0	8.0	7.3	7.3	7.3	7.3

TEST DATA - MRT TRACK 50M AWAY FROM BUILDING

Acoustical Indices	MRT - 50M Bedok Central				MRT - 50M Bedok South Ave 2			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	66.5	63.5	60.5	57.5	67.2	64.2	61.2	58.3
Mean Level, L_{mean} (dB)	21.9	18.0	14.8	12.1	25.5	21.0	17.4	14.3
Maximum Loudness, N_{max} (Sone)	19.8	16.3	13.3	10.9	19.3	15.9	12.9	10.6
Mean Loudness, N_{mean} (Sone)	20.0	16.5	13.5	11.0	19.5	16.2	13.3	10.8
Zwicker Loudness, $N_{ISO532B}$	21.2	17.5	14.4	11.7	22.5	18.6	15.3	12.5
Five Percentile Loudness N_5 (Sone)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Maximum Sharpness, S_{max} (Acum)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Mean Sharpness S_{mean} (Acum)	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5
Five Percentile Sharpness, S_5 (Acum)	5.5	5.3	5.1	4.8	11.7	11.2	10.9	10.6
Maximum Fluctuation Strength, Fmax (Centi Vacil)	4.9	4.7	4.4	4.3	7.7	7.4	7.3	7.0
Mean Fluctuation Strength, Fmean (Centi Vacil)	5.4	5.1	4.9	4.7	11.4	10.9	10.6	10.3
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	37.6	35.7	33.8	32.2	40.8	38.7	36.8	34.9
Maximum Roughness, R_{max} (Centi Asper)	32.2	30.5	28.7	27.2	31.7	30.0	28.4	26.9
Mean Roughness, R_{mean} (Centi Asper)	35.8	33.8	31.8	30.3	37.3	35.3	33.5	31.7
Five Percentile Roughness, R_5 (Centi Asper)	0.0	0.0	0.0	0.0	8452	8452	8452	8452
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	-18	-18	-18	-18	-11.8	-11.8	-11.8	-11.8
Maximum Tone to Noise Ratio, TNR	10394	10394	10394	10394	9612	9612	9612	9612
The Frequency of the Maximum Prominence, F_{PR} (Hz)	6.8	6.8	6.8	6.8	7.1	7.1	7.1	7.1
Maximum Prominance, PR_{max} (dB)	6.8	6.8	6.8	6.8	7.1	7.1	7.1	7.1
Mean Prominance, PR_{mean} (dB)	6.8	6.8	6.8	6.8	7.1	7.1	7.1	7.1

TEST DATA - MRT TRACK 60M AWAY FROM BUILDING

Acoustical Indices	MRT - 60M Choa Chu Kang Crescent				MRT - 60M Yishun St 20			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	68.0	65.0	62.0	59.0	66.6	63.6	60.6	57.6
Mean Level, L_{mean} (dB)	62.7	59.7	56.7	53.7	63.3	60.3	57.3	54.3
Maximum Loudness, N_{max} (Sone)	17.0	13.9	11.4	9.2	17.5	14.4	11.8	9.6
Mean Loudness, N_{mean} (Sone)	15.0	12.2	9.9	8.1	14.0	11.4	9.3	7.5
Zwicker Loudness, $N_{ISO532B}$	14.9	12.1	9.9	8.0	14.5	11.9	9.7	7.8
Five Percentile Loudness N_5 (Sone)	16.1	13.3	10.8	8.7	16.8	13.8	11.2	9.1
Maximum Sharpness, S_{max} (Acum)	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4
Mean Sharpness S_{mean} (Acum)	1.2	1.2	1.2	1.2	1.3	1.2	1.2	1.2
Five Percentile Sharpness, S_5 (Acum)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Maximum Fluctuation Strength, Fmax (Centi Vacil)	6.2	5.8	5.4	5.0	8.0	7.5	7.2	6.8
Mean Fluctuation Strength, Fmean (Centi Vacil)	4.8	4.4	4.2	3.8	6.8	6.4	6.1	5.7
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	6.1	5.7	5.4	4.9	8.0	7.5	7.2	6.8
Maximum Roughness, R_{max} (Centi Asper)	37.7	35.6	33.4	31.3	41.1	38.7	36.2	34.0
Mean Roughness, R_{mean} (Centi Asper)	29.9	28.0	26.3	24.8	31.5	29.5	27.7	25.8
Five Percentile Roughness, R_5 (Centi Asper)	34.9	33.0	30.9	29.0	38.3	36.0	33.7	31.5
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Tone to Noise Ratio, TNR	-18	-18	-18	-18	-18	-18	-18	-18
The Frequency of the Maximum Prominence, F_{PR} (Hz)	5320	5320	5320	5320	10394	10394	10394	10394
Maximum Prominance, PR_{max} (dB)	3.8	3.8	3.8	3.8	6.4	6.4	6.4	6.4
Mean Prominance, PR_{mean} (dB)	3.8	3.8	3.8	3.8	6.4	6.4	6.4	6.4
Mean Level, L_{mean} (dBA)	3.8	3.8	3.8	3.8	6.4	6.4	6.4	6.4

TEST DATA - MRT TRACK 70M AWAY FROM BUILDING

Acoustical Indices	MRT - 70M Jurong East St 21				MRT - 70M Woodlands St 32			
	+3 dB	Ref dB	-3 dB	- 6 dB	+3 dB	Ref dB	-3 dB	- 6 dB
Mean Level, L_{mean} (dBA)	67.0	64.0	61.0	58.0	64.3	61.3	58.3	55.3
Mean Level, L_{mean} (dB)	61.6	58.6	55.6	52.6	59.4	56.4	53.4	50.4
Maximum Loudness, N_{max} (Sone)	15.9	13.1	10.6	8.6	15.1	12.3	10.0	8.1
Mean Loudness, N_{mean} (Sone)	14.0	11.4	9.3	7.5	13.0	10.5	8.5	6.9
Zwicker Loudness, $N_{ISO532B}$	14.2	11.6	9.4	7.6	13.1	10.7	8.7	6.9
Five Percentile Loudness N_5 (Sone)	15.0	12.3	9.9	8.0	14.5	11.8	9.6	7.8
Maximum Sharpness, S_{max} (Acum)	1.3	1.3	1.3	1.3	1.7	1.7	1.7	1.7
Mean Sharpness S_{mean} (Acum)	1.2	1.2	1.2	1.2	1.4	1.4	1.4	1.4
Five Percentile Sharpness, S_5 (Acum)	1.3	1.3	1.3	1.3	1.5	1.5	1.5	1.6
Maximum Fluctuation Strength, Fmax (Centi Vacil)	4.1	3.8	3.5	3.3	13.3	12.9	12.6	12.6
Mean Fluctuation Strength, Fmean (Centi Vacil)	3.6	3.3	3.1	2.9	8.2	7.8	7.7	7.7
Five Percentile Fluctuation Strength, F_5 (Centi Vacil)	4.1	3.8	3.5	3.3	12.8	12.4	12.1	12.1
Maximum Roughness, R_{max} (Centi Asper)	35.6	33.8	31.6	29.3	36.9	34.7	33.1	30.5
Mean Roughness, R_{mean} (Centi Asper)	28.7	27.3	25.7	23.8	28.6	27.2	25.6	23.5
Five Percentile Roughness, R_5 (Centi Asper)	34.1	32.2	30.3	28.2	33.3	31.5	30.0	27.4
Frequency of the Maximum Tone to Noise Ratio (TNR), F_{TNR} (Hz)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum Tone to Noise Ratio, TNR	-18	-18	-18	-18	-18	-18	-18	-18
The Frequency of the Maximum Prominence, F_{PR} (Hz)	9509.8	9509.8	9509.8	9509.8	1003.4	1003.4	1003.4	1003.4
Maximum Prominance, PR_{max} (dB)	6.2	6.2	6.2	6.2	5.2	5.2	5.2	5.2
Mean Prominance, PR_{mean} (dB)	6.2	6.2	6.2	6.2	5.2	5.2	5.2	5.2
Mean Level, L_{mean} (dBA)	6.2	6.2	6.2	6.2	5.2	5.2	5.2	5.2

APPENDIX E : CLUSTER SAMPLED NOISE SURVEY QUESTIONNAIRE

SECTION A: PERSONAL PROFILE

1. **Which category of age group do you belong to?**

☐ < 20 Yrs ☐ 20~30 Yrs ☐ 31~40 Yrs ☐ 41~50 Yrs ☐ 51~60 Yrs ☐ 61~70 Yrs ☐ > 70 Yrs

2. **What is the highest education level you have achieved?**

☐ No formal education ☐ Pre-Primary ☐ Primary ☐ Secondary ☐ Upper Secondary

☐ ITE ☐ Diploma ☐ Degree ☐ Post graduate ☐ Doctorate

3. **How many years have you been living in this apartment?** ________ years

4. **What is the type of apartment you are living in and what is the total number of occupants?**

☐ HDB Apartment ☐ Private Apartment ☐ Landed House

☐ 2 Rooms ☐ Total no. of Occupants: _______ No. of young Children (Pre/Pri Sch): _______

☐ 3 Rooms ☐ Total no.of Occupants: _______ No. of young Children (Pre/Pri Sch): _______

☐ 4 Rooms ☐ Total no. of Occupants: _______ No. of young Children (Pre/Pri Sch): _______

☐ 5 Rooms ☐ Total no.of Occupants: _______ No. of young Children (Pre/Pri Sch): _______

☐ Executive ☐ Total no. of Occupants: _______ No. of young Children (Pre/Pri Sch): _______

5. **Do you generally work in a noisy environment?** ☐ Yes ☐ No ☐ I do not work

6. **How would you rate your sensitivity to noise?**

(1) Not Sensitive (2) A little Sensitive (3) Sensitive (4) Very Sensitive (5) Extremely Sensitive

SECTION B: SUBJECTIVE EVALUATION

1. **How would you rate noise as an important aspect of your living environment?**

1 (Least) 2 3 4 5 (Average) 6 7 8 9 10 (Most)

2. **In general, how would you rate the noise level in your living environment (Surrounding area)?**

(1) Very Quiet (2) Quiet (3) Acceptable (4) Noisy (5) Very Noisy

3. **In general, how would you rate the noise level in your apartment?**

(1) Very Quiet (2) Quiet (3) Acceptable (4) Noisy (5) Very Noisy

4. **In general, what is the extent of comfort with respect to sound/noise in your apartment?**

(1) Very Comfortable (2) Comfortable (3) Neither comfortable nor uncomfortable

(4) Uncomfortable (5) Very Uncomfortable

5. **How do you rate the noise in your apartment made by your neighbours?**

Upstairs: (1) Not at all loud (2) A little loud (3) Loud (4) Very loud (5) Extremely loud

Downstairs: (1) Not at all loud (2) A little loud (3) Loud (4) Very loud (5) Extremely loud

Adjacent right: (1) Not at all loud (2) A little loud (3) Loud (4) Very loud (5) Extremely loud

Adjacent left: (1) Not at all loud (2) A little loud (3) Loud (4) Very loud (5) Extremely loud

6. Which area in your apartment you find noisy?

Upstairs: ☐ Master bedroom ☐ Common bedroom ☐ Living room ☐ Study room ☐ Dining room ☐ All areas ☐ N/A

