A SOUNDSCAPE APPROACH FOR ASSESSING INDOOR AURAL COMFORT SUBJECTED TO ROAD TRAFFIC NOISE

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Abstract

Soundscape is defined as the acoustic environment as perceived and understood, by people, in context. It relates the aural space to the living environment towards the enhancement of acoustic experience. Soundscape approach is mostly used to investigate people's positive perception of outdoor environmental noise such as in parks, town squares, rural environments and recreational areas etc. However, it is rarely used in indoor residential context to assess acoustic comfort subjected to different environmental noises, for example road traffic noise - a major source of noise annoyance in cities. In addition, the use of psychoacoustic investigation is rather limited in literature in context of acoustic comfort in residential environment which often is useful in identifying specific soundscape quality.

In this research a psychoacoustic experiment was carried out to investigate indoor acoustic comfort subjected to road traffic noise. A multidimensional evaluation by semantic differential analysis was carried out about subjective perceptions of different road traffic sounds. Statistical analyses were then carried out to correlate different psychoacoustic quantities with different perception dimensions in the semantic space. The research investigation revealed that subjective perception across different bipolar perception dimensions investigated are strongly and significantly correlated to Loudness and Roughness of the road traffic noise.

1. Introduction

There has been a growing interest recently on positive assessment of different noises (sounds) in our built environment that had been evaluated for annoyance in the past decades. This is particularly evident for different outdoor noise sources in public places where people often like to appreciate the aural environment. “Soundscape” approach is the one that is used to investigate people’s positive perception of outdoor environmental noise such as in parks, town squares, rural environments and recreational areas etc. Soundscape is emerging as an evaluation method that could change the paradigm for evaluating the sonic environment, and improve the quality of life for all [1]. The acoustic environment as perceived and understood, by people, in context, is a definition of soundscape that may be adopted in a future acoustic standard [2].

Soundscape is often perceived in the outdoor places that are related to different recreational and communal activities. The context in which the acoustic environment is experienced (person-place-activity) is critical to soundscape perception [2]. The aural environment of this context can be described by different acoustical and non-acoustical factors which have been used for decades to describe noise annoyance. Because virtually every survey was a "noise annoyance" survey in the past, the response was in a negative scale. Hence, it is difficult to investigate the positive perception factors other than positive attitudes towards the noise source [1]. From literature it is known that the negative relationship between the outdoor environmental noise and indoor acoustic perception in the residential environment (in home context) is well established, however, much less is known about the positive perception of noise in terms of aural comfort.

This paper endeavours to investigate the relationship between positive acoustic perception in residential context and outdoor environmental noise (traffic noise in particular) in high-rise naturally ventilated buildings using soundscape approach.

2. Soundscape Approach for Assessing Indoor Aural Environment

Marquis [3] noted in her literature investigation that one often speaks about annoyance (the negative perception of noise) and less about the positive perception of sound as a comfort. She added that many 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 [3].

'Soundscape' is a relatively 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 [4]. Soundscape research is different from conventional noise reduction in that it contemplates people's interactions with the sound [5]. 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 [6]. Soundscape research has established that the energy-integrative approaches to sound measurement is an unsuitable approach of assessing the aural environment as the perception of soundscapes depends critically on distinguishing between different sound sources and whether particular sounds are wanted or unwanted in that context [2]. Hence, unlike the current approach to managing the acoustic environment, soundscape planning is not primarily about reducing sound levels [7]. Recent research also reveals that A-weighted level is unable to consider mutual masking among the components in a complex sound and also the asymmetry of masking patterns produced in the auditory system [8] that has an influence on the judgments assessing an aural environment [9]. Rationally, A-weighted noise level is found as a poor indicator of loudness and annoyance. This is the missing link which is not connected to the assessment of indoor aural 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 contrary to the traditional noise assessment approach, Soundscape approach investigates the “quality” of the sound that enhances (or degrades) the aural environment in a particular context. Sound quality is not an inherent property of the sound, rather something that develops when listeners are exposed to the sound and judge it with respect to their desires and/or expectations in a given context [10].

