

'NOISE INVESTIGATION AND MODELLING OF URBAN TRAFFIC UNDER DYNAMIC CONDITIONS'

A thesis submitted in partial fulfillment
of the requirement for the award of the degree of

Doctor of Philosophy

Submitted by

Daljeet Singh

Regn. No. 951008006

Under the supervision of

Dr. S.P. Nigam

Former Visiting Professor,
Mechanical Engineering Department
Thapar University, Patiala

Dr. V.P. Agrawal

Former Visiting Professor,
Mechanical Engineering Department
Thapar University, Patiala

Dr. Maneek Kumar

Professor,
Civil Engineering Department
Thapar University, Patiala



MECHANICAL ENGINEERING DEPARTMENT

THAPAR UNIVERSITY, PATIALA-147004, INDIA

(Declared as Deemed to be University u/s 3 of UGC Act, 1956 Vide Notification No. F9-12-84-U.3 of G.O.I)

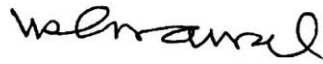
December 2017

CERTIFICATE

Certified that the work presented in the thesis entitled, "*Noise Investigation and Modelling of Urban Traffic Under Dynamic Conditions*", which is being submitted by Mr. Daljeet Singh for fulfillment of the requirement for the award of the degree of '**Doctor of Philosophy**' in the Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of the candidate's own work carried out at this University under our supervision. The matter presented in this thesis has not been submitted either partially or fully to any other University or Institute for the award of any other degree.



Dr. S. P. Nigam
Former Visiting Professor
Mechanical Engineering Department
Thapar University,
Patiala – 147004 (India)



Dr. V.P. Agrawal
Former Visiting Professor
Mechanical Engineering Department
Thapar University,
Patiala – 147004 (India)



Dr. Maneek Kumar
Professor
Civil Engineering Department
Thapar University,
Patiala – 147004 (India)

ACKNOWLEDGEMENT

There are so many people who deserve special thanks and remembrance, at this stage of my life, which is the culmination of many years of hard work and perseverance. I express my heartfelt gratitude to my Ph.D. supervisor, Prof. S.P. Nigam, former Visiting Professor, Mechanical Engineering, Thapar University, without whose guidance and support, this journey would have been incomplete. His invaluable mentoring and advice at the various stages in the research work, sharing of rare and invaluable books and manuals, meticulous reading of manuscripts and thesis, comments for improvement and above all, his prayers for me, cannot ever be thanked enough. I am deeply indebted to him for always being there, not only on the academic and research front but also on the personal level. I thank Prof. V.P. Agrawal, former Visiting Professor, Mechanical Engineering, Thapar University, for his priceless support and guidance, as a supervisor in the research work. His continuous encouragement and motivation spurred me on to write papers based on the Ph.D. work which were ultimately published in reputed journals of the world. His faith in me gave me the courage and confidence to overcome many hurdles that are inevitable on this path. I would like to thank Prof. Manek Kumar, Professor, Civil Engineering and Dean of Student Affairs, Thapar University, for his enormous enthusiasm and drive in encouraging me to reach the different milestones and for his awesome support and guidance at all the important junctures in the successful completion of this work. His experience and meticulous observations were always a source of inspiration to reach greater heights in my research work.

I would like to express my sincere gratitude to Prof. Prakash Gopalan, honourable Director, Thapar University, Patiala, for providing me with opportunities, resources and facilities for the completion of my Ph.D. work. Special thanks are due to Prof. S.K. Mohapatra, Senior Professor and Head, Mechanical Engineering Department, Thapar University, for his tremendous support and guidance all along this overwhelming journey.

I extend special thanks to the doctoral committee members Prof. Naveen Kwatra, Head of the Department, Civil Engineering and Dr. J.S. Saini, Associate Professor, Mechanical Engineering, for their valuable inputs and cooperation over the years.

A deep sense of gratitude is felt towards Prof. R.S. Kaler, Deputy Director, Thapar University, Prof. O.P. Pandey, Dean of Research and Sponsored Projects, Prof. Ajay Batish, Dean of Contemporization and Accreditation, Prof. R.K. Sharma, Dean of Faculty Affairs

and Prof. S.S. Bhatia, Dean of Academic Affairs, Thapar University, for their able guidance, support and blessings.

I also thank the entire faculty and staff of Mechanical Engineering Department, Thapar University, Patiala for their continuous support and encouragement during all these years. I am very grateful to Dr. P.S. Rana, Assistant Professor, Computer Science and Engineering Department, Thapar University, Patiala, for his extensive support and guidance in the use of soft computing methods and resources. I would like to extend my sincere thanks to all the reviewers and editors of reputed journals in which the work presented in this thesis has been published, for their critical and meticulous observations and comments.

The present work could not have been completed without the love, support and blessings of family and friends. I express my gratitude and love for my grandparents and parents. My father, Dr. Balwant Singh and mother, Mrs. Harjeet Kaur inculcated in me the moral values and work ethic which can only be given by good upbringing. My father, an eminent educationist and a gifted orator, has always inspired me to work hard in life for noble causes. My parents' unconditional support and love for me has always been a source of strength for me. I express my deepest sense of gratefulness to my wife, Aman, and my adorable son, Bikram, who have been my pillars of support and strength. My apologies are also due to them for not giving them enough time because of the Ph.D. work. I am sure their prayers will be answered and their patience and sacrifice over the years gone by will be amply rewarded by the Almighty. And finally, the greatest sense of gratefulness and obeisance to the all-powerful God Himself who always held my hand and showed me the light on this path.

Daljeet Singh

Daljeet Singh

Date: 15 Dec 2017

ABSTRACT

Noise pollution as an environmental concern has lately found a lot of attention amongst environmentalists, engineers and general public. There are different sources of noise in the environment like traffic noise: rail, road and aircraft, use of loudspeakers during weddings and religious functions and machinery noise: industry or construction machinery. Vehicular traffic noise (emanating from vehicles plying on the roads) is a major contributor to the overall noise in the environment to which the general population is exposed. The number of vehicles on the roads (especially two-wheelers and cars) has been increasing relentlessly with growing population, demand, affordability and purchasing power. The high traffic noise levels have adverse health effects on the human population. Thus, it is imperative for the town planners and transport engineers to consider the noise aspect at the conceptual stage of the design of urban roads, residential and commercial buildings and market areas. Traffic noise prediction models help in the assessment of noise levels at the initial design stages and later stages when modifications are planned. They are also useful for environmental impact assessment (EIA) studies.

The present work describes the urban traffic noise problem with respect to the high noise levels present on the Indian roads, by taking the Patiala city as a representative case. The existing noise levels were assessed at various locations on the city roads by using the standard measuring equipment and procedure. The measurements revealed that the existing noise levels are much higher than the prescribed limits.

A Graph Theoretic (GT) approach which is a systems approach has been used to develop a new traffic noise model and also to propose a new traffic noise descriptor. An Urban Traffic Noise System (UTNS) has been proposed which consists of the subsystems: road traffic subsystem, human subsystem, environment subsystem, traffic network subsystem and urban prosperity subsystem. The first subsystem (road traffic subsystem) has been studied in detail in the present work. The different steps involved in the formulation of a traffic noise model have been illustrated. 'Permanent function' in the form of a composite noise index ('p') has been formulated and its calculation and correlation (in terms of 'log p') with the existing noise level descriptors like L_{eq} , have been illustrated with examples.

In the first example, the traffic situation presented in Nicol and Wilson's work (2004) has been taken to establish and illustrate the proposed methodology. The parameters considered

in the model are traffic volume, street width, height of measuring point above street level and average speed. GT approach is applied for developing the model. A permanent noise index 'p' which takes into account the effect of different traffic noise parameters and the interactions between them, is proposed and verified with the experimental data. The variation of 'p' with L_{eq} , L_{90} and L_{10} for the different measuring locations has been plotted, and equations for the three noise level descriptors and 'log p' have been formed using regression analysis. The values of multiple R, R^2 and error for the testing dataset show good correlation between the measured and predicted values of the traffic noise level, which match fairly well.

The second illustrative example is that of an urban traffic noise scenario in Patiala city, India. An experimental study has been carried out at the Fountain roundabout in the city in order to further validate the methodology developed using the GT approach. Data related to the road traffic subsystem (consisting of four parameters traffic volume, percentage of heavy vehicles, acceleration of vehicles and road width) has been collected. The permanent noise index 'p' is formulated using the GT approach and verified with the experimental data. The values of R, R^2 and error in the predicted noise level (L_{eq} dB(A)) indicate that the results are matching fairly well.

Another gap that was identified from a study of the literature was the use of **soft computing** methods in traffic noise modelling only in a limited way. Genetic algorithms (GAs) and artificial neural networks (ANNs) seem to have been used so far for the modelling purpose. There are many other state-of-the-art methods/techniques which intuitively were felt to have a potential of application in this area. Four different soft computing methods (*Generalized Linear Model, Decision Trees, Neural Networks and Random Forests*) have been explored and used in developing the models for typical road traffic conditions in Patiala. The traffic noise prediction models are developed, with equivalent sound pressure level, L_{eq} as the output (dependent variable) and the traffic noise variables: hourly traffic flow, percentage of heavy vehicles and average speed of vehicles, as the independent variables. The results obtained were analyzed and it was seen that the 'Random Forests' method excels over all the other techniques on the performance criteria of correlation, R^2 (coefficient of determination), RMSE (root mean square error) and accuracy.

The effect of honking on the noise level was also studied, as it is an important parameter in the urban Indian traffic scene. An experimental investigation was carried out at five different locations in Patiala city with different levels of traffic volume and honking. It has been seen,

as expected, that the overall traffic noise levels increase due to the presence of heavy honking. Though it is quite obvious, but some quantification of the effect of the horn noise was required, which has been addressed. Also, the improvement in the model by including the honking effect has been validated in an objective way.

A systematic acoustic design methodology for a noise barrier as an abatement measure is presented thereafter. The design methodology proposed is useful for determining the height of a barrier to achieve the desired attenuation based purely on acoustic considerations.

It is hoped that the work presented can be useful to urban town planners, pollution control bodies/authority, civil engineers working on road and infrastructure projects, acoustic engineers and officials working on environment impact assessment (EIA) studies with an objective of vehicular traffic noise prediction and abatement.

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NOTATIONS

λ	eigen value of a matrix
I	identity matrix
V	Variable Characteristic Matrix (VCM)
S_i	sub-systems i
e_{ij}	interactions between sub-systems S_i and S_j
SS_i	sub-subsystems i
per	permanent function
p	Permanent Noise Index
$\log p$	logarithm (base 10) of permanent noise index
$dB(A)$	decibels with 'A' frequency weighting
L_{eq}	equivalent continuous sound pressure level (expressed in dB(A))
L_n	statistical / percentile noise levels (expressed in dB(A))
L_{10}	noise level exceeded 10% of the measurement period (dB(A))
L_{50}	median level (dB(A))
L_{90}	background noise level (dB(A))
Q	traffic volume
v	average speed of vehicles (km/h)
H_v	percentage of heavy vehicles
F	Fresnel number

ABBREVIATIONS

AI	Artificial Intelligence
ANN	Artificial Neural Networks
ASJ	Acoustical Society of Japan
CNOSSOS-EU	Common Noise Assessment Methods in Europe
CoRTN	Calculation of Road Traffic Noise
EIA	Environmental Impact Assessment
FHWA	Federal Highway Administration
GA	Genetic Algorithms
GT	Graph Theory
IEC	International Electro-technical Commission
ISO	International Organization for Standardization
RF	Random Forests
REMEL	Reference Energy Mean Emission Level
RLS	Richtlinien für den Lärmschutz an Straben – Guidelines for Noise Protection on Streets
RTS	Road Traffic Subsystem
SaDE	Self-adaptive Differential Evolution
SLM	Sound Level Meter
TNM	Traffic Noise Model
UTNS	Urban Traffic Noise System
VCM	Variable Characteristic Matrix

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CHAPTER 1

INTRODUCTION

In this introductory chapter, some fundamental concepts of noise are presented, with a focus on the vehicular traffic noise, which is the main theme of the present research work. The research objectives, an outline of the work done and the structure of the thesis are also presented thereafter.

Vehicular traffic noise (emanating from vehicles plying on the roads) is a major contributor to the overall noise in the environment to which the general population is exposed. The high traffic noise levels have adverse health effects on the human population. Thus, it is imperative for the town planners and transport engineers to consider the noise aspect at the conceptual stage of the design of urban roads, residential and commercial buildings and market areas. Traffic noise prediction models (Cirianni and Leonardi, 2011) help in the assessment of noise levels at the initial design stage and also at later stages, when modifications are planned.

The present study is an endeavour to obtain new traffic noise prediction models for the Indian traffic conditions. An attempt has also been made to include the parameter of honking (use of vehicle horns) which is quite typical and predominant in Indian conditions. Acoustic design of a noise barrier has also been attempted.

A brief introduction to fundamentals of noise, which is relevant to the present work, is given below.

1.1 Noise – A Definition

Noise is generally described as unwanted sound. But this simple definition can change its implication depending on different contexts and people. Music to the ears of one may seem unwanted sound or noise to another. A certain kind of loud music which is liked by the younger generation might not be received very well by the older folks. But despite the age, gender, regional preferences, mood, qualification and profession, there is a general understanding and acceptance of the fact that loud, harsh sounds termed as noise are undesirable. The adverse health effects of the high noise levels (hearing impairment,

cardiovascular disorders, sleep disturbance, speech interference, annoyance etc.) have been reported in literature and the general population is also being sensitized towards them.

1.1.1 Noise Level Descriptors

The noise level measurements are represented by different acoustic descriptors like the energy based descriptor L_{eq} and percentile noise levels L_{10} , L_{50} , L_{90} etc. These descriptors are briefly explained below.

a. L_{eq} : It denotes the equivalent continuous sound pressure level. It is the equivalent noise level when the noise present in the system under consideration with continuous, non-fluctuating noise carries the same amount of total acoustic energy as the fluctuating noise over the considered time interval. The unit for L_{eq} is dB (the weighting that is used is expressed alongside, e.g. dB(A)).

b. L_{10} : It represents the sound pressure level that is exceeded 10 percent of the time for which the measurement is being done.

c. L_{50} : The median level is represented by the descriptor L_{50} , i.e. the level which is exceeded 50 percent of the time period under consideration.

d. L_{90} : It provides an indication of the background noise level during the measurement period. It is the level exceeded 90 percent of the time.

The units for the above descriptors are dB(A) or dB(C), depending on the weighting filter used.

1.1.2 Measurement of Noise

The instrument most commonly used for measuring the sound pressure level is called a Sound Level Meter (SLM). Though an instantaneous sound level reading in dB can be taken with the help of a simple SLM, an integrating type SLM with weighting filters is required for measuring the equivalent continuous sound pressure level, L_{eq} dB. A typical SLM consists of a microphone, pre-amplifier, an electronic integrating circuit with filters and a digital display. A windscreen is used to cover the microphone and pre-amplifier for protection from the wind effects. The SLM is portable in order to be effective for field use. Before taking the readings, the sound level meter (SLM) should be calibrated for accurate values of the noise level in dB. A class 1 SLM meets the IEC specifications (*IEC 61672-1: 2002, International*

Electrotechnical Commission, 2002). While taking the readings, the SLM is generally mounted on a tripod stand to avoid the impedance effects of the human body (which may happen if the SLM is held in hand). Also, it is more convenient for taking noise readings for long duration. For traffic noise data, the SLM is kept at a height of 1.2 m to 1.5 m above the ground level (ISO 362-1:2015) and at a suitable distance from the edge of the road.

1.2 Vehicular Traffic Noise

Environmental noise pollution has become a major health concern. A major part of the total environmental noise is contributed to by the powered vehicles commuting on the roads. The traffic noise is composed of many individual vehicle noise sources. The noise emitted by a single vehicle is made up of many components: the engine noise, exhaust noise, transmission noise, tyre-road interaction noise, aerodynamics noise, body and road rattle noise. In the



Fig. 1.1 An integrating type sound level meter with windscreen (B & K 2250)

Indian sub-continent, another component that is a major contributor to the overall traffic noise (70% according to some surveys, as reported) is ‘honking’ (use of vehicle horn by the drivers).

1.2.1 Why Study Traffic Noise?

A study of traffic noise and its contributing parameters is important in order to assess the traffic noise level in a region, predict future noise levels and to plan suitable noise control measures where required. In the past few decades, the number of powered vehicles plying on the roads has increased significantly. In particular, India has witnessed a large increase in the growth of both two-wheelers and four-wheelers, as can be seen in Table 1.1 and Fig. 1.2.