Downstairs: ☐ Master bedroom ☐ Common bedroom ☐ Living room ☐ Study room ☐ Dining room ☐ All areas ☐ N/A

Adjacent right: ☐ Master bedroom ☐Common bedroom ☐ Living room ☐ Study room ☐ Dining room ☐ All areas ☐ N/A

Adjacent Left: ☐ Master bedroom ☐ Common bedroom ☐ Living room ☐ Study room ☐ Dining room ☐ All areas ☐ N/A

7. What is the time period you find noisy?

Upstairs: ☐ 6am to 12pm ☐ 12pm to 6pm ☐ 6pm to 10pm ☐ 10pm to 6am ☐ whole day ☐ N/A

Downstairs: ☐ 6am to 12pm ☐ 12pm to 6pm ☐ 6pm to 10pm ☐ 10pm to 6am ☐ whole day ☐ N/A

Adjacent right: ☐ 6am to 12pm ☐ 12pm to 6pm ☐ 6pm to 10pm ☐ 10pm to 6am ☐ whole day ☐ N/A

Adjacent Left: ☐ 6am to 12pm ☐ 12pm to 6pm ☐ 6pm to 10pm ☐ 10pm to 6am ☐ whole day ☐ N/A

8. What is the type of noise made by your neighbours?

Upstairs: (1) Neighbours Speech (2) Music related noise (3) Speech from TV/Video
(4) Children Playing noise (5) Furniture dragging (6) Footsteps noise
(7) Dropping objects (8) Renovation (9)Others ___________
(10) Appliance noise (state: washing machine / workout station etc) ________ (11) None

Downstairs: (1) Neighbours Speech (2) Music related noise (3) Speech from TV/Video
(4) Children Playing noise (5) Furniture dragging (6) Footsteps noise
(7) Dropping objects (8) Renovation (9)Others ___________
(10) Appliance noise (state: washing machine / workout station etc) ________ (11) None

Adjacent right: (1) Neighbours Speech (2) Music related noise (3) Speech from TV/Video
(4) Children Playing noise (5) Furniture dragging (6) Footsteps noise
(7) Dropping objects (8) Renovation (9)Others ___________
(10) Appliance noise (state: washing machine / workout station etc) ________ (11) None

Adjacent Left: (1) Neighbours Speech (2) Music related noise (3) Speech from TV/Video
(4) Children Playing noise (5) Furniture dragging (6) Footsteps noise
(7) Dropping objects (8) Renovation (9)Others ___________
(10) Appliance noise (state: washing machine / workout station etc) ________ (11) None

9. What is the nature of the noise made by your neighbours?

Upstairs: ☐ Impulsive ☐ Hi pitched ☐ Low pitched ☐ Muffled

Downstairs: ☐ Impulsive ☐ Hi pitched ☐ Low pitched ☐ Muffled

Adjacent Right: ☐ Impulsive ☐ Hi pitched ☐ Low pitched ☐ Muffled

Adjacent Left: ☐ Impulsive ☐ Hi pitched ☐ Low pitched ☐ Muffled

10. Do you consider this noise as disturbing?

Upstairs: ☐ Yes ☐ No **Adjacent Right:** ☐ Yes ☐ No

Downstairs: ☐ Yes ☐ No **Adjacent Left:** ☐ Yes ☐ No

11. Which of your personal activity is most disturbed by this noise?

Upstairs: ☐ Sleep ☐ Rest ☐ Study ☐ Conversation ☐ Watching TV
☐ Listening to music ☐ Not disturbed at all ☐ Others __________

Downstairs: ☐ Sleep ☐ Rest ☐ Study ☐ Conversation ☐ Watching TV
☐ Listening to music ☐ Not disturbed at all ☐ Others __________

Adjacent Right: ☐ Sleep ☐ Rest ☐ Study ☐ Conversation ☐ Watching TV
☐ Listening to music ☐ Not disturbed at all ☐ Others __________

Adjacent Left: ☐ Sleep ☐ Rest ☐ Study ☐ Conversation ☐ Watching TV
☐ Listening to music ☐ Not disturbed at all ☐ Others __________

12. When you are at home, how disturbing are the following noise in general?

Environmental Noise:

a.	Traffic Noise	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing
b.	MRT Noise	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing
c.	Aircraft Noise	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing
d.	Construction Noise	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing

Community Noise:

a.	Playground	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing
b.	Waste disposal truck	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing
c.	School	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing
d.	Food Centre	(1) Not at all	(2) A little	(3) Disturbing	(4) Very	(5) Extremely disturbing

13. How likely would you choose each of the following action to achieve acoustic comfort when you experience uncomfortable noise condition in your home?

		Always	Very Often	Sometimes	Rarely	Never
a.	Close Window	1	2	3	4	5
b.	Close Door	1	2	3	4	5
c.	Go to another room	1	2	3	4	5
d.	Go out of the apartment	1	2	3	4	5
e.	Ask neighbour to stop noisy activity	1	2	3	4	5
f.	Go to Sleep	1	2	3	4	5
g.	Play Music	1	2	3	4	5
h.	Watch TV/Video	1	2	3	4	5
i.	Complain to Authority	1	2	3	4	5
j.	Feel helpless	1	2	3	4	5

SECTION C: INDOOR BACKGROUND NOISE MEASUREMENT

1. Current noise level (dBA) $L_{Aeq,30sec}$ _____

2. How would you rate the current noise environment?

(1) Very Quiet (2) Quiet (3) Acceptable (4) Noisy (5) Very Noisy

3. **File and Instrument number of measured data: a) Instrument No: __________ b) File: ________________**

SECTION D: SOUND TRANSMISSION LOSS MEASUREMENT

1. **If possible, will you allow our acoustics team to conduct some tests on both the party wall and floor in your apartment/house to measure their performance? It shall take about 2~3 hours. This is purely voluntary.**

   ☐ No ☐ Yes, Please give us your details:

2. **To investigation the disturbance due to neighbourhood noise, will you allow our acoustics team to conduct a noise measurement in your apartment/house to measure the noise? We shall place a noise measuring instrument to measure the noise during the time you feel disturbed. This is purely voluntary.**

   ☐ No ☐ Yes, Please give us your details:

   Name: __________________ Contact Tel No: ______________ Proposed Dates:_____________

SECTION E: ADDITIONAL INFORMATION (NOT TO BE ASKED)

1. **Gender** ☐ Male ☐ Female
2. **What is the address the apartment?**

   Floor No: ___________ Unit No: ____________ Street : ____________
3. **What is the total number of floors in the apartment?** ___________
4. **What is the major source of noise affecting the apartment?**

   ☐ ROAD ☐ MRT
5. **If the major noise source is road, what is the category of the road?**

   ☐ Expressway (Cat 1) ☐ Major Arterial Road (Cat2) ☐ Minor Arterial Road (Cat 3)

   ☐ Primary Access Road(Cat 4) ☐ Local Road (Cat 5)
6. **What is the approximate distance of the building from major noise source?**

   ☐ Road (from nearside road curb to building): _________ **m**

   ☐ MRT (from centre of nearside track to building) _________ **m**
7. **Date and time of the survey: Date**: _________________ Time: __________________
8. **How is the weather condition during the survey:** ☐ Dry ☐ Wet ☐ Windy ☐ Calm
9. **Background Noise Measurement outside the apartment:**

   $L_{Aeq,30sec}$ _____

   a) Instrument No: __________ b) File: ________________

Interview Conducted By: _______________

APPENDIX F : CHARTS FOR MULTIDIMENSIONAL EVALUATION

ROAD TRAFFIC NOISE

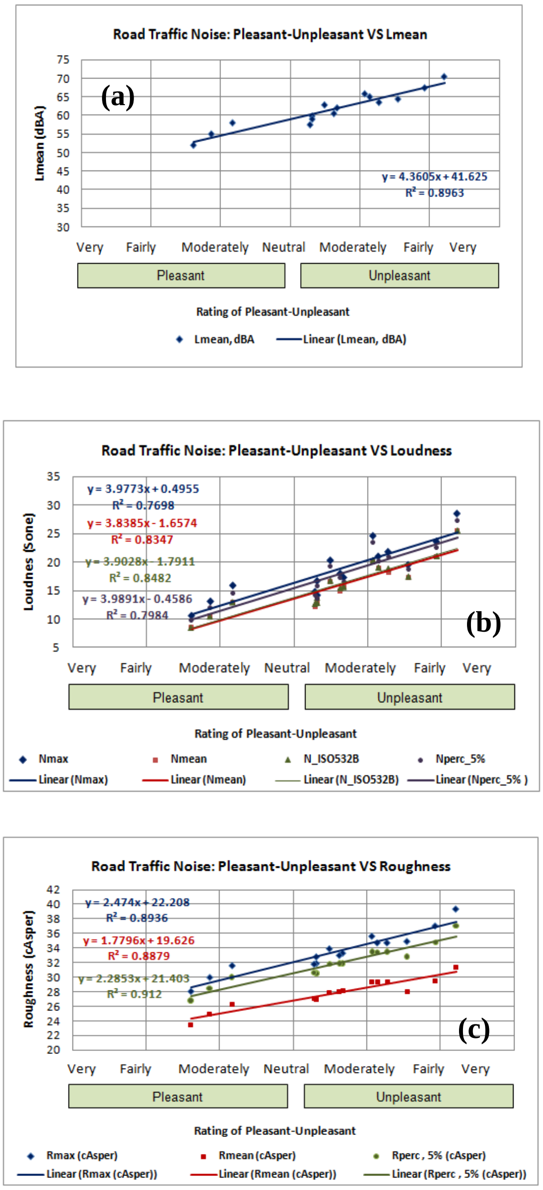

Figure: Relationships between pleasant-unpleasant and Lmean, Loudness and Roughness

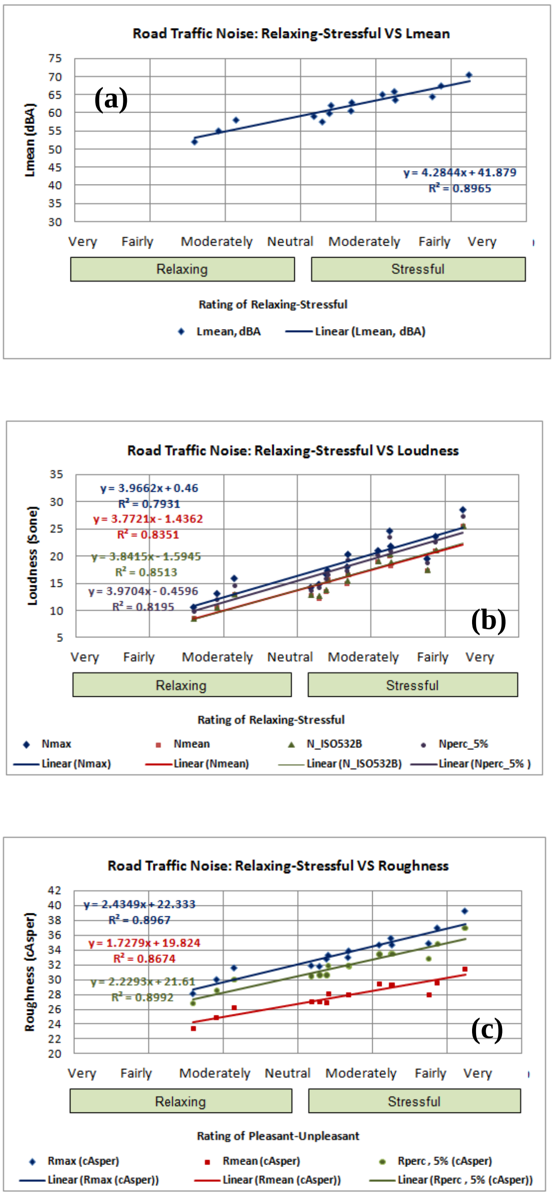

Figure: Relationships between relaxing-stressful and Lmean, Loudness and Roughness