The assessment of the 'quality' of an aural environment involves three sets of factors: Acoustical factors (related to physical sound evaluation), non-acoustical factors (psychological factors related to auditory evaluation) and psychoacoustic factors (related to auditory perceptions). Guski [11] observed that approximately one third of the variation in noise annoyance can be explained by acoustical factors (e.g. sound level, peak level, sound spectrum and number of noise events) and a second third by 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.

Psychoacoustic analysis is not very common in research on noise annoyance or aural comfort in relation to environmental noise in residential perspective. Genuit [12, 13] noted 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 an auditory event or not annoying and generates a pleasant aural impression.

Sound quality metrics named psycho-acoustic parameters/quantities are defined as the mathematical model of sound perception. Psychoacoustic factors that have been investigated widely in relation to noise annoyance include Loudness, Sharpness, Roughness and Fluctuation Strength. Human sensation perception that corresponds most closely to the sound intensity of the stimulus is loudness. 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 1kHz sine tone is defined as a loudness of 1 Sone [8]. 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 is employed in the computation of a sensory pleasantness metric and an unbiased annoyance metric [8]. Unit of sharpness is Acum'. 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. 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 [8]. The unit of fluctuation strength is 'Vacil'. One Vacil is defined as the fluctuation strength generated by a 1 kHz tone of 60dB which is 100% amplitude modulated at 4Hz. 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 [8]. 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. In addition, psychoacoustic metrics such as fluctuation strength and roughness are found to co-vary with non-sensory aspects such as noise sensitivity [14] which often are important for qualitative assessment of a noise environment.

In contrary to the negative evaluation of an aural environment based on energy-based acoustical indices, research on the positive assessment of indoor aural environment and its association with different psychological factors related to auditory evaluation and psychoacoustic parameters are very limited in the literature. In addition, acoustic comfort and its psychoacoustic correlations have not been investigated in high-rise built environment context. This research paper focuses on the assessment of indoor aural comfort of high-rise apartment dwellers in Singapore subjected to Road Traffic Noise and investigates its correlations with several psychological factors and psychoacoustic indicators in soundscape approach.

3. Context of the Aural Environment Under Study

This research study endeavours to assess the daytime 'Aural comfort' of high-rise apartment dwellers in tropical Singapore in Soundscape approach. In this paper, the term 'aural comfort' is defined as the condition of mind which articulates satisfaction (or dissatisfaction) with the surrounding aural environment. In temperate countries, windows and doors are generally 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. In 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 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. In this paper aural comfort of high-rise residential dwellers (in public housing) in tropical Singapore is assessed for road traffic noise in Soundscape approach.

4. Research Method

In order to investigate the qualitative aspects of traffic noise in soundscape approach, in residential context, a multidimensional evaluation technique was used. Semantic differential method by Osgood [15] was used to evaluate emotional meaning of sounds in this research investigation as an assessment technique. 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 (a bipolar scale). 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 [16].

Osgood [15] 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 sounds) is expected to be established in this research investigation. Osgood's [15] semantic differential method has been used widely for different multi-dimensional evaluation studies including sound quality, soundscape etc. [17- 23]. A total of twelve adjective pairs were chosen in this research for the multi-dimensional evaluation of different road traffic sounds. The pairs of adjectives assessed were: 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. These are some common characteristics (adjective pairs) that are generally used for perceptual evaluation of sound [16, 21, 24] in our surrounding environment. 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.

In addition to establishing the meaning of sound, 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 sounds and later relating them to different psychoacoustic quantities. This would help in establishing the characteristics of noise sources that influence the aural comfort and extracting the corresponding psychoacoustic indices and their magnitudes.

5. Experimental Design, Data Collection and Data Analysis

A psychoacoustic experiment was planned for this research investigation. For psychoacoustic assessment of different types of road traffic sounds, binaural recording of the sounds were carried out at different stratified sampled locations in Singapore. Stratification criteria were road traffic noise with varying levels of noise exposures to the residents. Binaural recordings were carried out at 10 different locations (two locations per each category among five different categories of roads) near different categories of roads such as Expressway, Major Arterial, Minor Arterial, Primary Access and Local Road. Recording of the sounds were generally carried out in front of the open window of the apartments (generally on the 10th floor of the building), facing the road. This was to ensure that the psychoacoustic evaluations are made for those stimuli which are experienced by the residents during their living in high-rise naturally ventilated buildings.