Table 1.1 Total number of registered motor vehicles (in thousands) in India

Year	Total	Two Wheelers	Cars, Jeeps, Taxis	Buses	Goods Vehicles	Miscellaneous*
1951	306	27	159	34	82	4
1961	665	88	310	57	168	42
1971	1865	576	682	94	343	170
1981	5391	2618	1160	162	554	897
1991	21374	14200	2954	331	1356	2533
2001	54991	38556	7058	634	2948	5795
2006	89618	64743	11526	762	4436	8311
2007	96707	69129	12649	1098	5119	8712
2008	105353	75336	13950	1156	5601	9309
2009	114951	82402	15313	1205	6041	9989
2010	127745	91597	19125	1220	6431	11167
2011	141865	101864	19231	1238	7064	12062
2012	159490	115419	21567	1296	7658	13109

(*Miscellaneous include: Omni buses/Tractors/Trailers/Others)

Source: Transport Research Wing, Ministry of Road Transport and Highways (*Total Number of Registered Motor Vehicles in India, 2016*)

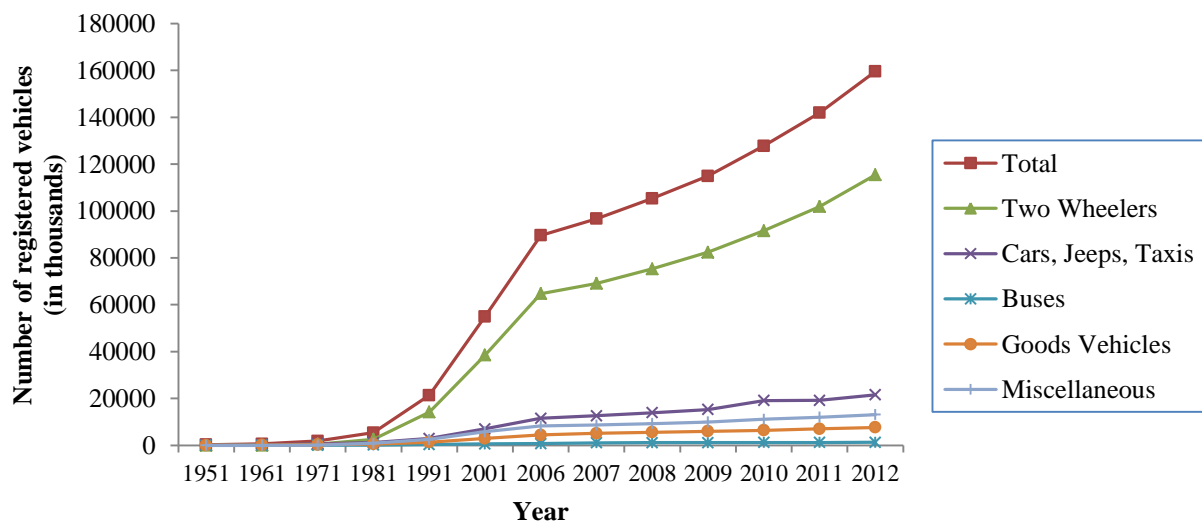


Fig. 1.2 A trend showing the rise in number of vehicles (in India)

Owing to an unabated increase in the number of vehicles on the roads, the traffic noise pollution is also rising significantly and cannot be ignored. There is a lot of awareness about the adverse effects of the traffic noise pollution on the general population. Some of the health effects and the relevant literature have been presented in the literature review (Chapter 2). So, there is a growing need to study the problem and find new solutions for noise prediction and control.

1.2.2 Traffic Noise Level Descriptors

The traffic noise level at a particular location is assessed by using different descriptors. These descriptors are used to capture the time varying nature of traffic noise, because of short-term and long-term fluctuations in the noise level. L_{eq} and L_{10} are the commonly used descriptors in traffic noise assessment and abatement studies.

L_{10} denotes the noise level exceeded 10 percent of the time during the measurement period, usually the noisiest hour of the day. L_{eq} denotes the constant average sound pressure level that contains the same amount of acoustic energy as the fluctuating levels of noise during the measurement period. L_{eq} has been very frequently used as a standard descriptor to evaluate noise near urban roads, highways, residential and commercial areas.

The equivalent continuous sound pressure level, L_{eq} (Crocker, 2007) is given by

$$\begin{aligned} L_{eq} &= 10 \log \left[\frac{p_{rms}^2}{p_{ref}^2} \right] = 10 \log \frac{1}{T} \int_0^T 10^{L(t)/10} dt \\ &= 10 \log \frac{1}{N} \sum_{i=1}^N 10^{L_i/10} \end{aligned} \tag{1.4}$$

where

p = A-weighted instantaneous acoustic pressure

p_{ref} = reference acoustic pressure = 20 (μ Pa)

The averaging time T can be one minute, one hour, one day and so on. The sound pressure levels L_i can be aggregated and the overall level obtained for a particular time period using equation 1.4. 'A' weighting filter (Harris, 1991; Crocker, 2007) is generally used to process the sound pressure level. Though L_{10} is easy for people to understand, L_{eq} is considered more useful and relevant, and is internationally accepted for most of the traffic noise analyses. Also, it can be used for summing up noise level of different sources, and then included in the analyses. L_{eq} is generally 3dB(A) less than L_{10} for same traffic conditions.

Some other noise descriptors include the L_{90} (the background noise level), L_{50} and L_{dn} (day night average sound level).

1.3 Traffic Noise Prediction Modelling

The traffic noise level depends on various parameters like traffic volume/total number of vehicles, percentage of heavy vehicles, average speed of vehicles, acceleration/deceleration of vehicles, use of horns/honking, road surface, gradient/inclination of road etc. Mathematical models or equations with these parameters as the independent variables and the required output, i.e. the traffic noise level (in terms of acoustic descriptors like L_{eq} , L_{10} etc.) as the dependent variable are formed. These models or equations are called the prediction models as they can be used to predict the traffic noise level in future from the given traffic data, without the need for actual acoustical noise measurements at the considered site. They are very useful during the planning of new road and infrastructure projects. They are also used for environmental impact assessment (EIA) studies and form a part of the statutory regulations in different parts of the world.

1.3.1 Urban Traffic Noise Dynamics

When a traffic noise study is carried out on a highway, free-flow conditions can be assumed. This means that a uniform speed can be assumed for the different vehicles and an average value can be used for the modelling. But this kind of a scenario does not exist in urban areas or on roads inside the cities. Here, the presence of intersections, roundabouts, traffic lights, traffic congestion etc. leads to non-uniform flow and acceleration-deceleration of vehicles. So, a mixed heterogeneous traffic flow is present on the urban roads. Another factor which is peculiar to the Indian roads and urban areas is the presence of incessant and heavy honking (use of horns by the drivers) which contributes about 70% of the total traffic noise. In order to formulate accurate traffic noise prediction models in urban areas, the above parameters have to be taken into account.

1.3.2 Existing Models

Some of the existing traffic noise prediction models are FHWA, CoRTN, ASJ, RLS-90 etc. These models have been developed by different countries and are region-specific. Though the basic philosophy is almost the same in these models, there are some differences which are discussed in detail in the chapter on literature review. Artificial intelligence has also been used by many researchers for developing these traffic noise prediction models. Some of these are based on Genetic Algorithms (GAs) and Artificial Neural Networks (ANN). Recent

traffic noise models include the Son road model, Harmonoise project, Nord-2000 model, NMPB-Routes-2008 and CNOSSOS-EU model.

The past few decades have seen a lot of research in the area of traffic noise assessment and prediction modelling, both in the urban and non-urban traffic situations in different parts of the world. Some of the work done in this area has been presented in the subsequent chapter on literature review (chapter 2). The gaps that have been found after the literature review and the research objectives formulated thereafter are presented in chapter 2.

The research **objectives** of the present work are summarized below:

1. To assess the noise level (by using the descriptors like L_{eq} , L_{10} , L_{50} , L_{90}) and its variation in urban traffic situation on city roads in Patiala.
2. To find out new descriptors which can represent the traffic dynamics present on the city roads.
3. To verify the efficacy of existing models taking traffic dynamics into account, for Indian road conditions.
4. To develop a traffic noise prediction model, which can take into consideration the noise variation due to the dynamic nature of urban traffic (due to signalized intersections, roundabouts, traffic congestion, speed breakers etc.) as per Indian road conditions.
5. To suggest suitable noise mitigation measures at the plausible sites having high noise levels. To propose noise barrier as an abatement strategy.

In order to work in the direction of the above identified objectives, two different approaches for vehicular traffic noise assessment and prediction have been developed, which are presented in the subsequent chapters. The first one is the graph theoretic (GT) approach, which has been applied in a traffic noise problem probably for the first time. The graph theoretic approach, along with its applications in different areas is presented in Chapter 3. It can be used for problems which are subjective and vague or fuzzy in nature, and is helpful for decision-making in such scenarios.

The second approach which has been used is the soft computing approach, which is more appealing for problems that are particularly quantitative in nature and deal with variables / parameters that can be precisely measured or easily quantified. The related literature for this technique is also presented in Chapter 4. The effect of horn noise or honking in the Indian traffic scenario is presented in Chapter 5. Acoustic barrier design has been presented for a specific site having high traffic noise level, in Chapter 6. Finally, the conclusions are presented in Chapter 7.

An outline of the work done for attaining the research objectives is given in Fig. 1.3.

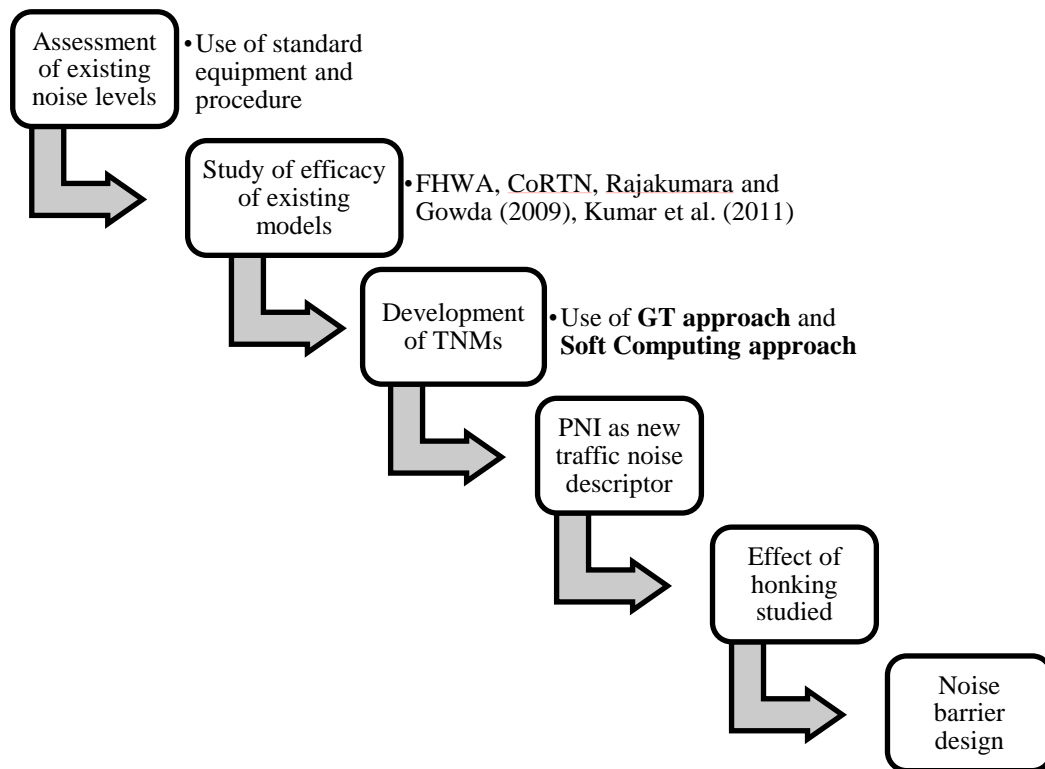


Fig. 1.3 An outline of the present work

CHAPTER 2

LITERATURE REVIEW

A review of the literature related to vehicular traffic noise prediction modelling is presented in this chapter. It consists of different types of traffic noise prediction models, different modelling techniques used and the research done in this area at the national and the international level. The review starts with the adverse effects of high traffic noise levels and then discusses the early traffic noise prediction models, country-specific models, hybrid models, recent models and artificial intelligence based models. Thereafter, the Indian traffic noise studies have been presented, and the chapter is concluded with identification of the gaps and formulation of the research objectives.

The world is witnessing an exponential rise in the number of vehicles on the roads, leading to an increase in the traffic noise levels. Noise pollution is one of the biggest environmental problems the world faces today. Road traffic noise is a major contributor to this type of pollution. There has been an astronomical rise in the number of vehicles on the roads, with little thought given to its effects on the environment and ultimately on the mankind. The automotive trade journal *Ward's Auto* has given estimates that the total crossed 1 billion vehicles in 2010 (Sousanis, 2011). Between 2010 and 2013 there was a 16% increase in the number of registered vehicles in the world (*Number of registered vehicles*, 2017). The total number of vehicles in India increased from 0.3 million in 1951 to 182.4 million in 2013 (*Total Number of Registered Motor Vehicles in India*, 2016). It is significant to note that the number of two-wheelers has increased considerably, with 132.5 million two-wheelers in India, in the year 2013. If the present trend continues, there are estimates that the global vehicle count would cross 2 billion by the year 2035 (Voelcker, 2014).

The high noise levels, associated with the increased vehicular traffic have been shown to affect the health and well-being of a considerable section of society, especially those living in close proximity of highways and urban roads (Banerjee, 2012). The hearing loss induced by high noise levels was reported by (Brookhouser *et al.*, 1992; Koh and Jeyaratnam, 1998; Win *et al.*, 2015). Ingle *et al.* (2005) presented the adverse effects of high traffic noise levels in terms of hearing loss observed in traffic policemen, in Jalgaon, India. Öhrström *et al.* (2006) have carried out surveys in Sweden to assess the health effects of traffic noise on different soundscapes in residential areas. In the Indian context, Goswami (2009) observed

that the traffic noise levels were higher than the permissible limits in all the six investigated locations in Balasore, Orissa. The noise related health problems have also been highlighted in his work. Studies in different parts of the world, like, Bogota, Columbia (Ramírez and Domínguez, 2013), and Sicily, Italy (Guarnaccia *et al.*, 2014) have also shown that in many cases the noise levels are higher than the prescribed limits set by the regulating agencies, for a particular region. Some of the other effects of high traffic noise levels on the nearby population include speech interference (Naish *et al.*, 2013), cardio-vascular disorders (Babisch, 2003; Lee *et al.*, 2014), sleep disturbance (Öhrström, 1995; Frei *et al.*, 2014), annoyance (Yoshida *et al.*, 1997; Sato *et al.*, 1999) and other psychological problems.

There have been numerous attempts across the globe, which have tried to find methods to study, predict and mitigate the road traffic noise levels (Chevallier *et al.*, 2009; Garg and Maji, 2014; Kephelopoulos *et al.*, 2014; Singh *et al.*, 2016a,b). Steele (2001) has presented a review of different traffic noise models that includes both the early models and the country-specific models developed later on. Chevallier *et al.* (2009) presented a traffic noise prediction model for roundabouts. This model can take care of the dynamic aspects of traffic noise due to congestion of vehicles and their interactions, near roundabouts. A traffic flow microsimulation tool along with noise emission laws and a sound propagation model are used in this approach. The CNOSSOS-EU (Common Noise Assessment Methods in Europe) project by the European commission for the EU member states (Kephelopoulos *et al.*, 2014) is underway, in which a comprehensive and strategic noise mapping in all regions of European member states is being recommended. Garg and Maji (2014) have presented an exhaustive review of some of the latest traffic noise models that include, apart from the traditional models (FHWA, CoRTN, RLS-90, ASJ RTN-Model 2008), some recent models like Harmonoise, SonRoad, Nord2000, NMPB-Routes-2008 and the CNOSSOS-EU model. Singh *et al.* (2016a,b) have presented traffic noise prediction methods, in Indian traffic conditions, using graph theory and soft computing approach. The different methods are presented in greater detail below.

2.1 Early Models

Some of the earliest road traffic noise models include the one published in the Handbook of Acoustic Noise Control (Bolt *et al.*, 1952), to which improvements were made by Nickson (1965) and Lamure (1965), and later by Johnson and Saunders (1968) and Galloway *et al.*

(1969). These models had L_{50} as a traffic noise level descriptor, and parameters like V (traffic volume in vehicles per hour), D (distance from the traffic lane, in feet), S (mean vehicle speed in mph) and T (the percentage of heavy trucks). A review of these models has been presented by Steele (2001).

The earliest road traffic noise model seems to be that given in the Handbook of Acoustic Noise Control (Bolt *et al.*, 1952). The model is a simple equation, based on the collected experimental data and regression analysis. It was applicable for speeds in the range 35–45 mph and distances greater than 20 feet. L_{50} (the 50th percentile) was calculated from an equation that contained the variables V , (traffic volume in vehicles per hour) and D (distance from the traffic lane, in feet).

In 1965, Nickson and Lamure developed independent models for L_{50} , using the parameters V and D . The equation consisted of a term V/D and a constant C .

Johnson and Saunders (1968) proposed an equation, in which the mean vehicle speed in mph was added as an important parameter. It was said to be applicable to the heavy vehicles percentage of up to 20%, but the experimental data and validation proved its accuracy within 01 dB for heavy vehicles in the range 0 to 40%. Ground attenuation and other corrections, for example gradients, were also added.

The parameter of percentage of heavy trucks, T was introduced by Galloway *et al.* (1969).

Later developments introduced more parameters and greater use of L_{10} and L_{eq} as the traffic noise descriptors.

A number of studies have been carried out in the area of road traffic noise and an effort has been made to analyze and develop a better mathematical model for noise prediction. Several researchers have proposed different mathematical models and found a good correlation with experimental results. Some of the important work in this area, done in the 70's and 80's, is discussed below.