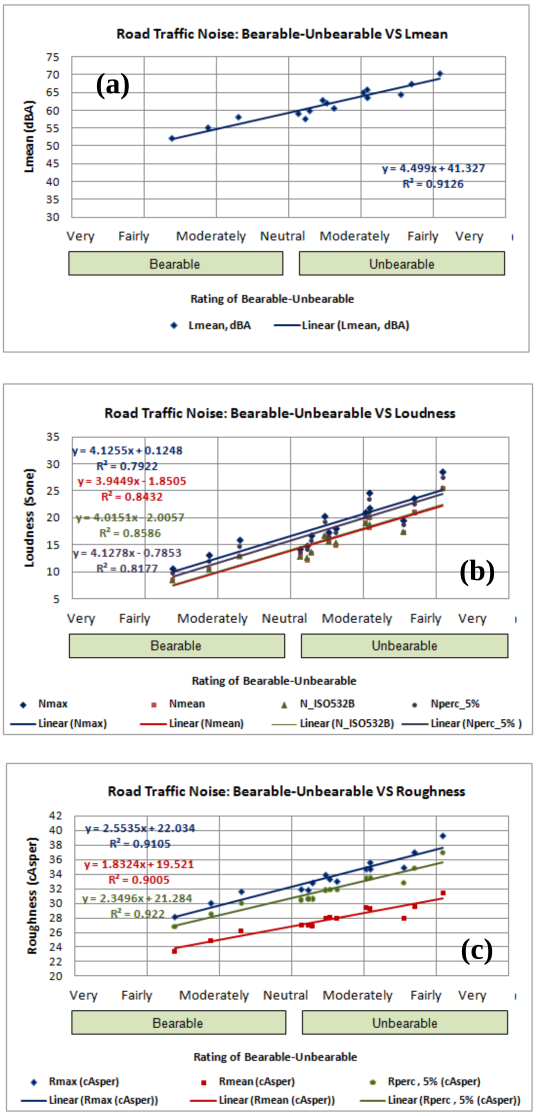

Figure: Relationships between bearable-unbearable and Lmean, Loudness and Roughness