Binaural Recording System from 01-dB Metravib was used for the measurement which utilizes a binaural headset to record the sound through dBSonic software on a laptop computer. Once recorded, each stimulus 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 as the 'Reference Level' (also called as 'Ref + 0 dB') for each respective class of road. Afterwards, the equivalent noise level of each stimulus was changed to three different levels such as +3 dB, -3 dB and -6 dB relative to the ‘Ref +0 dB’ level (L_{Aeq}). As a result, a total of 40 binaural road traffic sounds were generated for psychoacoustic evaluation. In addition to the overall noise level (L_{Aeq}), psychoacoustic quantities such as loudness, sharpness, fluctuating strength and roughness were examined. The recorded stimuli were analysed in dBSonic software and different psychoacoustic quantities were then computed in dBSonic software. Each of the 40 stimuli was of 6 seconds in length. Studies showed that the duration of listening session (length of stimulus) does not influence the ratings of noise annoyance if the evaluation question refers to the home situation [25]. As a result, shorter session length with the evaluation question relating to home environment reduces the experimental time significantly.

The study on aural comfort requires a conducive environment to carry out the psychoacoustic research experiment. Based on the experimental design, criteria for such environment included a signal-to-noise ratio of 10 dB and thermal, visual and spatial comfort. 'Staff Lounge', generally used for the resting of the academic staff of the school, was deemed to satisfy all the requirements and hence selected for the experiment. 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).

A total of 50 subjects volunteered for the psychoacoustic experiment. However 36 subjects completed all the experiments with valid data. For inclusion of the subjects in the psychoacoustic experiment, subjects were required to undergo audiometric test to confirm that they had a normal hearing condition as per Goodman criteria [26]. Each subject was expected to evaluate a maximum of 10 sessions per day which generally takes about 30 minutes. A maximum of 13 subjects were scheduled per day (during the weekdays only) starting from 10am in each 30 minutes interval.

The listening system for the stimulus evaluation was operated and controlled by the Jury Test software package from 01 dB Metravib. Stimuli were sent from Jury Testing Software on a notebook computer equipped with a 24 bit professional sound card to a binaural headset (Sennheiser HD650) for listening. The headset was factory calibrated. 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. A mixed approach is used (combination of direct and paired comparison evaluation approaches) for the jury testing. 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. [27,28] demonstrated that this method allowed for a good trade-off between quick assessment and precise pair comparison.

The psychoacoustic indices that were computed to examine loudness include: a) Maximum loudness of the sound signal (Nmax), b) Mean loudness of the sound signal (Nmean), 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 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 Nmean. The five percentile loudness (N_5) is also examined as much research has shown its correlation with perceived noise annoyance [29].

Psychoacoustic indices relating to sharpness were computed using dBSonic, these include, a) Maximum sharpness (Smax), b) Mean sharpness (Smean) 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 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 aural comfort in this research investigation.

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 centered 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).

Data analysis showed that the average reference noise levels for Category 1 to Category 5 roads were approximately 71 dBA, 66 dBA, 65 dBA, 63 dBA and 58 dBA respectively (generally at a distance of 20m-25m and at 10th floor level of a building facing the road traffic). Mean loudness of the reference stimuli varied between 12 Sone and 25 Sone. Mean sharpness for these traffic noises ranged between 1.2 Acum and 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.

6. Research Findings

6.1 Semantic profile analysis

Subjective perceptions about road traffic sounds of varying levels (0 dB, -3 dB and -6 dB) were measured through the psychoacoustic experiment using mixed evaluation technique on a semantic differential scale having 12 different bipolar adjective pairs. Semantic differential profiles are established for different classes of roads with varying levels and presented in Figure 2 to Figure 4. 'Reference Level' (also called as 'Ref + 0 dB') in Figure 2 is referred to the binaurally recorded stimulus' sound levels of different categories of roads with a time and amplitude equalisation of 6 sec and 75 dBA respectively.