Harman and Burgess (1973) carried out a traffic noise study in Portsmouth (U.S.A.). The study was based on surveys done for 33 different sites, for 18 hours a day. Noise modelling was done for free-flowing traffic. A comparison was done with existing models. A traffic noise survey for rush hour traffic, in various sites of Historical center of Rome was carried

out by Cannelli (1974). The measured noise levels L_{90} , L_{50} , L_{10} were observed to be close to those of Madrid city but higher than the noise levels measured in a 'London Noise survey'. Some nuisance indices of noise were also calculated and compared with each other. Clayden *et al.* (1975) developed a model by using stationary noise sources, plans of buildings and other structures, and a grid of coordinates. The noise level at grid coordinates was calculated from the attenuation due to reflection, diffraction and direct propagation. But the validation with measurement results was not reported. Delany *et al.* (1976) worked on predicting L_{10} in England and Wales. The method was used for planning purposes, as per Noise Insulation Regulations, 1975. A method was presented by Burgess (1977) for traffic noise prediction and comparison with experimentally observed values of noise in Sydney Metropolitan Area, Australia. A formula for L_{10} and L_{eq} calculation for urban traffic was given by using multiple regression analysis and NPL equation. Yeow *et al.* (1977) used digital simulation to find the time averaged mean square sound pressure level for a system of roads in an urban area. The validation with experimental values was also done. The technique was said to be useful for planning new road networks and routes in cities. Barry and Reagan (1978) developed the FHWA traffic noise prediction model, based on reference energy mean emission level (REMEL) equations obtained from single vehicle (treated as monopole or single point source) pass-by tests. The data (required to form the regression equations) were collected in different states in US, for three vehicle types: automobile, medium truck and heavy truck. To the mean emission level, propagation effects due to distance, air absorption, ground divergence etc. were added to obtain the overall L_{eq} , 1h level. It was done for free-flow conditions on highways. The subjective response of residents to different noise exposure levels in the city of Jeddah was studied by El-Sharkawy and Aboukhashaba (1983). The noise levels L_{10} , L_{50} , L_{90} were measured, Traffic Noise Index (TNI) and Noise Pollution Level (NPL) were calculated, and a prediction model was developed. The dissatisfaction level and noise exposure were correlated using linear regression. Sy *et al.* (1985) carried out a daytime traffic noise study in Singapore. The values of L_{10} , L_{50} , L_{90} were measured and NPL and TNI were calculated. A correlation between volume of traffic and noise level was obtained. An improved method to calculate the impact of road traffic noise level, by incorporating the factors of tire noise and design of vehicles was suggested by Hood (1987). The method, termed as insulation, was used to determine compensation entitlement for residents, affected by the high noise levels. Hammad and Abdelazeez (1987) calculated the noise level, L_{10} for 1 hour and 18 hours, in the greater Amman (Jordan), and compared the results with measured

values. The 90's also witnessed some novel work done in the area of traffic noise modelling, with the researchers including new aspects and parameters in their work.

Chew (1995) presented a traffic noise model based in Singapore that considered the inclinations of buildings close to the expressways. This kind of a model is particularly helpful for places where there is scarcity of land and buildings are flanking both sides of the roads. But it was concluded that inclining the buildings even up to 40° did not have a significant influence on the reduction of noise level. Öhrström (1995) conducted a study on twelve persons, for eight nights, in a laboratory which had home-like settings for sleeping. The subjects were exposed to different number of noise events of recorded traffic noise levels, with a maximum noise level of 45 dB(A), and the sleeping behavior was observed. It was seen that the subjects had difficulty sleeping, or took longer to sleep when the noise events were higher. Observations were also made for body movements during sleep, tiredness and performance on a test the next day. Makarewicz (1997) worked on the propagation of traffic noise by ground divergence and refraction, and gave equations that could be used for prediction of traffic noise level, L_{eq} dB(A) a few tens of meters above the ground. A steady flow of vehicles with constant speed was assumed. A path model for assessing the community response to traffic noise was presented by Yoshida *et al.* (1997). The data was collected from respondents who lived near a trunk road in Tokyo. The annoyance from traffic noise was reported to be a main factor for dissatisfaction with the living environment.

2.2 Country-Specific Traffic Noise Prediction Models

An increasing awareness of the adverse effects of high traffic noise levels led to the development of country-specific traffic noise assessment and prediction models, prominent among which are FHWA of USA, CoRTN of UK, ASJ of Japan, RLS-90 of Germany, MITHRA of France and StL-86 of Switzerland. These models were developed by different countries in order to address the concerns for growing traffic noise pollution, which was an inevitable fallout of the increasing number of automobiles plying on the roads.

Most of these models predict noise levels using equations that are developed from the data collected from roads in different regions (parameters generally considered are traffic volume, average speed, percentage of heavy vehicles and geometric parameters of the site). To the reference energy mean emission level (the A-weighted, peak, pass-by noise level generated by a single vehicle and measured by a sound level meter placed 1.5 m above the ground and

15 m from the centre of the traffic lane) some correction factors are also added for accurate results. These models have been used for the last so many years very successfully in the countries or regions where they have been developed. The algorithms have been incorporated in simple hand-held calculators or excel spreadsheets, and results can be calculated in a simple and fast way. There are standard parameters that are considered for which the data are collected and the noise level in dB(A) evaluated, for the particular highway or road section.

A brief description of these models is given below:

2.2.1 FHWA (Federal Highway Administration) Traffic Noise Prediction Model

It was developed by Barry and Reagan (1978) for the US Department of Transportation. This model assumes vehicles as individual acoustic point sources, travelling at a constant speed. It is applicable to straight flat roads, with the sound propagation calculated from the distance effects. Many correction factors are added to the base or reference mean noise emission level, to get accurate results. The correction factors or adjustments are: adjustment for traffic flow, adjustment for distance between road and receiver, and length of the roadway, adjustment for shielding effects and ground divergence. The noise level descriptor used is $L_{eq,1h}$. The detailed equations and algorithms can be found in *FHWA Traffic Noise Model* (1998).

2.2.2 CoRTN (Calculation of Road Traffic Noise) Model

It was developed by the Road Research Laboratory for the Department of Transport in UK (*CoRTN, Calculation of Road Traffic Noise*, 1988). The model is based on curve fitting and empirical data. The parameters considered are hourly traffic flow, percentage of heavy vehicles and average traffic speed. Some of the salient features of this model are:

- (i) It uses L_{10} (1h and 18h) as the noise level descriptor.
- (ii) It assumes the vehicular traffic as a line source (analogous to fluid flow), and a constant free flow speed of the vehicles.
- (iii) The corrections factors or adjustments made to the basic noise level (L_{10} for 1h or 18h, at a reference distance of 10 m from the nearest carriageway edge of the highway), are: distance adjustment, traffic flow adjustment, gradient adjustment, pavement type adjustment, shielding and angle of view adjustment and reflection adjustment.

2.2.3 RLS 90 Model

The RLS 90 (*Richtlinien für den Lärmschutz an Straßen* – Guidelines for Noise Protection on Streets) is the German legal noise standard. The original model proposed in 1981 was revised in 1990. It has two distinctive features: prediction of traffic flow or volume (a pre-requisite for predicting traffic noise), where not available, and a program for parking lots. The parameters considered are: traffic volume per hour and percentage of heavy trucks. L_m is the A-weighted mean noise emission level, which is dependent upon the traffic volume and percentage of heavy vehicles. The correction factors added to this mean level are: correction for speed limit, pavement surface, rises and falls along the streets, absorption properties of building surfaces and attenuation due to distance from receiver, air absorption, ground divergence, meteorological effects, houses and foliage.

2.2.4 ASJ Model

The prediction method was reported by Koyasu and first published by the Acoustical Society of Japan, in 1975. Some of the significant improvements in the ASJ model have been reported by the researchers Tachibana and Sasaki (1994). Since 1993, it has been updated every five years by the Acoustical Society of Japan. The latest model, which can take into consideration junctions, signalized intersections, acceleration and deceleration effects and many more features, is called ASJ RTN-Model 2013. First, the sound power level L_w is calculated from the vehicle speed, from an empirical equation given by Yamamoto (2010). Then the different correction factors are calculated, namely, a correction factor for asphalt pavement, for road gradient and for sound radiation directivity. The propagation is calculated by an engineering method, taking into account ground absorption, divergence, air absorption, diffraction etc.

2.2.5 MITHRA

MITHRA was developed by the French firm, O1 dB. It is a commercial software based on ray tracing techniques, that has the option for prediction of traffic noise both from road and railways. It has been functional as a software program since 1987. The traffic stream is assumed to be a line source in the model. Different types of roads and road surfaces are also incorporated in the model. Ray tracing is used for calculation of propagation of sound by reflection, diffraction, atmospheric and ground effects.

2.2.6 StL-86

StL-86 was developed by the Swiss Federal Office. It contains the options for prediction of traffic flow as well as the traffic noise level. The model has two parts, one for emission and the other for the propagation. It considers the parameters average speed, percent of trucks, flow rate and a correction factor for road surface type and gradient. The model was updated in 1997 and became StL-86+ (Aballea *et al.*, 2009).

Some researchers have modified these models to suitably apply them in their region (Givargis and Mahmoodi, 2008).

As can be seen, the above models are based on collection of data for variables like traffic volume, percentage of heavy vehicles, average speed of vehicles (for different categories of vehicles like light vehicles, heavy vehicles, two-wheelers etc.) and then using statistical techniques (e.g. linear regression) to arrive at equations which are standardised for the mean emission level, to which correction factors are added. These corrections or adjustments are mainly the propagation effects which are calculated from the geometrical factors, like attenuation due to divergence, ground effect, air absorption, shielding due to barriers, housing, foliage etc.

2.3 Recent Traffic Noise Prediction Models

There are various traffic noise prediction models which have been developed in the recent years, some of which are listed below.

2.3.1 Son Road Model

It is a replacement of the StL-86 model used earlier in Switzerland. The model consists of passenger cars and trucks as the standard vehicle categories. The single vehicle pass-by level is calculated at a distance of 7.5 m and a height of 1.2 m, to which correction for road surface type and road gradient are added (Heutschi, 2004). The propagation calculation is based on *ISO 9613-2:1996 (Acoustics - Attenuation of sound during propagation outdoors - Part 2: General method of calculation)*, with some deviation in calculation of ground effect.

2.3.2 Harmonoise Project (Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management of Environmental Noise) (Watts, 2005)

It was developed for the member states of the European Union, to have a common and reliable model for traffic noise prediction. The model consists of standard vehicle categories, which are represented by point sources with contributions of sound power from rolling and propulsion. The base level of sound power from the two sources (rolling and propulsion) depends on the vehicle speed, and is calculated from equations which consist of coefficients obtained from octave band analysis. To this basic level, the propagation effects from the usual media (air absorption, distance effects, ground divergence, diffraction etc.) are added to obtain the final noise level.

2.3.3 Nord 2000 Model

It was developed by DELTA (Denmark) and SP (Sweden), for road and rail traffic noise prediction, during 1996-2001. The model includes most of the noise attenuation mechanisms (Kragh *et al.*, 2002). It was revised in 2005-2006.

2.3.4 NMPB-Routes-2008 Model

The original model developed and adopted by France for the road traffic noise prediction was NMPB-Routes-1996. It was designed to account for meteorological effects on the propagation of sound. The model was revised in 2008 to make it more accurate by replacing some of the propagation mechanisms (Dutilleux *et al.*, 2010).

2.3.5 CNOSSOS –EU Model

The CNOSSOS-EU (Common Noise Assessment Methods in Europe) project by the European commission for the EU member states is underway (Kephalopoulos *et al.*, 2014). A comprehensive and strategic noise mapping in all regions of European member states is being recommended. The approach used for calculating the noise levels, the noise level descriptors, point source or line source representation of road traffic flow, vehicle classification, and sound propagation calculation methods are being standardized by involving different stakeholders. The criteria to be used for evaluating the different methods include simplicity, accuracy, precision, computational speed and flexibility.

2.4 Hybrid and other Miscellaneous Models

Various models have been developed that involve both the data based regression methods and calculation of propagation effects using standard methods from ISO 9613, or other sources (Harris, 1991).

The different parameters that have been considered by researchers for developing these models, apart from traffic volume in vehicles per hour, distance from the traffic lane, vehicle speed and percentage of heavy trucks are, gradient percentage (Tang and Tong, 2004), ratio of building height to road width (Nicol and Wilson, 2004; Gündoğdu *et al.*, 2005), shielding, angle of view, reflection (Thorsson and Ögren, 2005), type of road or pavement surface (Cho and Mun, 2008; Yu and Lu, 2013), type of vehicles, equivalent number of vehicles (Rahmani *et al.*, 2011), and many more.

Other parameters or aspects that relate to the traffic dynamics are road bumps/speed breakers (Abbott *et al.*, 1997), traffic signal cycle, traffic congestion (Stoilova and Stoilov, 1998; Can *et al.*, 2008), acceleration and deceleration of vehicles, length of vehicles and their interaction (Iannone *et al.*, 2011), driver's behaviour, skill, age, reaction time (Calvo *et al.*, 2012). All the above mentioned parameters relate to the road traffic dynamics.

The above parameters have been used by researchers worldwide, for traffic noise modelling and analysis.

Pamanikabud and Vivitjinda (2002) formulated a model of highway traffic noise based on vehicle types, in Thailand. The reference energy mean emission level (REMEL) equations were developed for each category of vehicles by using experimental data of L_{eq} (10 s). To this basic noise level, corrections for other parameters were added to make the model accurate. Gaja *et al.* (2003) used 5 years of experimental noise data collected in Victoria (Spain) in order to assess different sampling strategies. It was concluded that six randomly chosen days should be used for data collection, which are necessary to accurately represent the annual equivalent noise level from the measurement of 24 hour noise level. Tang and Tong (2004) carried out a study on the free flow traffic noise on the inclined urban roads in the densely populated and mountainous city of Hong Kong. They found the UK based CRTN model suitable for traffic noise prediction. Also, the influence of tire noise was highlighted.

Nicol and Wilson (2004) have considered the parameters street width and height of measuring point for traffic noise prediction and modelling the reduction in noise level with the height of the buildings in urban canyons. The experimental study was based in nine streets of Athens.

De Coensel *et al.* (2005) developed a model for predicting urban traffic noise using a microsimulation package, vehicle emission laws and a propagation method, in Gentbrugge, Belgium. The model could take care of the time-based noise fluctuations in urban traffic noise dynamics scenario. Tansatcha *et al.* (2005) developed a traffic noise model based on the perpendicular propagation analysis technique, for Bangkok-Chonburi roadway. The parameters considered were traffic volume, categories of vehicles, average speed of different vehicle types and the condition of the roadway. The propagation effect due to ground divergence was added to the mean noise level. The model performed well in the statistical tests. A traffic noise prediction model was developed for the free-flow conditions present on highways by Pamanikabud *et al.* (2008) in Thailand. The concept of an 'equivalent noise level over 20 s' was used in their approach. The propagation due to the ground effect was estimated using an iterative procedure. The model performed well in the goodness of fit tests.

Chevallier *et al.* (2009) presented a traffic noise prediction model for roundabouts. This model can take care of the dynamic aspects of traffic noise due to congestion of vehicles and their interactions, near roundabouts. A traffic flow microsimulation tool along with noise emission laws and a sound propagation model are used in this approach.

Wang and Kang (2011) have studied the relation of urban density of traffic and urban morphology in the cities of Wuhan in China and Greater Manchester in U.K. Noise mapping was done using Cadna/A, and noise levels were compared in the two cities. The ground noise L_{\max} and L_{10} was found to be higher in Wuhan, but L_{avg} and L_{50} were lower in Wuhan than that of Greater Manchester. The urban morphology was found to have significant effects on the noise levels. Lam and Ma (2012) have done noise-mapping studies in Hong Kong for residential complexes built in the last 50 years, i.e. between 1950 and 2000. The study aimed at finding the results of efforts to reduce the traffic noise levels. Paviotti and Vogiatzis (2012) studied the noise produced by PTW (Powered Two Wheelers), mainly scooters and motorbikes in Athens, Greece. They worked on the factors like maximum noise level and roughness that leads to annoyance for the pedestrians. Ramirez and Dominguez (2013) have

compared different existing international traffic noise prediction models by carrying out a study in the city of Bogota, Columbia. They have developed stochastic and deterministic models to predict urban traffic noise under dynamic conditions and found the results better than some existing models. The drawbacks of using regression models have also been outlined. The modelling was based on noise curves of different classes of vehicles, their speed and fit of single noise function, $L_{i,17 \text{ sec}}$.

Guarnaccia (2013) has proposed the use of advanced tools for traffic noise prediction at intersections, roundabouts and congested traffic situations. The author has emphasized that the standard TNMs (Traffic Noise Models) fail in these situations, and new and more advanced tools are required to model and analyse such traffic noise scenarios. Different approaches like cellular automata, traffic flow theory, dependence of source power on speed and acceleration of vehicles etc. have been presented in the study. Guarnaccia *et al.* (2014) have modelled the noise exceedances during a given time interval, using the non-homogeneous Poisson processes. The rate function used is of the Weibull type. This model is useful for studying the noise exposure and also for predicting the noise level. It has been applied to traffic noise data from Messina, Sicily in Italy.

Zhao *et al.* (2015) have suggested an improvement in highway traffic noise prediction by proposing $L_{\text{eq},20\text{s}}$ as the basic vehicular noise, instead of the mean energy emission level, used in FHWA. The experimental investigation has also been done for a receiving point on a flat road near a highway tunnel portal. Gulliver *et al.* (2015) have developed an open-source traffic noise model for estimating noise exposure, using a geographic information system (GIS), in the British cities of Leicester and Norwich.

2.5 Artificial Intelligence Based Models

Various Artificial Intelligence based techniques like Artificial Neural Networks and Genetic Algorithms have been used by researchers all over the world for traffic noise prediction modelling.

2.5.1 ANN Based Models

Many researchers have used Artificial Intelligence techniques for developing traffic noise prediction models. *Artificial Neural Networks (ANNs)* have been used for the modelling by

Cammarata *et al.* (1995), Avsar *et al.* (2004), Genaro *et al.* (2010), Givargis and Karimi (2010), Kumar *et al.* (2014), Garg *et al.* (2015) etc.

Cammarata *et al.* (1995) applied the ANN technique for prediction of road traffic noise by collecting data for commercial, residential and industrial areas, and developing the prediction equations that involved three parameters; equivalent number of vehicles, average height of the buildings and width of the street. Later, the parameters, number of cars, motorcycles and trucks were included instead of the single parameter of number of vehicles. Now, the model had five inputs and one output, with 20 neurons in the hidden layer. The result obtained using the BPN (Back Propagation Network) approach, was compared with some classical models and the results obtained were found to be more accurate.

Avsar *et al.* (2004) developed a multilayer neural network by using the experimental noise data of 16 different points in a Turkish campus location. The inputs considered were: position of the measuring point, distance from the source to the point of action, wind speed and direction, air temperature, relative humidity and time of day. The output obtained was the equivalent sound pressure level, $L_{A_{eq}}$.

ANN was also used by Givargis and Karimi (2010) for the prediction of $L_{A_{eq, 1h}}$ in Teheran. The data used for developing the model was partitioned into training and testing subsets. 60% of the data was used for training, 20% for testing and the remaining 20% was used as a holdout subset for the validation of the model.