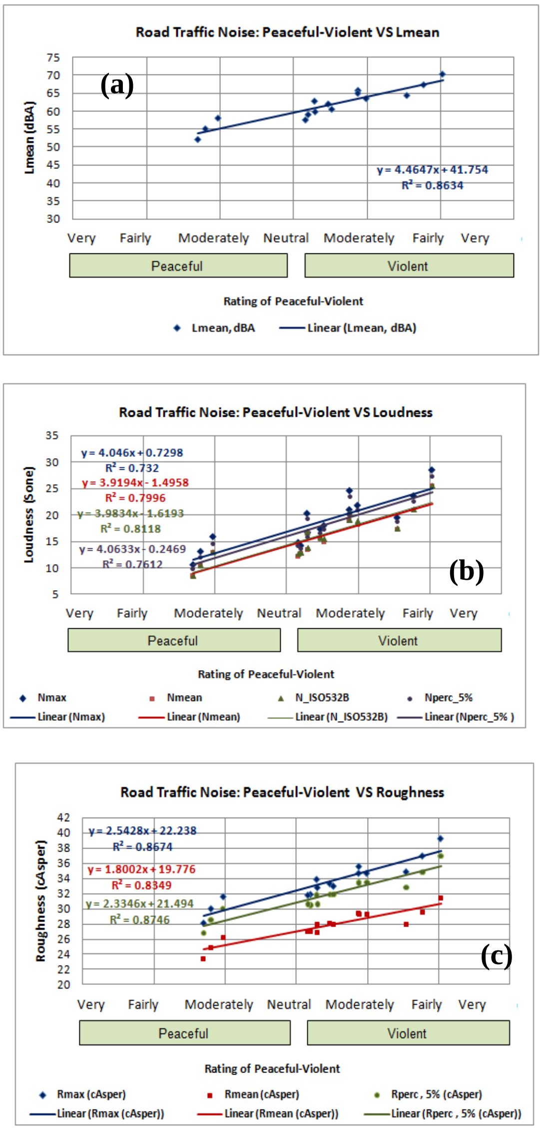

Figure: Relationships between peaceful-violent and Lmean, Loudness and Roughness

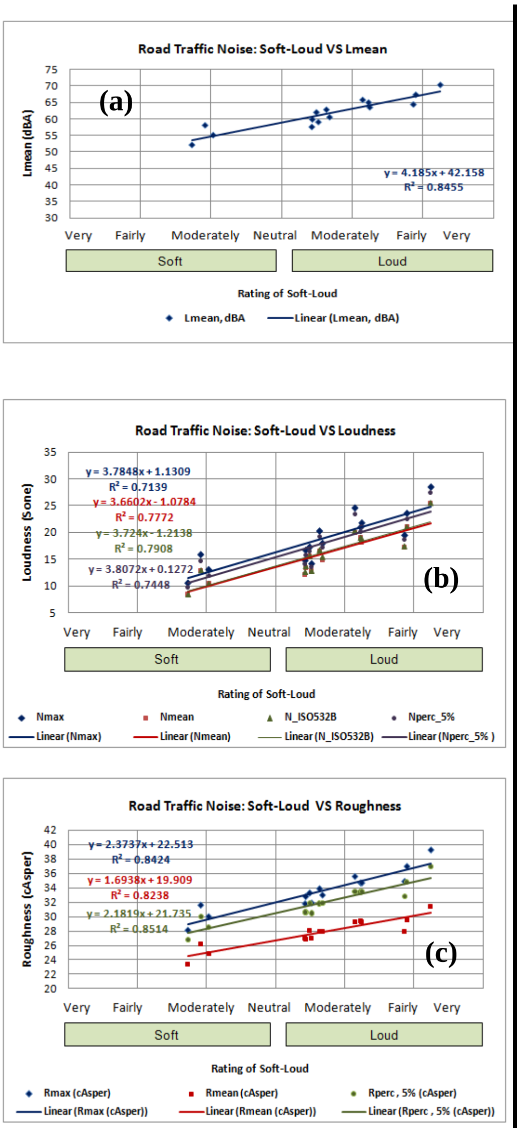

Figure: Relationships between soft-loud and Lmean, Loudness and Roughness

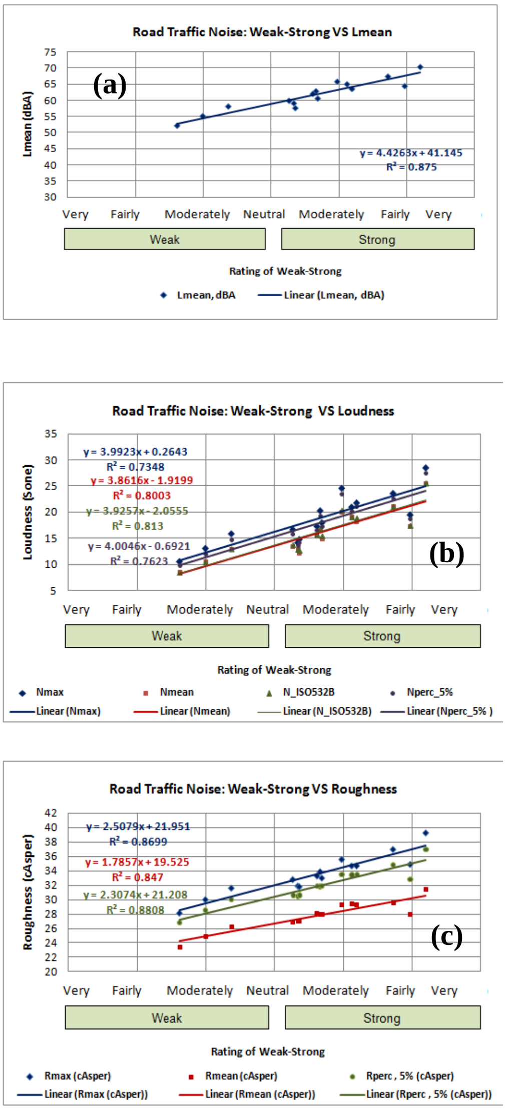

Figure: Relationships between weak-strong and Lmean, Loudness and Roughness

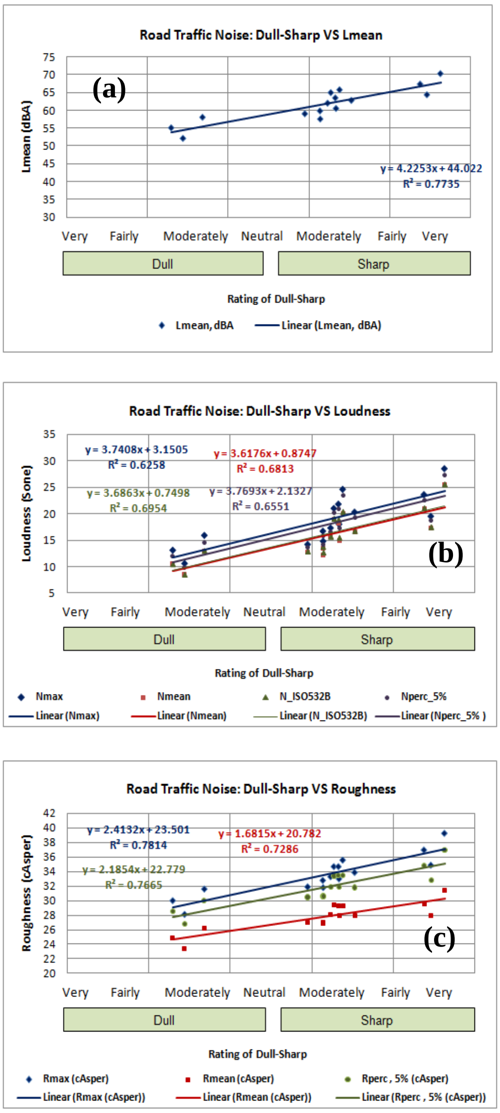

Figure: Relationships between dull-sharp and Lmean, Loudness and Roughness

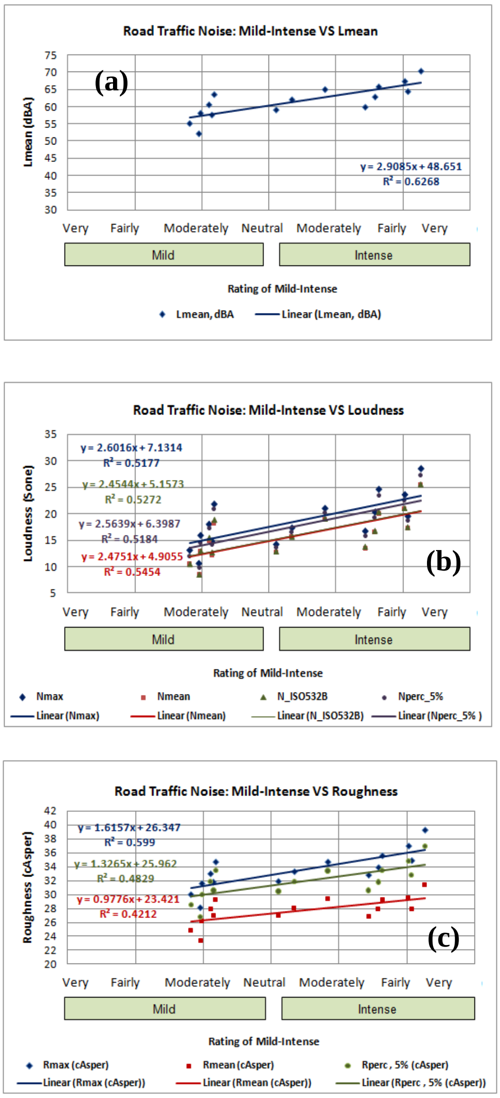

Figure: Relationships between mild-intense and Lmean, Loudness and Roughness

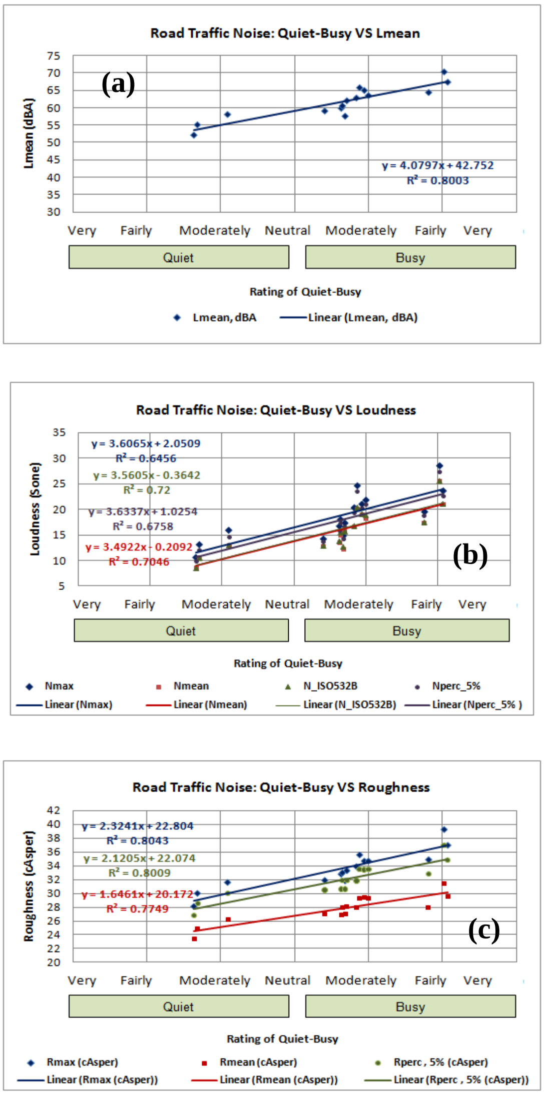

Figure: Relationships between quiet-busy and Lmean, Loudness and Roughness

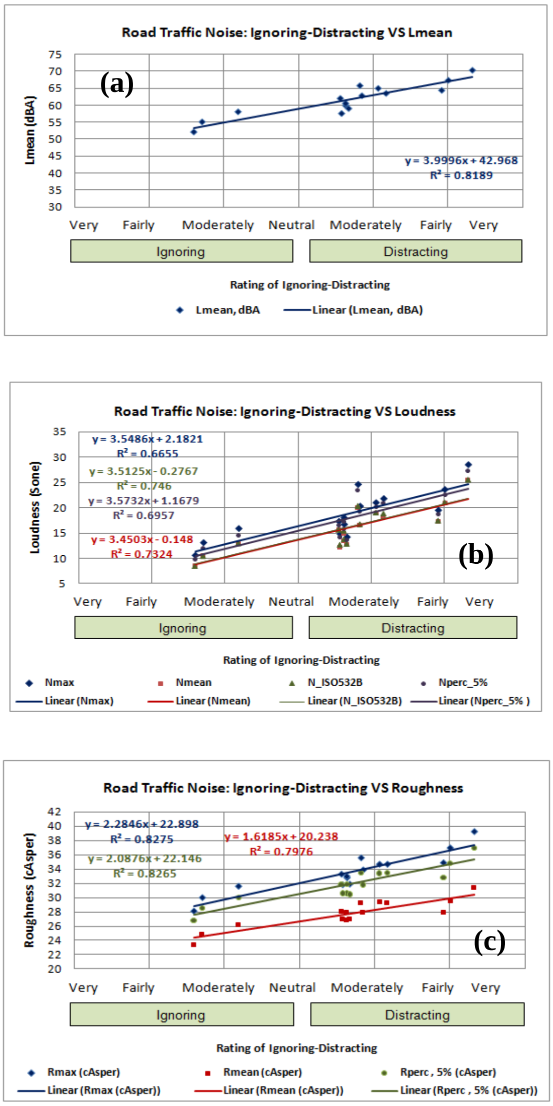

Figure: Relationships between ignoring-distracting and Lmean, Loudness and Roughness

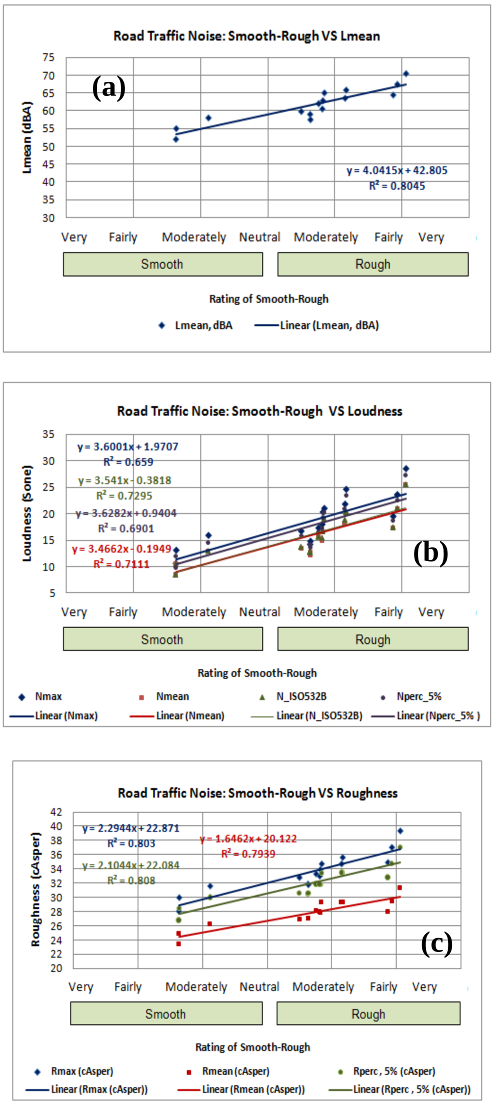

Figure: Relationships between smooth-rough and Lmean, Loudness and Roughness

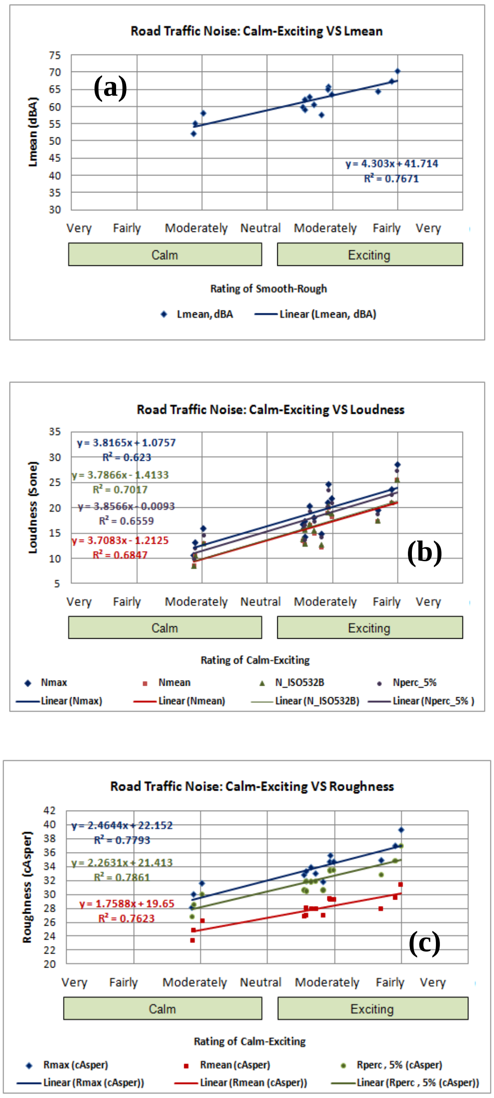

Figure: Relationships between calm-exciting and Lmean, Loudness and Roughness

MRT TRAIN NOISE

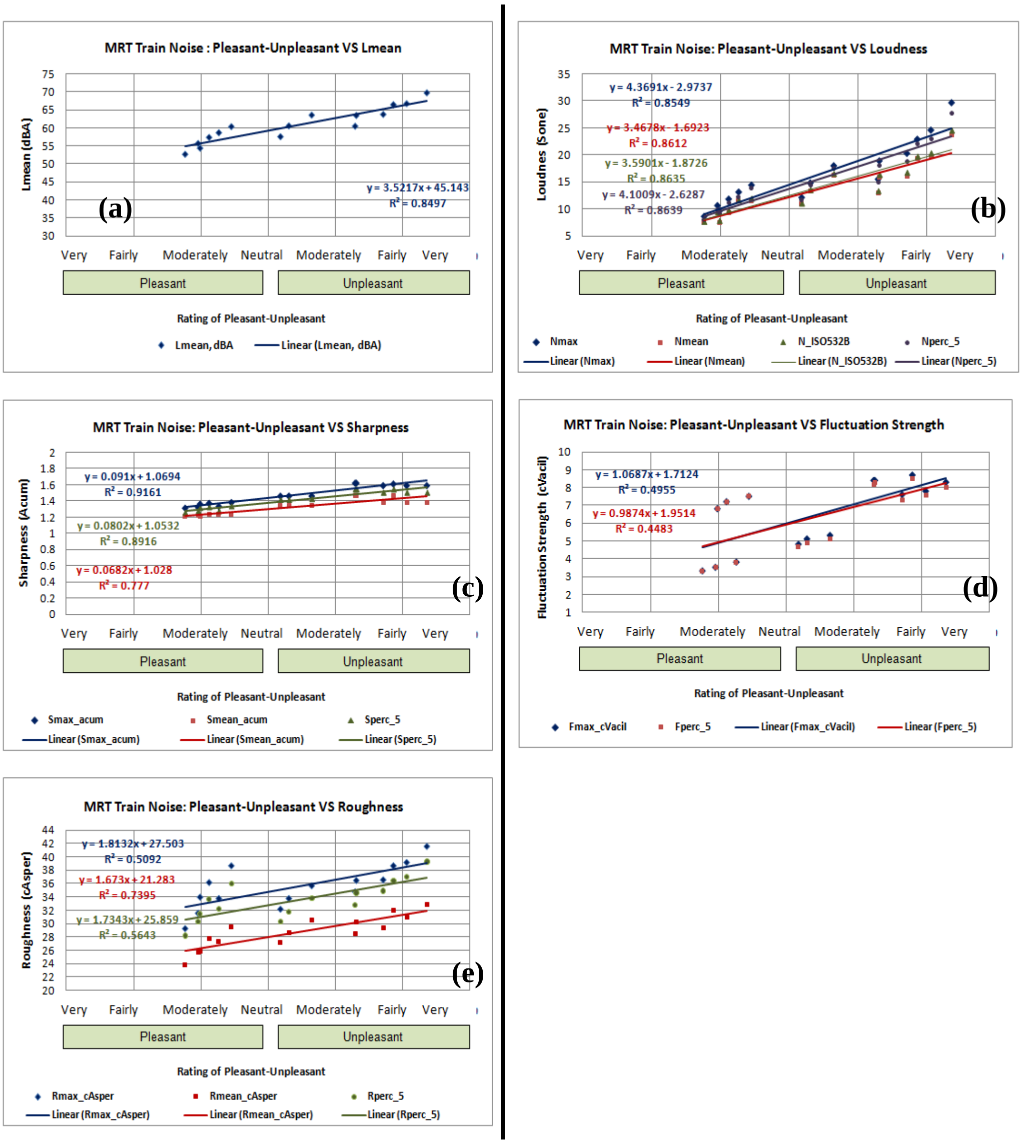

Figure : Relationships between pleasant-unpleasant and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