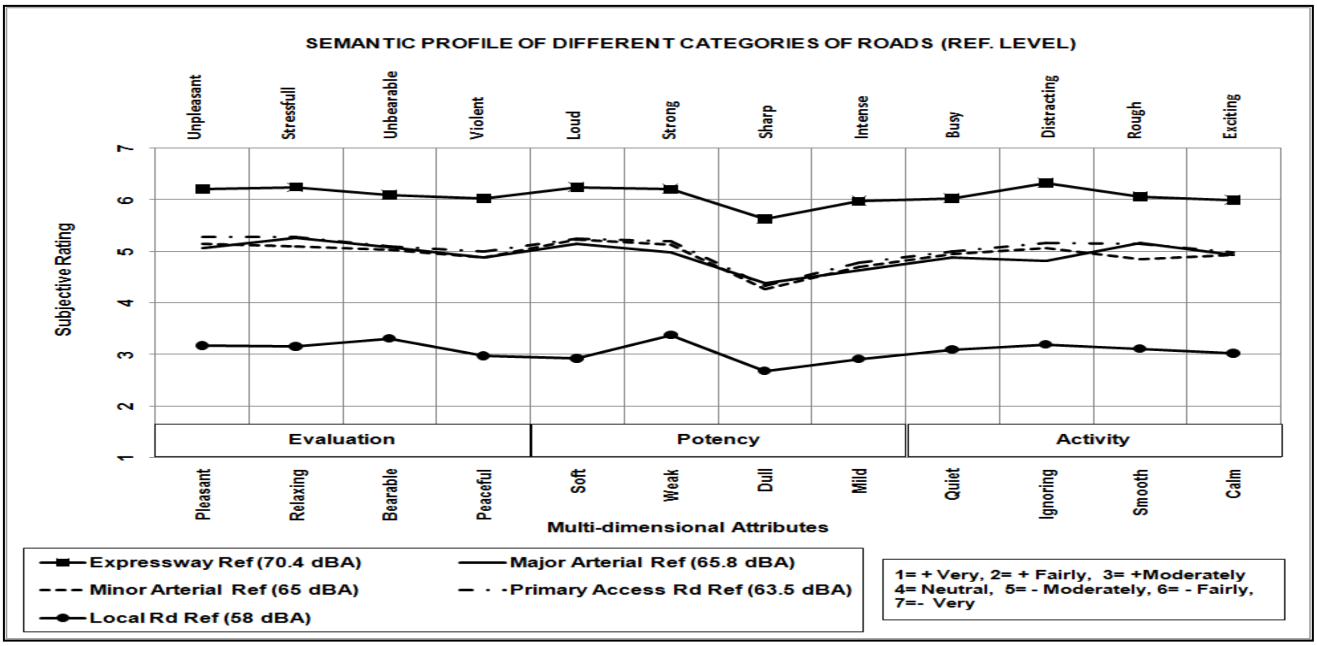

Figure 2. Semantic profiles of different classes' road traffic noise (Ref. Level)