Genaro *et al.* (2010) concluded from their studies that a greater number of variables should be included in the models for improved accuracy. The authors used ANN for modelling urban noise in Granada, Spain and compared their model with other mathematical models. It was found that the use of ANN resulted in higher accuracy in the results and therefore, was an improvement over the existing models.

Kumar *et al.* (2014) applied the multilayer feed forward back propagation (BP) neural networks for traffic noise prediction in the Patiala city, India. The one-layer neural architecture consisting of 3 input neurons, 8 hidden layer neurons and 2 output neurons was found to be the best, during training and testing for both, L_{eq} and L_{10} traffic noise descriptors.

Garg *et al.* (2015) have applied neural networks using BPN approach, for traffic noise prediction in various locations of Delhi city, in India. They have compared the results with multiple linear regression models, using total traffic flow and equivalent traffic flow. The ANN approach is shown to outperform the linear regression models.

2.5.2 GA Based Models

Genetic Algorithms (GAs) have also been used for vehicular traffic noise prediction by Gündoğdu *et al.* (2005) and Rahmani *et al.* (2011), by using data from the respective regions where the models have been developed. Though most of these studies have been done for flat roads, Gündoğdu *et al.* (2005) have also taken the parameters road gradient and ratio of building height to road width, in their models. They have used GA for modelling traffic noise in eastern Turkey. Three input variables were considered in the development of the traffic noise prediction model: traffic volume (vehicles per hour) and composition, road gradient (m/m) and ratio of building height to road width (m/m). Genetic algorithms (GA) were used in the optimization of the objective function, written in the form of the square of the error between the measured and computed noise levels.

Rahmani *et al.* (2011) developed a model using Genetic Algorithm, for predicting the traffic noise on the roads in Iran. The parameters considered were vehicle speed, composition and traffic volume. The objective function known as a fitness function in the GA literature was the minimization of the standard square error. Two models, time dependent and time independent, were developed.

2.6 Traffic Noise Studies in India

The traffic noise assessment and modeling is gaining importance in India too, amidst the growing awareness in the international community of its adverse effects on the urban population and some other indirect implications like the loss in a nation's GDP. Though there is no standard traffic noise model specified in India, but a lot of research has been done in this area. Rao and Rao (1991) carried out a traffic noise study in Visakhapatnam, and developed equations for the prediction of the noise level descriptor, L_{A10T} . The parameter considered by them was the number of heavy and light vehicles per hour. Kumar and Jain (1994) carried out traffic noise surveys in Delhi and measured A-weighted noise levels and

power spectra of some typical vehicle types (buses, trucks, cars, auto-rickshaws). It was observed that the noise level was the highest in auto-rickshaws, though the power spectra were similar for all vehicle types. Chakrabarty *et al.* (1997) collected traffic noise data in Calcutta, and found the values of different noise level descriptors like $L_{eq(24)}$, L_{dn} , L_{10} , L_{90} , L_{99} , L_{np} and TNI. They formed regression equations with L_{eq} as a function of logarithm of the equivalent number of vehicles per hour. Nirjar *et al.* (2003) formed regression equations from the data collected from eight different sites in Delhi. The results obtained from the model matched fairly well with the measured values. A comparison was also done with the results from other models like FHWA, CoRTN and 'Stop and Go' model. Ingle *et al.* (2005) presented the adverse effects of high traffic noise levels in terms of hearing loss observed in traffic policemen, in Jalgaon, India. Tyagi *et al.* (2006) carried out a study in Delhi, in which they concluded that vegetation belts can be used as a barrier to abate traffic noise. But traffic noise modeling has not been done in this work. Gorai *et al.* (2007) highlighted the importance of traffic noise prediction tools for ensuring a noise pollution free environment. The study was done in Dhanbad, Jharkhand. The prediction model was based on the traffic volume of different types of vehicles on the basis of their assigned weights. Banerjee *et al.* (2008) developed a traffic noise model in the town of Asansol, West Bengal. They considered the parameters of traffic flow per hour, percent heavy vehicles and the road width in the model that was developed using regression analysis. But the limitation of this model is that land use data, aerial photographs and ground truth verifications are required. Padhy and Padhi (2008), measured the noise levels (L_{eq}) in different zones of Bolpur - Santiniketan areas, and found the noise levels to be very high and beyond the acceptable limits. Goswami (2009) carried out a noise measurement study in the town of Balasore, Orissa, and concluded that the different areas in the town are prone to the high noise pollution levels, and there is awareness of the pollution caused by high traffic noise levels. However, more work needs to be done to make people fully aware of its health effects. Rajakumara and Mahalinge Gowda (2009) developed a model for the Bangalore city, using the acceleration-deceleration approach at the signalized intersections for interrupted traffic flow. The parameters used were: equivalent traffic flow (vehicles per hour), equivalent traffic speed (km per hour), the position of sound level meters (meters) and the queue of waiting vehicles on the deceleration lane (meters). The descriptor used for noise level measurement was L_{eq} . Tandel *et al.* (2011) carried out a noise pollution study in Surat. They have highlighted the growth of vehicles on the roads in the city, and the importance of developing traffic noise models for prediction purposes. The model developed

by them (using regression analysis), consists of parameters: PCU (Passenger Car Units), building height along the road and open space but the road width has not been considered therein. Agarwal and Swami (2011) developed a traffic noise prediction model from empirical studies in the city of Jaipur. They have considered an equivalent traffic density number for developing the model. Pandey *et al.* (2011) have done traffic noise assessment on National Highway No. 28 in India (near Gorakhpur city in U.P.) using the FHWA model. They have analyzed the Federal Highway Administration's Traffic Noise Model (TNM) versions 2.1 and 2.5 to determine their functionality in the Indian traffic conditions. But the modeling was done only for the free flow conditions on the highway. Kumar *et al.* (2011) developed a model using regression analysis, based on the Calixto model, for the Indian road conditions. The model was developed for a highway (NH-58), where the free-flow conditions exist, unlike the city roads, where traffic dynamics (like change in vehicle speed due to signalized intersections, roundabouts, speed breakers, interrupted flow) are present.

Subramani *et al.* (2012) developed a mathematical model in Coimbatore city (Tamil Nadu) for Dindigul – Bangalore road (NH-209) for predicting L_{eq} and L_{10} , by using regression analysis. The parameters considered were total vehicle volume per hour, average vehicle speed in kmph, atmospheric temperature in °C, surface temperature in °C and relative humidity in %. The modelling was done for un-interrupted free flow conditions only. Kumar *et al.* (2012) have summarized their findings regarding the application of neural networks in traffic noise prediction. But, modelling using ANN approach has not been done in this work.

The high noise levels due to the increased vehicular traffic affect the health and well-being of a considerable section of society in India, especially those living in close proximity of highways and urban roads, as concluded by Banerjee (2012) from a study of the literature in this area. The effect of horn events and traffic flow characteristics in Indian urban traffic conditions has been studied by Vijay *et al.* (2015) and Kalaiselvi and Ramachandraiah (2016). The Graph Theoretic approach and the Soft Computing approach has been presented by Singh *et al.* (2016a,b) for the assessment and modelling of urban traffic noise, in Patiala city.

So, it can be seen that a lot of work has been done by the Indian researchers over the past many years, in the area of traffic noise evaluation and modelling. But more work needs to be

done in the area of urban traffic noise and new techniques which are simple to use, reliable, robust, holistic, accurate and fast, need to be developed and applied in this area.

2.7 Summary

The literature reveals that many researchers have developed models for prediction of noise levels. The standard models available earlier have been replaced by more advanced techniques in road traffic noise modelling and prediction. The task is quite complex, since there are many traffic scenarios like urban roads, rural roads, highways, roundabouts, flyovers, intersections etc. Further, city / country specific traffic situations are quite different. The kind of vehicles like two-wheelers, four-wheelers, buses, trucks etc. contribute differently to overall noise level. The driving conditions, environmental conditions, topographical differences vary from place to place. None of the existing models are universally applicable, because of the different traffic conditions, driving behaviour, rules and regulation, topography of the region etc. For example, the traffic conditions in the Indian scenario are driven by the typical driving behaviour, where the drivers are tempted to indiscriminate use of horns, especially in the congested urban traffic conditions. Also, the type of vehicles and the condition of the vehicles make them quite peculiar to the Indian sub-continent. All these reasons have led to the development of varieties of models which are site / city / country specific. The modelling techniques adopted like regression models taking a few important contributing parameters, ANN approach, GA approach, Traffic dynamics approach, GIS technique, modelling using Poisson processes etc. have been applied by different researchers.

2.8 Formulation of Research Objectives

As seen from the literature review, specific models suitable to the Indian scenario need to be developed to better equip ourselves with novel and advanced methods to take care of the variety of traffic noise situations and the related aspects, some of which have been presented above. Some of the **gaps** which have been identified from the literature survey are summarized below:

1. Many of the models have been developed for the highway traffic noise, which cannot be directly applied to assessment of urban traffic noise. Therefore, to cater to the above factors,

there is a need to develop new models which are specifically suited to the urban Indian traffic conditions, preferably based on new modelling techniques.

2. The quantitative techniques applied might not be very appropriate / suitable in case of subjective, vague or fuzzy inputs, and decision making involving human perception. So, a new approach is desirable which can take care of these aspects as well.

3. A systems approach which considers the interactions between the different subsystems of the urban traffic noise system seems to be missing. An application of the graph theoretic (GT) approach in the area of traffic noise has not been reported so far.

4. For the case of quantitative techniques, which can be applied when precise quantitative data is available, some AI (Artificial Intelligence) techniques like ANN and GA have been applied, and also compared with linear regression models. But there are other AI and soft computing methods which have not been explored for traffic noise prediction modelling and compared with these traditionally applied AI/soft computing techniques. The techniques like 'Random Forests' and 'Decision Trees' which have not been explored in the area of traffic noise, show a lot of potential in the development of traffic noise prediction models.

5. The barrier design that has been reported in literature is of ad-hoc nature, where a barrier is constructed on the site and then the noise reduction is measured. A systematic design of barriers based on acoustic principles needs to be attempted.

6. Sufficient studies have not been undertaken to systematically include the effect of honking (use of horns by vehicle drivers) in the models. It is an important parameter, especially in the typical urban traffic conditions in the Indian sub-continent.

Keeping the above factors in mind, the research **objectives** that have been formulated are given below.

1. To assess the noise level (by using the descriptors like L_{eq} , L_{10} , L_{50} , L_{90}) and its variation in urban traffic situation on city roads in Patiala.
2. To find out new descriptors which can represent the traffic dynamics present on the city roads.
3. To verify the efficacy of existing models taking traffic dynamics into account, for Indian road conditions.

4. To develop a traffic noise prediction model, which can take into consideration the noise variation due to the dynamic nature of urban traffic (due to signalized intersections, roundabouts, traffic congestion, speed breakers etc.) as per Indian road conditions.
5. To suggest suitable noise mitigation measures at the plausible sites having high noise levels. To propose noise barrier as an abatement strategy.

In order to work in the direction of the above identified objectives, two different approaches for vehicular traffic noise assessment and prediction have been developed, which are presented in the subsequent chapters. The first one is the graph theoretic (GT) approach, which has been applied in a traffic noise problem probably for the first time. The graph theoretic approach, along with its applications in different areas is presented in **Chapter 3**.

The second approach which has been used is the soft computing approach, which is more appealing for problems that are particularly quantitative in nature and deal with variables / parameters that can be precisely measured or easily quantified. The related literature for this technique is also presented in **Chapter 4**. The effect of horn noise or honking in the Indian traffic scenario is presented in **Chapter 5**. Acoustic barrier design has been presented for a specific site having high traffic noise level, in **Chapter 6**. Finally, the conclusions are presented in **Chapter 7**.

CHAPTER 3

MODELLING AND ANALYSIS OF URBAN TRAFFIC NOISE SYSTEM USING GRAPH THEORETIC APPROACH

In this chapter, the traffic noise measurements carried out at different locations in the Patiala city are presented. It is shown that the existing models cannot be directly applied in the Indian traffic conditions. A novel approach based on Graph Theory is then presented, with a step-by-step methodology and application of the model to two real life traffic scenarios.

In order to assess the existing noise levels in the Patiala city, as per the identified objectives, traffic noise measurements were carried out at various locations in the city using the standard procedure (ISO 362-1:2015). The measurements of the traffic noise levels have revealed that the existing noise level in terms of L_{eq} dB(A) is in the range 70 dB(A) to 75 dB(A) in residential areas and 75 dB(A) to 80 dB(A) in busy urban areas with traffic congestion (during day time) whereas the prescribed noise limits are 55 dB(A) in residential areas and 65 dB(A) in commercial areas (Noise pollution, 2000). The different locations where the traffic noise data was collected are shown in Fig. 3.1. The corresponding noise levels (L_{eq} and L_{10}) are presented in Table 3.1. The high noise levels pose a threat to the resident population, shopkeepers, vehicle drivers and traffic policemen, as they are directly exposed to the road traffic noise. In a stark contrast, the residential areas in many European countries have buffer zones so that direct exposure to noise is not there, which is not so in the Indian scenario.

In line with the above objective, a study was undertaken to verify the efficacy of existing models as applied to urban Indian road conditions. Some of the models that were tested in this study were: CoRTN, FHWA, Rajakumara and Mahalinge Gowda (2009) and Kumar *et al.* (2011). The data was collected as per the input and output parameters considered in these models, namely traffic volume, percentage of heavy vehicles, average speed of vehicles, L_{eq} dB(A) and L_{10} dB(A) in Patiala city. It was seen that the error between the predicted and measured values was quite large and was as high as 11 dB(A) in some cases. Also, the models CoRTN and FHWA do not have the parameters like acceleration, honking etc. which are significant in the urban Indian road traffic conditions. A study of the literature also confirmed this. The traffic noise studies undertaken by Kalaiselvi and Ramachandraiah

(2016) in Chennai, India, have shown a significant difference of upto 10 dB(A) between the measured and predicted values calculated using the existing models RLS 90, FHWA, CoRTN, Statens planwerk etc. The authors have emphasized the fact that the factors like vehicular dimensions, speeds, honking, narrow road width and lack of lane discipline make the traffic characteristics in India quite different from other countries where the above models have been developed.

Therefore, it can be safely concluded that the existing models cannot be directly used in the Indian conditions and warrant the need for new models to be developed. These models may be based on novel approaches/ methods that have the potential of addressing the urban traffic noise problem.

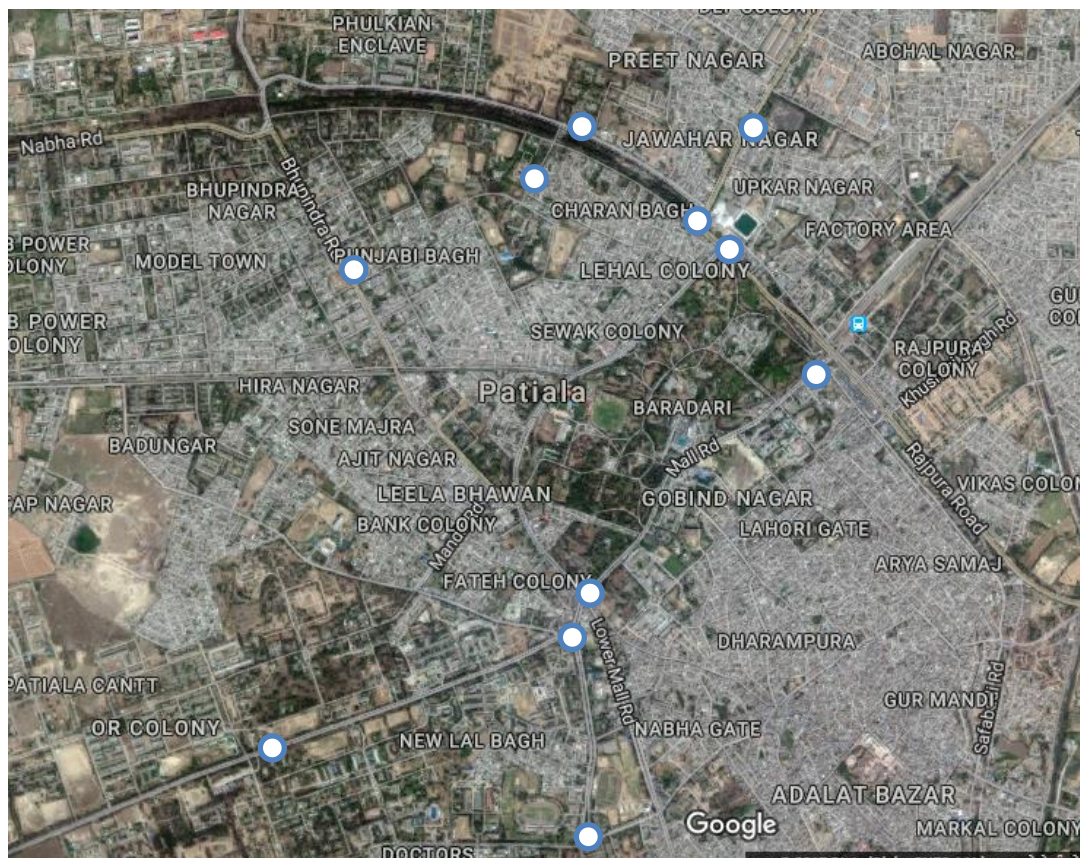


Fig. 3.1 (a) Locations for data collection in the Patiala city (source: Google Earth)