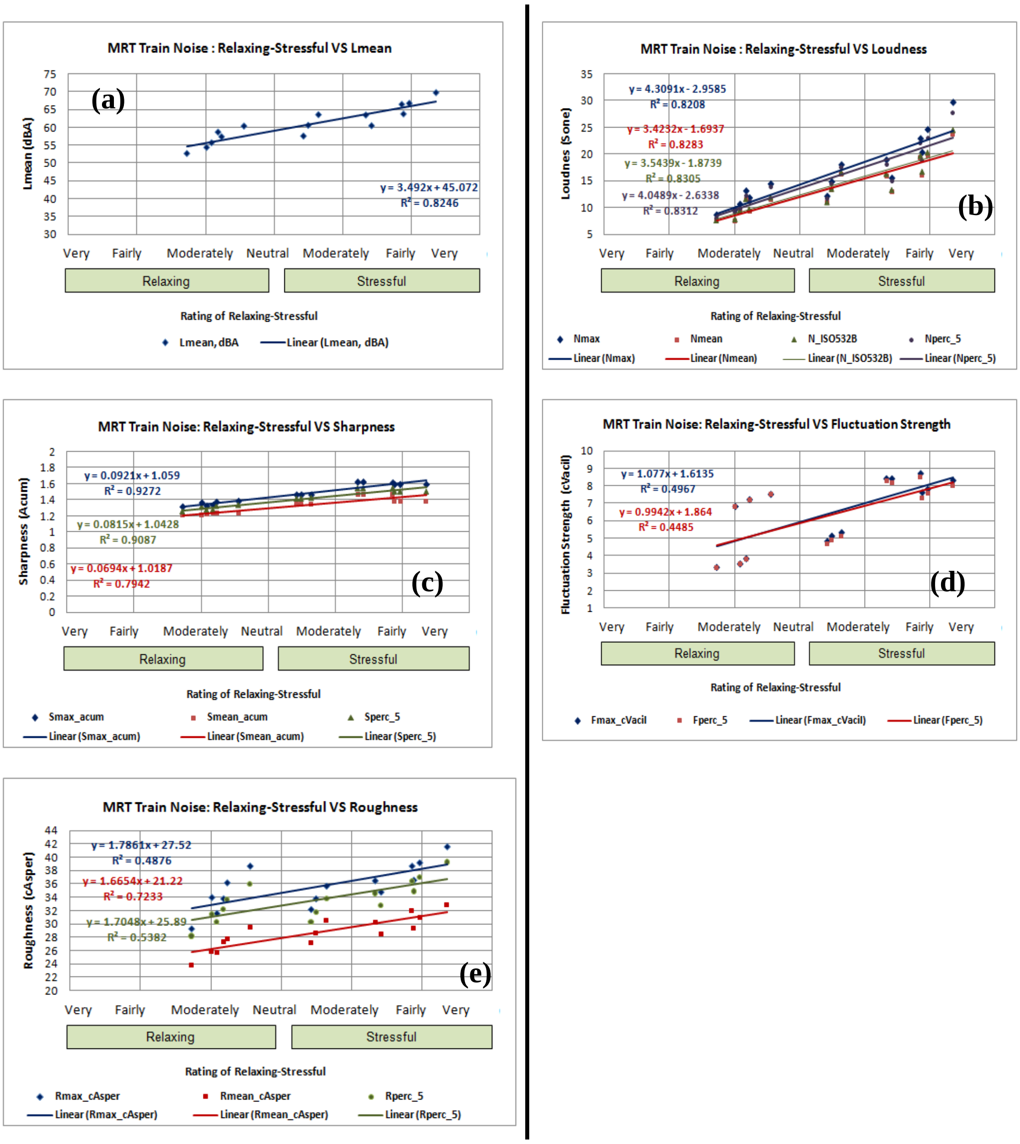

Figure : Relationships between relaxing-stressful and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

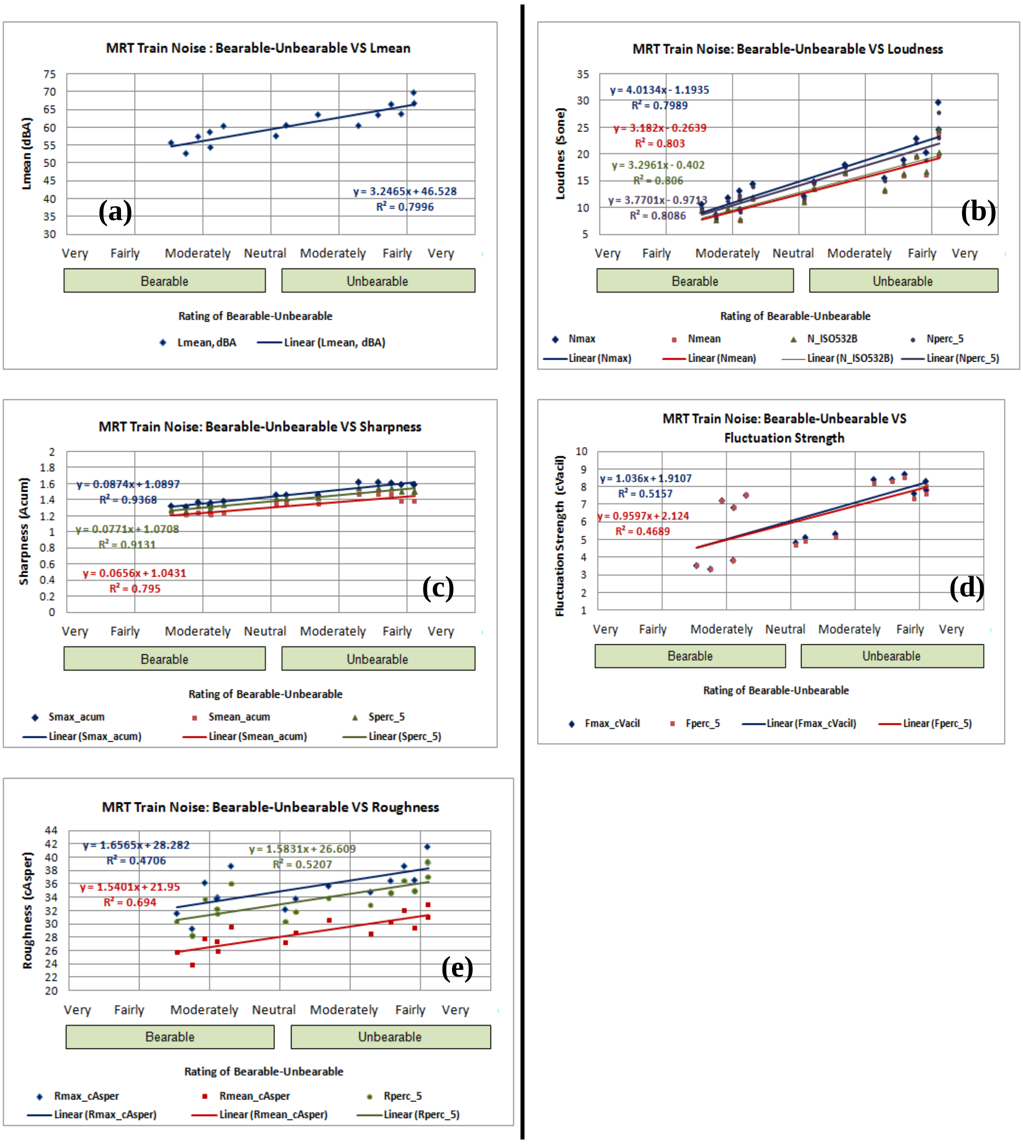

Figure : Relationships between bearable-unbearable and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

