NOISE EMISSION SPECTRA OF CNG DRIVEN VEHICLES

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CERTIFICATE

The research work embodied in this dissertation entitled "**Noise emission spectra of CNG driven vehicles**" has been carried out at the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi. The work is original and has not been submitted in part or in full for any other degree or diploma in any other university/institution.

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Chapter 1

INTRODUCTION

Noise pollution in urban areas is now being recognised as a major environmental issue around the world. With the increasing awareness of the adverse impacts of noise on human health, more and more people are becoming less tolerant to environmental noise. A great deal of effort has been devoted to extensive noise surveys and modelling studies in various cities of the world. Griffiths et al. [1] studied the subjective effects of traffic noise exposure in human beings in London area. A similar study, that focussed on the behaviour of human beings exposed to traffic noise was carried out in two French cities by Lambert et al. [2]. Traffic noise criteria for assessing the annoyance caused by traffic noise have also been studied. Scholes [3], found that the A-weighted equivalent sound pressure level L_{Aeq} and a Traffic Noise Index (TNI) based on the A-weighted (10 and 90 percentile) levels L_{A10} and L_{A90} correlate satisfactorily with human annoyance. The use of percentile levels as the noise criteria was further investigated by Langdon and Griffiths [4]. L_{A10} is now generally adopted in traffic noise control practices. Tempest and Bryan [5] have developed a technique for low frequency sound measurement in vehicles and showed that much of the sound energy is in the low frequency and infrasonic regions.

Physical noise measurements were also conducted by researchers all over the world. Examples are the works of Ko [6] in Hong Kong, Cannelli [7] in Rome, Rao and Rao [8] in Visakhapatnam, Kumar and Jain [9] in Delhi, Chakrabarty et al [10] in Calcutta and most recently Sanyogita et al., [11] on the noise in CNG driven modes of transport in Delhi. However, this list is by no means exhaustive. Based on these studies, traffic noise emission depends on various factors discussed below:

1.1 VEHICLE SPEED AND WEIGHT

Vehicle speed is an important parameter affecting noise levels. The primary cause for this behaviour according to Stephenson and Vulkan [12] is that for vehicles moving at fast speed, both tyre and aerodynamic noise become important, whereas in normal traffic, engine noise predominates. Johnson and Sanders [13] provided an empirical law for L_{50} as a function of $\bar{v}$ the average speed of vehicle as

$$L_{50} = 51.5 + 10 \log_{10} \frac{Q}{d} + 30 \log_{10} \frac{v}{40} \text{ dBA}$$

Where Q/d= flow/distance.

A further generalization has been made by Olson [14] on the basis of vehicle gross weight. On the basis of sound level measurements of some 215 passenger cars, 181 light trucks, 125 medium trucks, 102 empty dump trucks, 58 loaded dump trucks and 32 tractor trailers, he obtained a noise level vs. weight category, the slope of which corresponds to 3.5 dB(A) increase in noise level for each doubling of gross vehicle weight. The recent works of Sanyogita et al., [11] on CNG modes of transport in Delhi also suggests that the noise levels from these vehicles increase with their speed. The study included auto-rickshaws, RTVs, buses and taxis.

1.2 TRAFFIC DENSITY

A definite correlation between noise level and traffic density has been found by various studies [15-16]. Kumar et al. [17] in their studies in Delhi city found that noise levels are primarily determined by vehicular traffic and that vegetation also has a role in attenuating noise levels. Chakrabarty et al [10] proposed a regression equation connecting the hourly equivalent noise level $L_{eq(h)}$, combined with the term representing plying traffic distance and the traffic density for the city of Calcutta. A systematic and comprehensive study of the road traffic noise level of Visakhapatnam was made by Rao and Rao [8] who developed a regression equation for predicting the noise level as a function of traffic density. Only a small difference in values between the computed and measured values was observed. J. Ramis et al [18] in their studies in the noise effects of reducing traffic flow through a Spanish town of Motilla de Palancar observed a reduction in noise levels between 3.0 to 7.5 dB(A) after reduction of traffic flow.

1.3 EFFECTS OF ROAD SURFACE, GRADIENT AND INTERSECTION

There are some deviations in noise level measurements because of road surface, road gradients, and the interruption of traffic flow at intersections [12,19]. Adjustment due to uphill gradient applies primarily to heavy duty trucks. An uphill gradient will require a substantial increase in engine power and hence an adjustment in noise level. When traffic is controlled at an intersection by a stop sign or a signal, there will also be an increase in traffic noise. Buses or trucks accelerating after a stop will contribute intrusive noise with 5 dB or more 'peaks' over steady state traffic noise levels, and there will be a lesser noise increment because of accelerating passenger cars. Thus residents in the immediate vicinity of hills or intersections will be exposed to higher traffic noise levels than for level-uninterrupted flow. Adjustments have been recommended accordingly.

1.4 ATTENUATION BY BARRIERS

Traffic noise levels generated by a given traffic volume may be decreased by means of a depressed roadway, roadside barriers, shielding by structures and landscaping [20]. The depressed roadway is costly to construct but it provides an acoustically opaque mass of earth between the roadway and the adjacent property. Roadside barriers are usually less effective than depressed roadways, primarily because there are practical limits to barrier heights. The effectiveness of shielding by structures depends on structure type and spacing and landscaping provides little actual sound attenuation. Attenuation by vegetation has also been reported [17].

1.5 PREDICTIVE MODELS

Scale model studies have also been made by Liu [21] and Picaut and Simon [22], where the architectural complexity of building facades, which is the fundamental cause of the sound diffusion in streets is simulated. However, measurements in scale model with large scale factors requires tricky digital processing, linked to the compensation of excess atmospheric attenuation in the scale model in comparison with the full scale. Sound level forecasting models for city centres were developed by

Waliyah et al [23-26]. With this model, sound level due to a road within an urban canyon, effect of source model parameters on sound level in built up area, a road lane structure influence on sound level within urban canyon and vehicles stream parameters influence on sound level distribution within a canyon street have been successfully predicted using a computer simulation program PROP5. Calixto et al [27] have developed experimentally and mathematically, models for predicting L_{eq}, L_{10} and L_{90} for Brazilian roads.

Traffic noise prediction models in the 1950s and 1960s were designed to predict a single vehicle sound pressure level (L_p) at the roadside. These models were based on constant speed experiments, the predicted levels then being expressed as functions of speed and with zero acceleration [13]. Later models predicted (L_{eq}) under interrupted and varying flow conditions. Models in recent use [28] include FHWA Traffic Noise Model Version 1.0 in USA, Calculation of Road Traffic Noise (CoRTN) in UK, Richtinem furden Larmschutz an Straβen (Guidelines for Noise Protection on Streets) or RLS-90 in Germany, MITHRA in France, StL-86 Version 1 by the Swiss Federal Office for environmental Protection and ASJ Method-1993 by the Acoustical Society of Japan. Within their range of validity, the models meet the requirements of government regulations and many designers. All models have acoustic energy descriptors explicit as L_{eq}. The L_{eq} models admit of easy corrections for interrupted flow, multiple streams and multiple roads. However these models do not meet the requirements of other traffic model users. A reliable noise prediction method on which there is a consensus by the different users is the Nordic prediction method for road traffic noise [29].

Statistical modelling is also a hot research topic as a known noise distribution can reduce the number of acoustical parameters required to describe an environment affected by traffic noise. Foxon and Pearson [30] concluded from the results of a site measurement that the distribution of traffic noise is Gaussian-like. However Kurze [31] has showed mathematically and experimentally that the noise intensity distribution due to freely flowing traffic follows the Gamma distribution. The more recent results of Don and Rees [32] suggest complicated distributions depending on the compositions of road vehicles and they have developed a model based on the superposition of Gaussian distributions for the estimation of traffic noise probability distribution. However, their proposed model has not been widely adopted in the traffic noise prediction. Despite the efforts of previous researchers, a commonly agreed distribution function for traffic noise has not been sought, not to say its shape under different flow conditions.

Owing to the large variation of the indoor acoustical condition, the noise from traffic transmitted indoors through the building facades is a big problem. Ko [33] showed the existence of a fairly good correlation between indoor and outdoor traffic noise levels in the open window case under free traffic flow conditions. Tang and Au [34] showed that the general shapes of indoor noise level distributions depend mainly on the traffic flow pattern and the skewness of the distributions. They have concluded that indoor noise level statistics reveal the Gaussian distribution under the free traffic flow condition while the interrupted flow can be approximated by the Pearson Type I curve.

Delhi, the capital city of India, with a population of 13.8 million and having approximately 3.5 million vehicles, is widely known to be one of the most polluted cities in the world. To combat the serious problem of air pollution in the city, the Supreme Court of India in its judgement directed the Government of Delhi to run its public transport system entirely on Compressed Natural Gas (CNG) fuel. Such a major policy decision concerning the public modes of transport has prompted the present study with a view to examining the levels of noise and its spectral characteristics in CNG driven vehicles on roads of Delhi.

Chapter 2 provides basic concepts related to noise pollution. Experimental methodology and statistical analysis are given in Chapter 3. Results are presented and discussed in Chapter 4. Finally Chapter 5 gives main conclusions of the study alongwith future scope of work.

Chapter 2

NOISE POLLUTION – BASIC CONCEPTS

2.1 INTRODUCTION

We live in a world of sound. No other form of energy so pervades every facet of our living. It is the primary medium for communication and without sound the continuous transfer of knowledge of the world around us would almost disappear. Sound is caused by vibration of substances, which may be in solid, liquid or gas. The substances that produce sound are called sound sources or generators. The sound can be heard only when the vibrations are transmitted from sound sources to our ear by means of some elastic intermediary substance (medium) such as in air. The pressure variations caused by the vibrations in air caused auditory sensation in our ear, called sound, the feeling of hearing. Thus a sound wave is a modulation of the atmospheric pressure that is discernable to the human ear. A more general, purely physical definition states that sound is an alternation in pressure, stress, particle displacement, or particle velocity, which is propagated in an elastic material, or the superposition of such propagated vibrations. Based upon this later definition, signals outside the range of human hearing would be included. The definition is also rather broad in specifying the type of physical disturbance that is being propagated. The sound may constitute a single pulse or transient, an irregular though repetitive modulation, or a simple periodic change.

The number of complete oscillations that a sound undergoes per second is termed as the frequency, f. The unit of frequency is cycles per second or Hertz (Hz). The sound with frequency less than 20 Hz is called infrasonic while that above 20000 Hz is called ultrasonic. The sound with frequency between 20 Hz to 20000 Hz is called audible sound or simply sound. Sound wave is also characterised by a wavelength λ, defined as the distance that sound travels during each complete vibration or cycle of the sound source. The frequency and wavelength of the sound source are related by the simple formula:

$$c = f\lambda \qquad (1)$$

where

c = velocity of propagation, in m/sec

f = frequency, in Hz (cycles/sec)

λ = wavelength, in meters.

The pressure variations caused by the vibrations in air can be measured by a sound level meter in decibel (dB). The decibel in acoustic is defined as 20 times the logarithm (to the base 10) of the ratio of the sound being measured P_1 to a reference level P_2. i.e., magnitude in dB = $20 \log_{10} \frac{P_1}{P_2}$. The reference level is chosen as 20 µPascal, which is approximately the hearing threshold for a healthy human being.

Noise is considered as the sound that is unpleasant and unwanted by the listener because of its bothersome nature, interference with the perception of wanted sound or its harmful physiological and psychological effects of individuals or population. It is the wrong sound, in the wrong place, at the wrong time. Noise level is the sound pressure level in decibel (dB) weighted in accordance with one of the frequency weighing A, B or C. "A-weighted" means making graded adjustments in the intensities of the sound of various frequencies for the purpose of noise measurement so that the sound pressure level measured by an instrument reflects the actual response of the human ear to the sound measured. Once a sound has been measured in A-weighted decibels, it is known as sound or noise level and expressed in dB(A). L_{eq} (Equivalent Sound Energy Level) is the steady sound pressure level for the whole measurement duration as the averaging time. L_N is the level equalled or exceeded N% of the total measuring time. Ambient noise is the total noise associated with a given environment and usually comprises sounds from various sources both near and far. In our modern, rapidly expanding environment one of the most important problems is noise pollution.

2.2 NOISE POLLUTION

The uncontrolled growth of activities in modern cities is degrading the quality of the urban environment not only through polluted air and water, traffic congestion and disappearance of open spaces, but also through a mounting volume of noise. Noise intrudes upon the privacy of an increasing number of people and is reaching levels which interfere with their activities and has recently become an object of serious social concern. However, it cannot be isolated from other social concerns, and is extricably linked with the many facets of contemporary civilization, accompanying man's essential as well as non-essential activities and his way of life. Noise differs significantly from air pollution and also from thermal pollution, in the sense that it decays almost instantaneously and leaves no residue. Yet, noise is a persistent pollutant and it degrades the quality of life. It may soon rank among the major sources of dissatisfaction with urban living.

Although quantities such as temperature, humidity and air velocity can be measured with a considerable degree of accuracy, it is far from simple to find any very precise correlation between such physical measurements and any one individual's personal feeling of comfort. The same problem arises in interpreting sound measurements and in particular in deciding how the amplitudes and frequencies are related to the feeling of loudness. In spite of the difficulty of all subjective measurements, it is necessary to have some means of estimating how people are likely to react to a sound of known physical qualities. Thus, the basis of all sound criteria is a statistical investigation into the reactions of a large number of people. By means of such investigations, a considerable amount of information has been obtained about the way a human ear responds to acoustic vibrations.

In actual practice, a noise rarely consists of a single frequency. Usually it is a combination of a number of frequencies. Such a noise is commonly classified into the following two categories:

(1) Wide band noise (comprising a wide range of frequencies; and

(2) Narrow band noise (incorporating only a few frequencies)

The frequency composition of the noise is known as its "frequency spectrum" (or simply spectrum). Noise may be classified by its occurrence in time as follows

(1) Steady state noise (i.e., continuous and unvarying);

(2) Impact noise (single impulses of short duration at regular or irregular intervals); and

(3) Intermittent noise

The unpleasantness and harmful effects of noise depend on one or more of the following: (1) Intensity of sound waves (2) Frequency (3) Time of exposure (4) Intermittence or continuation of sound. For simplicity, noise pollution can be divided into three categories: (i) Industrial noise (ii) Community noise, and (iii) Traffic noise. The industry noise depends on machinery, tools etc. while community noise occurs due to religious functions, marriages, elections or public functions and the third, traffic noise, depends upon vehicles of all types including road breaking disturbances and is the most prominent source of noise pollution in urban areas around the world. It is not surprising, therefore, that traffic noise is the most widely researched subject as far as the noise in urban environment is concerned.

2.3 TRAFFIC NOISE

Noise from road vehicles disturbs more people than any other source of noise. Traffic noise is a result of our highly mobile civilization where one uses conveyances that dissipate large amounts of energy, a fraction of which is dissipated as unwanted sound or noise. As the energy requirements of a society increase, the noise levels also tend to increase. And, as the noise levels in the cities intensify, the spreading population and the proliferation of machines extend traffic noise into previously quiet areas. Traffic vehicles that contribute a substantial portion of environmental noise include automobiles, trucks, utility vehicles, buses and motorcycles. Due to increasing growth of vehicles, metropolitan cities have become noisiest cities in the world. Noise can be from individual vehicles or from continuous flow of vehicles of all types. Vehicular noise can be classified into two distinct categories:

Those related to engine speed: Noise from vehicles can be from engine, intake, exhaust, cooling fan, gear box, horns and from accessories such as air compressor, hydraulic pump, electrical generators etc.

Those related to road speed: related to road speed include engagement of gears, rolling noise produced by tyres and aerodynamically generated noise.

Collectively these noise sources combine to produce broadband noise that includes frequencies from the infrasonic to about 10000 Hz. Overall the factors of traffic noise depend on the following:

(1) Traffic parameters: Vehicle volume (number of vehicles passing a location per unit time), vehicle mix and average speed

(2) Roadway characteristics: Pavement width, gradient and surface finish

(3) Observer characteristics: Observer distance, element size, shielding and observer's relative height.

2.4 EFFECTS OF NOISE

In addition to its auditory effects (temporary and permanent threshold shifts, noise induced deafness, etc.), noise can also produce many non-auditory effects. Noise can disturb our work, rest, sleep, communication and also evoke other psychological, physiological and possibly pathological reactions. However, because of complexity, variability and the interaction of noise with other environmental factors, the adverse health effects of noise do not lend themselves to a straightforward analysis.

2.4.1 Hearing impairment:

Hearing impairment can either be temporary or permanent. Noise-induced temporary threshold shift (NITTS) is a temporary loss of hearing acuity experienced after a relatively short exposure to excessive noise. Pre-exposure hearing is recovered fairly rapidly after cessation of the noise. Noise induced permanent threshold shift (NIPTS) is an irreversible loss of hearing that is caused by prolonged noise exposure. Both kinds of loss, together with presbyacusis, is the permanent hearing impairment that is attributed to the natural ageing process, can be experienced simultaneously. Noise induced hearing impairment occurs predominantly in the higher frequency range of 3000-6000 Hz, with the largest effect at 4000 Hz.

2.4.2 Speech interference:

Speech interference is basically a masking process, in which simultaneous interfering noise renders speech incapable of being understood. The inability to understand speech results in a large number of personal handicaps and behavioural changes. Problems with concentration, fatigue, uncertainty and lack of self confidence, irritation, misunderstandings, decreased working capacity, problems in human relations, and a number of stress relations have been identified. Particularly vulnerable are the hearing impaired, the elderly, and children in the process of language and reading acquisition, and individuals who are not familiar with spoken language. Speech intelligibility in everyday living conditions is influenced by speech level, speech pronunciation, talker to listener distance, sound level and characteristics of the interfering noise, hearing acuity and by the level of attention. Indoors speech communication is also affected by the reverberation characteristics of the room.

2.4.3 Physiological effects:

In workers exposed to noise, and in people living near airports, industries and noisy streets, noise exposure may have a large temporary, as well as permanent impact on their physiological functions. After prolonged exposure, susceptible individuals in the general population may develop permanent effects, such as hypertension and ischaemic heart disease associated with exposure to high sound levels. The magnitude and duration of the effects are determined in part by individual characteristics, lifestyles, behaviours and environmental conditions.

2.4.4 Sleep disturbance:

Sleep disturbance is a major effect of environmental noise. Uninterrupted sleep is known to be prerequisite for good physiological and mental functioning of healthy persons. It may cause primary effects during sleep, and secondary effects that can be assessed the day after nigh-time exposure. The primary effects of sleep disturbance are difficulty in falling asleep, awakenings and alteration of sleep stages or depth, increased blood pressure, heart rate etc. The secondary, or after effects the following morning or day(s) are reduced perceived sleep quality, increased fatigue, depressed mood or well being and decreased performance.

2.4.5 Annoyance:

Noise annoyance may be defined as the feeling of displeasure evoked by noise. The annoyance inducing capacity of noise depends upon its physical characteristics, including the sound pressure level, spectral characteristics and variations of these properties with time. However annoyance is not necessarily directly related to these parameters. It may be influenced by a number of subjective factors (such as familiarity and personal attitudes) and by some physical factors (such as microclimate).

Annoyance caused by noise is partly an individual response and varies with persons and situations.

2.4.6 Performance:

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

2.4.7 Fatigue:

It has been suspected for long time that noise can induce fatigue in exposed individuals, but it is not easy to prove that employees become more tired working in a noisy environment than in a quiet one. Fatigue may result from having to talk more loudly or from the extra effort caused by misunderstandings.

2.4.8 Mental health effects:

The association between exposure to high noise levels and the impairment of mental health is still a controversial one. It has often been suggested that noise is not a direct cause of mental illness, but it may accelerate the development of latent neurosis. Research in recent years has shown the lack of association between the noise exposure and mental morbidity. However, a greater prevalence of mental disorders among those who had reported that they were very annoyed by the noise has been confirmed by recent research.

2.5 LEGAL ASPECTS

Efforts to abate traffic noise fall into two main categories: reduction of noise at the source and reduction of the area in which noise can be regarded as intrusive. The later, though certainly important in urban design, is of local significance only. The former brings benefits to the whole urban community. A number of countries already have or intend to enact standards concerning permissible noise emissions. In India, the Ministry of Environment and Forests has notified Noise Pollution (Regulation and Control) Rules, 2000, covering various aspects of noise pollution. There are other provisions, notified under various acts, in India, for control of noise pollution. The existing legal provision for vehicular noise emission, in our country is summarized below:

Table 1. Noise limits for vehicles in India applicable from 1st January, 2003

S.No.	Type of vehicle	Noise limits in dBA
1.	Two wheeler	
	Displacement upto 80 cm^3	75
	Displacement more than 80 cm^3 but upto 175 cm^3	77
	Displacement more than 175 cm^3	80
2.	Three wheeler	
	Displacement upto 175 cm^3	77
	Displacement more than 175 cm^3	80
3.	Passenger car	75
4.	Passenger or commercial vehicle	
	Gross vehicle weight upto 4 tonne	77
	Gross vehicle weight more than 4 tonne but upto 12 tonne	80
	Gross vehicle weight more than 12 tonne	82

Chapter 3

PRINCIPLES AND METHODOLOGY

3.1 OCTAVE BANDS

Any continuing vibration can be expressed as a Fourier series of pure sine waves of differing frequency, amplitude and phase. Fig. 3.1 illustrates one example of a non-sinusoidal wave which is made up of three different sine waves. The frequencies audible to the human ear range from 20 Hz to about 20000Hz, one Hz being one cycle per second. To be heard, even a very deep or low frequency sound must last for several cycles. During this time, it may be heard together with any number of other sounds, all of different frequency and amplitude. It is therefore important that we should always take into account the actual frequencies of sound, or the frequencies of the components of sound. To avoid having to deal with a vast number of frequencies, it is normal to divide the range into octave bands. Usually either 1-octave or 1/3rd –octave bands frequencies are employed. For 1-octave band the top frequency of each band is twice the bottom frequency of that band, and the top frequency of one band is the bottom frequency of the next. For more precise work, one may use 1/3-octave bands. The centre frequencies and associated bandwidths are given in Table 3.1.