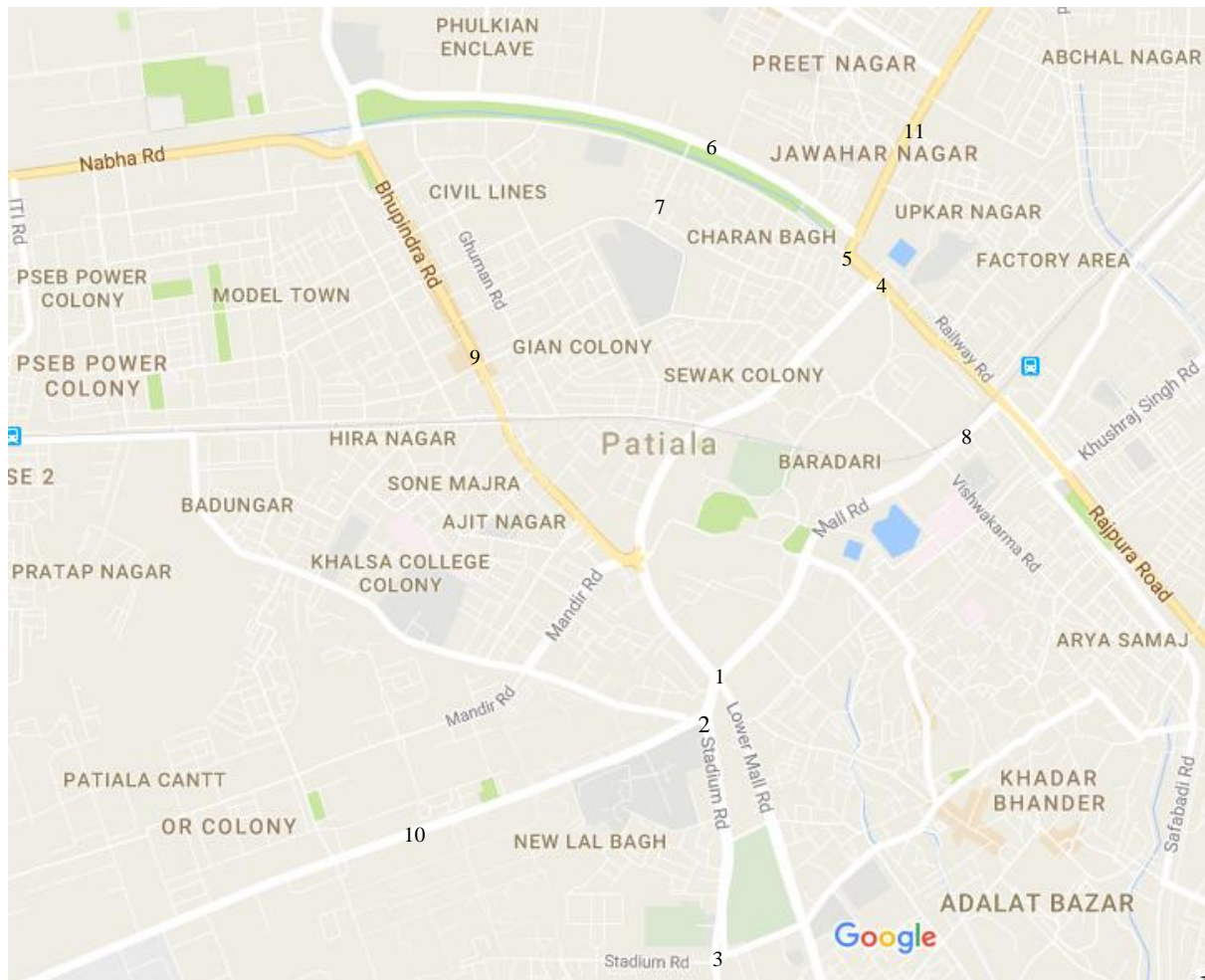


Fig. 3.1 (b) Locations for data collection in the Patiala city (source: Google, map view)

The numbering of the locations in Fig. 3.1 (b) has been done according to the locations presented in Table 3.1.

Table 3.1 Traffic noise levels at different locations in Patiala city

Sr. No.	Location	L_{eq} dB(A)	L_{10} dB(A)
1.	Fountain roundabout	77.1	80.0
2.	Thikriwala roundabout	75.4	78.3
3.	YPS roundabout	71.3	74.3
4.	Gurdwara Dukhniwaran Sahib (near traffic lights)	79.2	82.1
5.	Gurdwara Dukhniwaran Sahib (Passy road entrance)	74.3	77.2
6.	Secretariat road (near Shani temple)	74.5	77.4
7.	Passy road (near Modi temple)	69.9	72.9
8.	Bus stand (near Corner hotel)	76.8	79.7
9.	Bhupindra road (near CCD restaurant)	70.3	73.2
10.	Patiala - Sangrur road	76.5	79.5
11.	Sirhind road	74.7	77.6

As a step ahead in this direction, an attempt has been made in the present work to develop a **Graph Theory (GT)** based traffic noise model. The GT approach has proven its worth in many disciplines like reliability engineering (Gandhi *et al.*, 1991), automotive vehicles (Venkatasamy and Agrawal, 1997), power plants (Mohan *et al.*, 2003), composite product systems (Prabhakaran *et al.*, 2006), water resources management (Ratha and Agrawal, 2015) etc. One of the benefits of this approach is that it is a systems approach, in which the interdependencies or interactions between different subsystems are taken into account. All real life systems behave in an integrated and interactive way. The GT approach is very appropriate from this perspective, as the interactions between different subsystems are considered explicitly, being an integral part of this technique. The existing traffic noise models do not seem to take care of this aspect. A large number of contributing factors can be considered using the GT approach and the complete Urban Traffic Noise System (UTNS) can be analyzed in a holistic and systematic manner.

The Graph Theoretic approach has many benefits, some of which are summarised below:

1. The GT approach is simple, easy to use in general, and can be applied in different situations, where the traditional models may not be suitable. For example, in the traffic noise scenario presented in the illustration of Athen's streets by Nicol and Wilson (2004), models like FHWA, CoRTN, RLS-90 etc. are not directly applicable, and for which new models need to be developed.
2. The interactions between different parameters are not presented explicitly in the traditional models, only their overall impact on the noise level generated is considered. In the systems approach, different parts of a system are interdependent and affect each other considerably. Therefore, these interdependencies should not be neglected. The parameters in a traffic noise system also interact with each other and are interdependent. In order to consider their interdependency, GT approach is quite suitable.
3. It being a matrix method, is useful for computer programming when the number of parameters is large.
4. The inclusion of subjective inputs, human judgement and opinion, and presence of fuzziness in real life scenarios, is possible in a GT model.

Some of the benefits mentioned above are illustrated in the work presented below by applying the GT approach to an urban traffic noise system. Two illustrative examples are

presented to show the application of this approach to a real traffic noise scenario in an urban area.

3.1 Introduction

The present work highlights the importance of using a systems approach in a real life urban traffic noise scenario. The permanent function based GT approach has been applied for the first time in the urban traffic noise system in the present work. The different steps involved in the formulation of a traffic noise model have been illustrated. ‘Permanent function’ in the form of a composite noise index has been formulated and its calculation and correlation with the existing noise level descriptors like L_{eq} , have been illustrated with examples.

3.2 Identification of Subsystems and Structural Constituents of Subsystems

The different subsystems that can be considered responsible for the Urban Traffic Noise include: road traffic subsystem, human subsystem, environment subsystem, traffic network subsystem and urban prosperity subsystem. This identification of subsystems is an important step to model formulation and to analyze the different aspects of the urban traffic noise. The classification is general and has been used to illustrate the proposed methodology. The different subsystems consist of various sub-subsystems which are nothing but their constituent parameters and they are given below:

- Road Traffic Subsystem (S1): type of vehicles (cars, buses, trucks, two-wheelers, three-wheelers etc.), volume of vehicles or traffic flow, percentage of heavy vehicles, average speed of vehicles, road gradient, road width, acceleration of vehicles etc.
- Human Subsystem (S2): drivers’ attributes like skill, age, experience, reaction time etc.
- Environment Subsystem (S3): air absorption, geometric divergence, wind, temperature, humidity, foliage etc.
- Traffic Network Subsystem (S4): major and minor urban roads, flyovers, roundabouts, traffic signals, traffic regulation etc.
- Urban Prosperity Subsystem (S5): malls and shopping areas, showrooms, residential and commercial property etc.

These five subsystems are supposed to include all possible sub-subsystems, which in the present case are the parameters associated with the five subsystems, presenting a general noise problem.

3.3 Interactions between Subsystems

The various subsystems and the interactions between them are represented by a schematic GT diagram shown in Fig. 3.2.

The different interactions show that all the subsystems are related and influence each other to contribute to the overall urban traffic noise and must be studied in an integrated manner, to get an in-depth understanding of the total traffic noise scenario.

Road Traffic Subsystem (S1) can be considered to be one of the most important subsystems of UTNS, as it consists of parameters like volume of vehicles, percentage of heavy vehicles, acceleration of vehicles etc. which contribute directly to noise emission.

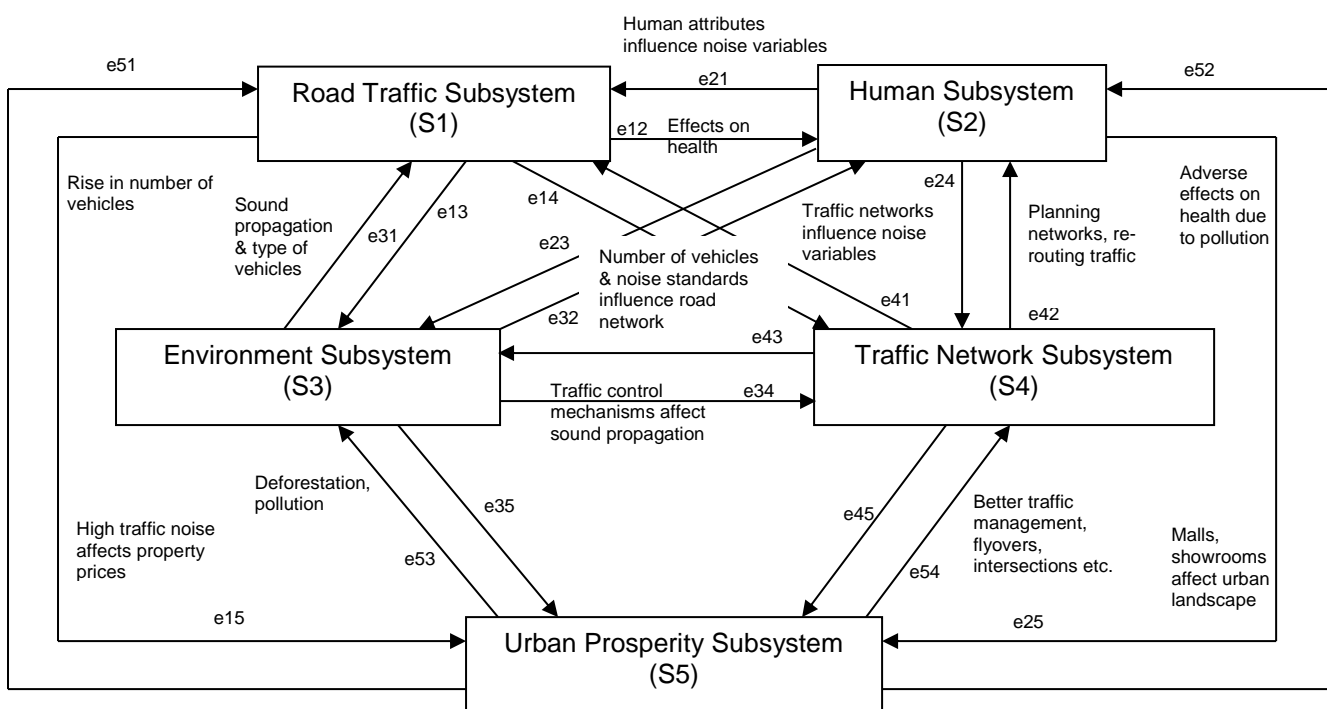


Fig. 3.2 Schematic GT diagram of urban traffic noise system

The Environment subsystem (S3) is responsible for the propagation of sound through the medium (i.e. air) up-to the receiver, by various means like air absorption, geometric divergence, ground effect, wind etc. Other subsystems (Human Subsystem (S2), Traffic Network Subsystem (S4) and Urban Prosperity Subsystem (S5)) are also important as they affect the UTNS directly or indirectly, through the various parameters/factors shown in the schematic GT diagram, in Fig. 3.2.

3.4 Graph Theoretic Model of the Urban Traffic Noise System (UTNS)

A schematic representation of the Urban Traffic Noise System, as shown in Fig. 3.2, is useful for understanding the structure of the system, with all the subsystems (S_i) shown by blocks and the directional interactions (e_{ij}) between them by arrows, but it is not a mathematical entity. It is not possible to carry out mathematical operations with this representation, to derive any meaningful results. The following steps are developed in order to analyse the UTNS.

3.4.1 Matrix representation for UTNS

The schematic diagram of Fig. 3.2 is converted into the matrix form to carry out mathematical operations and also to have a computer friendly representation. The steps followed for this are given below:

- First, an adjacency matrix (Deo, 2004) for the UTNS is written as:

$$[A] = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 & 5 \end{matrix} & \begin{matrix} \text{Subsystems} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{matrix} \\ \begin{matrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{matrix} & & \end{matrix} \quad (3.1)$$

In the above matrix $[A]$, the diagonal elements are zero as there is no interaction of a subsystem with itself. The off-diagonal elements are 1, indicating the presence of interactions between different subsystems. To characterize this system, a characteristic matrix is defined in the next step.

- The adjacency matrix $[A]$ (of the previous step) is representing only the inter-relationships between subsystems. In order to characterize the system, another matrix $[B]$ (the UTNS characteristic matrix) is defined, which is expressed as $[\lambda I - A]$,

1	2	3	4	5	Subsystems
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$$[B] = [\lambda I - A] = \begin{bmatrix} \lambda & -1 & -1 & -1 & -1 \\ -1 & \lambda & -1 & -1 & -1 \\ -1 & -1 & \lambda & -1 & -1 \\ -1 & -1 & -1 & \lambda & -1 \\ -1 & -1 & -1 & -1 & \lambda \end{bmatrix} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{matrix} \quad (3.2)$$

where λ represents the eigen values for the matrix and I is an identity matrix of the same order as [A].

The matrix [B] contains diagonal elements(λ) which are all equal, which might not be true in practice, as the subsystems may have different characteristics depending on the parameters associated with them. Also the interactions between subsystems might be variable, rather being equal, as in eq. (3.2). In order to represent the varying characteristics of the diagonal terms and the varying degree of influence of one subsystem over other subsystems, another matrix called the variable characteristic matrix (VCM) is proposed.

- The constant diagonal and off-diagonal elements of matrix [B] have to be replaced by variable terms, as discussed above. In order to achieve this and formulate a variable characteristic matrix, a diagonal matrix [D] with elements S_i (the subsystems S_1 to S_5) and another matrix [C] with diagonal elements zero and off-diagonal elements as e_{ij} , which represent the interactions between the subsystems, are used. The VCM is then defined as,

$$[V] = [D]-[C]$$

The matrix [V] is given below,

1	2	3	4	5	Subsystems
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$$[V] = \begin{bmatrix} S_1 & -e_{12} & -e_{13} & -e_{14} & -e_{15} \\ -e_{21} & S_2 & -e_{23} & -e_{24} & -e_{25} \\ -e_{31} & -e_{32} & S_3 & -e_{34} & -e_{35} \\ -e_{41} & -e_{42} & -e_{43} & S_4 & -e_{45} \\ -e_{51} & -e_{52} & -e_{53} & -e_{54} & S_5 \end{bmatrix} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{matrix} \quad (3.3)$$

The above matrix contains the diagonal elements as S_1 to S_5 , which contain the information about the attributes of the structural elements of the urban traffic noise

system, and the off-diagonal elements as e_{ij} , which represent the varying degree of interactions between the subsystems.

- The determinant of matrix $[V]$ would yield a multinomial with different terms representing the contribution from all the diagonal and off-diagonal elements. But, when numerical values of S_i and e_{ij} are substituted in the above matrix $[V]$, and the determinant calculated, there is loss of information due to the presence of negative signs. To take care of this, the negative signs are replaced by positive signs and a ‘permanent matrix’ $[P]$ (Marcus and Newman, 1962; Marcus and Minc, 1965; Jurkat and Ryser, 1966) is obtained as:

$$\begin{array}{cccccc}
 & 1 & 2 & 3 & 4 & 5 & \text{Subsystems} \\
 [P] = & \begin{bmatrix} S_1 & e_{12} & e_{13} & e_{14} & e_{15} \\ e_{21} & S_2 & e_{23} & e_{24} & e_{25} \\ e_{31} & e_{32} & S_3 & e_{34} & e_{35} \\ e_{41} & e_{42} & e_{43} & S_4 & e_{45} \\ e_{51} & e_{52} & e_{53} & e_{54} & S_5 \end{bmatrix} & \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{matrix} & & (3.4)
 \end{array}$$

It is a general representation of the five subsystem model of the urban traffic noise system. If some of the interactions/interconnections are absent, the corresponding terms will be replaced by zero. The multinomial, which is obtained by calculating the determinant of the above permanent matrix $[P]$, is known as the ‘**permanent function**’, which contains all the information related to the urban traffic noise system. The process results in a multinomial representation which has got physical significance with respect to the urban traffic noise system.

- The matrix representation discussed above is not unique, as by changing the numbering of subsystems or rows, new matrices can be obtained. It can be seen that the terms obtained in permanent function/multinomial are unique (Prabhakaran *et al.*, 2006; Ratha and Agrawal, 2015) and represent UTNS uniquely and conclusively, irrespective of change in numbering of subsystems in the matrix. The permanent function is a mathematical model and represents the traffic noise system uniquely.

The permanent function can be used as a composite noise index (termed as **permanent noise index, 'p'**) consisting of the effect of different traffic noise parameters and the interactions between them. In order to establish the methodology, only the subsystem S1 has been considered in the present work. The different steps for evaluating the permanent noise index are described below with the help of an illustrative example.

3.5 Application of GT approach to an Urban Traffic Noise Situation

In order to illustrate the above steps of the GT approach, a real urban traffic noise situation is taken. Out of the five subsystems of UTNS described earlier, only the RTS (Road Traffic Subsystem) is taken as an illustration to establish the procedure for obtaining the 'permanent noise index' (p) and to establish its correlation with L_{eq} .