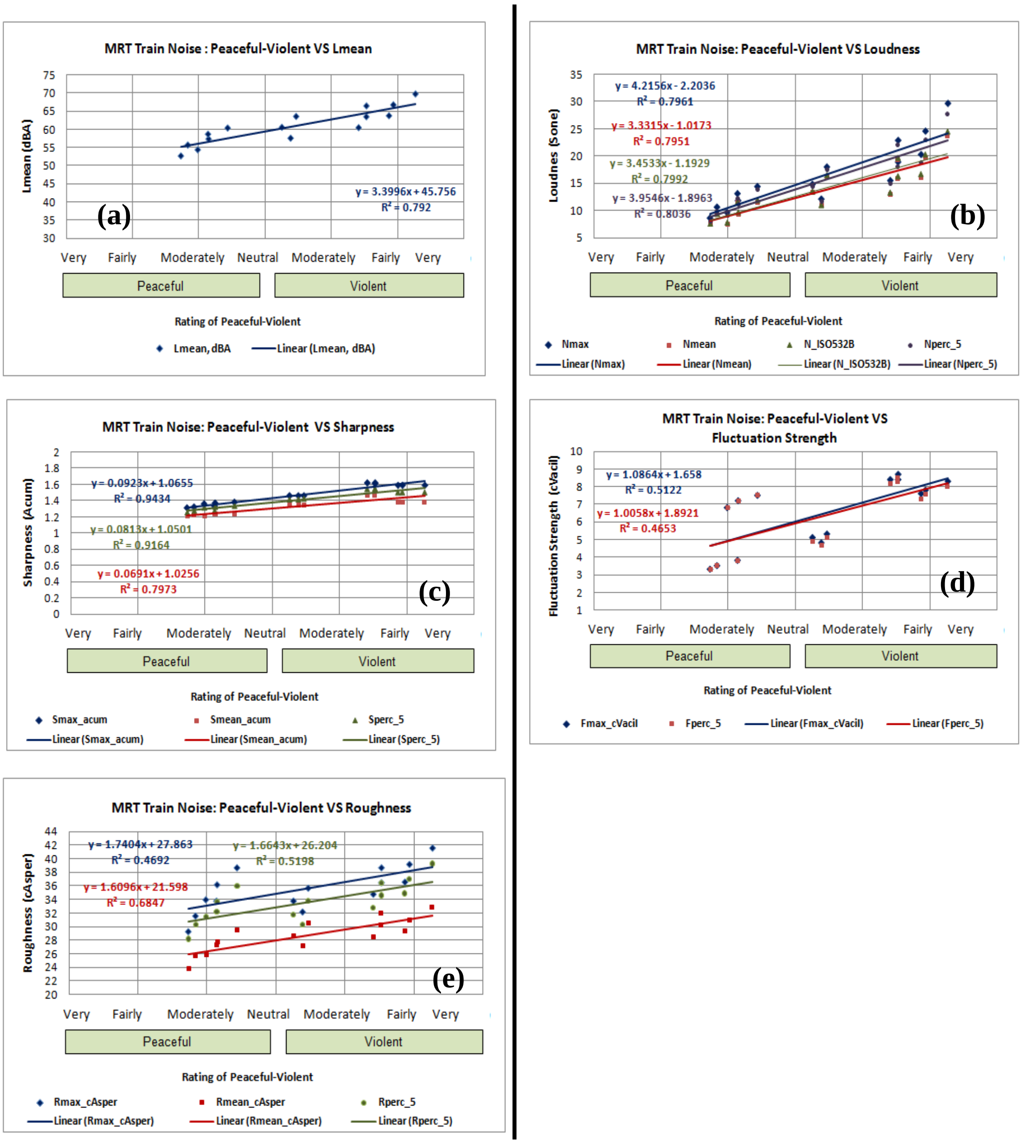

Figure : Relationships between peaceful-violent and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

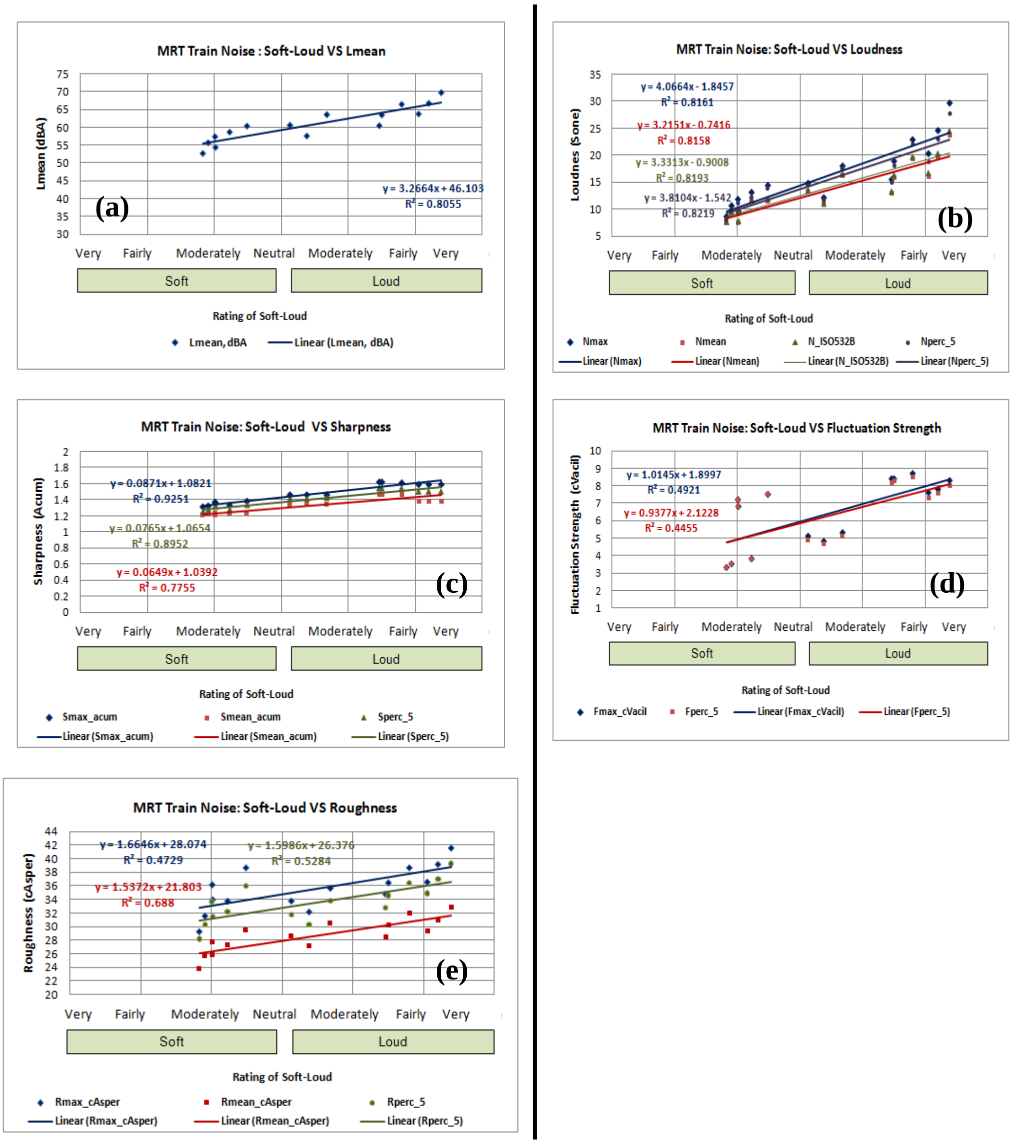

Figure : Relationships between soft-loud and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

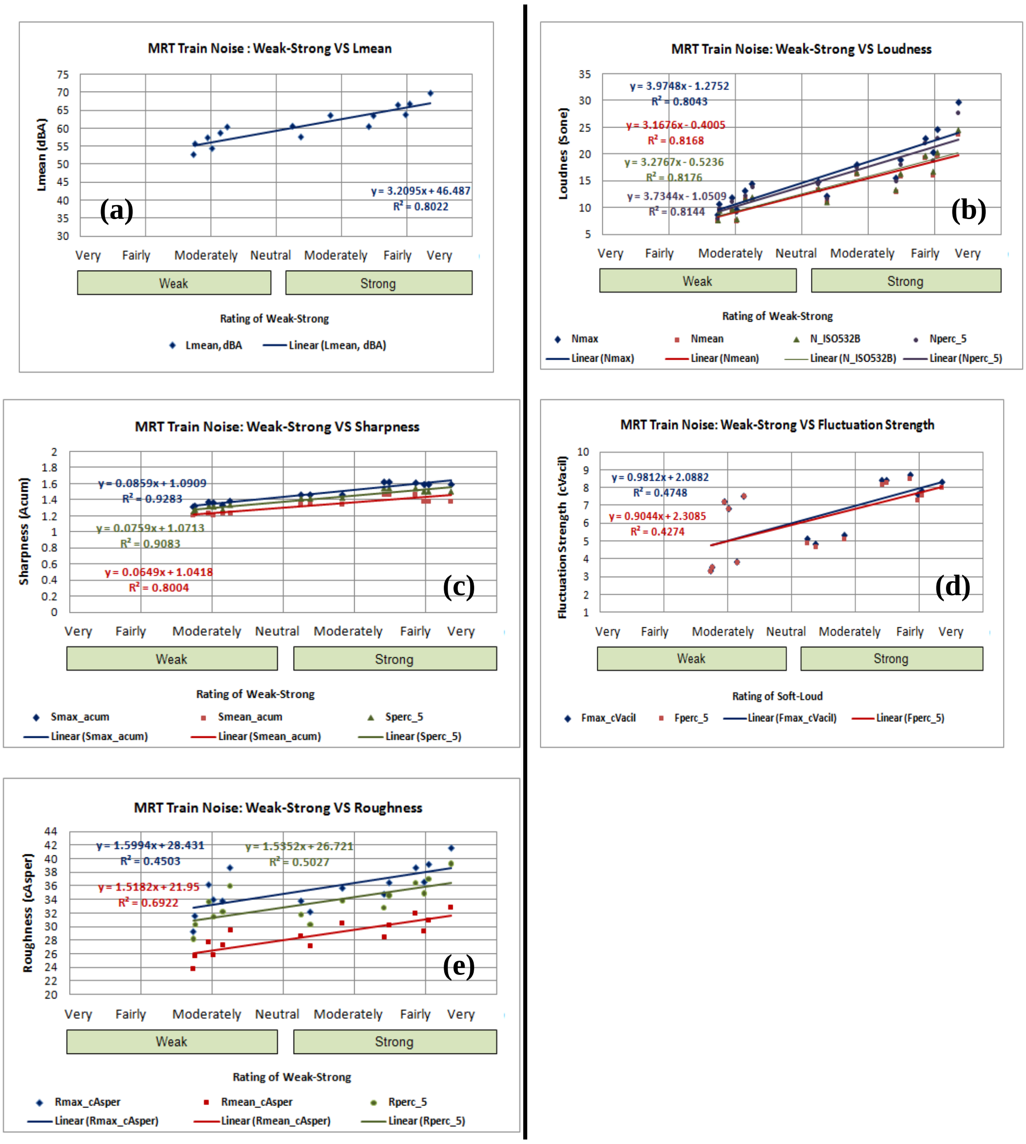

Figure : Relationships between weak-strong and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