Table 3.1. Octave band frequencies.

Centre-frequency (Hz)	Frequency bandwidth (Hz)
63	44 to 88
125	88 to 177
250	177 to 355
500	355 to 710
1000	710 to 1420
2000	1420 to 2840
4000	2840 to 5680
8000	5680 to 11260

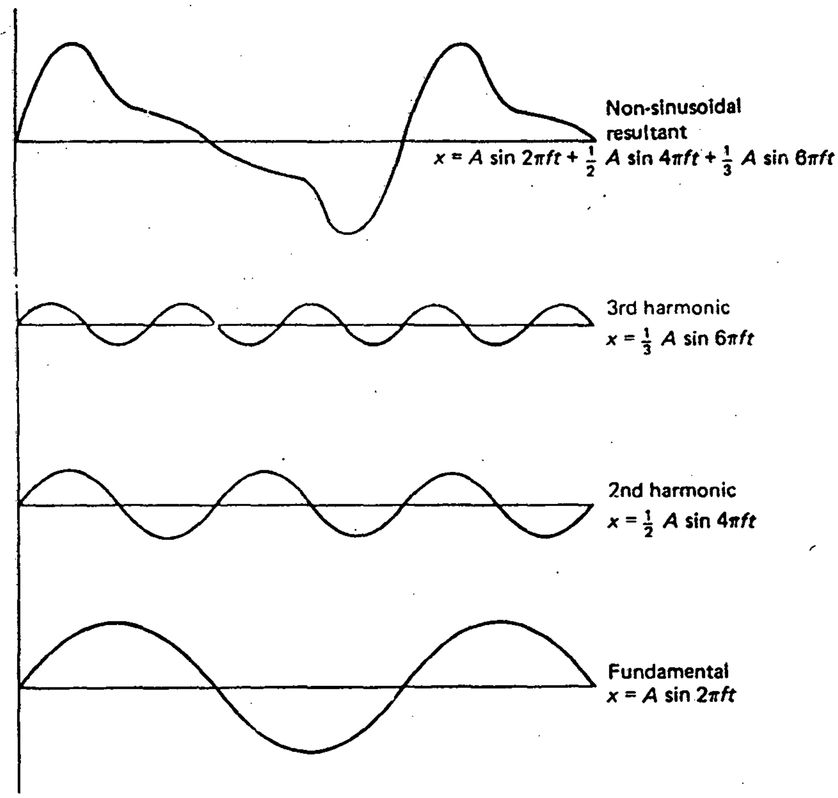


Fig. 3.1. Example of a Fourier Series

3.2 SOUND PRESSURE

Sound travels as a wave of compression and rarefaction with an associated wave of pressure variation. In most practical problems, it is the pressure variation that is of greater importance and of greater interest. The acoustic pressure at any point is the difference between the actual pressure at that point in the presence of sound and the pressure that would exist at that point, under identical conditions, in the absence of any sound. This acoustic over pressure at any point varies sinusoidally with time, and it is convenient to use the root mean square or r.m.s., value. This is defined as the square root of the average of the squares of the instantaneous pressures. In mathematical notation,

$$p_{r.m.s}^2 = \frac{1}{T}\int_0^T p^2 dt \qquad (3.1)$$

If two sounds of different frequencies act together, then the total r.m.s. sound pressure p_t is given by,

$$p_{t,r.m.s}^2 = p_{1,r.m.s}^2 + p_{t,r.m.s}^2 \qquad (3.2)$$

If a sound covers a continuous band of frequencies, then we have,

$$p_{t,r.m.s}^2 = \int p_{r.m.s}^2 df \qquad (3.3)$$

This illustrates a matter of fundamental importance, namely that r.m.s. sound pressures of different frequencies cannot be added linearly or arithmetically.

3.3 INTENSITY

A source of sound radiates power which is transmitted in the form of sound. The sound power of a source is the total power coming from it. It is the rate at which energy in the form of sound leaves the source. If we consider a point some distance from the source, and a small area perpendicular to the line joining the point to the source, then some of the power being generated by the source will be transmitted through the area. The amount of power transmitted will depend not only on the sound power of the source, but also on its directional properties, the distance of the area from the source and the presence of sound absorbing or sound reflecting materials. If the power passing through an area A is W, then we define the intensity I as power per unit area, or

$$I = \frac{W}{A} \tag{3.4}$$

Although the intensity of a sound is an important quantity, it is difficult to measure, whereas sound pressure can be measured quite readily. There is, however, a relationship between the two. This is

$$I = \frac{p_{r.m.s}^2}{\rho c} \tag{3.5}$$

where ρ is the density of the air or other medium and c is the velocity of sound in the medium.

The intensity, although fluctuating, is always positive. This is clear from a consideration of the physical meaning and from the mathematics. Since I is proportional to p^2 which must always be positive the time average of the intensity will also positive.

3.4 DECIBELS

Just as the frequencies in which we are interested cover a large range, so do the actual values of sound pressure, intensity and power, and it is therefore convenient to measure them on a logarithmic scale. The scale chosen for this is the decibel scale. The word decibel is fundamentally a ratio of powers. If we wish to compare two powers w_1 and w_2 watts, the definition is that

$$10\log\left(\frac{w_1}{w_2}\right) = \text{decibel level of } w_1 \text{ above } w_2,$$

Where the logarithms are taken to the base 10 and the numerical value is given in decibels, dB. However, a particular value of the decibel level does not specify the value of a quantity unless a reference value with which all values are to be compared is specified. The decibel scale is applied to sound measurements by means of the following definitions:

Sound Power Level SWL = 10 log (W/W_0) dB re W_0

Intensity Level IL = 10 log (I/I_0) dB re I_0

Sound pressure Level SPL = 20 log (p^2/p_0^2) dB re p_0

In these definitions all quantities are r.m.s. values.

The word level implies that the quantity is being measured as a ratio to a special reference magnitude, and the ratio is expressed in decibels. The terms re W_0, re I_0, and re p_0 simply mean that we are using W_0, I_0, and p_0 as standard reference values with respect to which all our measurements are going to be made. The usual values used in acoustics are:

$$W_0 = 10^{-12}\ \text{W}$$

$$I_0 = 10^{-12}\ \text{Wm}^{-2} = 10^{-16}\ \text{Wcm}^{-2}$$

$$p_0 = 0.00002\ \text{Nm}^{-2} = 0.0002\ \text{dyne cm}^{-2}$$

$$= 20\mu\text{Pa (micro Pascal)}$$

Decibels cannot be added arithmetically. In general, if two quantities x and y are measured on the decibel scale with respect to a reference value a, we have by definition

$$B_x = 10 \log (x/a)$$

$$B_y = 10 \log (y/a)$$

Then, the sum

$$B = 10 \log (x/a + y/a)$$

An advantage of the decibel scale is that it does correspond roughly to our subjective response to physical stimuli. This is expressed in the Weber-Frechner Law which states that the response varies as the logarithm of the stimulus [33].

3.5 SUBJECTIVE PARAMETERS OF HEARING

Although quantities such as temperature, humidity and air velocity can be measured with a considerable degree of accuracy, it is far from simple to find any very precise correlation between such physical measurements and any one individual's personal feeling of comfort. The same problem arises in interpreting sound measurements and in particular in deciding how the amplitudes and frequencies are related to the feeling of loudness. In spite of the difficulty of all subjective measurements, it is necessary to have some means of estimating how people are likely to react to a sound of known physical qualities. Thus, the basis of all sound criteria is a statistical investigation into the reactions of a large number of people. By means of such investigations, a considerable amount of information has been obtained about the way a human ear responds to acoustic vibrations.

3.5.1 LOUDNESS LEVEL CONTOURS (PHONS)

The three main subjective qualities of sound are its loudness, pitch and timbre. Of these by far the most important is loudness. The loudness corresponds largely to the intensity and sound pressure level, but it is also a function of frequency. If we plot sound pressure level along the *y*-axis and frequency along the *x*-axis, then any point on the graph represents a pure sound of one frequency and one intensity. Suppose a sound of some other frequency and intensity appears equally loud to a large number of people, or to the statistically average listener, we now have two points which can be described as equally loud. A line joining all points which appear to the average listener to be equally loud as the first sound is called an equal loudness contour. The process can be repeated for sounds of some other loudness to produce any number of such curves, and so build up a chart of equal loudness contours, such as shown in fig.3.2. The SPL at the point where the curve touches or crosses the 1000 Hz ordinate is called the loudness level in phons of that particular equal loudness contour. All points lying on the same contour have the same loudness expressed in phons. The loudness level of any sound in phons can be defined as the SPL of a pure tone of 1000 Hz which sounds equally loud to the average listener. This definition makes the phon scale logarithmic in exactly the same way as the decibel scale of SPL.

3.5.2 THE SONE SCALE

The development of the phon scale is fairly straightforward yet it is deficient in the sense that the numbers assigned to this scale do not correspond to a listener's intuitive evaluation of relative loudness. Stated another way, apparent loudness bears little relationship to loudness level. For example, a noise of 80 phons is judged by a typical listener to be much louder than twice that of 40 phons. Even a small change in loudness level, from 40 to 50 phons seems to correspond to a doubling of apparent loudness.

To resolve this difficulty the International Standards Organization, in 1947, adopted a new subjective scale called the sone scale. The intent of this scale was to establish a more reasonable relationship between loudness level and subjective loudness. The sone scale has the following features; first, a sone is defined as the loudness of a 1000 Hz tone of 40 dB intensity level. It is also the loudness of any sound having a

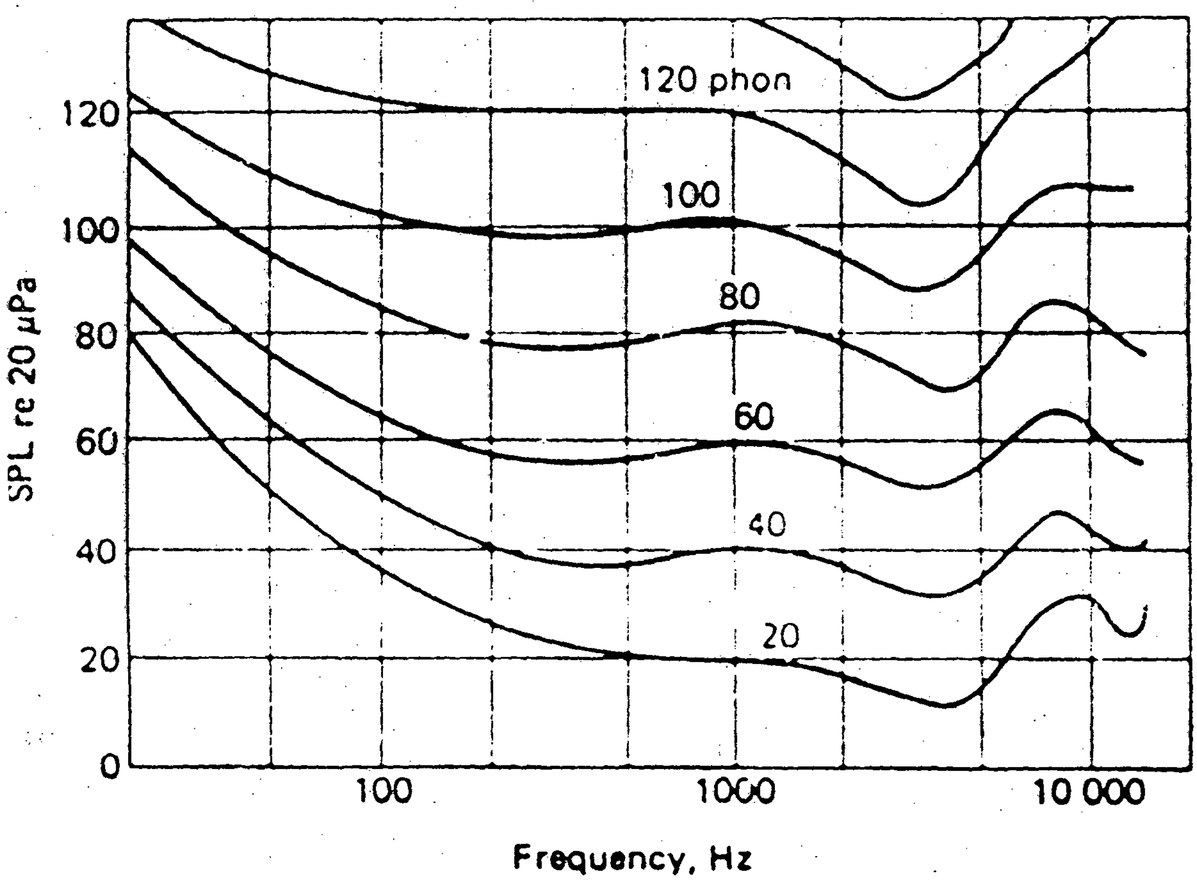


Fig. 3.2. Equal loudness contours

loudness level of 40 phons. Second, the sone scale is arranged so that a 10 phon change in the loudness level corresponds to a doubling or halving of loudness. On the basis of these two prerequisites and for loudness levels of 20 to 120 phons, the relationship between the numerical values of loudness level P (in phons) and loudness S (in sones) is given by

$$S = 2^{(P-40)/10}$$

Or

$$S = \text{antilog}\,[0.03(P-40)] \text{ sones} \qquad (3.6)$$

The sone scale has a definite advantage of representing loudness in terms of human hearing.

3.5.3. LOUDNESS INDEX, ANNOYANCE, AND PERCIEVED NOISE LEVEL

Most noise sources generate sound over a wide range of frequencies. Thus, it would be advantageous if we could relate sound intensity and spectral composition, using bands of frequencies, that is, octave, 1/3 octave, and so on. Also several investigators have attempted to determine what makes some sound more "annoying" than other sounds. In this paper, we shall be using two methods: (1) the loudness index of Steven's [36] based on octave and 1/3 octave-band analysis and (2) the Kryter [37] method for noisiness or annoyance.

STEVENS' METHOD

The Stevens' method of calculating loudness requires the use of Fig.3.3 or tables. Since this loudness index graph is based on loudness judgements of a large number of observers, it is useful in subjective measurements for persons of normal hearing. In this method, the sound pressure levels (Lp) in each of the eight octave band centre frequencies are recorded. Then the loudness index of the observed noise for each octave band is obtained from the graph. The total loudness of the noise in sones S_t, is given by $S_t = S_m + F(S - S_m)$ where S_m is the largest of all the loudness indices and S is the sum of the loudness indices of all of the bands. $F = 0.3$ for octave bands and $F = 0.15$ for 1/3 octave bands. The total loudness level is then obtained by converting the total loudness (in sones) to a calculated loudness, P, (in phons) by means of equation 3.6.

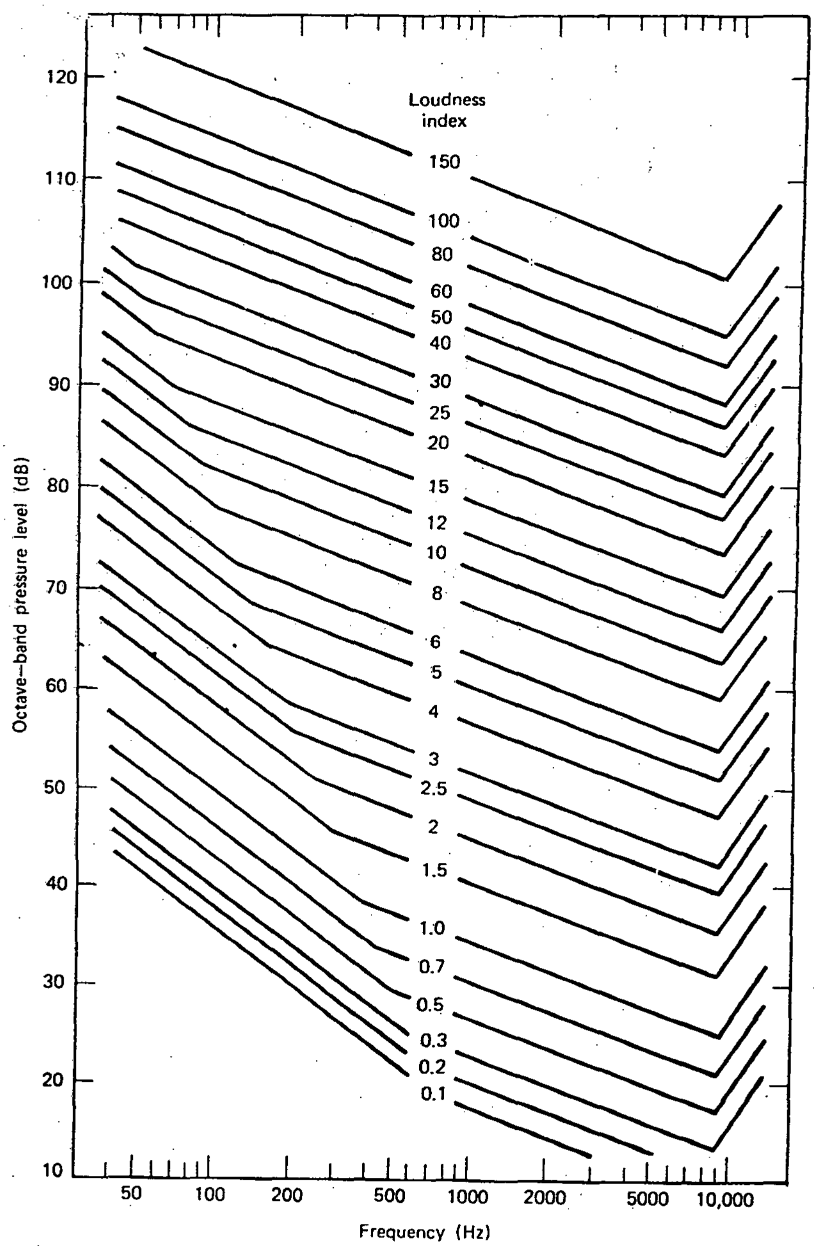


Fig. 3.3. Contours developed by Stevens. A loudness level index in sones can be determined by measuring the sound pressure level of the eight octave bands.

KRYTER'S METHOD

The degree to which sounds may be really annoying is more complex than determining loudness. Here we are faced with psychological effects. There is a general agreement that the following considerations relate to the degree of annoyance.

a. High frequencies are usually more annoying than low frequencies, at comparable sound levels
b. A continuous noise or one that is repeated periodically with only short intervening times is more annoying than infrequent periods of noise of short duration.
c. People do not object to noise of moderate intensities unless they can identify the source or at least the direction associated with the sound.
d. The annoying character of noise depends on the time of day and the activity of the listener
e. Noises produced by machines appear to be more annoying than natural sounds of equal loudness (rain, wind, waterfalls, surf).
f. Even loud sounds are not too annoying provided that the frequency of occurrence is very low.

The Kryter method for determining annoyance does not consider all of these factors. It does, however, give a greater weighting to the higher frequencies than does the Steven's criteria. Also, the Kryter scheme was designed to assess noisiness, rather than loudness, particularly with respect to sounds from aircrafts. Fig.3.4 shows Kryter's equal noisiness contours [38] for converting octave or 1/3 octave bands of noise into units that he denotes as noys. The annoyance N_t of noise is determined by summing the contributions of the various bands:

$$N_t = N_m + F\,(\Sigma N - N_m) \qquad (3.7)$$

Where N_t is the total annoyance, N_m is the largest contribution in noys of any band, ΣN is the sum of all the contributions, and the function $F = 0.15$ for 1/3 octave bands and 0.3 for octave bands.

The total noisiness N_t (in noys) can also be converted into a rating that is called the perceived noise level (PNdB), by using the Steven's formula for converting sones to phons. That is

$$N_t = 2^{(x-40)/10}$$

Hence

$$x = 40 + \frac{100}{3}\log_{10} N_t \quad (3.8)$$

where x is the perceived noise level in PNdB.