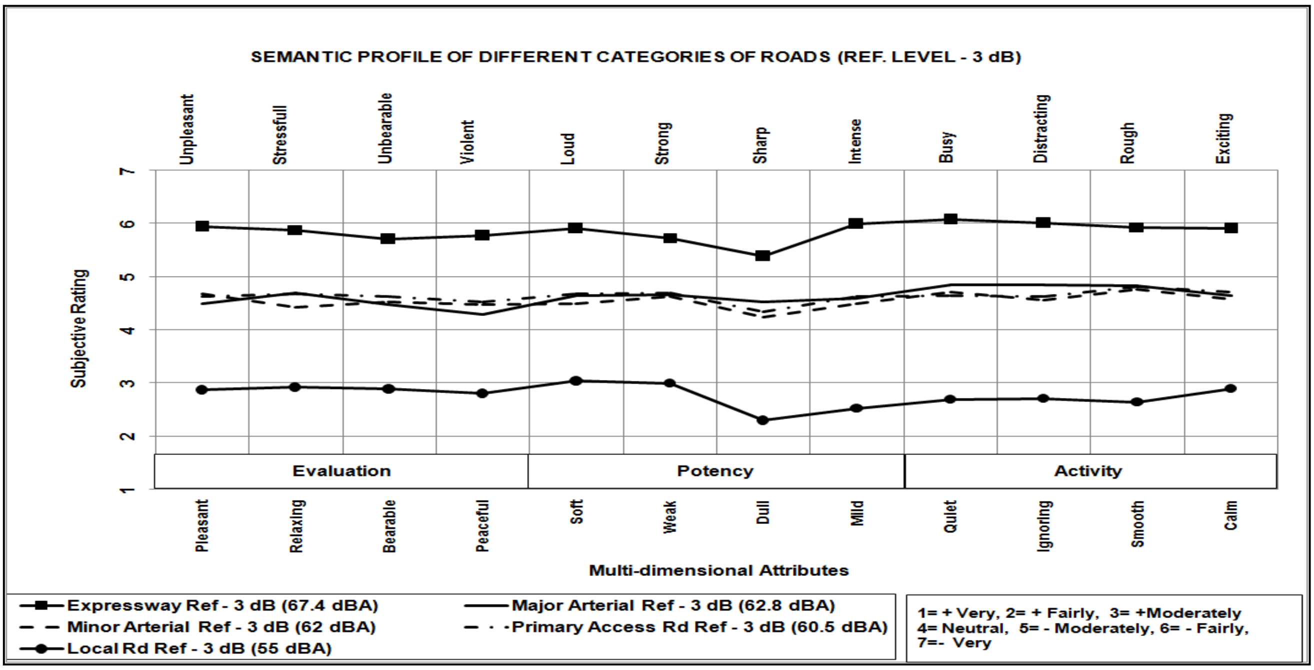

Figure 3: Semantic profiles of different classes' road traffic noise (Ref. Level - 3dB)