In order to illustrate the different steps of the proposed methodology, the work by Nicol and Wilson (2004) is taken as an illustration. They have studied the vertical variation of traffic noise in order to assess its natural reduction in commercial and residential buildings in nine canyon-like streets in different urban areas of central Athens. Relevant data extracted from Nicol and Wilson (2004) are given in Table 3.2; mainly four parameters affecting traffic noise: traffic volume (vehicles passing in 15 minutes), street width (m), height of measuring point above street level (m) and estimated speed (km/h) have been considered. Percentage of heavy vehicles has not been considered as a separate variable in the model. This may be due to the low number of heavy vehicles at the time of measurement because of traffic management policy. The traffic composition (consisting of heavy vehicles, light vehicles and motorcycles) is shown in Table 3.2. Only eight streets (where the data were available for all the measuring points, 'high', 'low' and 'street' level) have been considered. There are residential and office buildings of different heights on both sides of the streets. The facades of these buildings vary with many of them having balconies. On the ground level, stalls and other objects are present on the pavement. The equivalent sound pressure level, L_{eq} dB(A), percentile levels L_{90} dB(A) and L_{10} dB(A) have been measured. The application of the GT approach in developing the traffic noise model in this kind of a scenario and value of the 'permanent function' as noise index is presented in this section.

Table 3.2 Traffic data in different streets (Nicol and Wilson, 2004)

Street	Number of vehicles passing in 15 min				Street width (m) (SS_2)	Height of measuring point (m); 'High' (SS_3)	Height of measuring point (m); 'Low' (SS_3)	Estimated speed (km/h) (SS_4)	Average speed (km/h)
	Heavy	Light	Motorcycles	Total (SS_1)					
AKE	32	386	356	774	19	25.5	11.5	0-40	20
AME	4	185	199	388	10	22	11.5	0-40	20
HAR	8	117	62	187	10	11.5	8	0-15	7.5
MII	3	83	107	193	9.5	12	8	8	8
MIM	5	102	106	213	9.5	22.5	18.5	25-30	27.5
OTE	16	153	359	528	22	18.5	8	10-15	12.5
PED	-	-	2	2	3.5	22	15	-	-
SOL	7	187	147	341	10	15	11.5	10-20	15

The different steps that are used to formulate the permanent noise index for the considered traffic situation are given below.

3.5.1 Graph Theoretic Model of the Road Traffic Subsystem (RTS)

A Graph Theoretic model of the Road Traffic Subsystem (RTS) for the above situation is formulated as shown in Fig. 3.3. The noise parameters are shown by vertices (SS_i) and the directional interactions as edges (e_{ij}) between them by arrows. A matrix representation of the model is obtained in order to do the mathematical analysis of the system.

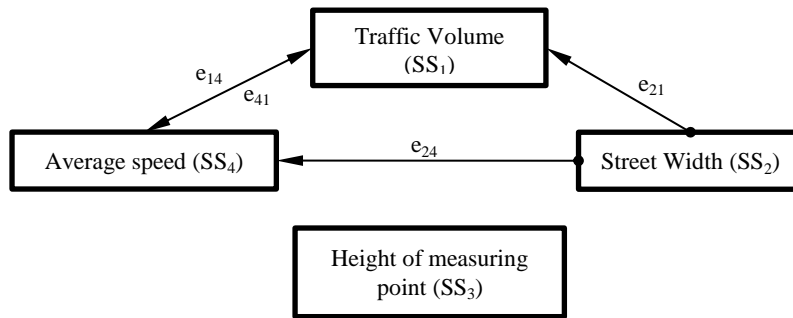


Fig. 3.3 Graph Theoretic model of constituents of RTS

3.5.2 Matrix representation for RTS

The Graph Theoretic model of Fig. 3.3 is represented in a matrix form $[N]$ and the permanent function per $[N]$. The 'permanent noise function', $per [N]$ of the road traffic system, consisting of the four traffic noise parameters and the corresponding interaction coefficients is presented in eq. (3.5).

$$per [M] = per \begin{bmatrix} SS_1 & e_{12} & e_{13} & e_{14} \\ e_{21} & SS_2 & e_{23} & e_{24} \\ e_{31} & e_{32} & SS_3 & e_{34} \\ e_{41} & e_{42} & e_{43} & SS_4 \end{bmatrix} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \quad (3.5)$$

where $[M]$ is a square 4×4 matrix consisting of the four traffic noise parameters as the diagonal terms, SS_i ($i = 1$ to 4), and the interactions between these parameters as the off-diagonal terms, e_{ij} . Here, e_{ij} represents the influence of parameter i on j , and e_{ji} , influence of parameter j on i .

In order to evaluate the permanent function, there is a need to assign suitable weights to the diagonal (SS_i) and off-diagonal terms (e_{ij}), for which Table 3.3 and Table 3.5 are used. These tables are based on the standard scales available in text (Cross, 1989). Table 3.3 consists of a description of the noise categories of sub-systems with weights assigned on a scale of 1 to 5. Table 3.5 consists of the categories for interactions between parameters of a sub-system with weights assigned on a scale of 1 to 4 (Cross, 1989).

Table 3.3 Noise categories of subsystems

S.No.	Description of noise category	Weights
1.	Low	1
2.	Below average	2
3.	Average	3
4.	Above average	4
5.	High	5

The values of the noise parameters are assigned weights, on the basis of the scale given in Table 3.3: traffic volume ranges from 2 (street PED) to 774 (street AKE), so the weights assigned are 1 and 5 to the lowest and highest value, respectively. For the remaining streets, the weights for traffic volume are calculated using proportionate scaling, and are shown in Table 3.4. The values of street width range from 3.5 m to 22 m, so the weights 1 and 5 are assigned to these extreme values, and proportionate scaling is used for the remaining values. For the case of height of measuring point, which varies from street level to 33 m, a weight of 5 is assigned to street level and 1 to 33m, with proportionate scaling for the rest, since there is noise reduction as one moves up the multi-storey buildings. The average estimated speed for different streets ranges from 7.5 km/h to 27.5 km/h, so the weights of 1 and 5 are assigned to these values, respectively and proportionate scaling done for the remaining values of speed.

Table 3.4 Weights assigned to different noise parameters

Street	Weight W_1 for Traffic volume	Weight W_2 for Street width (m)	Weight W_3 for Height of measuring point (m); 'High'	Weight W_3 for Height of measuring point (m); 'Low'	Weight W_3 for Height of measuring point (m); Street level	Weight W_4 for Average speed (km/h)
AKE	5	5	2	4	5	4
AME	3	3	2	4	5	4
HAR	2	3	4	4	5	1
MI1	2	3	4	4	5	1
MIM	2	3	2	3	5	5
OTE	4	5	3	4	5	2
PED	1	1	2	3	5	1
SOL	3	3	3	4	5	3

Using Table 3.5, the interactions (e_{ij}) between the noise parameters are assigned the values as shown in Table 3.6.

Table 3.5 Categories of interactions between subsystems

S.No.	Categories of interaction	Weights
1.	Strong	4
2.	Medium	3
3.	Weak	2
4.	None	1

The values assigned to the interactions (shown in Table 3.6) are based on correlation analysis (Nicol and Wilson, 2004), logic and intuitive judgement. As the street width (SS_2) and traffic volume (SS_1) have a high correlation, the weight corresponding to the category 'strong' i.e. 4 is assigned to the interaction (e_{21}) (as seen in the Table 3.6). Here, e_{21} means the influence of factor 2 on 1; e_{12} would mean influence of 1 on 2. In this case, there is no influence of traffic volume (SS_1) on street width (SS_2), so a weight of 1 is assigned. Traffic volume and estimated speed strongly influence each other, as seen from the 'fundamental diagram' in traffic flow theory (Gerlough and Huber, 1975), so the weight assigned is 4. The variable SS_3 , 'height of measuring point above ground' does not affect traffic volume, street width or the estimated speed, so the weight corresponding to the category 'none' i.e. 1 is assigned. Similarly the weights are assigned to the other interactions, as shown in Table 3.6.

Table 3.6 Noise factors and their degree of influence

Factors	Characteristics	Degree of influence of noise factor i on noise factor j (e_{ij})			
		Traffic volume	Street width	Height of measuring point above ground	Estimated speed
Traffic volume (SS ₁)	Constant, free-flow, single line, interrupted flow, heavy congested flow	1	1	1	4
Street width (SS ₂)	Constant, varying width, canyon-like streets, approach width, width of driving lanes, aspect ratio	4	1	1	3
Height of measuring point above ground (SS ₃)	Reference point, observation point, low, high, aspect ratio	1	1	1	1
Estimated speed (SS ₄)	Average speed, constant and varying speed, speed limit	4	1	1	1

(Strong ($e_{ij}=4$), Medium ($e_{ij}=3$), Weak ($e_{ij}=2$), None ($e_{ij}=1$))

The ‘permanent function’ for the street ‘AKE’, for the ‘high’ measuring point, as given in eq. (3.5) and using the above values, comes out to be,

$$per(AKE) = per \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 \end{matrix} \\ \begin{bmatrix} 5 & 1 & 1 & 4 \\ 4 & 5 & 1 & 3 \\ 1 & 1 & 2 & 1 \\ 4 & 1 & 1 & 4 \end{bmatrix} & \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \end{matrix} \quad (3.6)$$

Similarly, the permanent function can be formulated for all the other streets at different height above the ground (i.e. high, low and street level).

In order to remove the human inconsistencies while assigning the weights, eigen value formulation is done. It takes care of the error due to inaccurate human judgements during decision making (Yoon and Hwang, 1981). Eigen value formulation is done as $(N - \lambda I)w^T = 0$, where $[N]$ is the permanent noise matrix; λ is the eigen vector, I is an identity matrix, and w^T is the transpose of the weight vector ($w_1 w_2 \dots w_n$). The solution gives either $(N - \lambda I) = 0$ or $w^T = 0$.

As $w^T = 0$ yields a trivial solution, so $(N - \lambda I) = 0$. Its solution yields the eigen spectrum, i.e. $(\lambda_1 \lambda_2 \dots \lambda_n)$. Then, λ_{\max} is selected to calculate the weight vector such that $\sum w_i = 1$. w_i is a weight vector for modification of the i^{th} column of the permanent matrix, $[N]$. $[N]$ is multiplied with the weight vector to obtain the updated permanent matrix.

Weights calculated for the permanent function, per (AKE) for the ‘high’ measuring point, using eigen value formulation (in MATLAB R2010a) are:

$$w_1 = 0.2761; w_2 = 0.3675; w_3 = 0.1072; w_4 = 0.2493$$

These weights would be different for the different streets and heights, as per the permanent function formulated. The updated permanent function obtained after multiplication of the elements given in eq. (3.6) with the above weight vectors, for this case, is obtained as,

$$per(AKE) = per \begin{bmatrix} 1 & 2 & 3 & 4 \\ 1.3803 & 0.3675 & 0.1072 & 0.9973 \\ 1.1042 & 1.8373 & 0.1072 & 0.7480 \\ 0.2761 & 0.3675 & 0.2143 & 0.2493 \\ 1.1042 & 0.3675 & 0.1072 & 0.9973 \end{bmatrix} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \quad (3.7)$$

The value of the permanent noise index ‘p’, calculated using MATLAB R2010a, comes out to be 1.87. Similarly, permanent function, weight vectors and ‘p’ for other streets at different measuring points have been obtained. The values of ‘p’ along with the corresponding L_{90} , L_{eq} and L_{10} values are given in Table 3.7.

Table 3.7 Values of ‘Permanent Noise Index (p)’ for different streets

Name of Street	High				Low				Street			
	P	L_{90} dB(A)*	L_{eq} dB(A)	L_{10} dB(A)	P	L_{90} dB(A)	L_{eq} dB(A)	L_{10} dB(A)	P	L_{90} dB(A)	L_{eq} dB(A)	L_{10} dB(A)
AKE	1.87	69.8	74.3	76.6	3.62	71.5	76.8	79.5	4.66	72.1	78.6	81.7
AME	1.30	64.9	69.9	72.2	2.42	69.1	74.8	77.4	3.07	70.1	77.8	80.7
HAR	1.69	63.1	70.3	73.2	1.69	63.2	71.6	74.3	2.08	62.8	74.9	77.8
MII	1.69	62.1	67.3	69.4	1.69	63.5	69	71.1	2.08	63.8	73.2	75.3
MIM	1.23	61.5	65.6	67.6	1.73	63.2	69.7	71.9	2.91	64	72.9	75.1
OTE	1.94	67.7	73.4	73.9	2.59	67.2	75.1	75.1	3.31	66.1	74.4	75.1
PED	0.67	55.4	57.8	59.9	0.89	59.8	63.2	65.5	1.31	62	66.1	68.5
SOL	1.70	64.8	71.9	74.7	2.24	66.3	73.2	76.1	2.82	66.9	76.0	79.1

* L_{90} , L_{eq} and L_{10} values are obtained from Nicol and Wilson (2004)

The values of ‘p’ and the noise levels L_{90} , L_{eq} and L_{10} for the different streets are compared in the graphs shown in Fig. 3.4, in order to see the correlation between the permanent noise index and the noise descriptors.

It can be seen in Fig. 3.4 that by and large, the permanent function values correlate well with the noise levels in each case (the equivalent (L_{eq}) and percentile (L_{90} , L_{10}) traffic noise levels in the different streets). In order to verify and measure the correlation, regression analysis is done, the results of which are presented in Table 3.8. The regression is done using Excel spreadsheets, by taking the noise level as the dependent variable and ‘log p’ as the independent variable. The variation of noise levels vs. log p instead of p was intuitively chosen since noise levels are intrinsically logarithmic.

Table 3.8 Regression statistics for the different descriptors (L_{90} , L_{eq} and L_{10})

L_p	Equation	Multiple R	R Square	P-value of Coefficients**	
				Intercept	‘log p’
L_{90} (high)	$L_{90} = 24.51 \log p + 59.76$	0.86	0.74	6.02E-09	0.00606
L_{90} (low)	$L_{90} = 20.12 \log p + 59.55$	0.96	0.91	5.72E-10	0.00020
L_{90} (street)	$L_{90} = 18.32 \log p + 58.31$	0.84	0.71	1.51E-07	0.00836
L_{eq} (high)	$L_{eq} = 32.37 \log p + 63.66$	0.93	0.87	1.94E-09	0.00080
L_{eq} (low)	$L_{eq} = 23.71 \log p + 64.69$	0.97	0.95	1.64E-10	3.93E-05
L_{eq} (street)	$L_{eq} = 20.07 \log p + 65.84$	0.86	0.74	8.81E-08	0.00637
L_{10} (high)	$L_{10} = 31.88 \log p + 65.86$	0.92	0.84	2.46E-09	0.00128
L_{10} (low)	$L_{10} = 23.19 \log p + 67.03$	0.96	0.91	6.99E-10	0.00021
L_{10} (street)	$L_{10} = 20.22 \log p + 68.20$	0.80	0.64	2.94E-07	0.01731

** confidence level is 95%

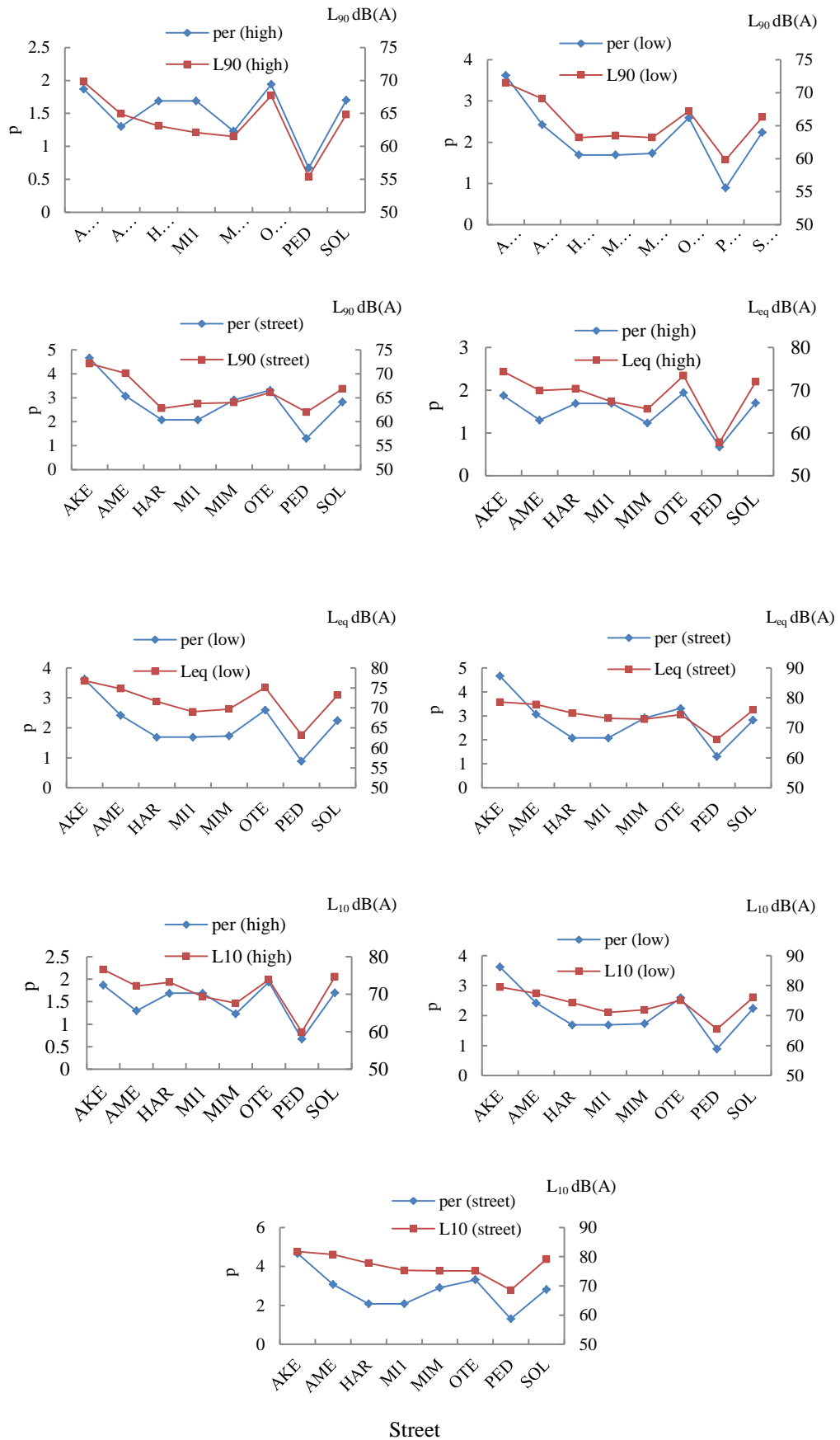


Fig. 3.4 Permanent Noise Index 'p' and L₉₀, L_{eq}, L₁₀ values for different streets

A comparison of the results with those obtained by Nicol and Wilson (2004) shows that a higher value of R^2 has been obtained for most of the descriptors, in the present work. Against an overall value of 0.81 for R^2 for the descriptor L_{eq} , in Nicol and Wilson's work, a higher value of 0.87, for L_{eq} (high) and 0.95 for L_{eq} (low) have been obtained using the presented methodology.