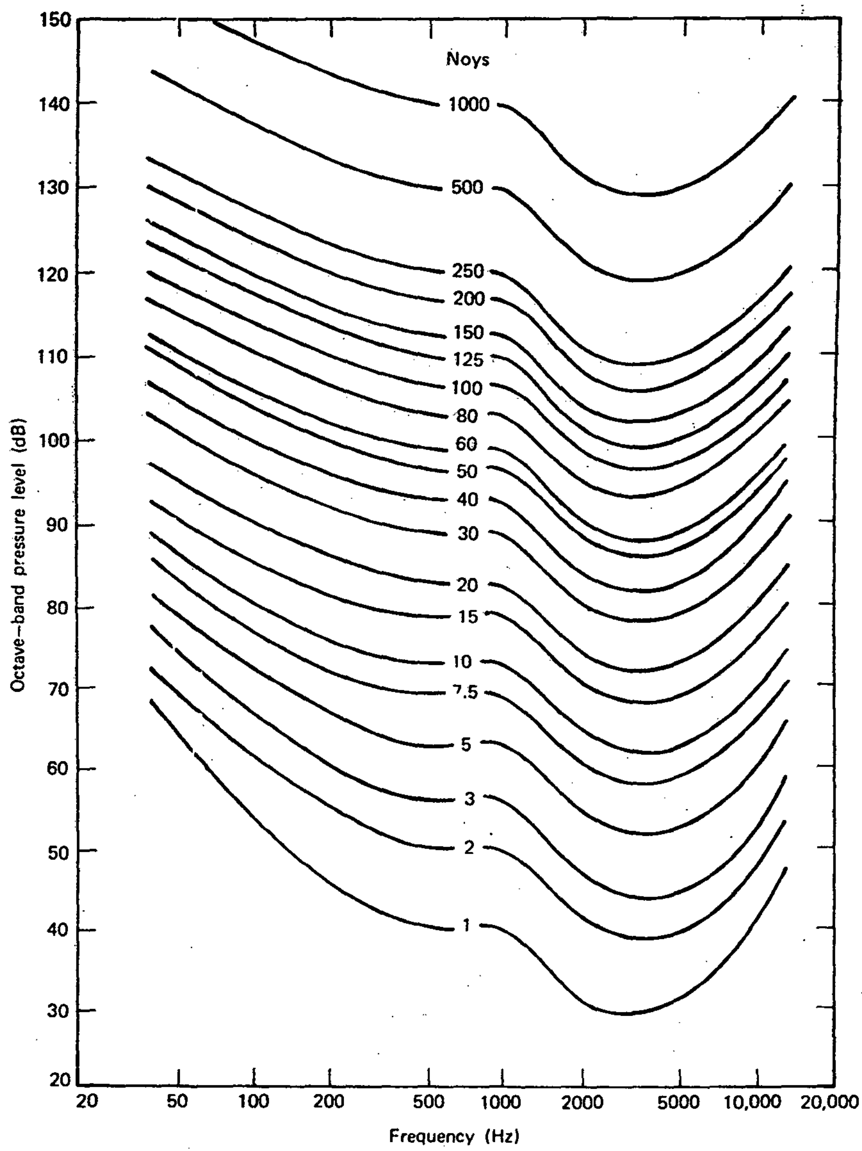


Fig. 3.4. Kryter's contours of perceived noisiness (noys) that are used to determine annoyance.

3.6. STATISTICAL ANALYSIS

PEARSON'S DISTRIBUTIONS

Given a set of observations from a population, the first question that arises in our mind is about the nature of the parent population. A vague idea is provided by the frequency polygon (or the frequency curve) but the information is totally inadequate and unreliable, because the sample observations may not cover the entire range of the parent distribution. Moreover, an unusually high frequency in one class, arising out of sheer chance, may completely distort the shape of the frequency curve.

Consequently, to determine the frequency curve, we resort to the technique of curve fitting to the given data. The failure of the normal distribution to fit many distributions which are observed in practice for continuous variables necessitated the development of generalised system of frequency curves. Since a trial and error approach is clearly undesirable, an elastic system of frequency curves must be evolved, which should incorporate, if not all, at least the most common of the distributions. Pearsonian system of frequency curves is one of the most important approaches in this direction, in which we decide about the shape of the curve on the basis a 'criterion κ' calculated from the sample observations.

Frequency distributions rise from a low frequency to a maximum frequency and then again fall to the low frequency as the variable x increases. This suggests a unimodal frequency curve $y = f(x)$ with high contact at the extremities of the range, i.e., $\frac{dy}{dx} = 0$ when $y = 0$. Accordingly, Karl Pearson [40] proposed the following differential equation for the frequency curve $y = f(x)$,

$$\frac{dy}{dx} = \frac{y(x-a)}{F(x)} \qquad (3.11)$$

where $F(x)$ is an arbitrary function of x not vanishing at $x = a$, the mode of the distribution. Expanding $F(x)$ by Maclaurin's theorem, we get $F(x) = b_0 + b_1 x + b_2 x^2 + \ldots..$ and retaining only the first three terms we get the differential equation of the Pearsonian system of frequency curve as

or,
$$\frac{dy}{dx} = \frac{y(x-a)}{b_0 + b_1x + b_2x^2}$$
$$\frac{df(x)}{dx} = f'(x) = \frac{(x-a)f(x)}{b_0 + b_1x + b_2x^2} \qquad (3.12)$$

where a, b_0, b_1 and b_2 are the constants to be calculated from the given data, given by

$$b_0 = -\frac{\mu_2(4\mu_2\mu_4 - 3\mu_3^2}{2(5\mu_2\mu_4 - 9\mu_2^3 - 6\mu_3^2)} = -\frac{\sigma^2(4\beta_2 - 3\beta_1)}{2(5\beta_2 - 6\beta_1 - 9)}$$
$$a = b_1 = -\frac{\mu_3(\mu_4 + 3\mu_2^2)}{2(5\mu_2\mu_4 - 9\mu_2^3 - 6\mu_3^2)} = -\frac{\sigma\sqrt{\beta_1}(\beta_2 + 3)}{2(5\beta_2 - 6\beta_1 - 9)} \qquad (3.13)$$
$$b_2 = -\frac{(2\mu_2\mu_4 - 3\mu_3^2 - 6\mu_3^2)}{2(5\mu_2\mu_4 - 9\mu_2^3 - 6\mu_3^2} = -\frac{(2\beta_2 - 3\beta_1 - 6)}{2(5\beta_2 - 6\beta_1 - 9)}$$

where $\mu_2 = \sigma^2$, $\beta_1 = \frac{\mu_3^2}{\mu_2^3}$ and $\beta_2 = \frac{\mu_4}{\mu_2^3}$; μ_2, μ_3, and μ_4 are the second, third and fourth moments. Integrating equation 3.12, we get,

$$f(x) = \int \frac{(x-a)}{b_0 + b_1x + b_2x^2} dx = I(say),$$

where c is the constant of integration.

Therefore, $f(x) = c \exp [\, I \,]$

Thus f depends on I, which further depends on the roots of the equation

$$b_0 + b_1x + b_2x^2 = 0$$

We define $\kappa = \frac{b_1^2}{4b_0b_2}$ (3.14)

The value of κ determines the criterion for obtaining the form of the frequency curve.

Zero type (Normal curve): When $\beta_1 = 0$ and $\beta_2 = 3$, we have the normal distribution with mean zero and variance σ^2.

Pearson's Main Type I: This curve is obtained when the roots of the quadratic equation are real and of opposite sign i.e., when $\kappa < 0$. Beta distribution is a particular case of Type I distribution.

Type II: this curve is obtained when $\kappa = 0$

Type III: this is a transition type curve and is obtained when $\kappa \rightarrow \pm \infty$. The curve is usually bell shaped but becomes J-shaped when $\beta_1 > 4$.

Type IV: This curve is obtained when the roots are imaginary or when $0 < \kappa < 1$. The curve is skew and has unlimited range in both directions.

Type V: This is a transition type curve and is obtained when the roots are equal, i.e., when $\kappa = 0$.

Type VI: This curve is obtained when the roots are real and are of the same sign, i.e., when $\kappa > 1$.

3.7. SAMPLING AND MEASUREMENT PROCEDURE

A magnetic tape recorder (Sony TCM-400DV cassette-corder) was used for sampling of noise of the various CNG driven modes of public transport plying in the city of Delhi, viz, Delhi Transport Corporation (DTC) buses, Rural Transport Vehicles (RTVs) which were recently introduced as small passenger vehicles having a capacity of 10-15 seats, auto-rickshaws and taxies. The tape recorder has a frequency response of ±2dB from 50Hz to 12 kHz and signal to noise ratio of 50dB. The recorder is calibrated by recording a known sound pressure level at the octave band frequencies. The recorded signal is played back and the corresponding sound pressure levels are measured using an octave analyser (CRL, 2.37A). The analyser is a precision type I sound level meter with a facility to measure noise in linear mode at 1-octave band of central frequencies in the range of 31.5Hz to 16 kHz. The signal from the recorder is then recorded into a computer using GoldWave at a sampling rate of 16 kHz in stereo channel. GoldWave is a sound editor, player, recorder, and converter. It can create sound files for CDs, websites, answering machines, or Windows sounds. A full set of effects and editing features are included for professional sound production.

The number of vehicles in each mode of transport was 30 i.e., Buses (30), RTV (30), Auto-rickshaw (30) and Taxies (30). To examine the noise levels associated with different vehicles, lonely stretches of road were chosen as the sites for recording so that one can record the sound of a single vehicle as it passes by. Recording was done at a height 1m above ground level and the average speed of the vehicles at the time of recording were $\geq$ 30km/h i.e., under free flow condition. The measurements for each vehicle was made for a total duration of 10 seconds, 5 seconds as it approaches and 5 seconds as it recedes keeping in mind the sensitivity of the recorder.

The spectra of the recorded signals were analysed using PRAAT. PRAAT is computer program which can analyse, synthesize and manipulate sounds. With the help of this program, the spectro-temporal i.e., spectrogram of the signal is analysed. The horizontal direction of the spectrogram represents time, the vertical direction represents frequency and the time scale of the spectrogram is the same as that of the waveform. Darker parts of the spectrogram mean higher energy densities; lighter parts mean lower energy densities. The window length of the spectrogram was kept at 5ms. The spectral slice of the spectrogram gives the frequency content of the signal and the pressure levels at the octave band frequencies were noted at an interval of 1 second.

Chapter 4

RESULTS AND DISCUSSIONS

4.1. SPECTRAL CHARACTERISTICS

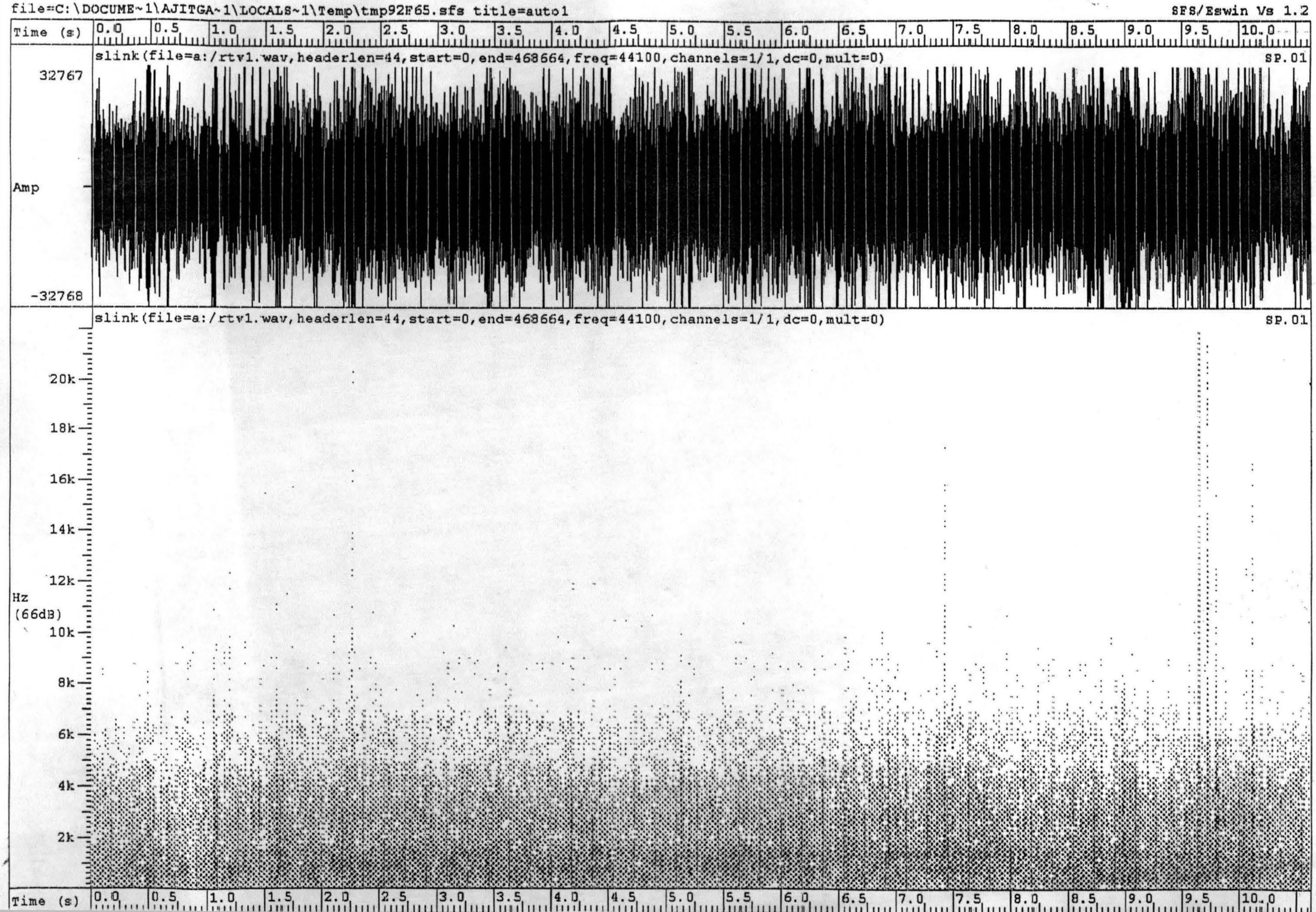
The spectrogram of the various modes of transport and their spectral slices are shown in fig.4.1-4.44. The spectrogram is a spectro-temporal representation of the sound. The horizontal direction of the spectrogram represents time and the vertical direction represents frequency. The time scale of the spectrogram is the same as that of the waveform as can be seen from the above figures. Darker parts of the spectrogram mean higher energy densities; lighter parts mean lower energy densities. The analysis window of the spectrogram has been fixed at 5 ms. This means that in order to know the spectrum at a particular time say 1sec. then signal information about all times 2.5ms before and after 1 sec. will be extracted. The spectral slice at a particular time shows the frequency contents of the signal and their energy densities at that time.

The spectral distribution for each type of vehicles at the octave band centre frequencies are shown in Fig.4.45 to Fig. 4.48. For all types of vehicles, the behaviours are similar, with 1000 Hz having the highest SPL, followed by 500 Hz. The SPL at 2000 Hz and 4000 Hz are comparable for all types of vehicles except for taxis where the difference in SPL between the two frequencies is appreciable. At the lower frequencies, i.e., 63 Hz, 125 Hz and 250 Hz, the 63 Hz has the highest SPL followed by 125 Hz and then 250 Hz. Not much difference exists between the SPL at 125Hz and 250 Hz for all types of vehicles except for RTVs where the value at 125 Hz is much higher. Of all the centre frequencies, the SPL at 8000 Hz fluctuated the most with time for all vehicle types as can be seen from the figures.

The spectral characteristics of the noise levels of each type of vehicles are compared at every octave band centre frequencies. These are shown in Figs. 4.49-4.56. At the lower frequencies, i.e., at frequencies up to 500 Hz, the SPL of RTVs was the highest, followed closely by Auto-rickshaws and buses. At all frequencies except at 8000 Hz, the level of taxis was the lowest. At 500 Hz, the levels of auto-rickshaws, RTVs and buses are comparable while at 4000 Hz, the levels of auto-rickshaws and RTVs are comparable in magnitude. An interesting observation is the spectral characteristics of auto-rickshaws and RTVs. It can be seen from the figures that for frequencies up to 500 Hz, their SPLs are comparable with the RTVs having slightly higher values except at 250 Hz where the value for auto-rickshaws take a dip. However, at frequencies higher than 1000 Hz, their difference is large with the auto-rickshaws having much higher values. As mentioned earlier, SPL fluctuations are quite pronounced at 8000 Hz for all types of vehicles as seen in fig. 4.56.

The time averaged noise levels (mean of SPL values over the duration of the measurement for a given frequency) as a function of frequency in all types of vehicles are shown in Fig.4.57. It is clear that noise levels in auto-rickshaws are appreciably higher than those of other vehicles. Though the general trend of noise levels as a function of frequency in all types of vehicles are similar, there are certain notable features. Whereas noise levels fall with increase in frequency from 63 Hz to 125 Hz and then increases from 125 Hz to 1000 Hz, for auto-rickshaws, noise levels decrease from 63 Hz to 250 Hz and then increases from 250 Hz to 1000 Hz at a much faster rate compared to other vehicles. Thereafter the behaviour of all four spectral curves is similar, with noise levels falling with increasing frequencies. However the rate of decrease in noise level from 4000 Hz to 8000Hz is much slower in taxis as compared to other vehicles.

It is worth noting from fig. 4.57 that the SPL levels are relatively higher between 500 Hz to 4000 Hz for all types of vehicles. Given the fact that the human ear is most sensitive around 1000 Hz to 4000 Hz, these vehicles are likely to induce adverse impacts on human health.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SFS/Eswin Vs 1.2
Time (s)
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Amp
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SP.01
20k
18k
16k
14k
12k
Hz
(66dB)
10k
8k
6k
4k
2k
Time (s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0

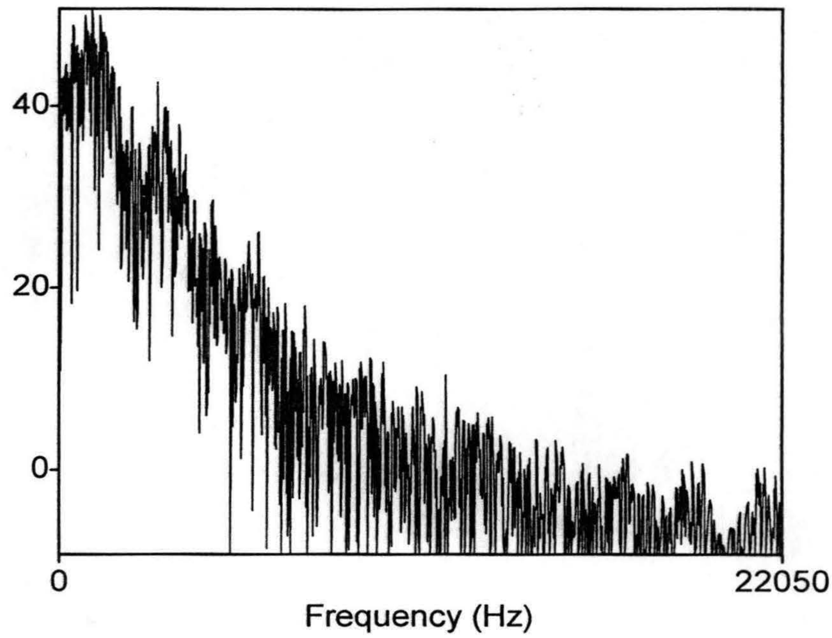


Fig.4.2. Spectrum slice at t = 1 sec. (Three wheeler)

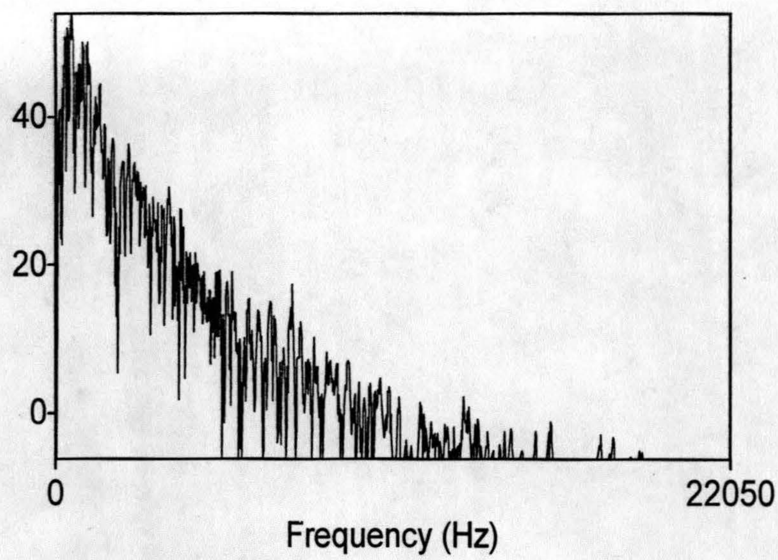


Fig.4.3. Spectrum slice at t = 2 secs. (Three wheeler)

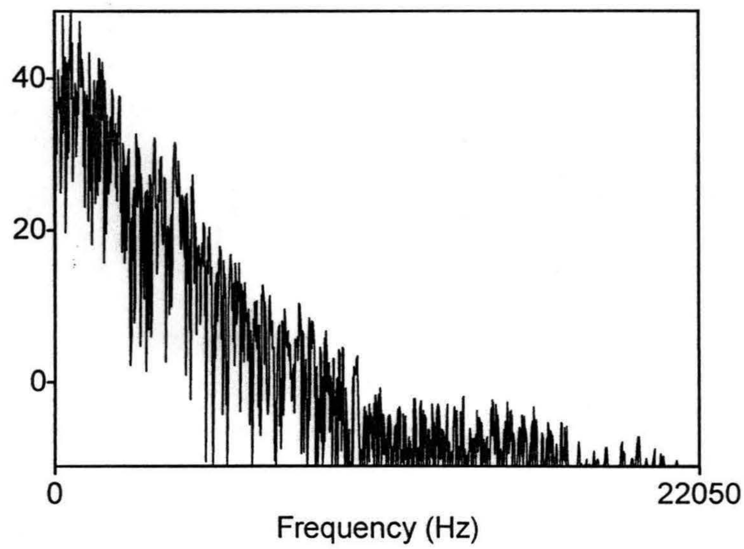


Fig.4.4. Spectrum slice at t = 3 secs. (Three wheeler)