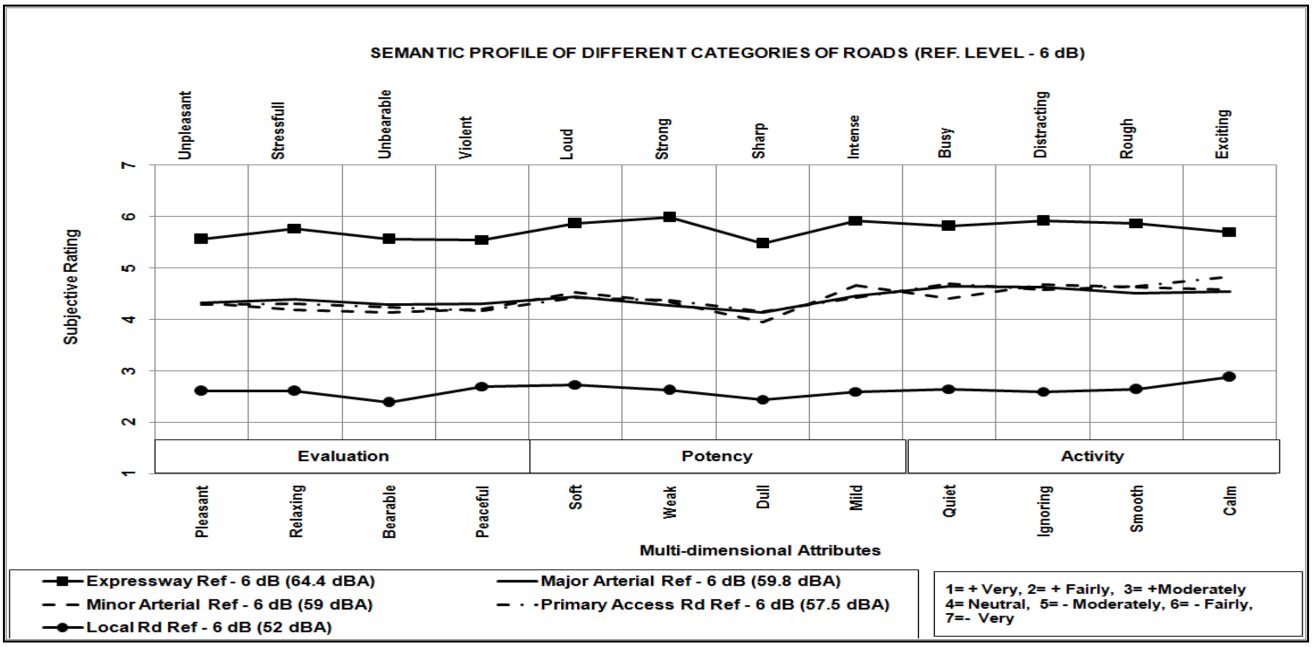

Figure 4. Semantic profiles of different classes' road traffic noise (Ref. Level - 6dB)

A comparison of road traffic sound of varying levels in the semantic space showed three distinct categories where the road traffic sounds were perceived equally. The first category is road traffic sounds from Expressways which 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 approximately equally perceived. 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 perceived as 'moderately' favourable semantic adjective pairs (for example, fairly pleasant, fairly relaxing, etc.).

6.2 Relationships between subjective qualities in semantic space and psychoacoustic quantities

Statistical analysis was carried out to establish the correlations between semantic space (12 adjective pairs) and several psychoacoustic quantities. The Pearson correlation coefficients illustrate that 'aural comfort' is strongly and significantly correlated with the 12 adjective pairs *(p*<0.5*)*. It is also noted that all 12 perception dimensions are strongly and significantly correlated with the 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.

The relationship between the pleasantness-unpleasantness and the psychoacoustic quantities that are strongly and significantly correlated to this dimension are graphically presented in Figure 5 and Figure 6. Analysis of the data shows that at about 10 sone Nmean 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 psychoacoustic quantities relating to roughness, 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.