A comparison between measured and predicted values is given in Table 3.9. The graphs of 'measured vs. predicted values' for log p and the corresponding descriptor for the noise level (L_{90} , L_{eq} and L_{10}) are shown in Fig. 3.5.

Table 3.9 Comparison between measured and predicted values of noise level

Name of Street	High									Low									Street level								
	L ₉₀ dB(A)			L _{eq} dB(A)			L ₁₀ dB(A)			L ₉₀ dB(A)			L _{eq} dB(A)			L ₁₀ dB(A)			L ₉₀ dB(A)			L _{eq} dB(A)			L ₁₀ dB(A)		
	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)	Measured	Predicted	error (dBA)
AKE	69.8	66.4	-3.4	74.3	72.4	-1.9	76.6	74.5	-2.1	71.5	70.8	-0.7	76.8	77.9	1.1	79.5	80.0	0.5	72.1	70.6	-1.5	78.6	79.3	0.7	81.7	81.7	0
AME	64.9	62.5	-2.4	69.9	67.3	-2.6	72.2	69.5	-2.7	69.1	67.3	-1.8	74.8	73.8	-1	77.4	76.0	-1.4	70.1	67.2	-2.9	77.8	75.6	-2.2	80.7	78.1	-2.6
HAR	63.1	65.4	2.3	70.3	71.1	0.8	73.2	73.2	0	63.2	64.2	1	71.6	70.1	-1.5	74.3	72.3	-2	62.8	64.1	1.3	74.9	72.2	-2.7	77.8	74.6	-3.2
MI1	62.1	65.4	3.3	67.3	71.1	3.8	69.4	73.2	3.8	63.5	64.2	0.7	69	70.1	1.1	71.1	72.3	1.2	63.8	64.1	0.3	73.2	72.2	-1	75.3	74.6	-0.7
MIM	61.5	62.0	0.5	65.6	66.6	1	67.6	68.7	1.1	63.2	64.3	1.1	69.7	70.3	0.6	71.9	72.6	0.7	64.0	66.8	2.8	72.9	75.1	2.2	75.1	77.6	2.5
OTE	67.7	66.8	-0.9	73.4	73.0	-0.4	73.9	75.0	1.1	67.2	67.9	0.7	75.1	74.5	-0.6	75.1	76.6	1.5	66.1	67.8	1.7	74.4	76.3	1.9	75.1	78.7	3.6
PED	55.4	55.4	0	57.8	58.0	0.2	59.9	60.2	0.3	59.8	58.6	-1.2	63.2	63.5	0.3	65.5	65.9	0.4	62.0	60.5	-1.5	66.1	68.2	2.1	68.5	70.6	2.1
SOL	64.8	65.4	0.6	71.9	71.1	-0.8	74.7	73.2	-1.5	66.3	66.6	0.3	73.2	73.0	-0.2	76.1	75.2	-0.9	66.9	66.6	-0.3	76.0	74.9	-1.1	79.1	77.3	-1.8

The regression analysis results show a high correlation of the logarithm of ‘permanent noise index’ with the noise level descriptors, with a high value of R and R² for the ‘high’, ‘low’ and ‘street’ level points. The predicted values of the different noise level descriptors are matching fairly well with the measured values, as can be seen from Table 3.8 and Table 3.9. The values of errors range between - 3.4 dB(A) to + 3.8 dB(A). The errors observed are minimum for the ‘low’ point for all the descriptors (L₉₀, L_{eq} and L₁₀) and maximum for L₁₀ ‘street’ and L₉₀ ‘high’. The errors range between (-2.0 dB(A) to + 1.5 dB(A)) for the low point. The higher errors in the case of L₁₀ ‘street’ may be due to the topology of buildings and other extraneous factors like horn noise, multiple reflections etc.

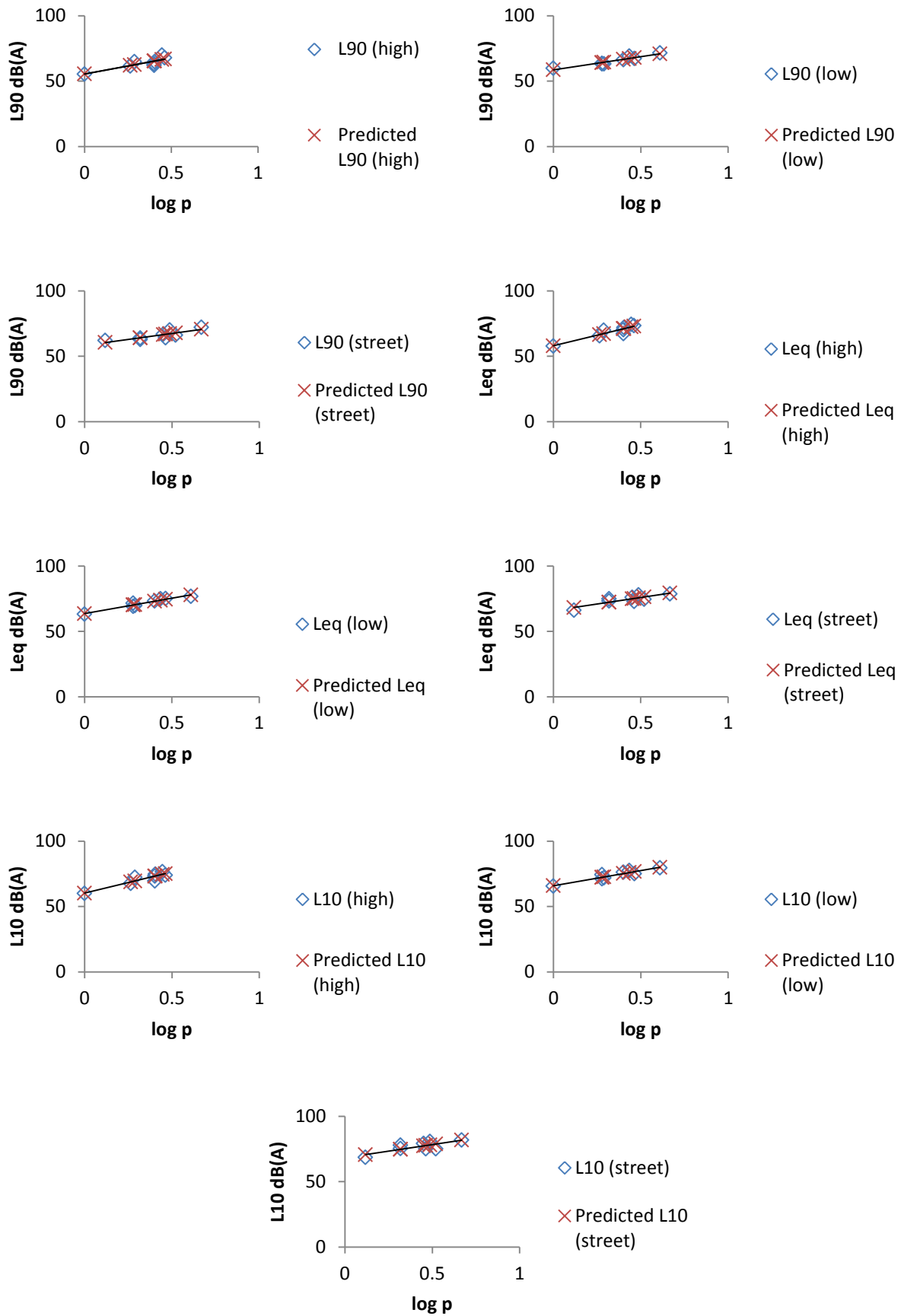


Fig. 3.5 Variation of traffic noise level (L_{90} , L_{eq} and L_{10}) with 'log p'

The present analysis is based on the datasets of 8 streets that were taken to obtain the regression models. Using the same dataset for modelling and verification, led to over-fitting, and more optimistic results. To overcome this drawback, the dataset has been partitioned into training and testing sets. Datasets of six streets (AKE, AME, MI1, MIM, OTE and PED) have been used to formulate a new model. This has been tested / verified with the remaining datasets of the two streets (HAR, SOL). The results are presented in Table 3.10 and Table 3.11.

Table 3.10 Regression statistics for the different descriptors (L_{90} , L_{eq} and L_{10}) for the training dataset

L_p	Equation	Multiple R	R Square	P-value of Coefficients**	
				Intercept	'log p'
L_{90} (high)	$L_{90} = 26.49 \log p + 59.96$	0.89	0.79	1.73E-06	0.016645
L_{90} (low)	$L_{90} = 19.84 \log p + 59.86$	0.96	0.92	4.92E-07	0.002336
L_{90} (street)	$L_{90} = 17.42 \log p + 58.88$	0.83	0.69	2.44E-05	0.03854
L_{eq} (high)	$L_{eq} = 32.58 \log p + 63.61$	0.92	0.86	1.22E-06	0.007382
L_{eq} (low)	$L_{eq} = 24.04 \log p + 64.34$	0.98	0.96	1.09E-07	0.000348
L_{eq} (street)	$L_{eq} = 21.55 \log p + 64.59$	0.91	0.83	8.18E-06	0.010743
L_{10} (high)	$L_{10} = 31.13 \log p + 65.69$	0.91	0.83	1.31E-06	0.010348
L_{10} (low)	$L_{10} = 23.49 \log p + 66.48$	0.97	0.95	1.81E-07	0.000707
L_{10} (street)	$L_{10} = 21.93 \log p + 66.65$	0.87	0.76	1.87E-05	0.022503

** confidence level is 95%

The regression statistics for the partitioned datasets for the different streets are presented in Table 3.10. The high values of R and R^2 show good correlation, and the values of p (<0.05) indicate the statistical significance of the variables. The values of error between predicted and measured (shown in Table 3.11) for the testing dataset are observed to be low (range between +2.8 dB(A) and -4.2 dB(A)), showing the results are matching fairly well.

Table 3.11 Comparison between measured and predicted values of noise level for the testing dataset

Name of Street	High									Low									Street level								
	L ₉₀ dB(A)			L _{eq} dB(A)			L ₁₀ dB(A)			L ₉₀ dB(A)			L _{eq} dB(A)			L ₁₀ dB(A)			L ₉₀ dB(A)			L _{eq} dB(A)			L ₁₀ dB(A)		
	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))	Measured	Predicted	error (dB(A))
HAR	63.1	65.9	2.8	70.3	71.0	0.7	73.2	72.8	-0.4	63.2	64.4	1.2	71.6	69.8	-1.8	74.3	71.8	-2.5	62.8	64.4	1.6	74.9	71.4	-3.5	77.8	73.6	-4.2
SOL	64.8	66.0	1.2	71.9	71.1	-0.8	74.7	72.9	-1.8	66.3	66.8	0.5	73.2	72.8	-0.4	76.1	74.7	-1.4	66.9	66.7	-0.2	76.0	74.3	-1.7	79.1	76.5	-2.6

As seen in Table 3.11, the measured and the predicted values of the noise level, for the testing dataset, are close enough in most of the cases. The errors range between +2.8 dB(A) and -4.2 dB(A). The errors are lower in the case of the ‘low’ point, ranging between -2.5 dB(A) to +1.2 dB(A). In some cases, like the street HAR, value of error at the high point is slightly high which may be due to the topology of the street and the balconies. Multiple reflections from the high rise buildings, presence of horns and other extraneous sources can be the cause for relatively higher error in case of L₁₀ values at the street level.

3.6 Integration of Different Subsystems of UTNS

In the present work, only four parameters of RTS have been taken and the methodology has been established and illustrated for developing the urban traffic noise model. More parameters of this subsystem can be incorporated in the GT model, and the new permanent noise index 'p' can be calculated. Other subsystems of the UTNS can also be integrated by using the same approach, i.e. calculating the permanent noise index 'p' of each subsystem separately, and then formulating the new permanent noise matrix with these 'p' values as the diagonal elements and the interactions between the subsystems as the off-diagonal elements. The value of the new permanent noise index, which acts as a composite score for evaluating the UTNS, is then calculated as per the GT approach suggested in the present work.

3.7 Summary

An urban traffic noise system consisting of different subsystems has been developed and presented. A graph theory based traffic noise model is proposed which takes into account the interactions between subsystems. The road traffic subsystem with the parameters traffic volume, street width, height of measuring point and average speed is taken to illustrate the GT approach adopted for developing the model. A permanent noise index which consists of the effect of different traffic noise parameters and the interactions between them is proposed. The traffic situation presented in Nicol and Wilson's work (2004) has been considered to establish and verify the methodology developed. This could be a useful tool for EIA (Environmental Impact Assessment) studies. The values of R, R^2 and error in the predicted noise level indicate that the results are matching fairly well.

Although, only four parameters of RTS have been considered in the present work, more parameters can be taken, as per requirement of the traffic noise situation. The integration of different subsystems of UTNS using the GT approach has also been discussed. It is hoped that the methodology developed in the present work has got a potential to consider various parameters affecting UTNS in a holistic manner and could be useful for town planners and concerned authorities involved in the management of traffic noise systems.

3.8 Application of GT approach – another Illustrative Example

As seen in the above illustrative example, an algebraic Graph Theoretic (GT) approach which has not been applied so far in the noise area has been attempted. Prima-facie, it appears that GT approach has got an exciting potential. The aim of the work presented below is to illustrate further the application of this approach to another traffic noise scenario. A different traffic noise scenario has been modelled by considering parameters which affect the UTNS. The permanent noise index 'p' has been formulated thus representing the noise scenario holistically.

In order to demonstrate the efficacy of the proposed methodology, a real urban traffic noise situation is taken in Patiala city, India. The traffic situation belongs to the urban major and minor roads near the Fountain chowk roundabout in the city. A layout of the roundabout location is given in Fig. 3.6. The roundabout has a diameter of 19 m. The dimensions of the different roads linked to it are shown in Fig. 3.6. These roads connect some of the main locations of the Patiala city and one of the roads provides an exit towards the highway leading to Sangrur city. The vehicular traffic composition consists of cars, SUVs (Sports Utility Vehicles), motorcycles, auto-rickshaws, trucks, buses and tractors. The different parameters (sub-subsystems) belonging to the road traffic subsystem that are considered in the study include: traffic volume (per 15 mins) (SS_1), percentage of heavy vehicles (SS_2), average acceleration of vehicles (SS_3) and road width (SS_4). The traffic noise level was measured using the standard class 1 B&K sound level meter (SLM). The SLM was kept at a height of 1.2 m above the ground, as per standards. The traffic count and the calculations for acceleration were done manually using a video camera. The traffic data that was used for the application of GT approach in the assessment of road traffic noise at the given location is presented in Table 3.12.