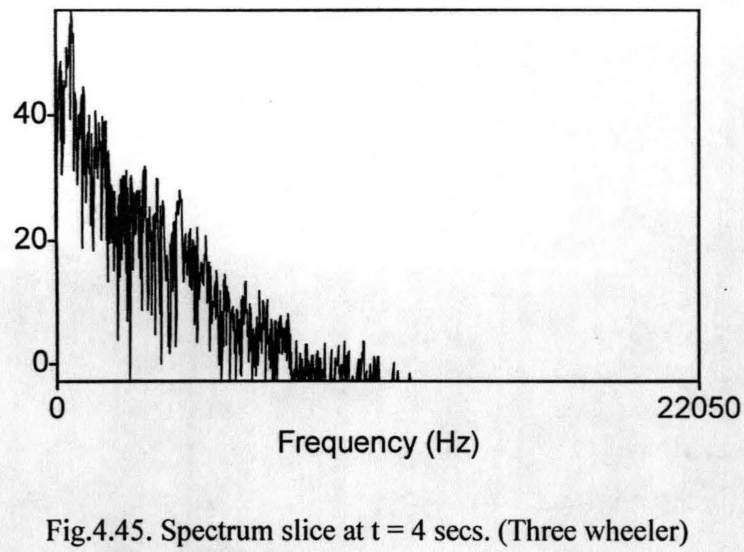


Fig.4.45. Spectrum slice at t = 4 secs. (Three wheeler)

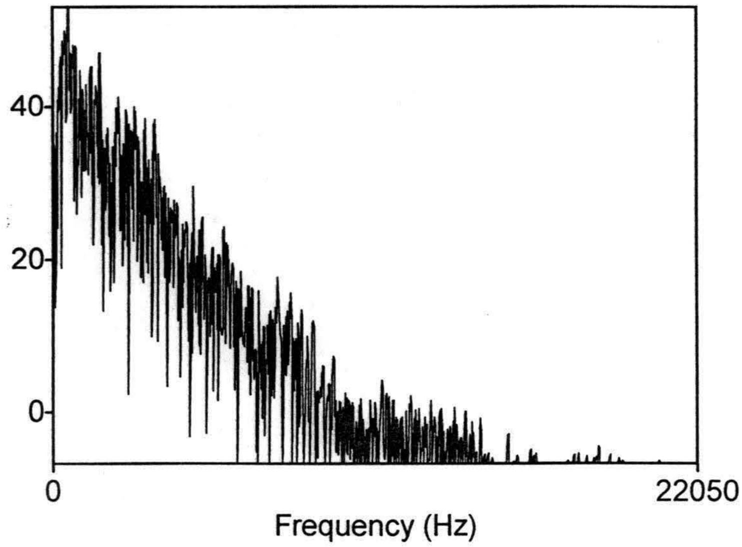


Fig.4.6. Spectrum slice at t = 5 secs. (Three wheeler)

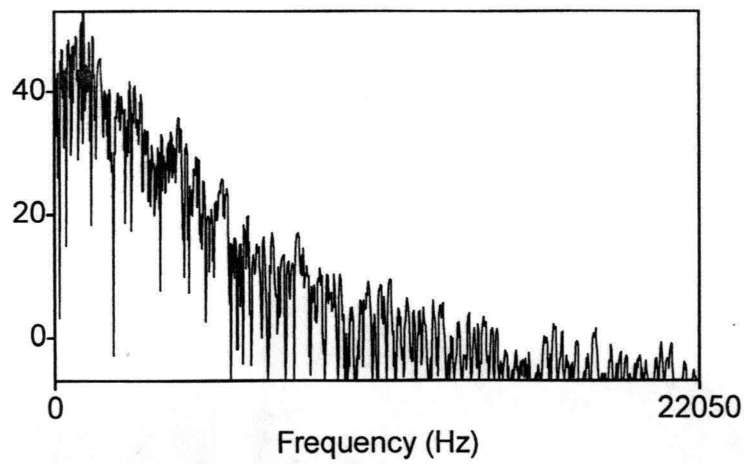


Fig.4.7. Spectrum slice at t = 6 secs. (Three wheeler)

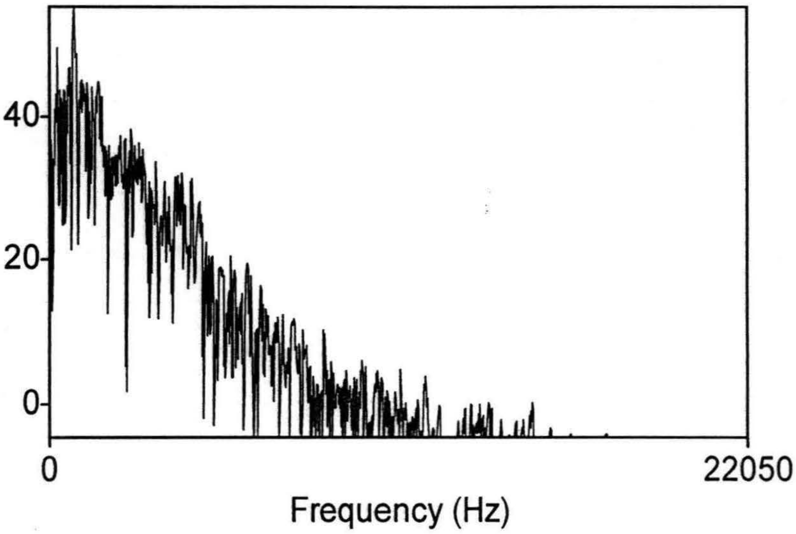


Fig.4.8. Spectrum slice at t = 7 secs. (Three wheeler)

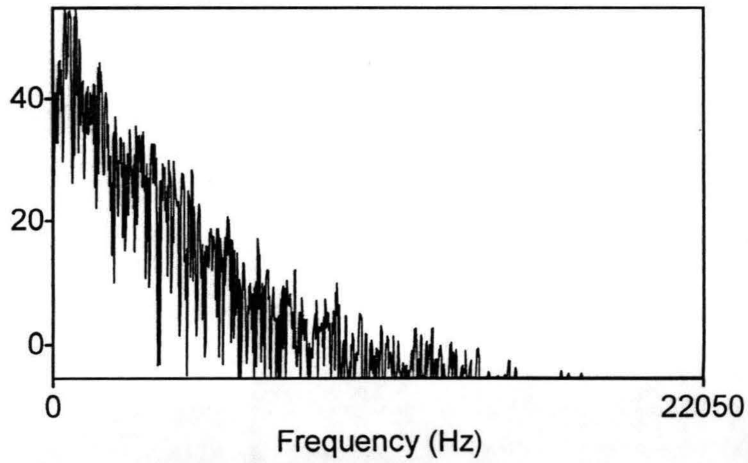


Fig.4.9. Spectrum slice at t = 8 secs. (Three wheeler)

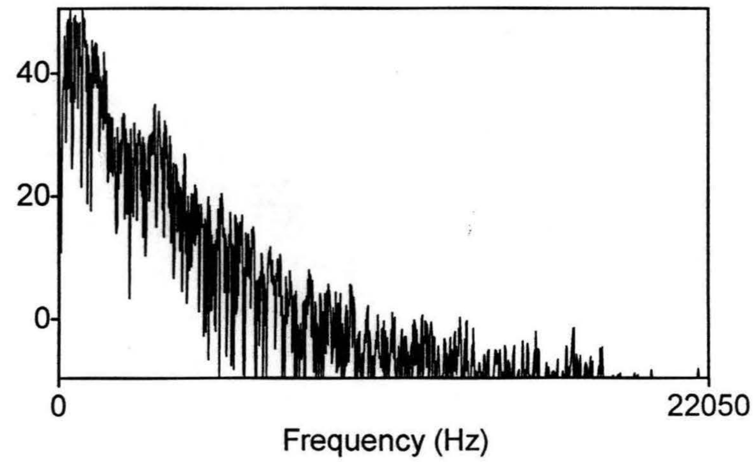


Fig.4.10. Spectrum slice at t = 9 secs. (Three wheeler)

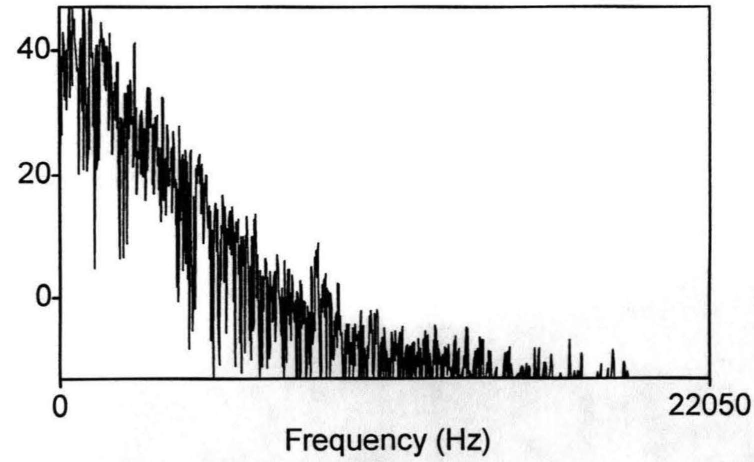


Fig.4.11. Spectrum slice at t = 10 secs. (Three wheeler)

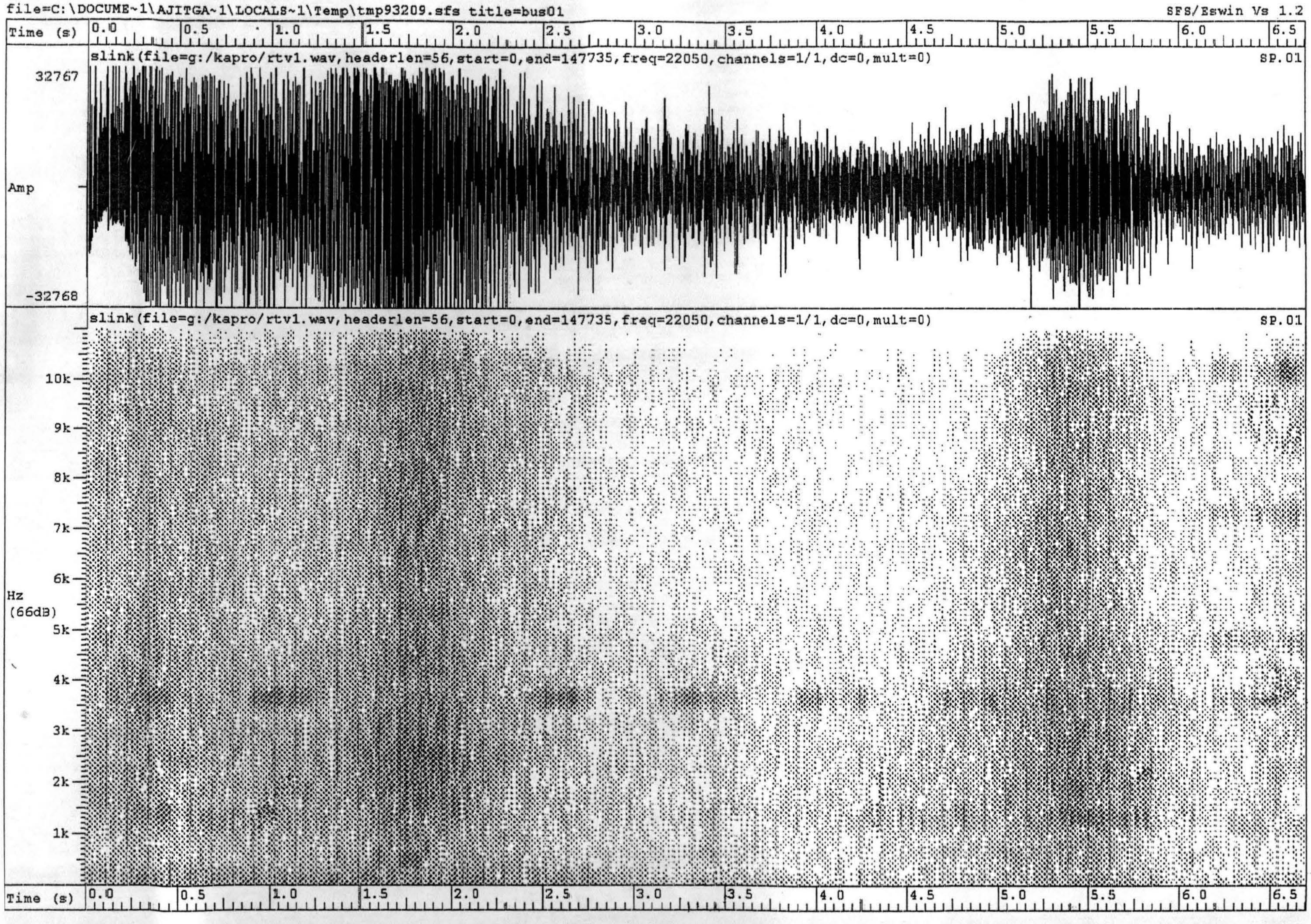


Fig. 4.12 Waveform and spectrogram for bus

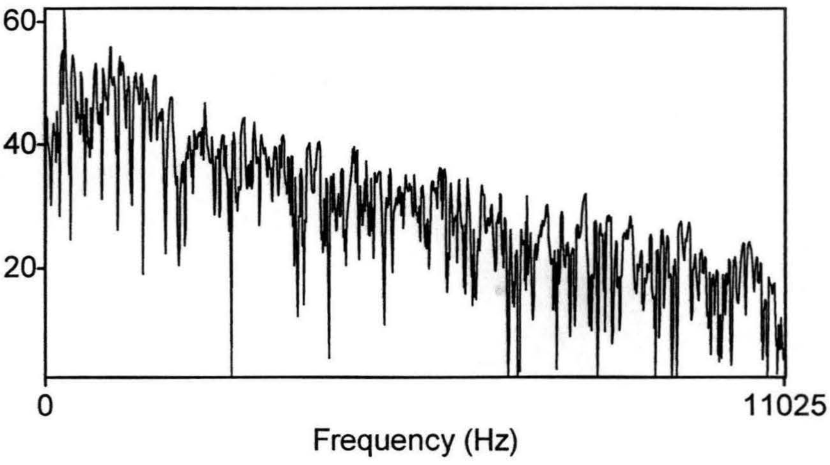


Fig.4.13. Spectrum slice at t = 1 sec. (Bus)

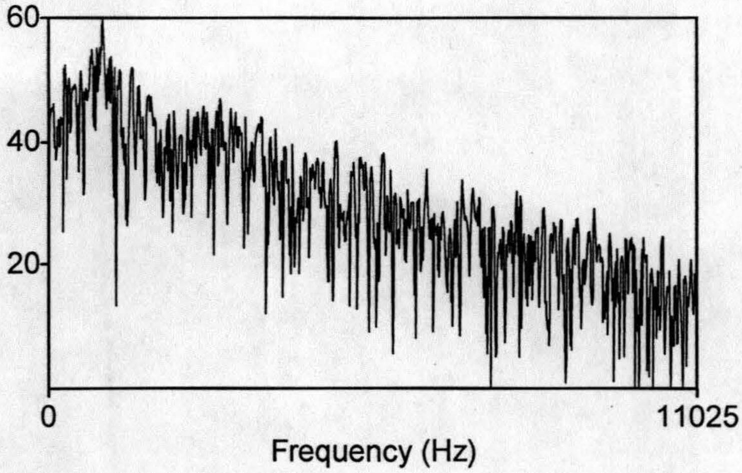


Fig.4.14. Spectrum slice at t = 2 secs. (Bus)

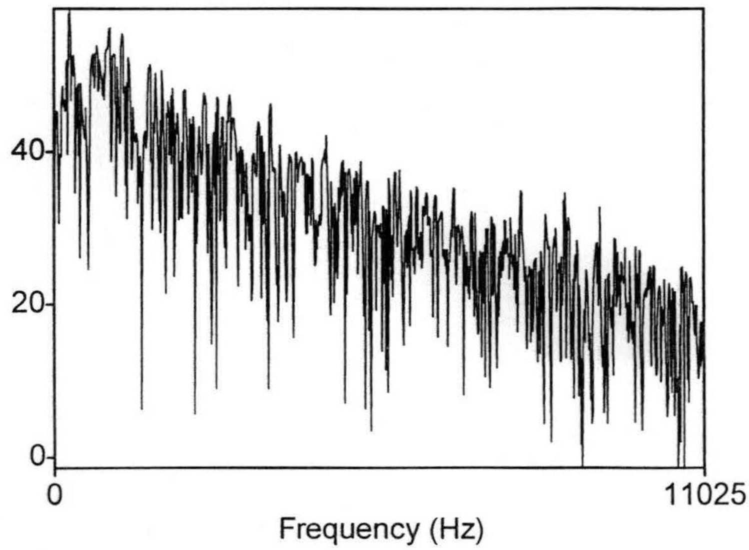


Fig.4.15 Spectrum slice at t = 3 secs. (Bus)

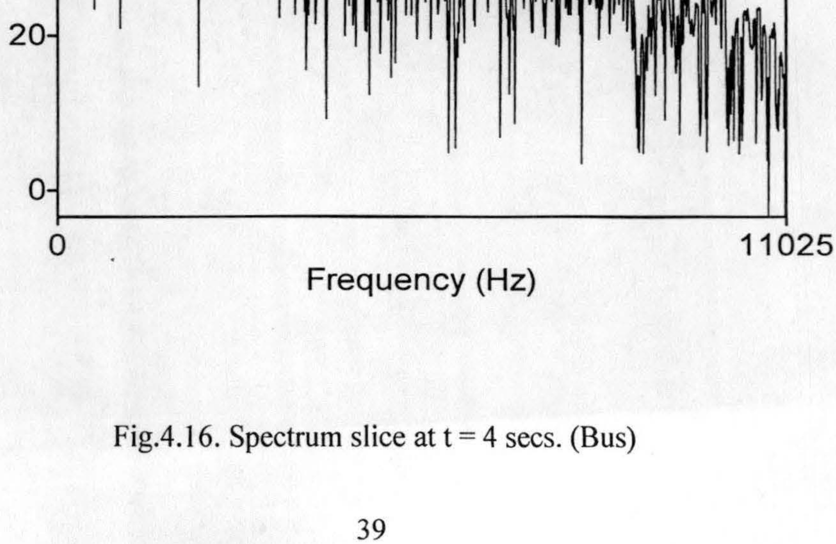


Fig.4.16. Spectrum slice at t = 4 secs. (Bus)

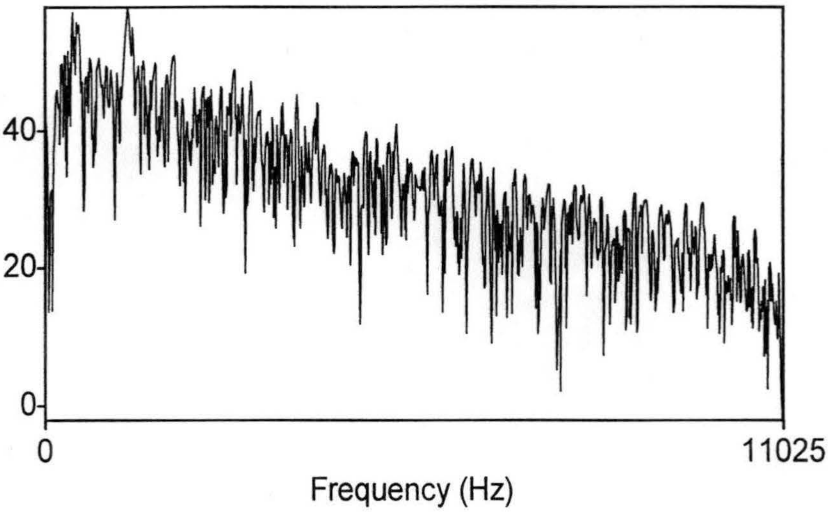


Fig.4.17. Spectrum Slice at t = 5 secs. (Bus)

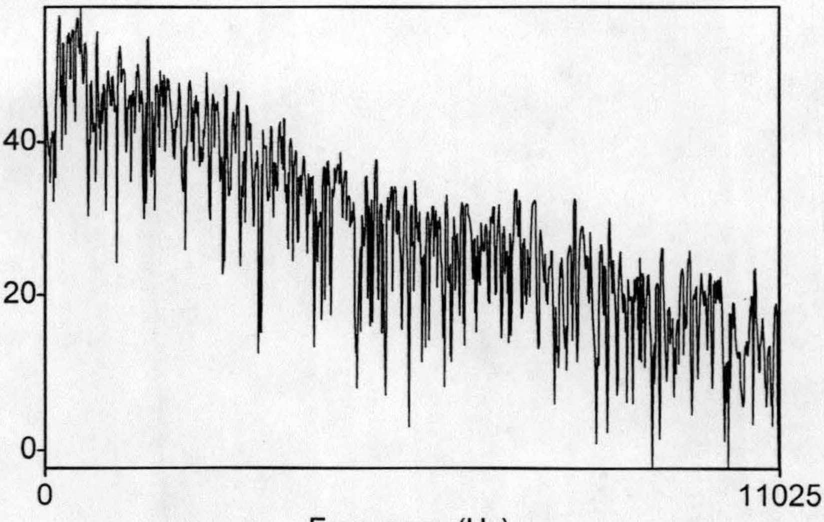


Fig.4.18. Spectrum slice at t = 6 secs. (Bus)