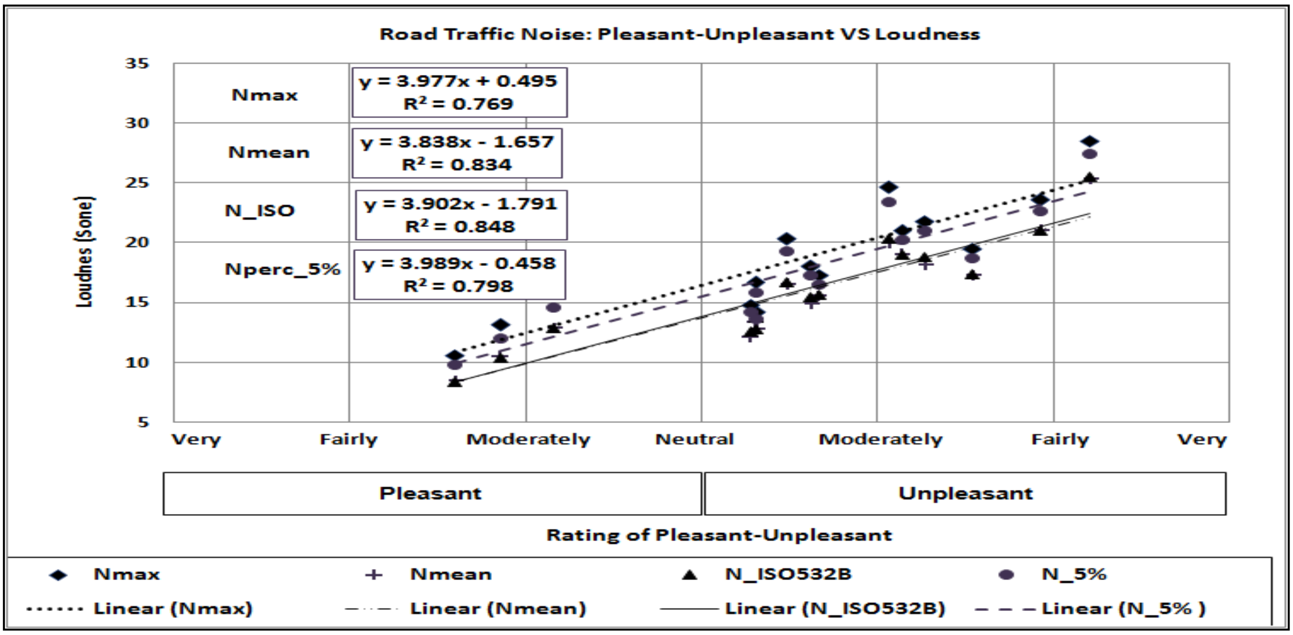

Figure 5. Relationships between pleasant-unpleasant and Loudness

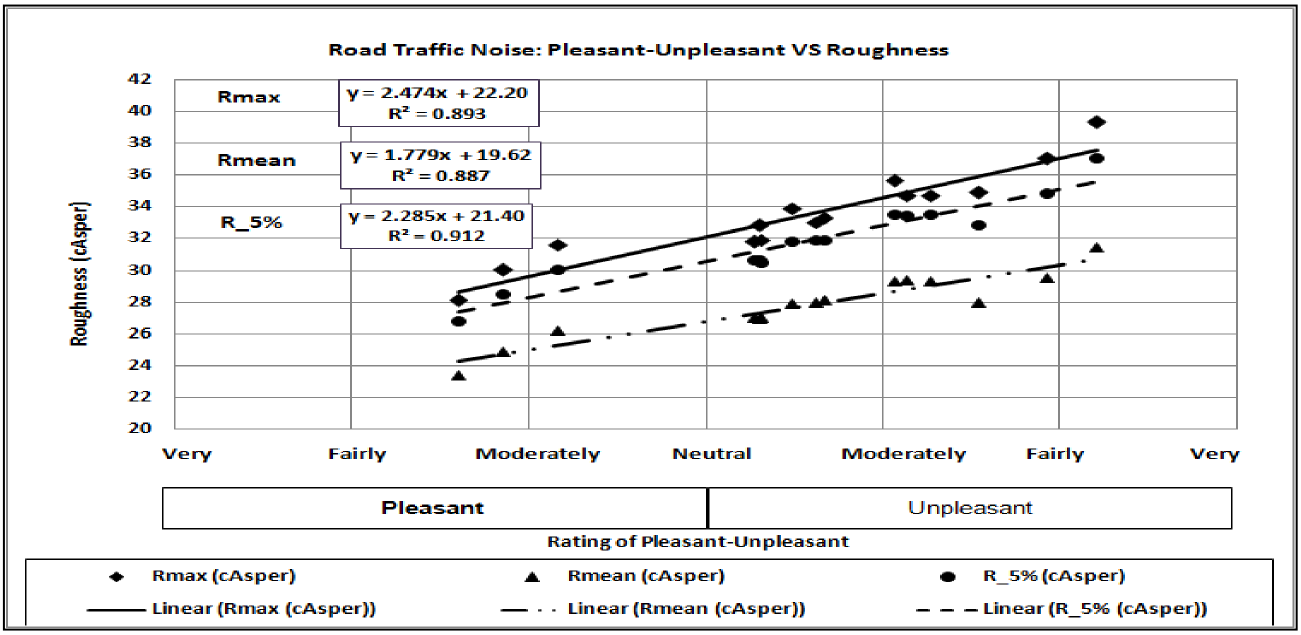

Figure 6. Relationships between pleasant-unpleasant and Roughness

7. Conclusion

In this research investigation an attempt has been made to assess the aural comfort within indoor environment in a soundscape approach. The subjective meaning of the aural comfort with regards to road traffic sound is translated into the semantic spaces which suggest that a moderate favourable perception is achievable in 12 different bipolar perception dimensions when overall traffic noise is 55 dBA for naturally ventilated buildings. The 12 pair perception dimensions were then correlated to different psychoacoustic quantities to investigate if the qualitative aspect of the aural environment could be quantified through the psychoacoustic indices. Analysis of the data showed that at about 10 Sone Nmean and 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. The semantic profile analysis discussed in this paper would be able to give an understanding of the emotional aspects of the road traffic noise while the psychoacoustic quantities such as loudness and roughness are found as the key indicators for aural comfort with regards to road traffic noise at indoor residential settings in high-rise naturally ventilated buildings. The authors believe that these findings 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 in tropical countries.

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