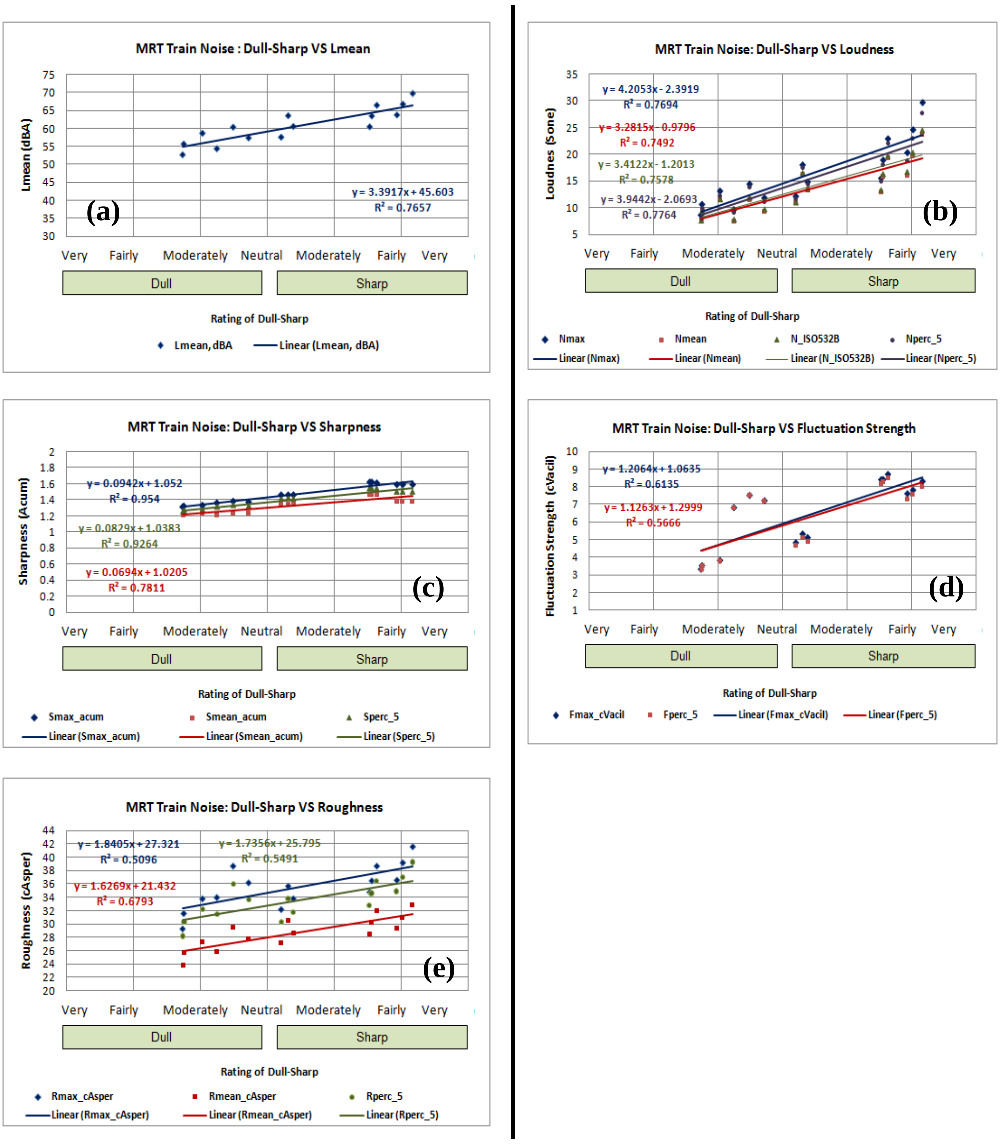

Figure : Relationships between dull-sharp and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

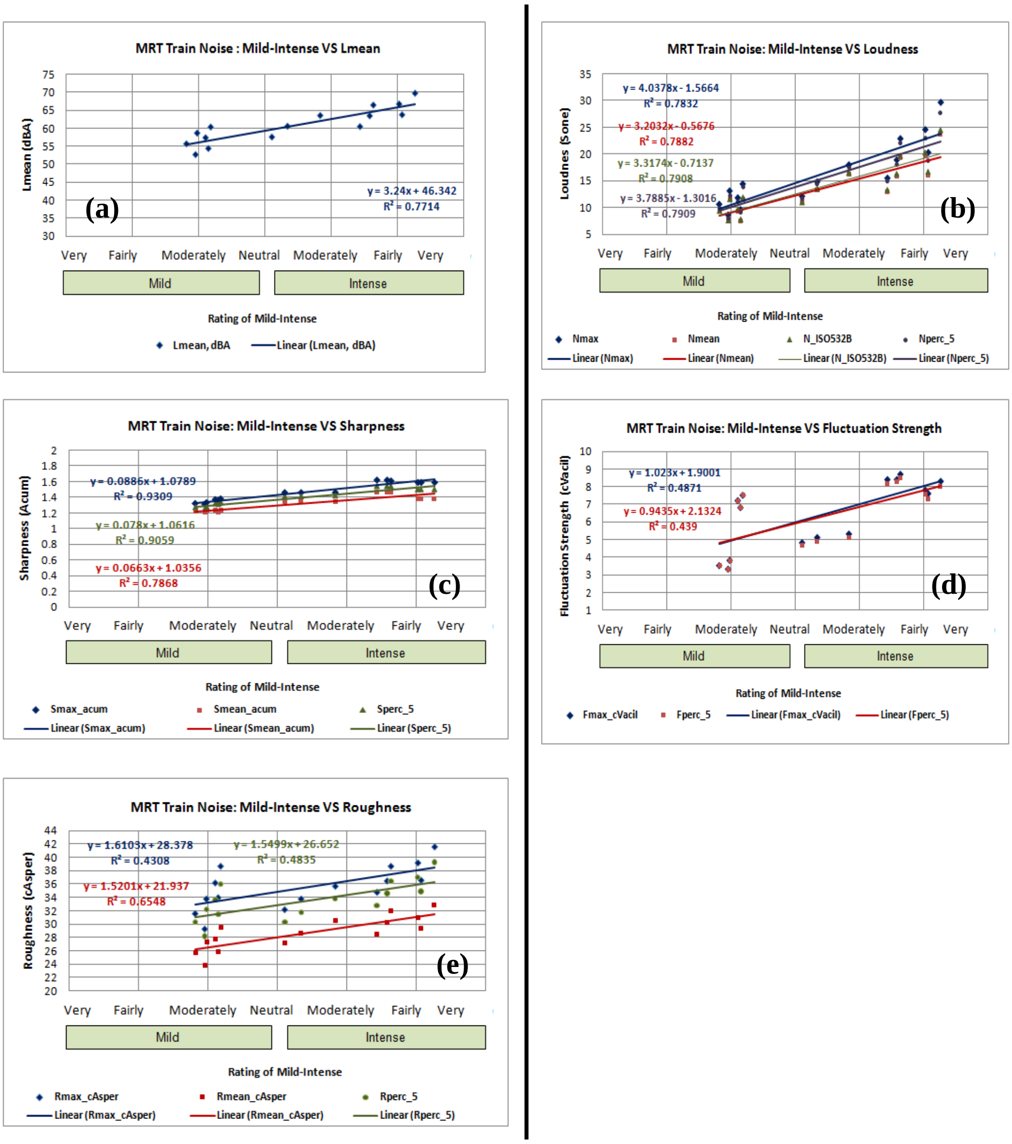

Figure : Relationships between mild-intense and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

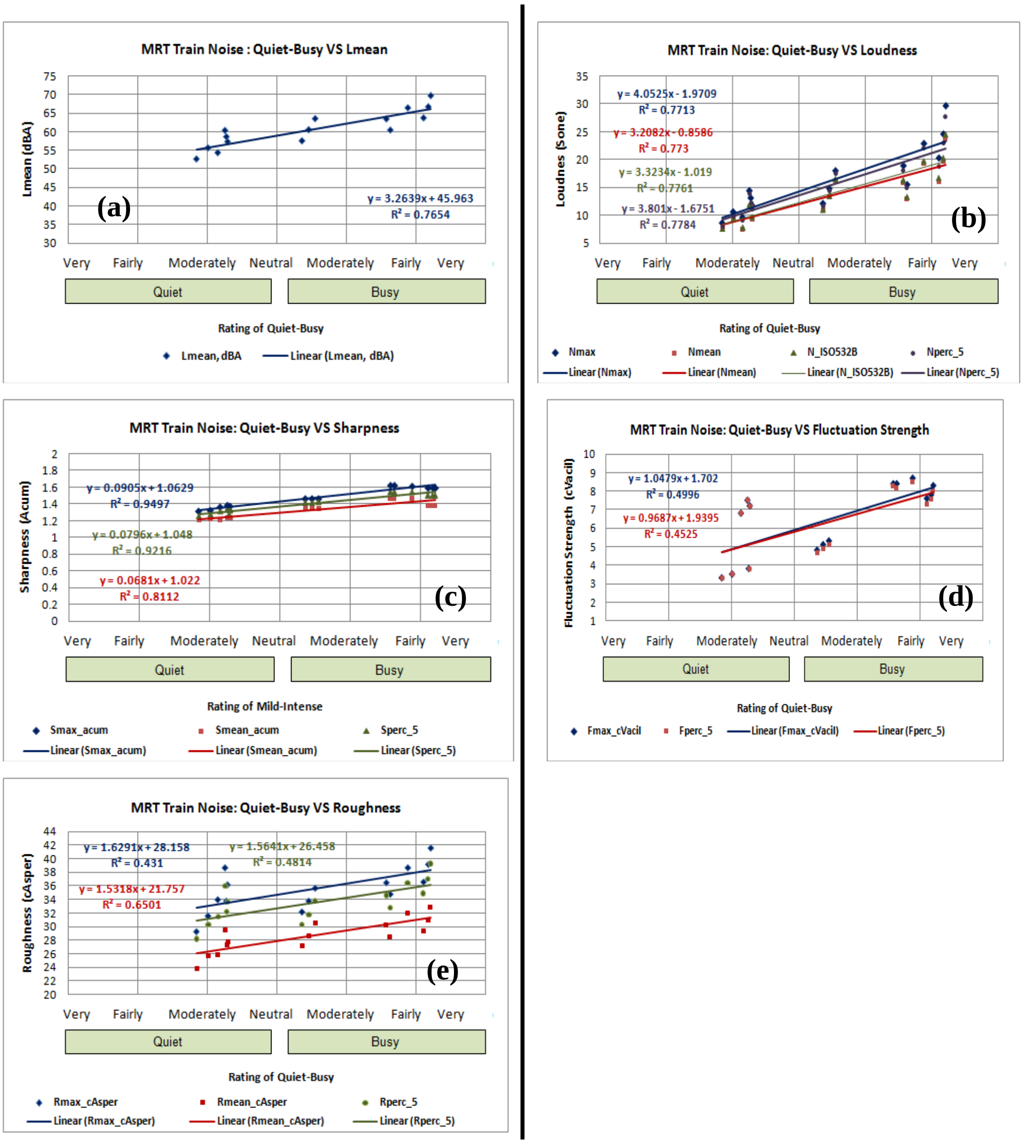

Figure : Relationships between quiet-busy and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