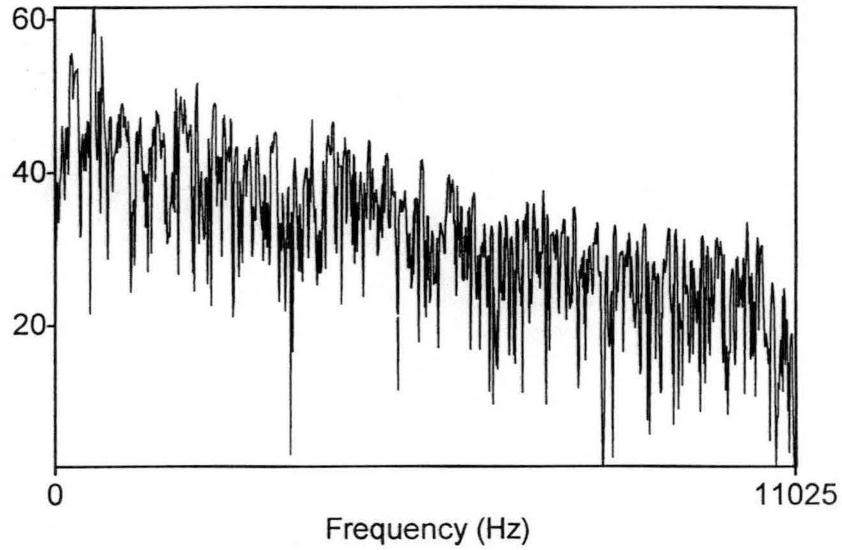


Fig.4.19. Spectrum slice at t = 7 secs. (Bus)

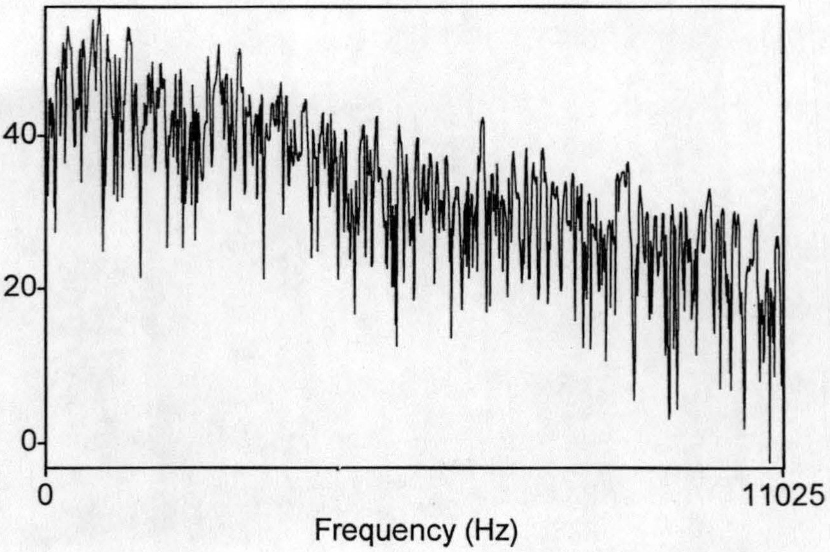


Fig.4.20. Spectrum slice at t = 8 secs. (Bus)

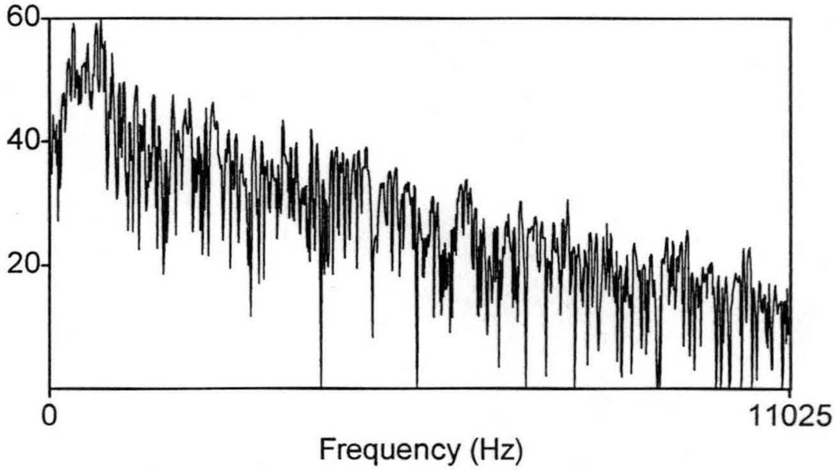


Fig.4.21. Spectrum slice at t = 9 secs. (Bus)

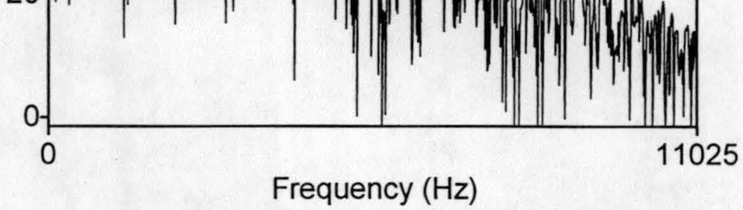
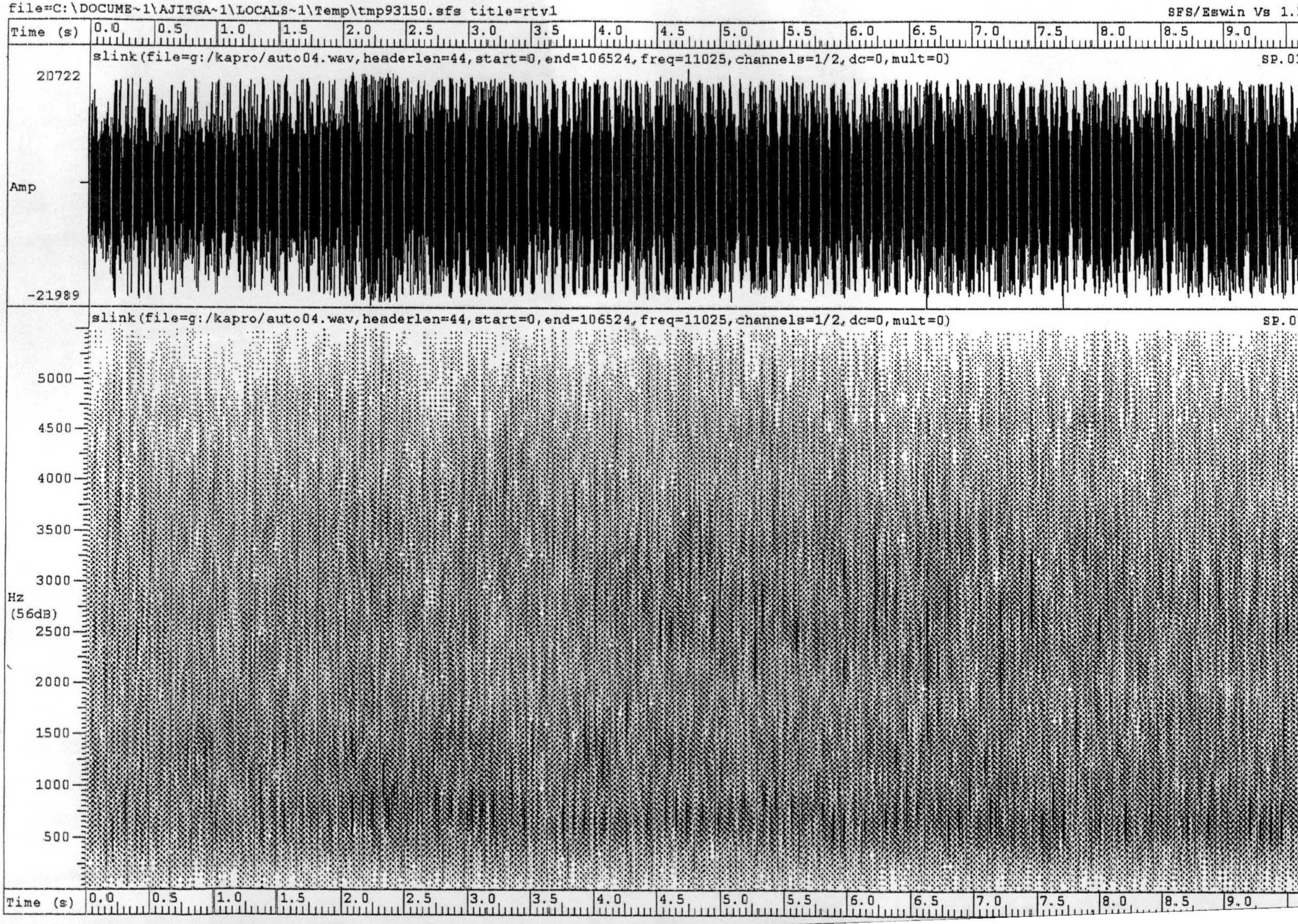


Fig.4.22. Spectrum slice at t = 10 secs. (Bus)



file=C:\DOCUME~1\AJITGA~1\LOCALS~1\Temp\tmp93150.sfs title=rtv1
SFS/Eswin Vs 1.2
Time (s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0
slink(file=g:/kapro/auto04.wav,headerlen=44,start=0,end=106524,freq=11025,channels=1/2,dc=0,mult=0)
SP.01
20722
Amp
-21989
slink(file=g:/kapro/auto04.wav,headerlen=44,start=0,end=106524,freq=11025,channels=1/2,dc=0,mult=0)
SP.01
5000
4500
4000
3500
3000
Hz
(56dB)
2500
2000
1500
1000
500
Time (s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0

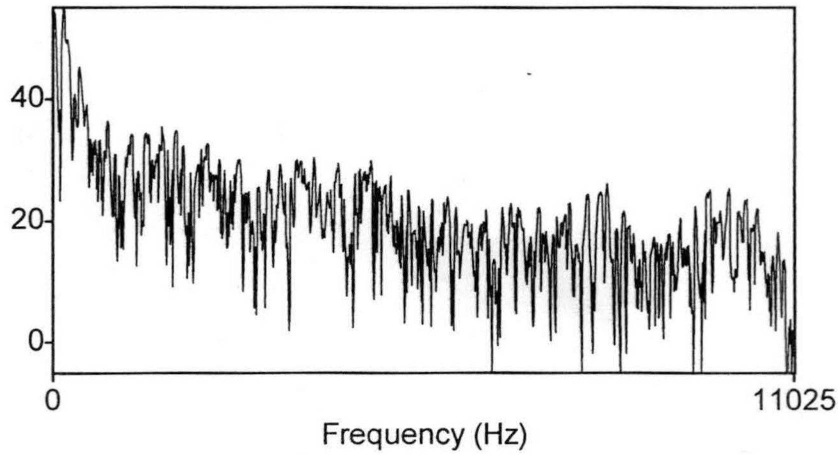


Fig.4.24. Spectrum slice at t = 1 sec. (RTV)

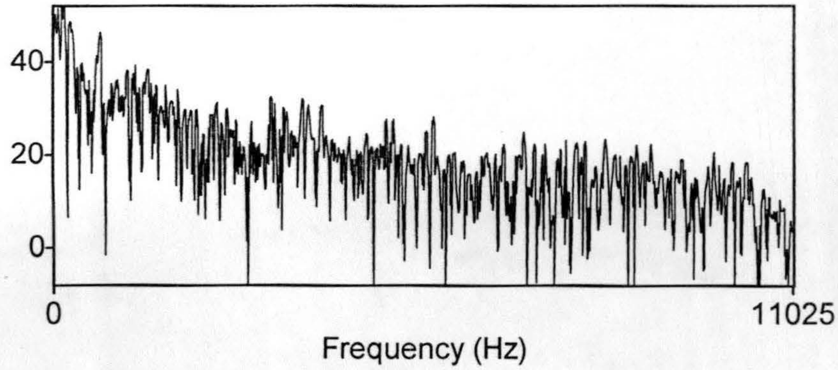


Fig.4.25. Spectrum slice at t = 2 secs. (RTV)

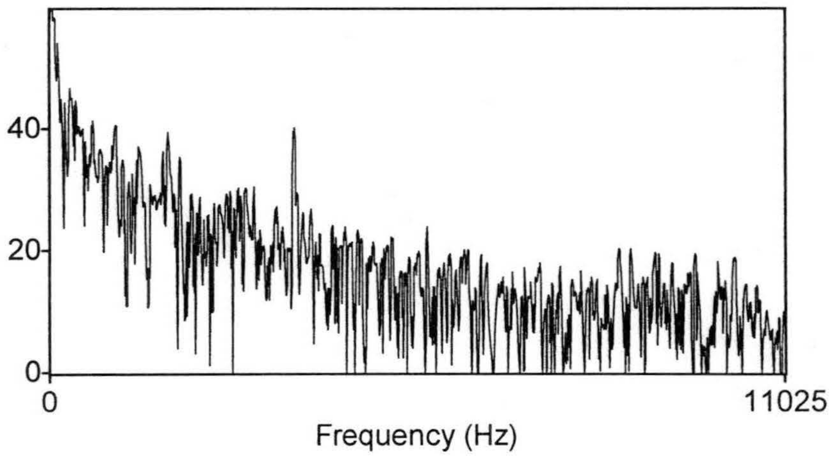


Fig.4.26. Spectrum slice at t = 3 secs. (RTV)

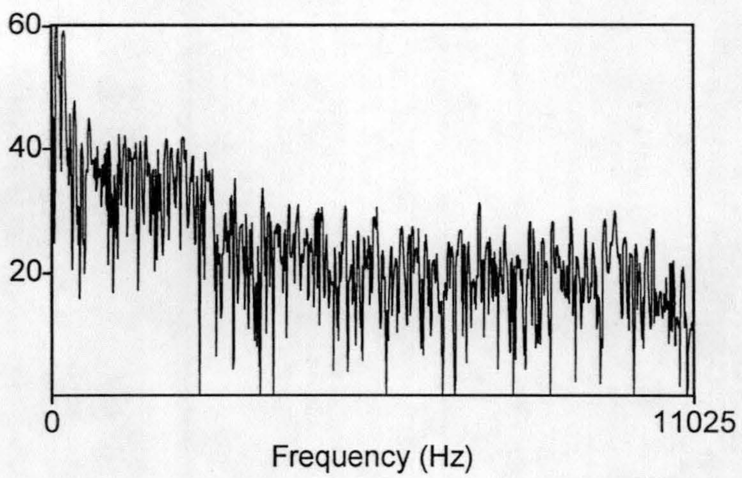


Fig.4.27. Spectrum slice at t = 4 secs. (RTV)

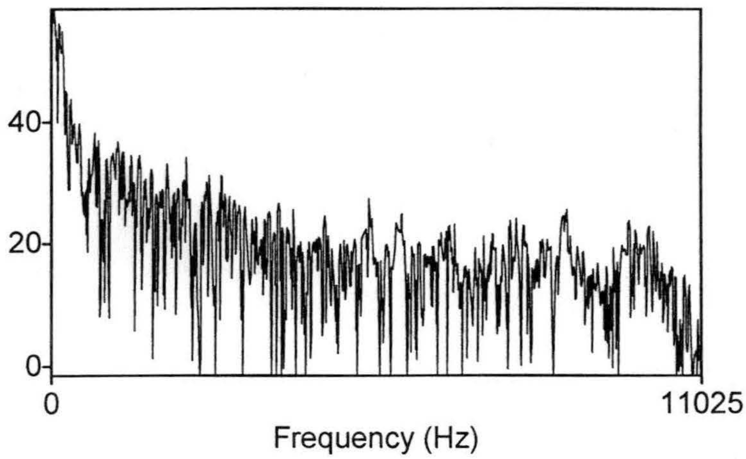


Fig.4.28. Spectrum slice at t = 5 secs. (RTV)

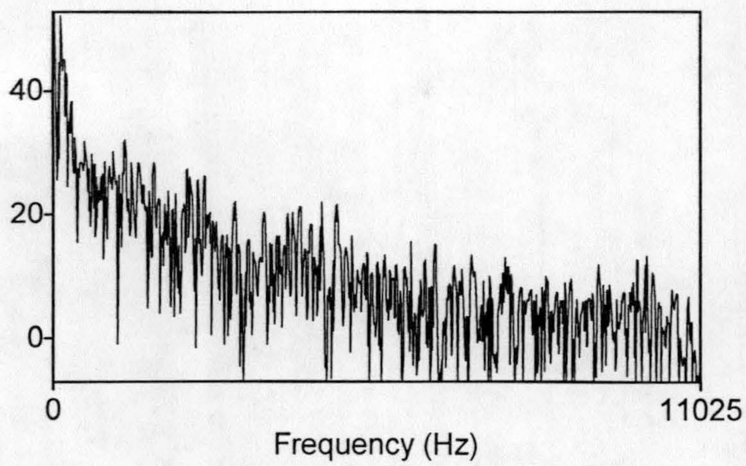


Fig.4.29. Spectrum slice at t = 6 secs. (RTV)

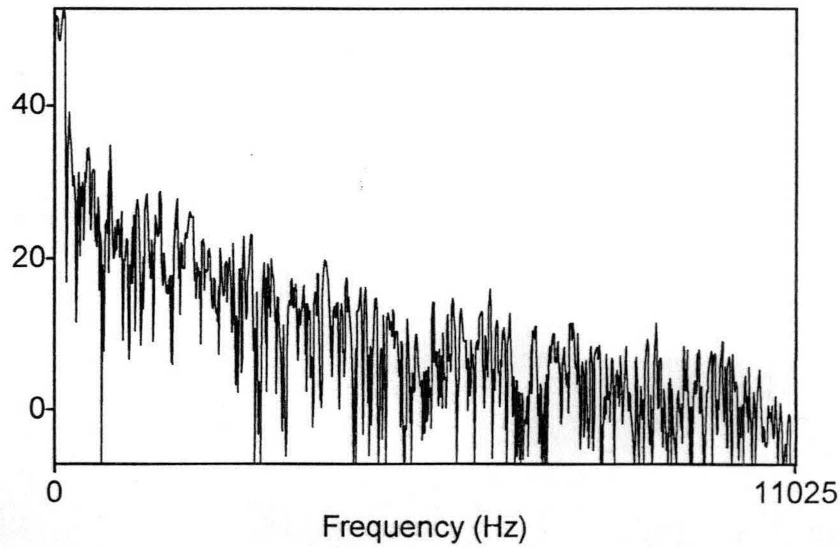


Fig.4.30. Spectrum slice at t = 7 secs. (RTV)

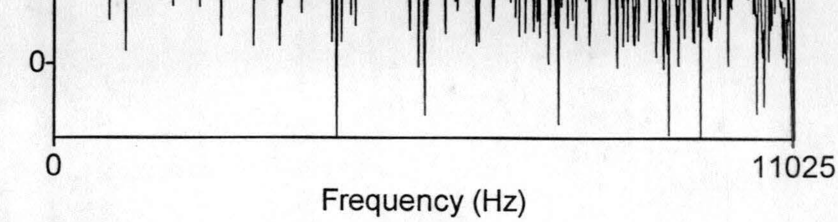


Fig.4.31. Spectrum slice at t = 8 secs. (RTV)

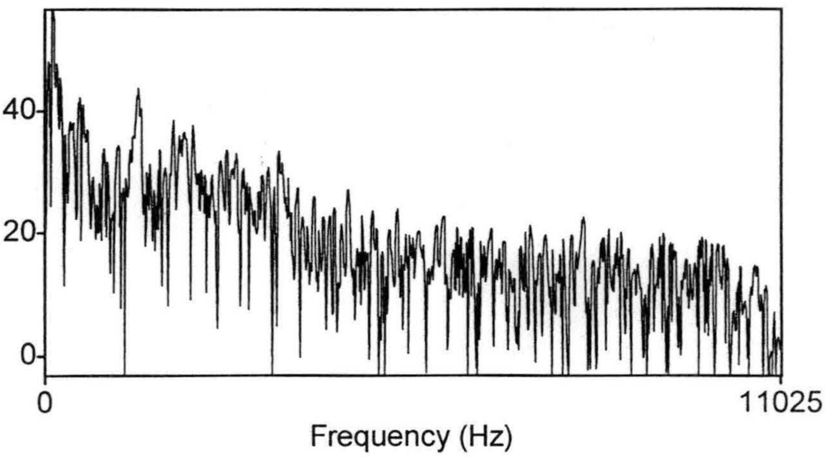


Fig.4.32. Spectrum slice at t = 9 secs. (RTV)

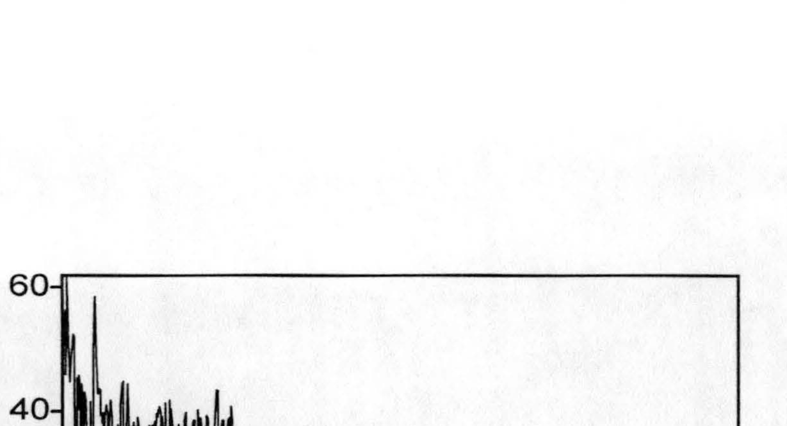
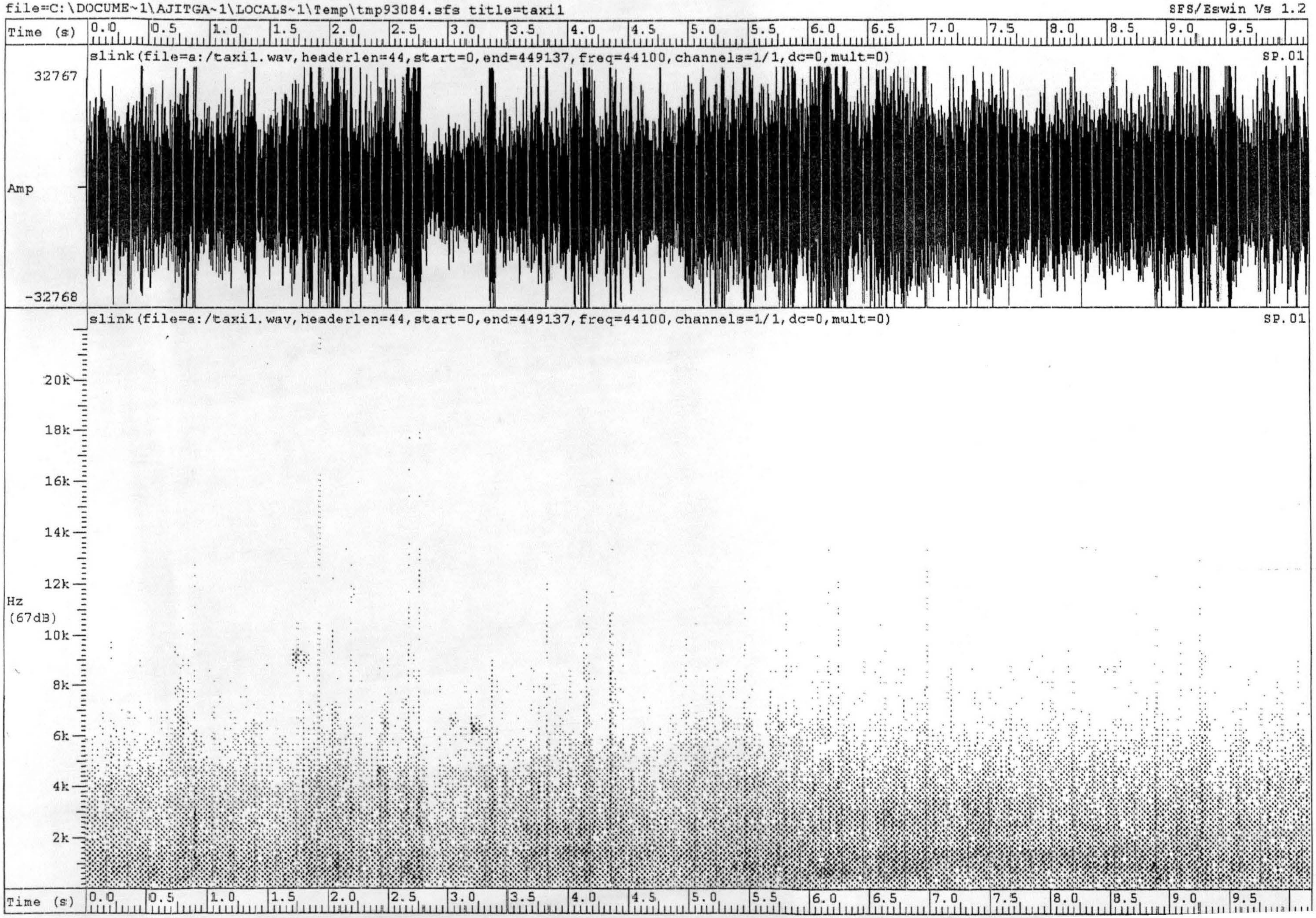


Fig.4.33. Spectrum slice at t = 10 secs. (RTV)



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SFS/Eswin Vs 1.2
Time (s)
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SP.01
32767
Amp
-32768
slink(file=a:/taxi1.wav,headerlen=44,start=0,end=449137,freq=44100,channels=1/1,dc=0,mult=0)
SP.01
Hz
(67dB)
Time (s)

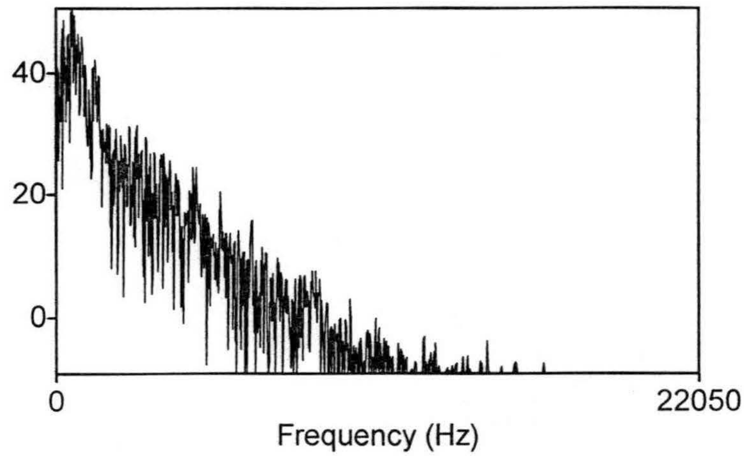


Fig.4.35. Spectrum slice at t = 1 sec. (Taxi)

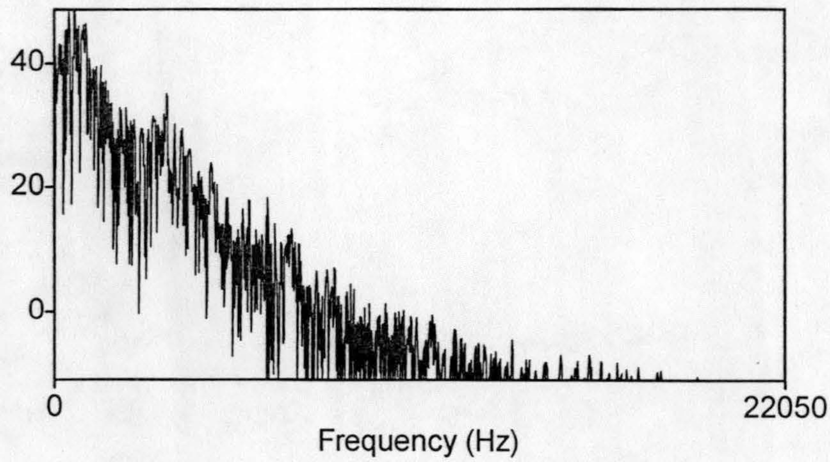


Fig.4.36. Spectrum slice at t = 2 secs. (Taxi)

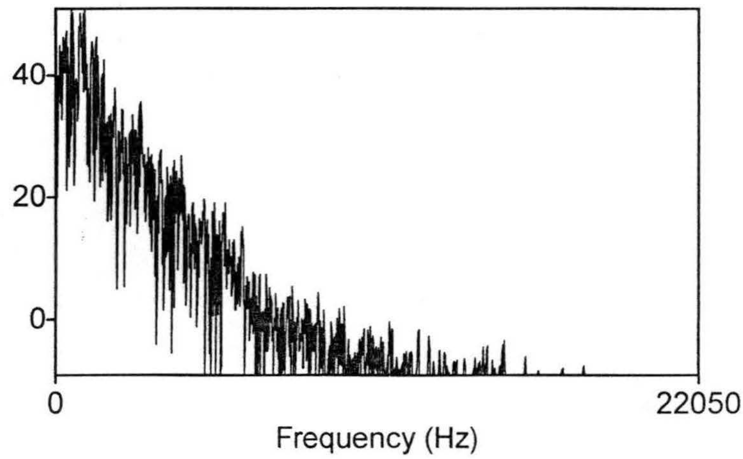


Fig.4.37. Spectrum slice at t = 3 secs. (Taxi)

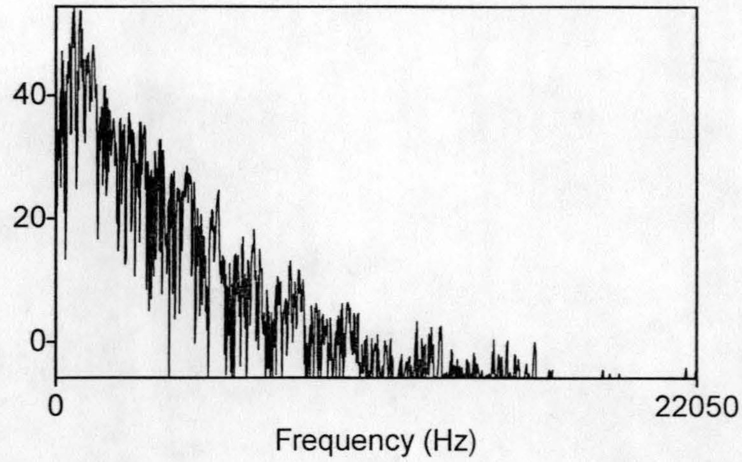


Fig.4.38. Spectrum slice at t = 4 secs. (Taxi)

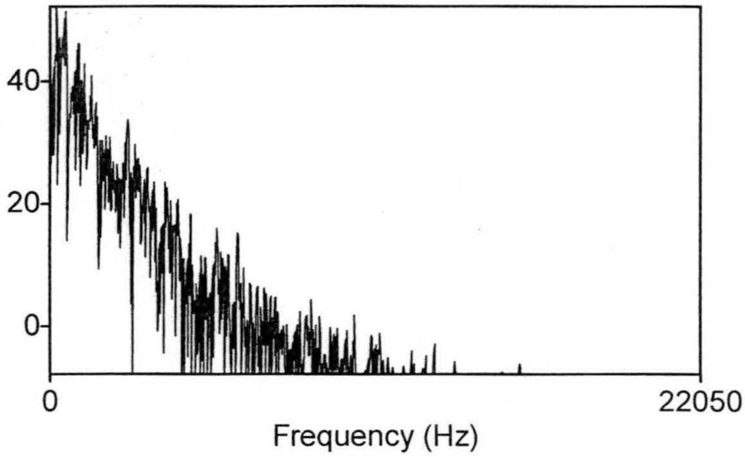


Fig.4.39. Spectrum slice at t = 5 secs. (Taxi)

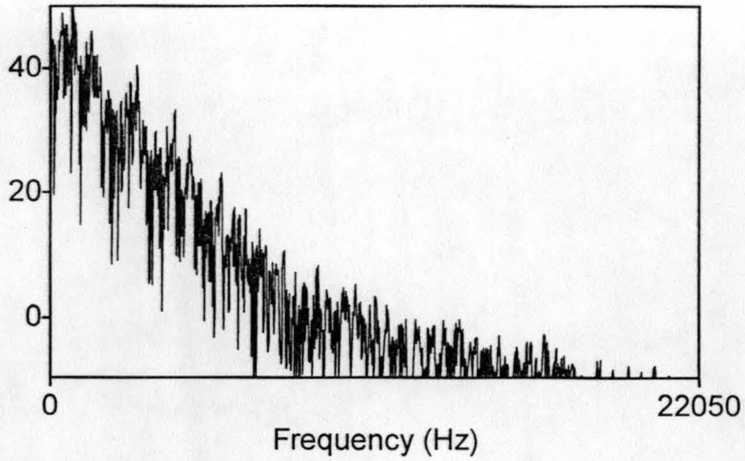


Fig.4.40. Spectrum slice at t = 6 secs. (Taxi)

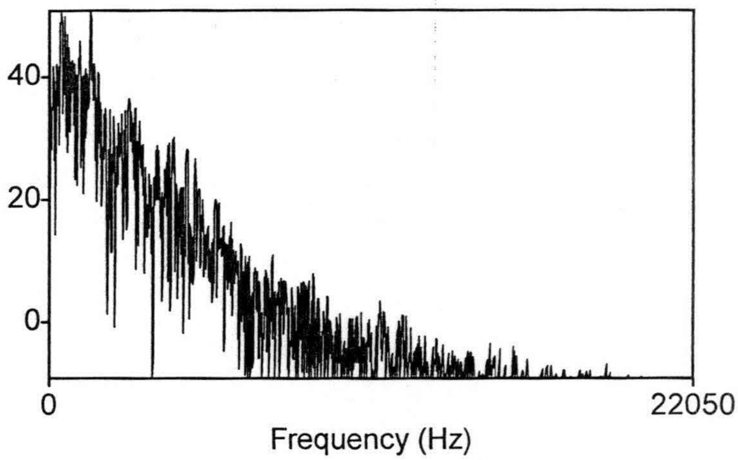


Fig.4.41. Spectrum slice at t = 7 secs. (Taxi)

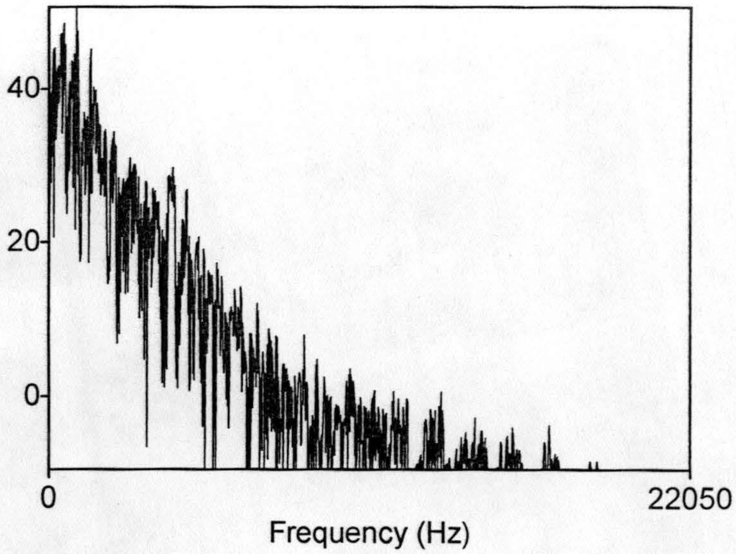


Fig.4.42. Spectrum slice at t = 8 secs. (Taxi)

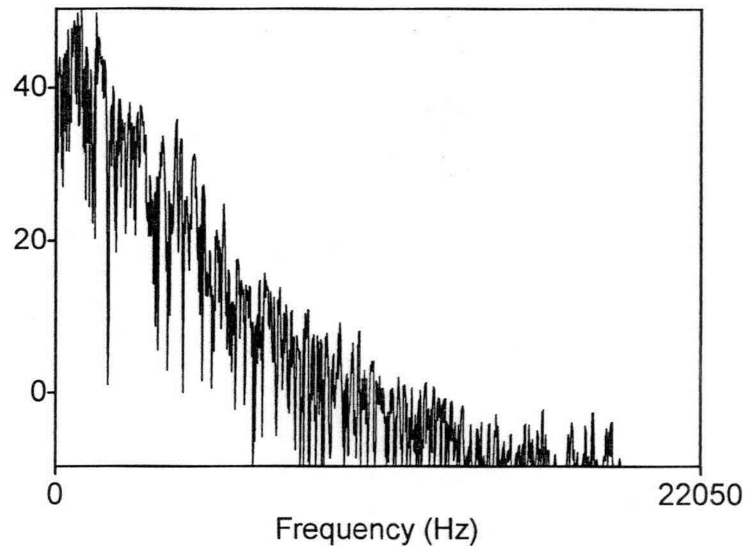


Fig.4.43. Spectrum slice at t = 9 secs. (Taxi)

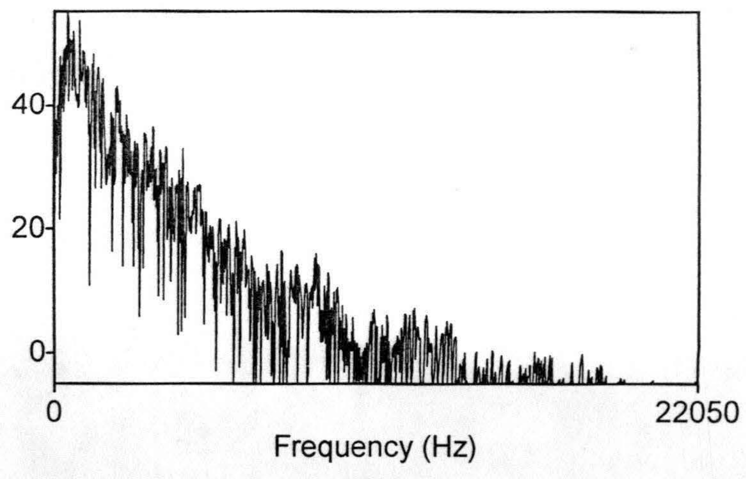


Fig.4.44. Spectrum slice at t = 10 secs. (Taxi)

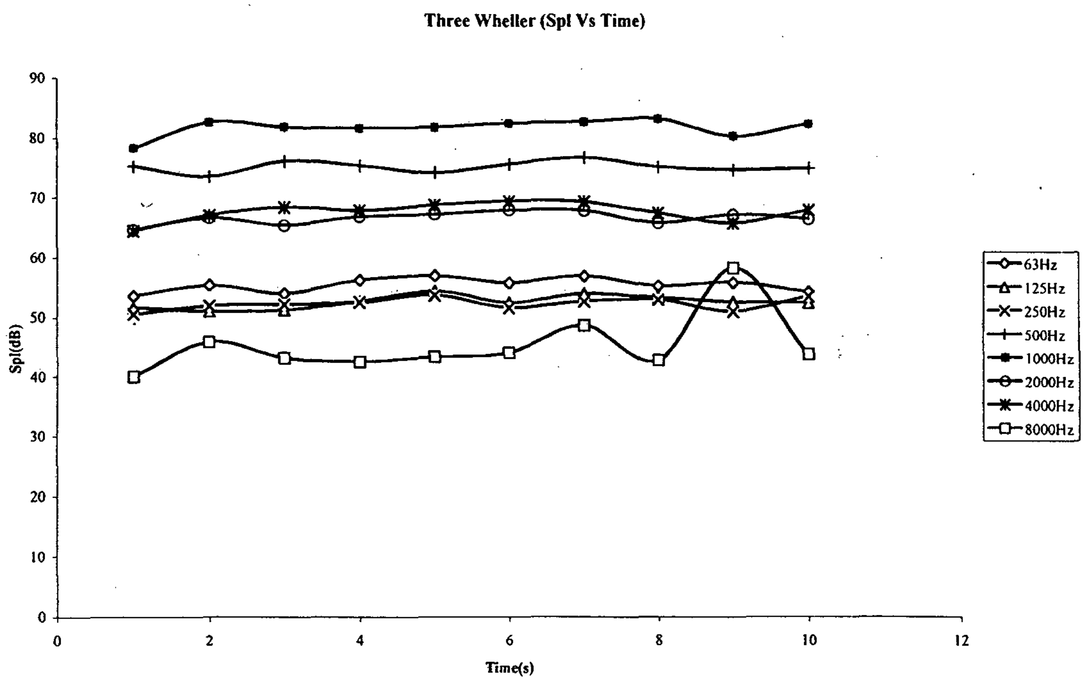


Fig.4.45. Temporal variation of SPL of three wheeler at octave band centre frequencies.

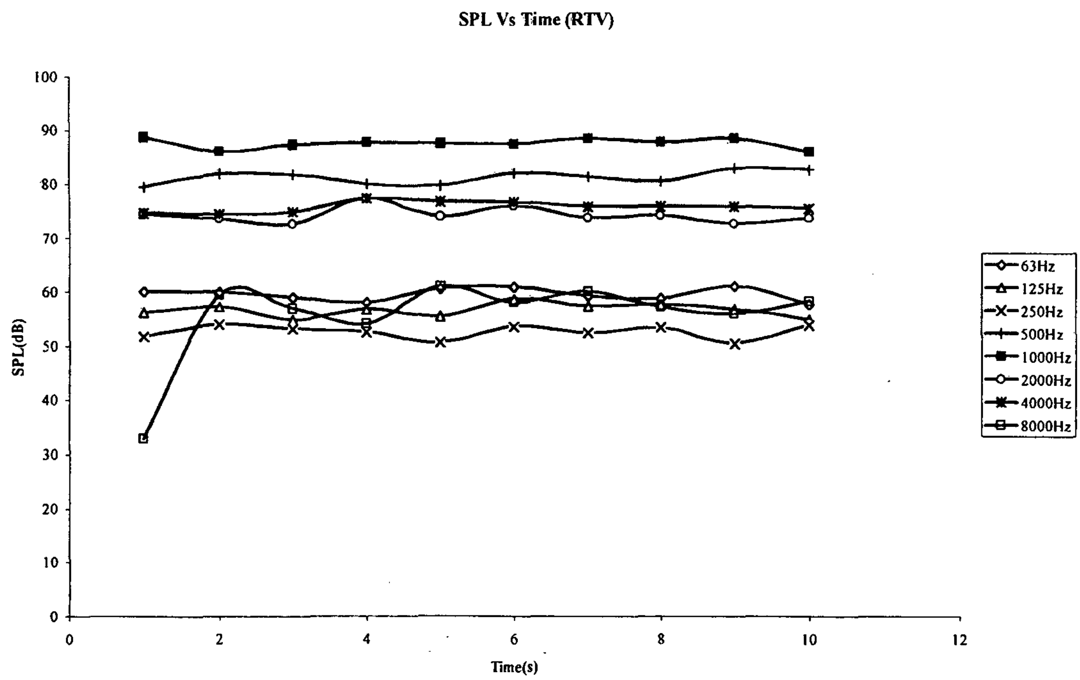


Fig.4.46. Temporal variation of SPL of RTVs at octave band centre frequencies.