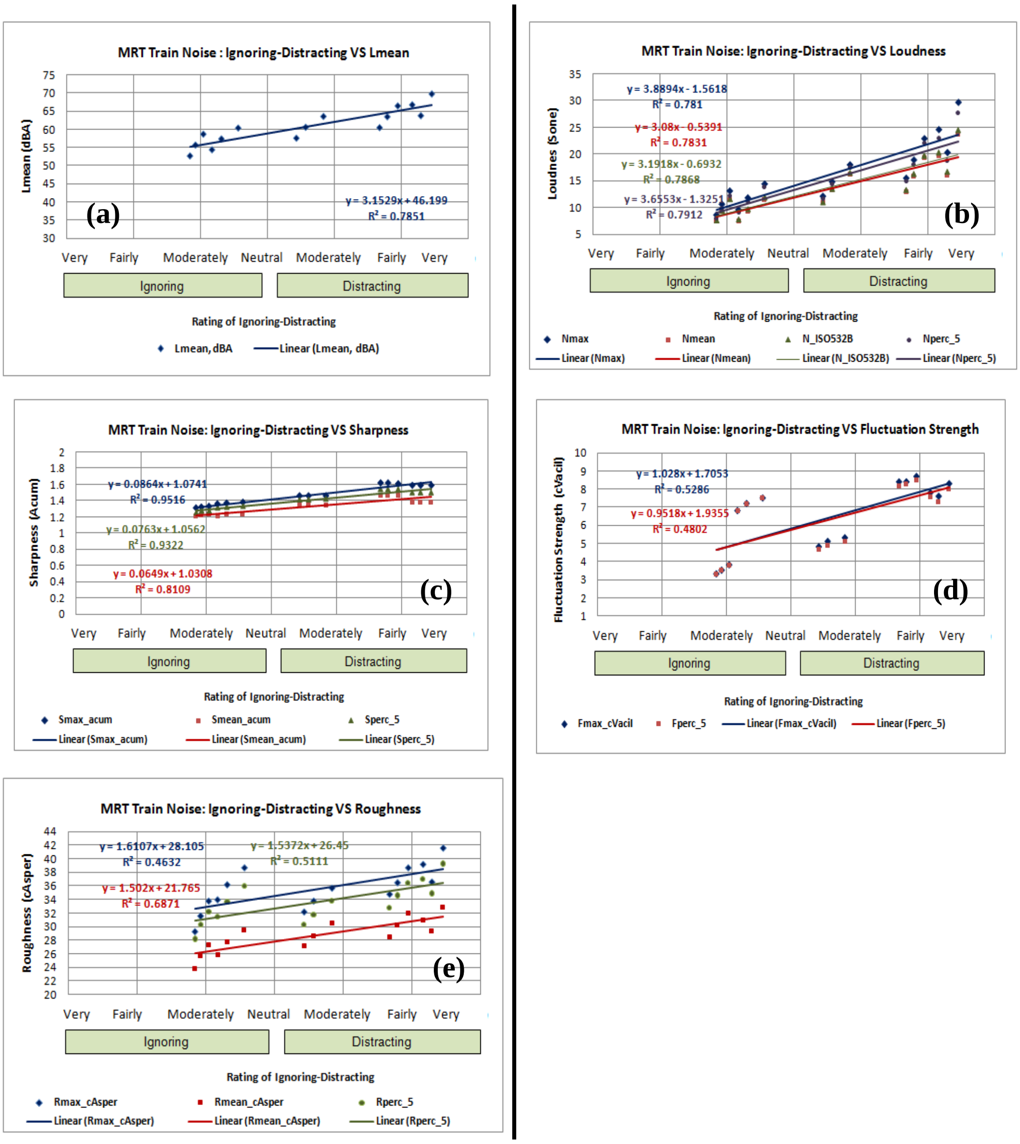

Figure : Relationships between ignoring-distracting and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

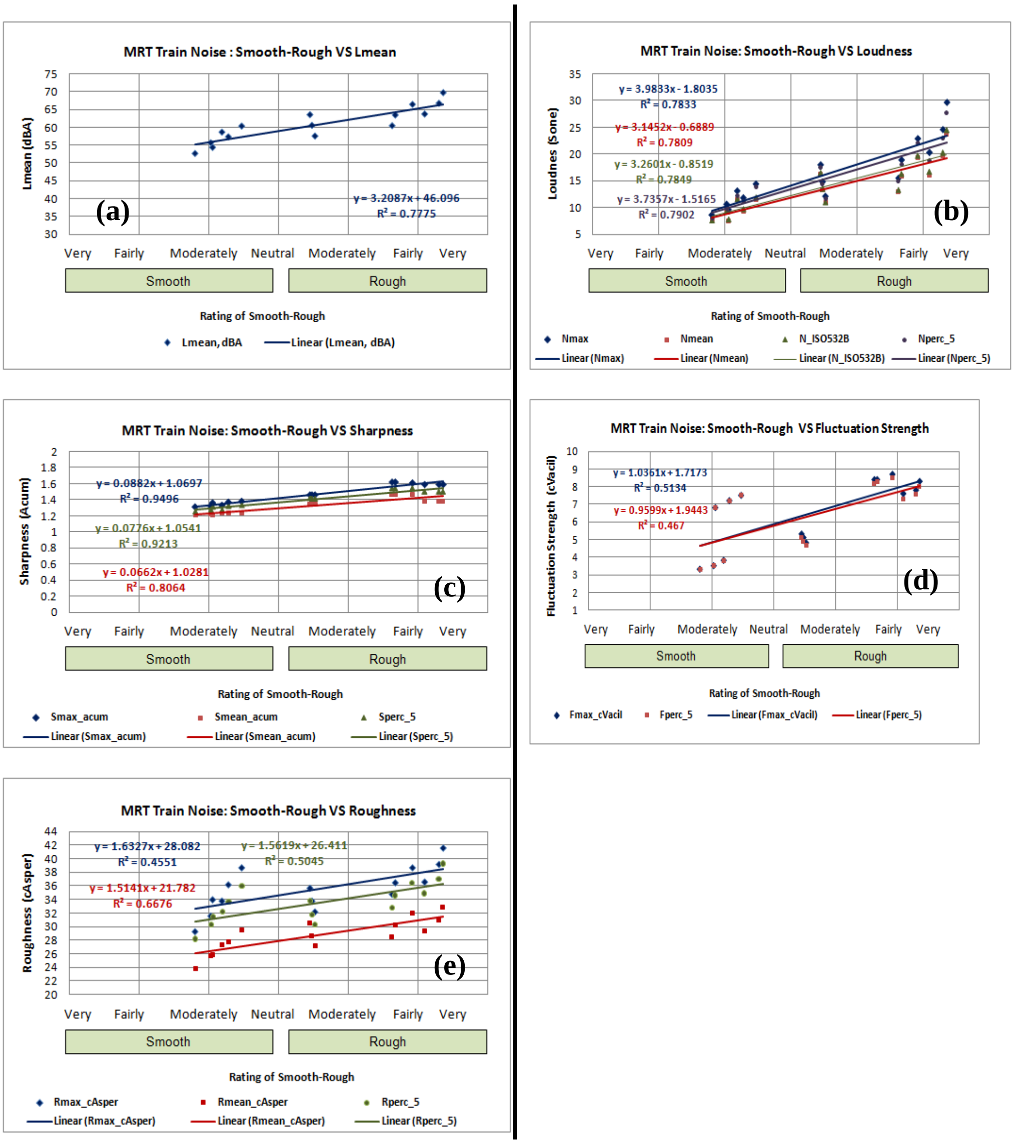

Figure : Relationships between smooth-rough and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

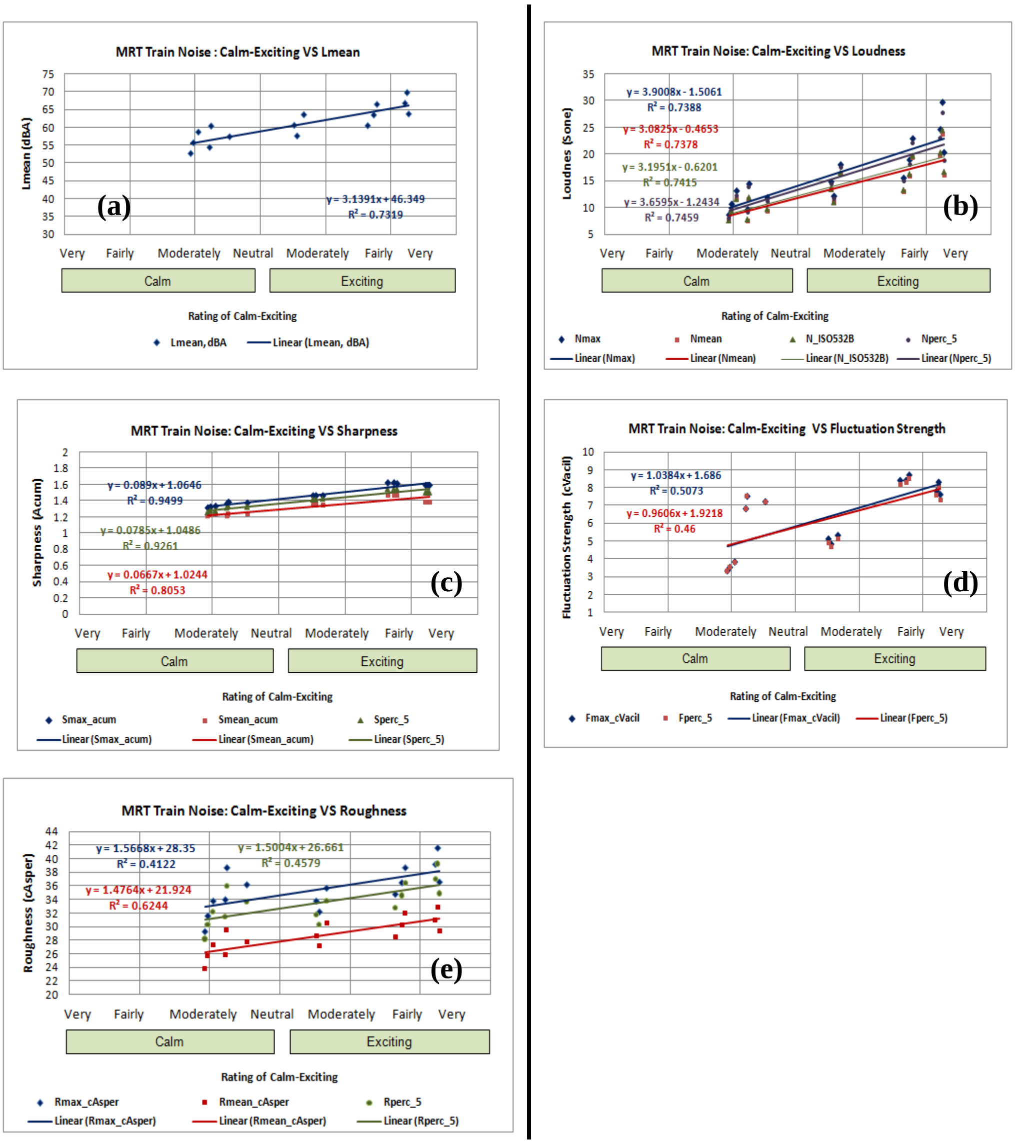

Figure 8-1 Relationships between calm-exciting and Lmean, Loudness, Sharpness, Fluctuation Strength and Roughness

APPENDIXD G : LIST OF PUBLICATIONS

PUBLISHED CONFERENCE PAPERS

1. Alam, S.M., Lee, S.E., and Johnny W.L.H.(2008). Vertical Noise Profile in High-rise Residential Environment. *Proceedings of Inter Noise 2008*, Shanghai, China.

2. Lee, S.E. Alam, S.M. and Johnny W.L.H.(2008). Establishment of an acceptable indoor noise level for residential developments. *Proceedings of Inter Noise 2008*, Shanghai, China.

3. Alam, S.M. Lee, S.E., and Johnny W.L.H.(2009). Vertical profile of train noise and indoor noise in high-rise residential environment. *Proceedings of Inter Noise 2009*, Ottawa, Canada.

4. Lee, S.E., Alam, S.M. and Johnny W.L.H.(2009). Vertical profile of traffic noise in high-rise residential environment. *Proceedings of Inter Noise 2009*, Ottawa, Canada.

5. Alam, S.M., Lee, S.E., Alan, T. and Tiong, S.T (2010). An acoustic comfort model for dwellers in high-rise built environment in the tropics. *Proceedings of ICA 2010*, Sydney, Australia.

6. Alam, S.M. and Lee, S.E. (2012). Evaluating aural comfort in tropical high-rise environment. *Proceedings of Acoustics*, Fremantle, Australia.

PUBLISHED PAPERS IN JOURNALS

1. Lee, S.E., Alam, S.M., Alan, T. And Tiong, S.T (2010). An investigation of community noise in high-rise residential environment. *Journal of the Acoustical Society of America.* 127(6), 3511-3518.

2. Alam, S.M., Kua, H.W. and Lee, S.E. (2010). A total building performance approach to evaluate building acoustics performance. *Journal of Architectural Science Review*. 53, 213-223.