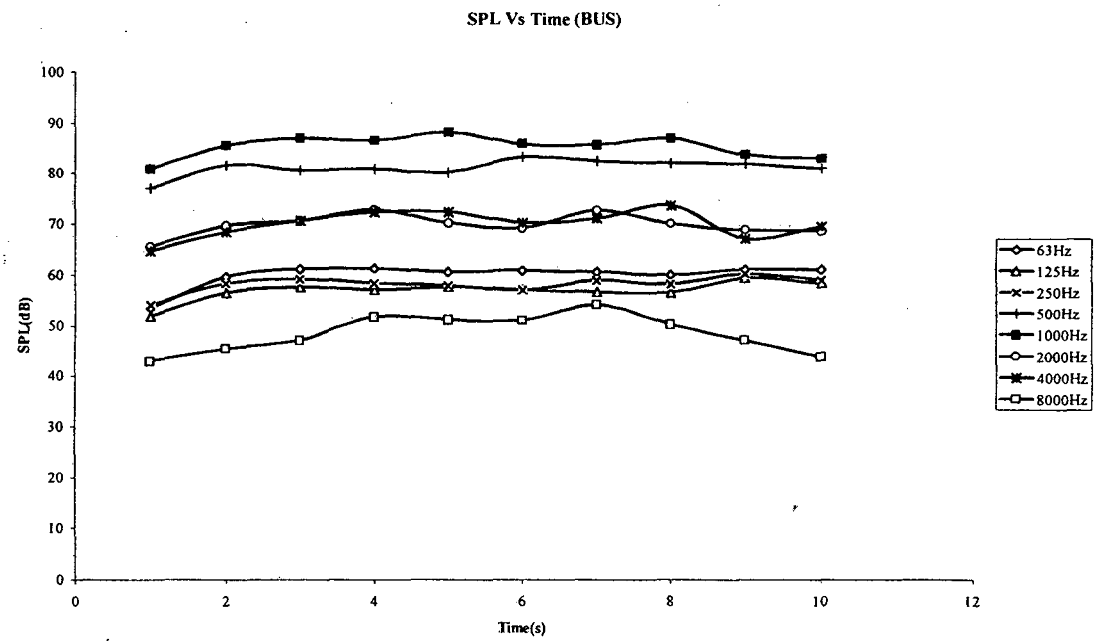


Fig.4.47. Temporal variation of SPL of buses at octave band centre frequencies.

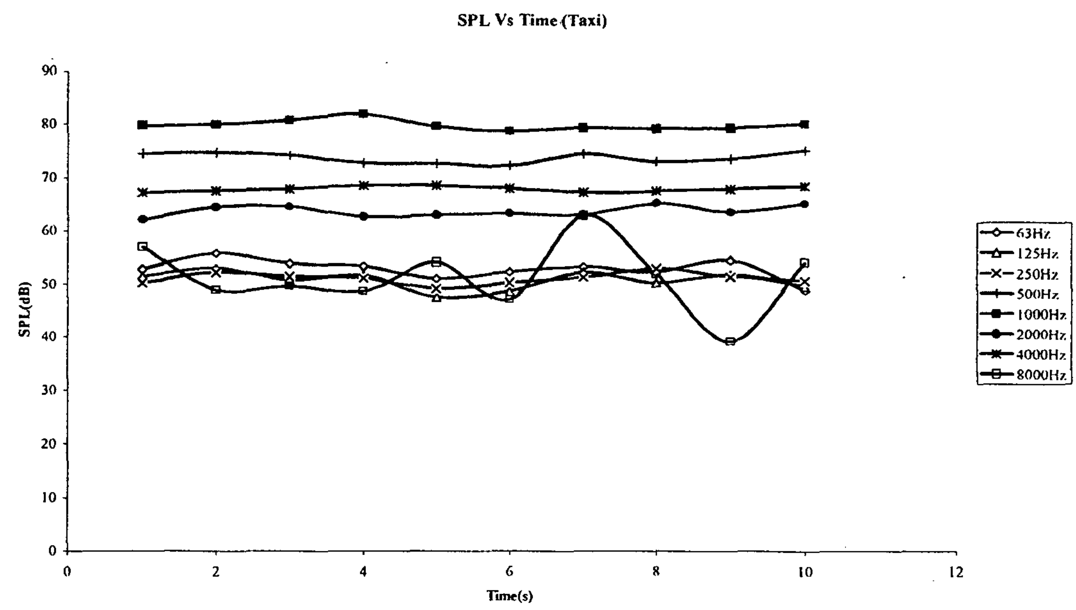


Fig.4.48. Temporal variation of SPL of taxis at octave band centre frequencies.

Fig.4.49.

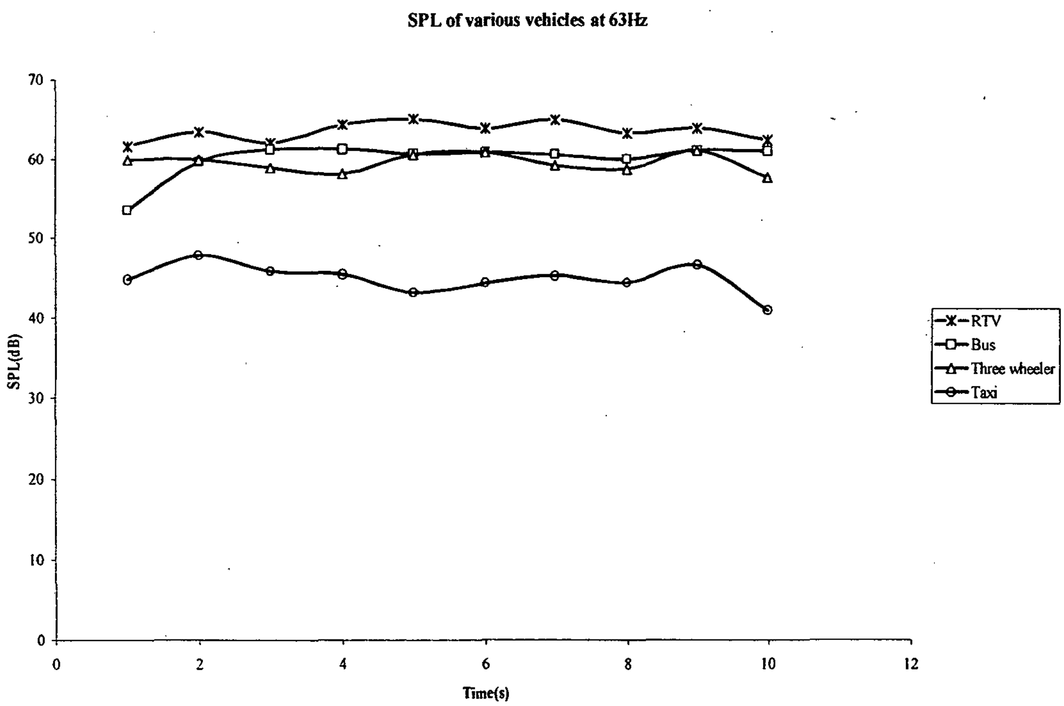


Fig.4.50.

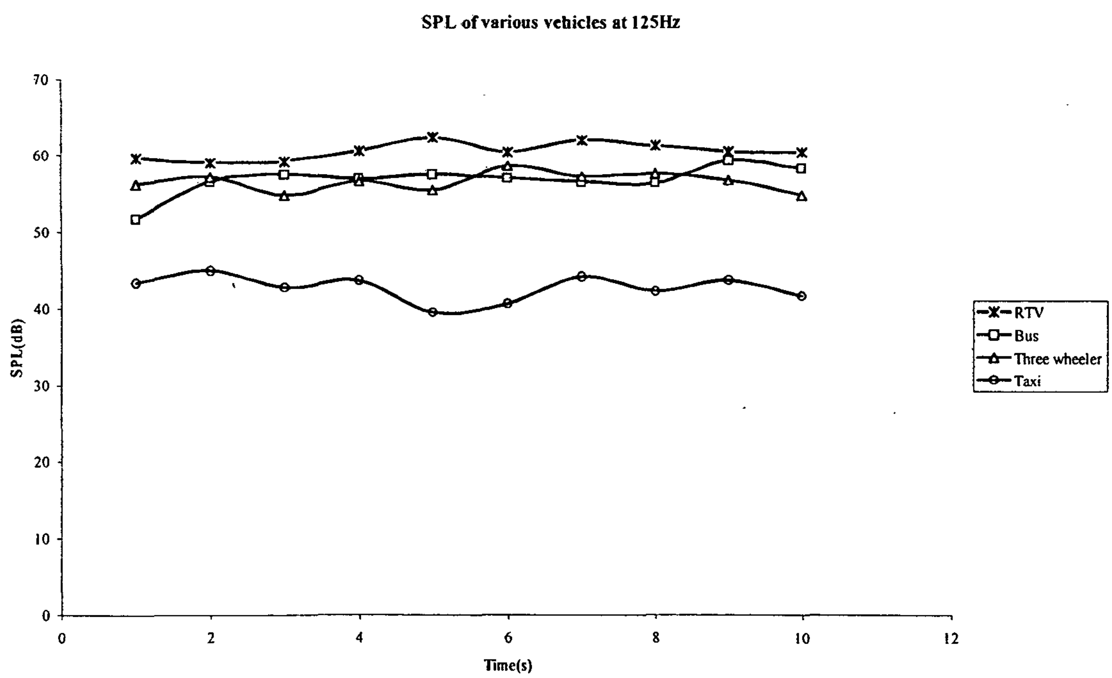


Fig.4.51.

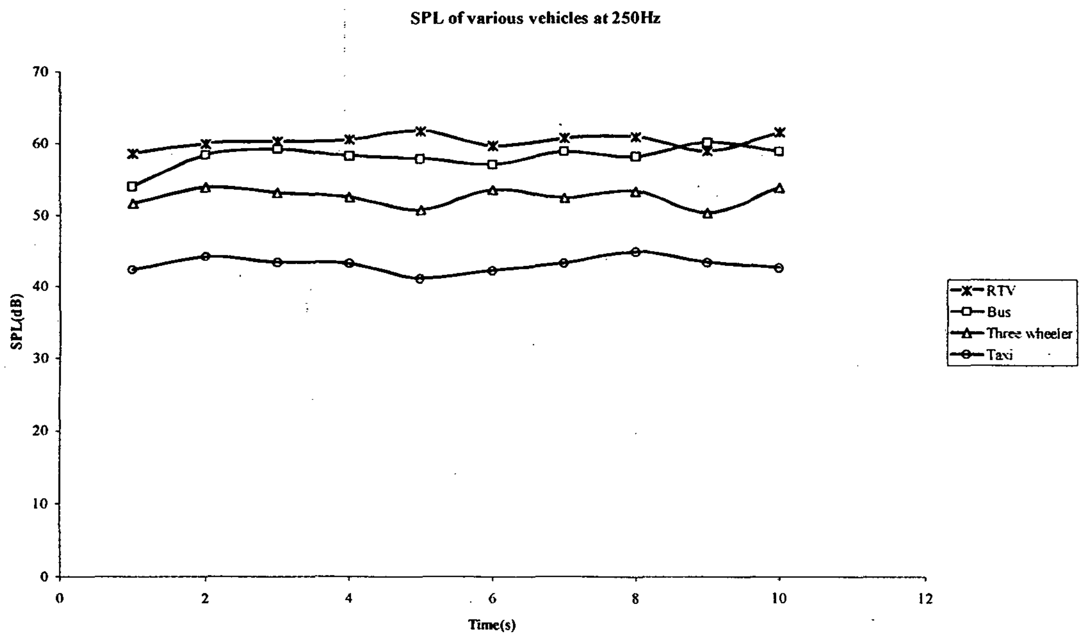


Fig.4.52

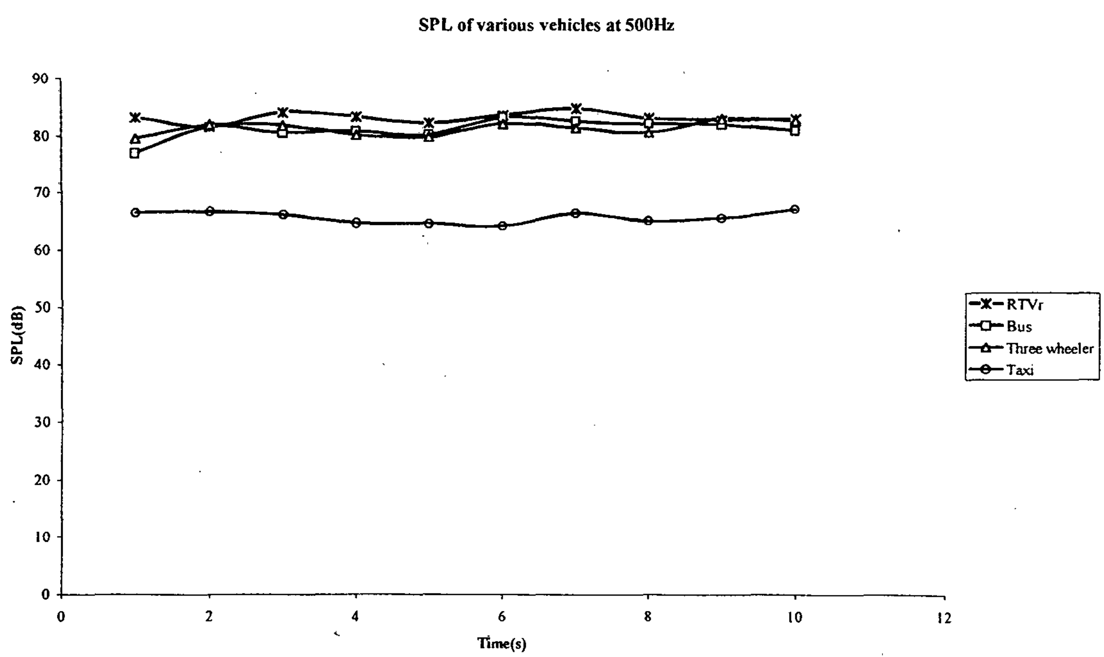


Fig.4.53

SPL of various vehicles at 1000Hz

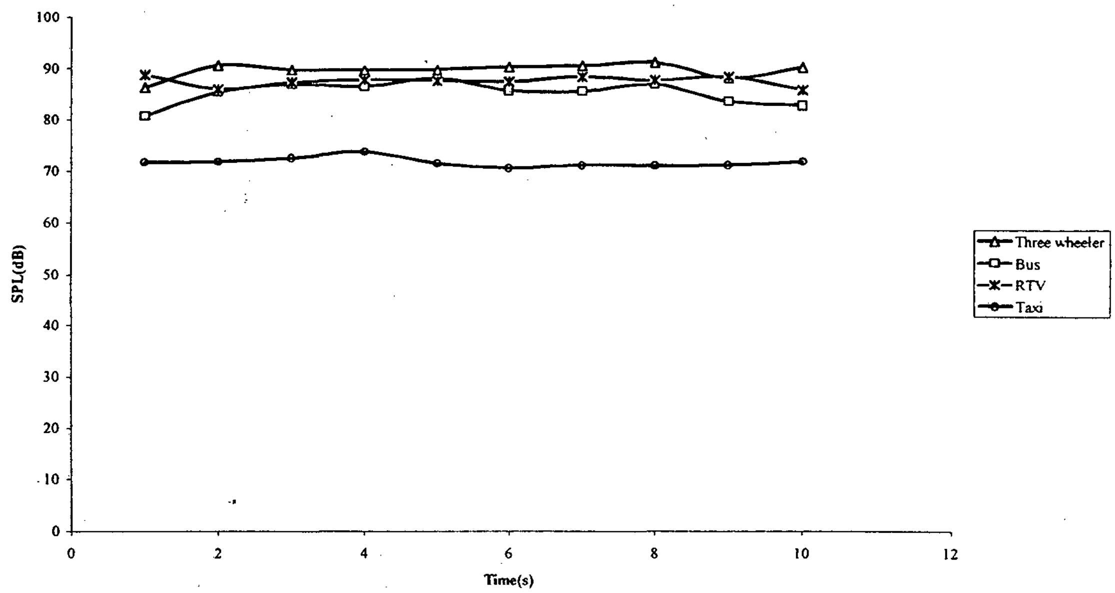


Fig.4.54.

SPL of various vehicles at 2000Hz

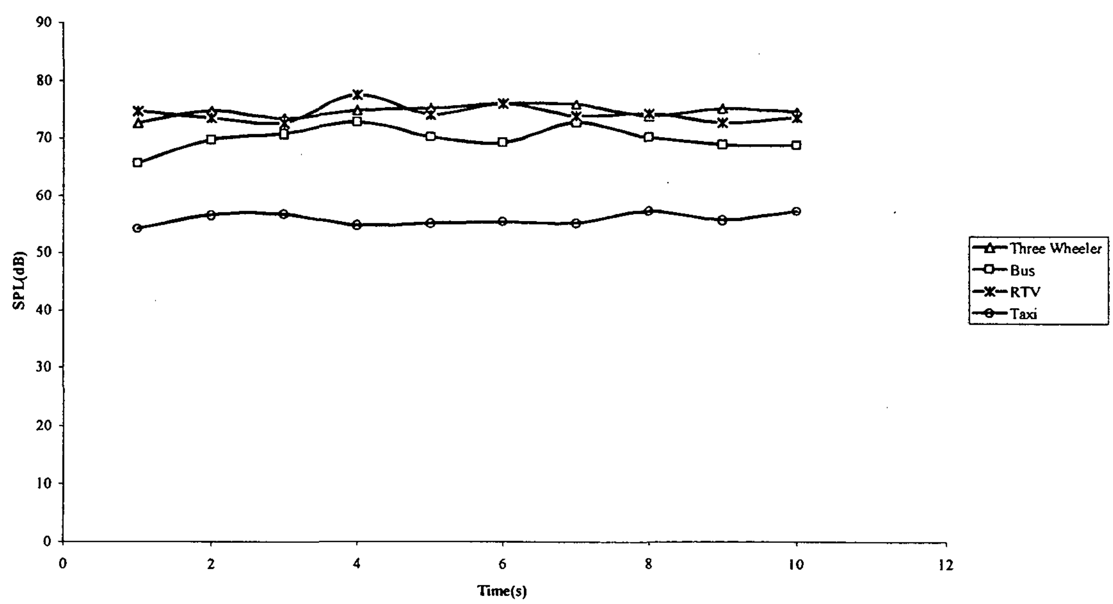


Fig.4.55.

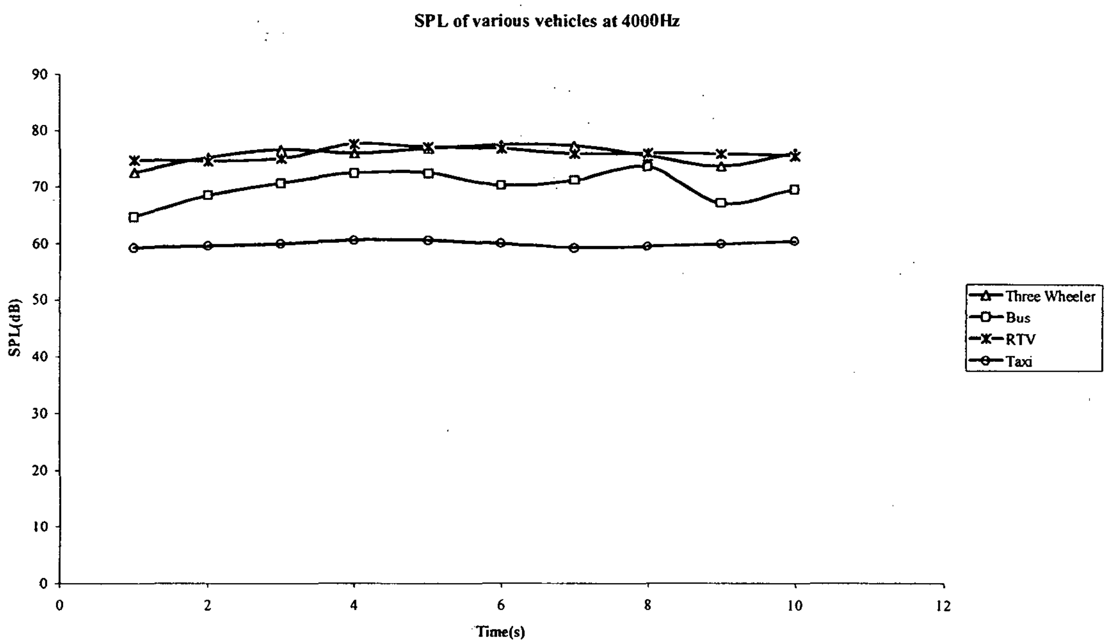


Fig.4.56.

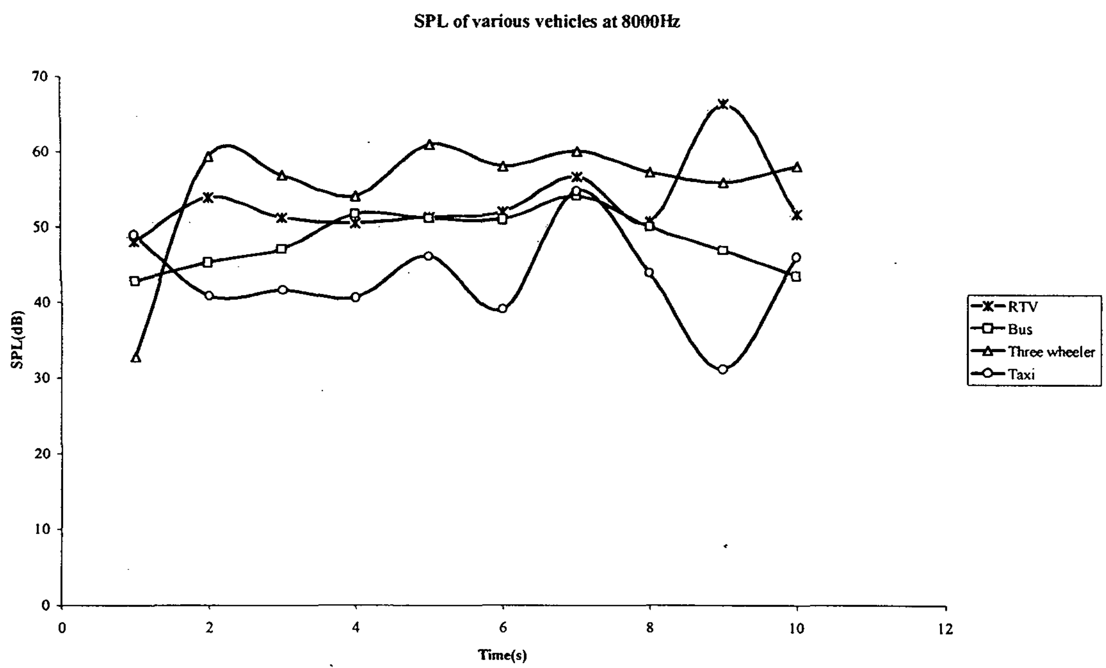
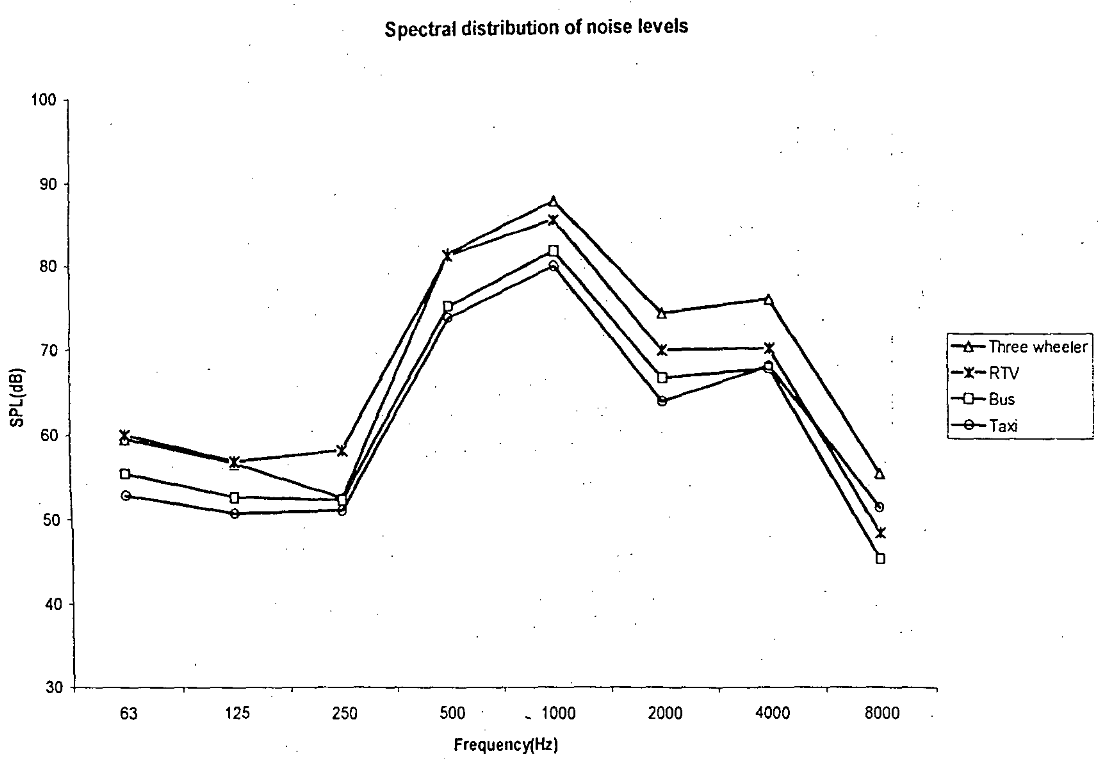


Fig.4.57.


Spectral distribution of noise levels
100
90
80
70
60
50
40
30
SPL(dB)
63
125
250
500
1000
2000
4000
8000
Frequency(Hz)
Three wheeler
RTV
Bus
Taxi

4.2. DETERMINATION OF PEAK (L_{10}), BACKGROUND (L_{90}) AND EQUIVALENT SOUND PRESSURE LEVELS (L_{eq})

All of the data recorded during the field investigations were stored in a computer. The noise levels were then sorted out for each vehicle in ascending order of magnitude through a simple computer program. From the sorted data, various percentile indices, i.e., L_{10}, L_{50} and L_{90}, were calculated using the following method. For the ungrouped data consisting of N readings arranged in ascending order of magnitude, if L_i represents the noise level which is exceeded by i% of the readings and iN/100 = N' (say), then, L_i is equal to the mean of the (N - N')th and (N - N'+1)th readings. L_{eq} levels were then estimated using the expression

$$L_{eq} = L_{50} + d^2/60$$

Where

$$d = L_{10} - L_{90}$$

From the measurements of A-weighted noise levels for the free flow conditions, statistical percentile indices L_{10}, L_{50}, L_{90} and equivalent sound pressure level L_{eq} values were estimated for each type of vehicle. Table 4.1 shows the values of the indices for various types of vehicles. Under free flow conditions, the factors contributing to the noise level are the engine noise, aerodynamic turbulence, rattling of window panes and body and the road surface tyre contact. It is found that the L_{10} indices (which represent peak noise) are maximum for auto-rickshaws followed by RTVs, buses and taxis. A similar inference was drawn in an earlier study by Sanyogita et.al. [11], although the study pertained to noise inside the vehicles.

For the L_{90} levels (which represent background noise), RTVs have maximum value followed by auto-rickshaws, buses and taxis. This result also follows conclusions of the earlier study [11], but the L_{90} values in this study are much lower by as much as 20 dB. The reason for this may be the fact that this study was conducted outside the vehicles and measurements were taken along a lonely stretch of road where only a single vehicle passes by at a time, whereas the earlier study was conducted for the noise inside the vehicles where the background noise due to people sitting inside the vehicles as well as due to other vehicles on the road may have an influence on the overall background noise level. For the L_{eq} values, auto-rickshaws have the highest values followed by buses, RTVs and taxis respectively. The reason for auto-rickshaws and buses having higher L_{eq} indices is due to their lower L_{90} levels compared with that of RTVs.

Table.4.1. L_{10}, L_{50}, L_{90} and L_{eq} levels for different modes of transport under free flow condition.

Types of vehicles	L_{10} [dB(A)]	L_{50} [dB(A)]	L_{90} [dB(A)]	L_{eq} [dB(A)]
Auto-rickshaws	91.3	72.4	51.8	89.7
RTVs	89.7	71.2	55.3	90.9
Buses	89.5	68.4	51.7	92.2
Taxis	82.5	64.4	49.6	82.4

Table.4.2. Comparison of average L_{10}, L_{50}, L_{90} and L_{eq} levels for different CNG vehicles inside and outside ~ 3 meters from the line of motion of the vehicle.

Types of vehicles	L_{10} [dB(A)]		L_{50} [dB(A)]		L_{90} [dB(A)]		L_{eq} [dB(A)]	
	Outside	Inside†	Outside	Inside†	Outside	Inside†	Outside	Inside†
Auto-rickshaws	91.3	78.3	72.4	74.7	51.8	68.3	89.7	76.6
RTVs	89.7	90.9	71.2	83.4	55.3	78.5	90.9	86.5
Buses	89.5	81.6	68.4	78.5	51.7	76.1	92.2	79.1
Taxis	82.5	75.3	64.4	70.0	49.6	66.7	82.4	71.3

† Ref:[11]

4.3. LOUDNESS INDEX, ANNOYANCE AND PERCIEVED NOISE LEVELS

Sound Pressure Level is not synonymous with loudness level, due to the ear's non-linear response to sound of different frequencies and intensities, although the A, B and C weighting networks have been devised from equal loudness level curves in an attempt to correct for this. Equal loudness curves are used to assess the loudness levels in phons for pure tones. However for complex sounds sone scale is used [50]. The total loudness level is obtained by converting the total loudness (in sones) to a calculated loudness level, P, (in phons) by means of the equation

$$S_t = 2^{(P-40)/10}$$

where S_t is the total sones and P the loudness level in phons. The sone scale is a ratio scale, whereas the decibel and phon scales are not.

In the sone and phon scales of loudness and loudness levels, auto-rickshaws have the highest values followed by RTVs, buses and taxis respectively as shown in table.4.4. However in terms of annoyance in the noy scale, RTVs have the maximum value followed by auto-rickshaws, buses and then taxis. The total noisiness N_t (in noys) can be converted into a rating that is called the perceived noise level (PNdB), by using the Stevens' formula for converting sones into phones. That is

$$N_t = 2^{(x-40)/10}$$

hence

$$x = 40 + \frac{100}{3}\log_{10} N_t$$

where x is the perceived noise level in PNdB. Perceived Noise Level (PNdB) follows the same order as in the noy scale.

The concept of perceived noise levels (PNdB) is an excellent one as this is a direct measurement of annoyance, but it has been devised for jet aircraft noise, which has a large high frequency component. It is unlikely that such a concept could be extended in general to road traffic noise, which is a continuous noise in contrast to discrete number of noises that enables each aircraft to be given annoyance value. Since in the present study, the measurements were made on noise due to individual vehicles, this concept of PNdB has been extended here to evaluate the extent of annoyance due to different types of individual vehicles. We can see from table 4.3 that RTVs have the highest annoyance value, followed by auto-rickshaws, buses and then taxis

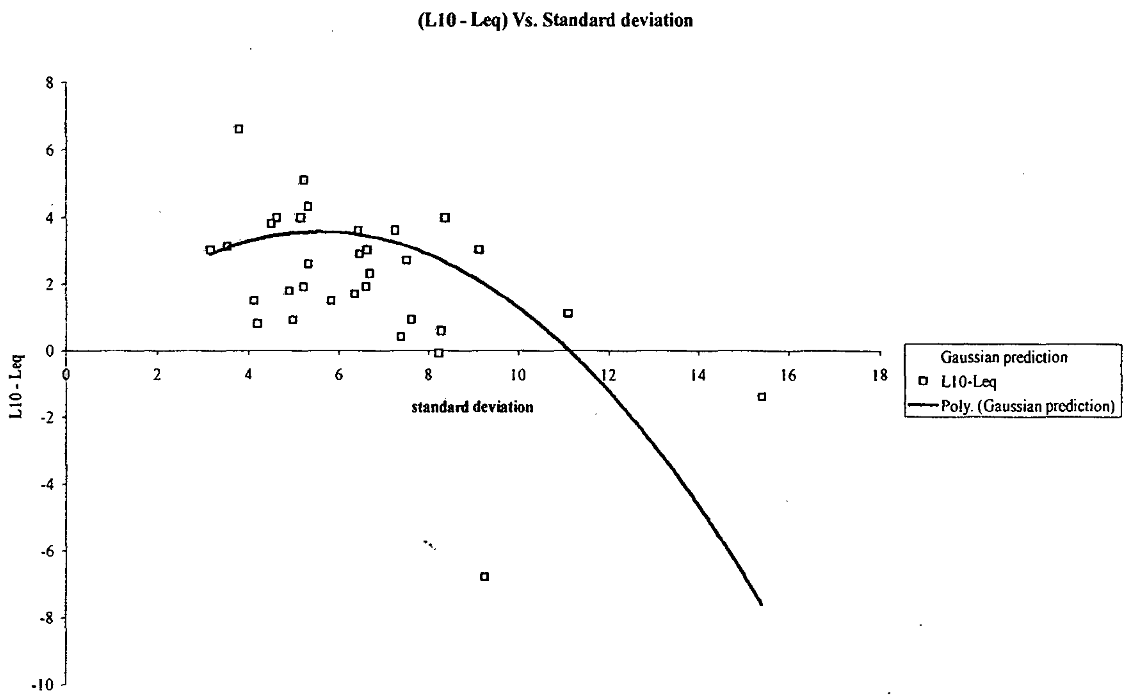
Table.4.3. Loudness, annoyance and perceived noise levels for different modes of transport.

Types of vehicles	Sones	Phon	Noy	PNdB
Auto-rickshaws	46.2	95.4	46.2	95.4
RTVs	39.1	93	48.6	96.2
Buses	34.9	91.2	34.4	91.2
Taxis	20.7	84	23.9	85.8

4.4. STATISTICAL CHARACTERIZATION

The statistical characterisation is carried out first by examining the relationship between the standard deviations σ of the noise levels and $L_{10} - L_{eq}$ as in Don and Rees [32]. The variations of the relationship between $L_{10} - L_{eq}$ does not tend to agree with that of the Gaussian distribution as shown in fig.4.58. Similarly, deviation from Poisson distribution was observed since $\beta_1 \neq 1/\mu_1$ and $\beta_2 \neq 3 + 1/\mu_1$. It has also been discussed theoretically by Kurze [31] that noise level distribution may approach Poisson or Gamma distributions only for the continuous free traffic flow cases.

Fig.4.58



In order to characterize the noise level fluctuations, the method of Pearson was employed [42]. This method is a powerful tool in characterizing the following distributions:

(i) Normal (ii) Gamma and (iii) Pearson type distributions (I to XII)

This method requires the values of skewness and kurtosis of a sample. Then the determination of the type of distribution function to describe the sampled data is done by comparing the obtained skewness and kurtosis. Since a known distribution function has its own statistical properties, a relationship between skewness and kurtosis therefore reflects the corresponding properties of the sampled data.

For auto-rickshaws as can be seen from table 4.4, majority of the noise level distributions at different frequencies can be approximated by the Pearson Type I distribution, where the criterion is $\kappa < 0$. However at 2000 Hz, the distribution is of type IV where the quantity κ lies between 0 and 1. For the criterion $\kappa = 0$, if $\beta_2 > 3$, the distribution is Type VII and it is Type II if $\beta_2 < 3$. At 4000 Hz, since $\beta_2 < 3$, the distribution is Type II.

For buses, the distribution is a mixture of Types I, IV , VI and VII distributions. At 63 Hz where the quantity κ is greater than unity, the distribution is Type VI. At 250 Hz, 500 Hz, 1000 Hz and 8000 Hz, the quantity κ is negative, the distribution can be approximated by the Pearson Type I distribution. The values of κ for 125 Hz and 2000 Hz indicate Pearson Type IV distribution. At 4000 Hz, where $\kappa = 0$ and $\beta_2 > 3$, the distribution is Pearson Type VII.

Majority of the noise level distributions at different frequencies for RTVs can be approximated by the Pearson Type I distribution with variations at 63 Hz (Type II) and at 4000 Hz (Type IV) respectively. For taxis, noise levels at 63 Hz, 250 Hz, and 500 Hz show Pearson Type I distribution, levels at 125 Hz, 1000 Hz and 8000 Hz show Type IV distribution whereas levels at 2000 Hz and 4000Hz show Type VII and Type VI distributions respectively.

It is clear from the above discussions that majority of the noise level fluctuations at different frequencies for various types of vehicles can follow either Type I or Type IV distributions. Pearson Type I distribution takes the form

$$f(x) \sim \left(1+\frac{x}{a_2}\right)^{m_1}\left(1-\frac{x}{a_2}\right)^{m_2}$$

where m_is and a_is are constants. The shape of the Pearson Type I curve can either be J-shaped or U-shaped depending on the values of the constants.

The Type IV distribution function takes the form

$$f \sim \left(1+\frac{x^2}{a^2}\right)^{-m} e^{-\nu \tan^{-1}\frac{x}{a}}$$

where m and a are constants. This distribution has unlimited range in both directions, tends to zero at infinity and is unimodal.

Two noise levels, 4000 Hz (auto-rickshaw) and 63 Hz (RETV) show Type II distribution which is given by

$$f \sim \frac{1}{a}\left(1-\frac{x^2}{a^2}\right)^{m}$$

This distribution is symmetrical about the origin and ranges from – a to + a. If m >0 it is unimodal with contact at the terminals of the range and if m < 0 it is U-shaped. If m = 0, the distribution becomes

$$f \sim \frac{1}{a}$$

the so-called "rectangular" distribution.

The Pearson Type VI distribution shown by the noise levels at 63 Hz (bus) and 4000 Hz (taxi) is given by

$$f(x) \sim x^{m_1}(x-a)^{m_2}$$

By a simple transformation y = a/x, this distribution reduces to the Type I form.

The distribution function of Pearson Type VII is given by

$$f \sim \frac{1}{a}\left(1+\frac{x^2}{a^2}\right)^{-m}$$

This has the same criterion $\kappa = 0$ with that of the Type II distribution. But the difference between this case and that of Type II lies in the fact that here $\beta_2 > 3$, whereas in the Type II case $\beta_2 < 3$.

Table 4.4 Statistical parameters for determination of type of distribution of noise levels.

3 wheeler	frequency	μ_2	μ_3	μ_4	β_1	β_2	b0	b1	b2	κ	Distribution
	63Hz	67.59	-267.41	12350.30	0.23	2.70	-1069.53	-35.29	2.01	-0.14	Type I
	125Hz	58.09	-274.82	9375.34	0.39	2.78	-746.14	-35.26	2.06	-0.20	Type I
	250Hz	56.26	-207.32	8243.92	0.24	2.60	-702.08	-26.59	1.95	-0.13	Type I
	500Hz	43.71	-175.05	5446.50	0.37	2.85	-687.18	-35.76	2.14	-0.22	Type I
	1000Hz	54.54	-373.22	11661.36	0.86	3.92	-1947.73	-129.04	2.00	-1.07	Type I
	2000Hz	52.68	50.91	9350.51	0.02	3.37	-2736.90	-23.82	-2.65	0.02	Type IV
	4000Hz	69.93	-15.84	14252.26	0.00	2.91	-2269.11	-3.73	0.48	0.00	TypeI
	8000Hz	123.37	793.86	41483.98	0.34	2.73	-1595.72	-48.16	2.03	-0.18	Type I
Bus	frequency										
	63Hz	44.72	-135.72	6714.44	0.21	3.36	-1876.78	-63.20	-0.32	1.68	Type VI
	125Hz	41.35	-253.16	8759.24	0.91	5.12	-4106.31	-277.89	-8.53	0.55	Type IV
	250Hz	28.44	-76.74	2482.30	0.26	3.07	-786.94	-39.38	1.51	-0.33	Type I
	500Hz	24.25	-143.80	2687.00	1.45	4.57	-868.95	-115.49	3.12	-1.23	Type I
	1000Hz	28.52	-151.36	3629.12	0.99	4.46	-1567.05	-146.19	0.15	-23.49	Type I
	2000Hz	34.00	-181.70	6093.16	0.84	5.27	-3886.25	-272.16	-12.45	0.38	Type IV
	4000Hz	68.60	8.14	22609.30	0.00	4.80	-9900.81	-6.96	-27.10	0.00	Type IV
	8000Hz	83.47	-2732.78	122493.00	12.84	17.58	-2464.56	-625.64	8.69	-4.57	Type I
RTV	frequency										
	63Hz	27.48	10.93	1859.92	0.01	2.46	-443.27	-3.56	1.79	0.00	Type I
	125Hz	26.61	-62.14	2157.96	0.20	3.05	-771.33	-35.36	1.30	-0.31	Type I
	250Hz	237.47	517.62	5753.36	0.02	0.10	355.84	29.11	-25.21	-0.02	Type I
	500Hz	20.37	-65.56	1264.32	0.51	3.05	-345.77	-30.98	2.28	-0.30	Type I
	1000Hz	16.92	-52.12	852.85	0.56	2.98	-219.06	-23.30	2.18	-0.28	Type I
	2000Hz	14.34	22.61	621.10	0.17	3.02	-419.60	-24.02	1.21	-0.28	Type I
	4000Hz	9.97	-15.62	388.96	0.25	3.91	-675.64	-49.21	-4.94	0.18	Type IV
	8000Hz	85.85	-1769.55	48267.36	4.95	6.55	2897.82	585.38	-23.05	-1.28	Type I
Taxi	frequency										
	63Hz	43.92	-96.06	5707.69	0.11	2.96	-1299.37	-33.50	1.05	-0.21	Type I
	125Hz	40.29	-246.51	7950.38	0.93	4.90	-3355.87	-239.52	-5.00	0.86	Type IV
	250Hz	27.46	-107.36	2436.39	0.56	3.23	-589.56	-46.47	2.30	-0.40	Type I
	500Hz	24.88	-115.52	1982.74	0.87	3.20	-230.76	-26.16	1.99	-0.37	Type I
	1000Hz	21.39	-15.06	1466.71	0.02	3.21	-939.69	-15.05	-1.18	0.05	Type IV
	2000Hz	17.57	0.65	1296.64	0.00	4.20	-1771.26	-1.60	-14.40	0.00	Type IV
	4000Hz	12.46	-22.31	541.37	0.26	3.49	-565.71	-40.02	-0.70	1.02	Type IV
	8000Hz	41.57	185.11	7774.10	0.48	4.50	-3660.28	-177.50	-8.33	0.26	Type IV

CHAPTER 5

CONCLUSIONS

1. The L_{10}, L_{50}, L_{90} and L_{eq} levels of auto-rickshaws were found to be the highest, followed by RTVs, buses and taxis respectively.

2. Auto-rickshaws were found to have the highest loudness levels in phons, followed by RTVs, buses and taxis.

3. On the noy scale it was found that RTVs have the highest annoyance levels, followed by auto-rickshaws, buses and taxis.

4. Perceived noise levels (PNdB) are highest for RTVs followed by auto-rickshaws, buses and taxis.

5. The skewness-kurtosis relationships derived from the measured noise data suggest that noise level fluctuations at different frequencies in majority of the cases can be approximated by either Pearson Type I or Pearson Type IV distributions.

FUTURE SCOPE

It would be worthwhile to study the spectral characteristics of noise outside and inside residential houses located near the main traffic flow. This would help in estimating the percentage contribution from outside road traffic noise to the interior noise in the living/bed rooms. A questionnaire based survey eliciting community response in terms of induced annoyance needs to be carried out to evaluate the effect of traffic noise on annoyance. Moreover, spectral characteristics of interior noise may help in establishing relationships, if any, between different frequencies of sound and degree of annoyance.

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