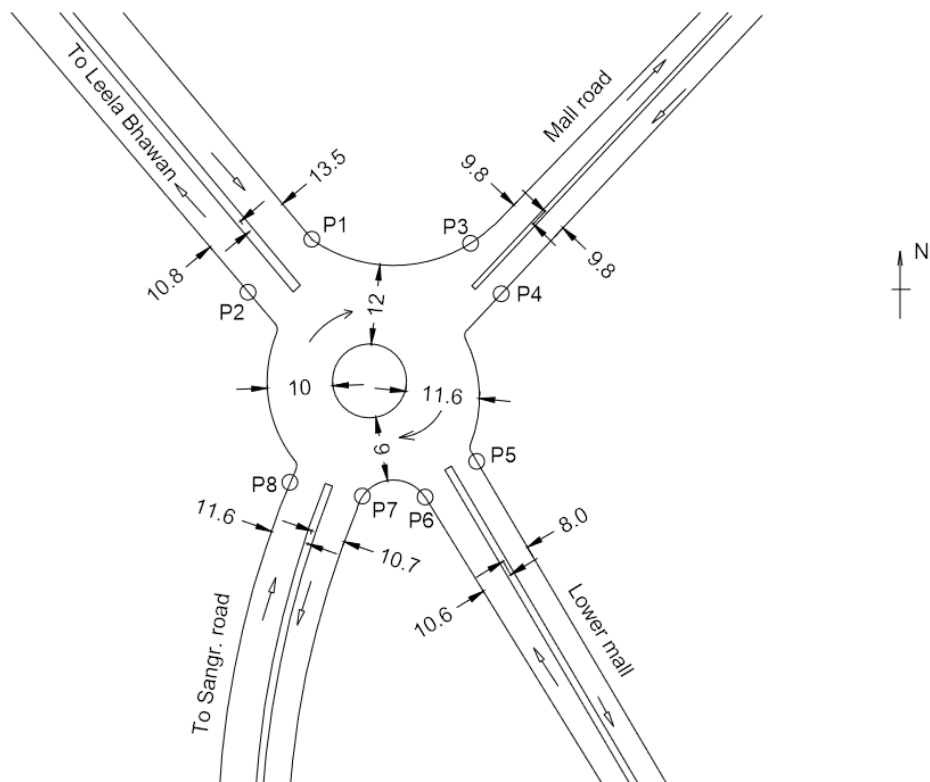


Fig. 3.6 An aerial view (source: Google Earth) and a schematic diagram of the Fountain Chowk roundabout (all dimensions are in meters)

Table 3.12 Traffic data near the ‘Fountain chowk’ roundabout

Sr. No.	Location	Date	Time	Traffic Volume (SS ₁)	Percent of Heavy Vehicles (SS ₂)	Average Acceleration (m/s ²) (SS ₃)	Road Width (m) (SS ₄)
1	P1 (morning)	23/6/15	09.00-09.15 am	678	2.21	3.70	24.30
2	P2 (morning)	24/6/15	11.00-11.15 am	535	2.99	3.12	24.30
3	P3 (morning)	26/6/15	11.00-11.15 am	340	0.29	2.80	19.60
4	P4 (morning)	27/6/15	09.00-09.15 am	403	1.49	2.90	19.60
5	P5 (morning)	28/6/15	09.00-09.15 am	460	0.65	1.95	18.60
6	P6 (morning)	30/6/15	11.00-11.15 am	442	1.36	1.79	18.60
7	P7 (morning)	01/7/15	11.00-11.15 am	419	5.01	4.18	22.30
8	P8 (morning)	02/7/15	09.00-09.15 am	650	3.08	4.09	22.30
9	P1 (evening)	23/6/15	04.00-04.15 pm	570	2.63	4.41	24.30
10	P2 (evening)	24/6/15	05.00-05.15 pm	612	3.10	3.18	24.30
11	P3 (evening)	26/6/15	04.00-04.15 pm	260	1.92	0.68	19.60
12	P4 (evening)	27/6/15	05.00-05.15 pm	328	1.22	0.57	19.60
13	P5 (evening)	28/6/15	05.00-05.15 pm	434	0.46	1.92	18.60
14	P6 (evening)	30/6/15	04.00-04.15 pm	407	0.49	2.81	18.60
15	P7 (evening)	01/7/15	04.00-04.15 pm	465	5.16	3.20	22.30
16	P8 (evening)	02/7/15	05.00-05.15 pm	518	4.63	3.43	22.30

The step-by-step methodology presented in sections 3.4 and 3.5 is used for developing the graph theoretic model and is given below.

- A graph theoretic model, showing the constituents of RTS and interactions between them, is formulated and is shown in Fig. 3.7. Here, the interactions e_{ij} are the interactions between the sub-subsystems, i.e. the four traffic noise parameters, SS_i .

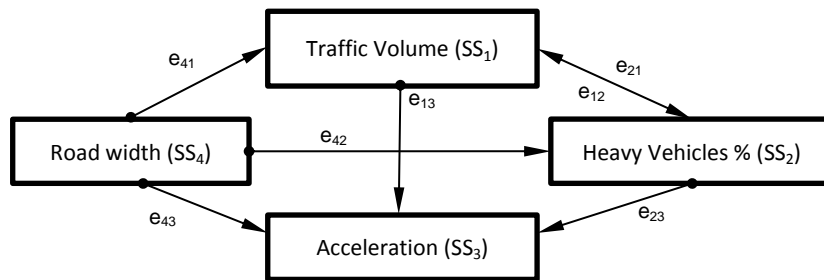


Fig. 3.7 Graph theoretic model of the constituents of RTS

- The Graph Theoretic model of Fig. 3.7 is represented in a matrix form $[N]$ and the permanent function per $[N]$. The ‘permanent noise function’, per $[N]$ of the road traffic system, consisting of the four traffic noise parameters and the corresponding interaction coefficients has been presented in eq. (3.5).
- In order to evaluate the permanent function, there is a need to assign suitable weights to the diagonal (SS_i) and off-diagonal terms (e_{ij}), for which Table 3.3 and Table 3.5 are used. Table 3.3 consists of a description of the noise parameters of sub-system with weights

assigned on a scale of 1 to 5 (Cross, 1989). Table 3.5 consists of the categories for interactions between parameters of a sub-system with weights assigned on a scale of 1 to 4 (Cross, 1989). The weights are assigned to the different diagonal terms using Table 3.3 and are given in Table 3.13. The weights are assigned to the off-diagonal terms using Table 3.5 and are given in Table 3.14.

A scale of 1 to 5 (Table 3.3) is used to assign the weights to the diagonal terms (SS_i). For the noise parameter ‘traffic volume’ (SS_1), the lowest value of ‘260’ (refer Table 3.12) is assigned a weight of ‘1’ (corresponding to ‘low’), and the highest value of ‘678’ is assigned a weight of ‘5’ (corresponding to ‘high’). The intermediate values are assigned weights using proportionate scaling. The lowest value of ‘0.29%’ for the parameter ‘percent of heavy vehicles’ (SS_2) is assigned a weight of ‘1’, and the highest value ‘5.16%’ is assigned a weight of ‘5’. The values in-between are assigned weights using proportionate scaling. For the parameter ‘acceleration’, the lowest value of ‘0.57 m/s²’ is assigned ‘1’, and the highest value of ‘4.41 m/s²’ is assigned ‘5’. In the case of ‘road width’, narrower the road, closer is the receiving point to the noise source line (Li *et al.*, 2002), and higher is the measured noise level. Thus, the highest value of road width, i.e. ‘24.30 m’ is assigned the lowest weight of ‘1’, and the lowest value of ‘18.60 m’ is assigned ‘5’. The intermediate values are assigned weights using proportionate scaling. The weights thus assigned to the different noise parameters are shown in Table 3.13.

Table 3.13 Weights assigned to different noise parameters

Sr. No.	'Traffic Volume' W_1	'Percent of Heavy Vehicles' W_2	'Acceleration' W_3	'Road width' W_4
1	5	3	4	1
2	4	3	3	1
3	2	1	3	4
4	3	2	3	4
5	3	1	2	5
6	3	2	2	5
7	3	5	4	2
8	5	3	4	2
9	4	3	5	1
10	4	3	3	1
11	1	2	1	4
12	2	2	1	4
13	3	1	2	5
14	3	1	3	5
15	3	5	3	2
16	4	4	4	2

The off-diagonal terms (e_{ij}) representing the interactions between subsystems, i.e. the four traffic noise parameters, considered in the present case, are assigned weights using Table 3.5. e_{ij} means the influence of i on j , and e_{ji} means the influence of j on i . The weights are assigned on the basis of correlation analysis, logic and intuitive judgement. The interaction between traffic volume and acceleration is strongly correlated, as higher the traffic volume, lesser is the acceleration possible for vehicles and vice-versa. So, e_{14} , which implies the influence of SS_1 on SS_4 , is assigned a weight corresponding to the category ‘strong’, i.e. ‘4’. But, ‘traffic volume’ (SS_1) does not have any influence on ‘road width’ (SS_4), so a weight corresponding to ‘none’, i.e. ‘1’ is assigned to e_{14} . The parameter ‘road width’ has a strong influence on traffic volume, percent of heavy vehicles and acceleration of vehicles, so a weight of ‘4’ is assigned to e_{41} , e_{42} and e_{43} . Similarly, the weights are assigned to other interactions terms e_{ij} , and are shown in Table 3.14.

Table 3.14 Noise factors and their degree of influence

S.No.	Factors	Characteristics	Degree of influence of noise factor i on noise factor j (e_{ij})			
			Traffic Volume	Percent of Heavy vehicles	Acceleration	Road width
1.	Traffic Volume (SS_1)	Constant, free-flow, single line, interrupted flow, heavy congested flow	1	2	4	1
2.	Percent of Heavy vehicles (SS_2)	Trucks, buses, Trailers	2	1	4	1
3.	Acceleration (SS_3)	Uniform or constant, negative, instantaneous	1	1	1	1
4.	Road width (SS_4)	Reference point, observation point, major and minor roads, arterial roads	4	4	4	1

(Strong ($e_{ij} = 4$), Medium ($e_{ij} = 3$), Weak ($e_{ij} = 2$), None ($e_{ij} = 1$))

Using the weights assigned to different diagonal and off-diagonal terms, as mentioned above, the permanent noise function for the different datasets can be formulated. The permanent function for the first dataset (sr. no. 1) is formulated, as given below:

$$per [N] = per \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 \end{matrix} \\ \begin{matrix} 5 \\ 2 \\ 1 \\ 4 \end{matrix} & \begin{bmatrix} 2 & 4 & 1 \\ 3 & 4 & 1 \\ 1 & 4 & 1 \\ 4 & 4 & 1 \end{bmatrix} \end{matrix} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \quad (3.8)$$

Weights calculated for the permanent function per [N], using eigen value formulation (in MATLAB R2010a, refer section 3.5) are:

$$w_1 = 0.3006; \quad w_2 = 0.2307; \quad w_3 = 0.1514; \quad w_4 = 0.3173$$

These weights would be different for different datasets. The updated matrix obtained after multiplying the elements of [N] with the weights w_1 to w_4 is given below for the first dataset.

The value of the permanent noise index is calculated like a determinant using MATLAB R2010a.

$$per [N] = per \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 \end{matrix} \\ \begin{matrix} 1.5029 \\ 0.6011 \\ 0.3006 \\ 1.2023 \end{matrix} & \begin{bmatrix} 0.4614 & 0.6056 & 0.3173 \\ 0.6922 & 0.6056 & 0.3173 \\ 0.2307 & 0.6056 & 0.3173 \\ 0.9229 & 0.6056 & 0.3173 \end{bmatrix} \end{matrix} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \quad (3.9)$$

The value of the permanent noise index, per [N] comes out to be 2.32. Similarly the values of the permanent noise index for other datasets are calculated and are given in Table 3.15, along with the corresponding L_{eq} values.

Table 3.15 Values of the Permanent Noise Index ('p')

Sr. No.	Value of Permanent Noise Index	L_{eq} dB(A)
1	2.32	79.1
2	1.86	77.7
3	1.31	72.5
4	1.79	75.8
5	1.22	71.5
6	1.46	70.6
7	2.66	79.0
8	2.66	79.8
9	2.48	79.0
10	1.86	78.9
11	0.90	66.2
12	1.05	66.1
13	1.22	73.5
14	1.47	77.1
15	2.25	77.8
16	2.75	80.1

The values of permanent noise index ‘p’ and L_{eq} dB(A) are plotted, as shown in Fig. 3.8. It is seen that the overall trend of variation of the two is similar for the different datasets. Looking at the trends, it is conjectured that permanent noise index ‘p’ can also be used as a traffic noise descriptor. The evaluation of ‘p’ is based only on physical data collection of the subsystem parameters (like traffic volume, percent of heavy vehicles, acceleration and road width), thus obviating the need of the actual acoustic noise measurements, with the help of sound level meters.

The highest value of ‘p’ is 2.75 (dataset no. 16) corresponding to L_{eq} value of 80.1 dB(A) and the lowest is 0.90 (dataset no. 11) corresponding to 66.2 dB(A).

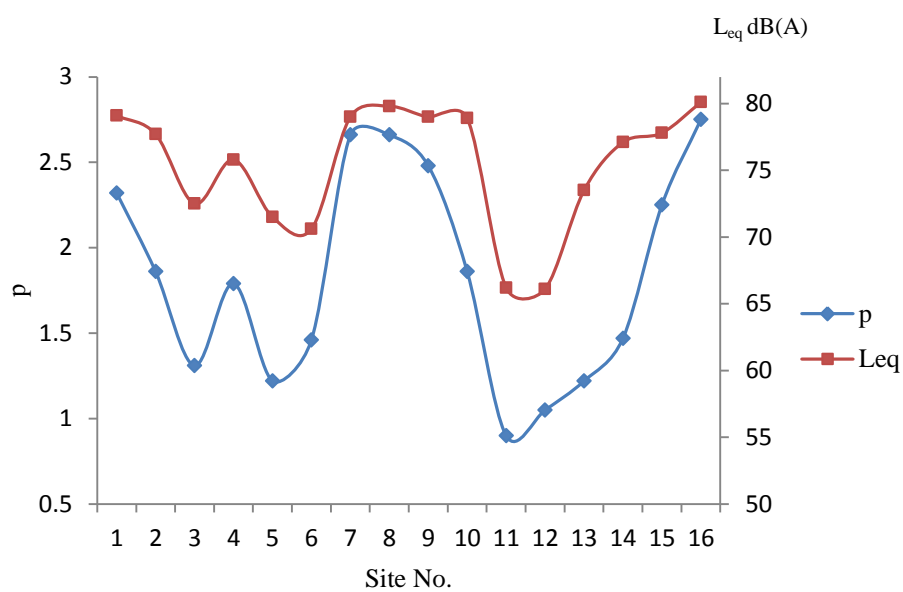


Fig. 3.8 Variation of permanent noise index ‘p’ and L_{eq}

In order to find the correlation between the permanent noise index (p) and L_{eq} , regression analysis was done, by taking L_{eq} as the dependent variable, and $\log p$ as the independent one. Since L_{eq} in dB(A) is a logarithmic value, the independent variable was intuitively chosen as ‘ $\log p$ ’. The results are shown in Table 3.16.

Table 3.16 Regression statistics for L_{eq}

L_p	Equation	Multiple R	R Square	P-value of Coefficients**	
				Intercept	'log p'
L_{eq}	$L_{eq} = 27.42 \log p + 68.80$	0.918	0.84	1.16E-19	7.47E-07

** confidence level is 95%

As seen in Table 3.16, a high value of R^2 is obtained by using the data from all the sixteen sets. The results are more optimistic and lead to over-fitting as the same dataset which is used for forming the equation, is used for verifying the results as well. In order to overcome this drawback, the dataset is partitioned into training and testing datasets. The data from twelve points is used for developing the regression model, and the data from the remaining four points (dataset no. 2, 3, 4 and 15) are used for testing purpose.

The new regression statistics obtained for the data are shown in Table 3.17. It is seen that the values of R and R^2 do not change significantly, even after partitioning into training and testing datasets. The value of correlation coefficient (R) indicates a measure of linear relationship between two sets of data. The value of R is observed to be 0.91. R^2 is known as the coefficient of determination and shows how closely the regression line fits the data. It is a measure of the amount of variance of the dependent parameter, which is explained by the regression model.

The value of R^2 lies between 0 and 1. Higher the value of R and R^2 , the better it is. The value of R^2 is observed to be 0.83, in the present case. The p-value is indicating that the correlation between the considered variables is significant at a confidence level of 95%. The p-value tests the null hypothesis that there is no effect of the considered variable, which is rejected for low p values, generally less than 0.05. This kind of hypothesis testing provides evidence of the statistical significance of the relationship between variables and shows that it is not just by random chance. As seen in the regression equation (Table 3.17), the p-values for the intercept and 'log p', are very small (<0.05), indicating the significance of the considered variables.

Table 3.17 Regression statistics for L_{eq} (for the training dataset)

L_p	Equation	Multiple R	R Square	P-value of Coefficients**	
				Intercept	'log p'
L_{eq}	$L_{eq} = 27.67 \log p + 68.63$	0.913	0.83	3.15E-14	3.26E-05

** confidence level is 95%

The scatter plot between the measured and predicted values of L_{eq} , for the above training dataset is shown in Fig. 3.9.

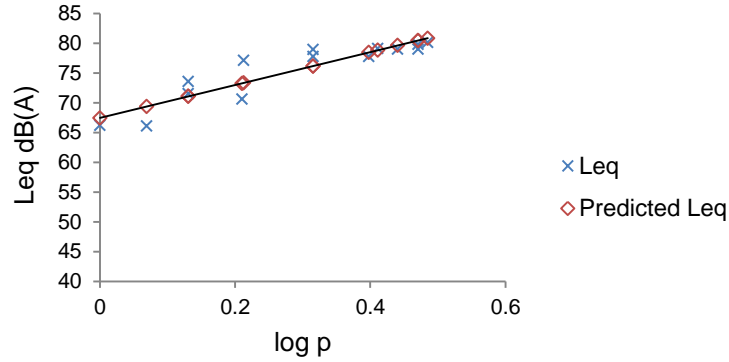


Fig. 3.9 Scatter plot between measured and predicted L_{eq} dB(A)

The error between the measured and predicted values of L_{eq} for the testing dataset is presented in Table 3.18.

Table 3.18 Comparison between the measured and predicted values of L_{eq} for the testing dataset

Sr. No.	L_{eq} dB(A)		
	Measured	Predicted	Error dB(A)
2	77.7	76.1	-1.6
3	72.5	71.9	-0.6
4	75.8	75.6	-0.2
15	77.8	78.4	0.6

As seen in Table 3.18, the error between the measured and predicted values of L_{eq} is small, indicating a good correlation and accuracy in the developed model.

The accuracy of the results depends upon both the experimental measurements and the prediction modelling. Before taking the readings, the sound level meter (SLM) was calibrated for accurate values of L_{eq} dB(A). It was a class 1 SLM, meeting the IEC *IEC 61672-1: 2002, International Electrotechnical Commission* (2002) specifications. Other readings like traffic count, value of acceleration etc. were calculated using videography, as it can be stored for reference and verified later.

Though in the study presented above, only four traffic noise parameters (traffic volume, percentage of heavy vehicles, acceleration and road width) have been taken, more parameters of RTS can be included in the GT model, as per requirement of the considered traffic noise scenario.

The results obtained in the present study, which are fairly accurate, suggest that the GT approach has exciting potential and can be used for the assessment of urban traffic noise levels in similar or different traffic conditions. The traffic noise level and the values of

important parameters, along with the environmental conditions and topography would of course be different for different sites. So, the pertinent data for that site needs to be collected and the presented GT methodology can then be applied to calculate the value of permanent noise index 'p', and correlated with the traffic noise level, L_{eq} dB(A).

3.9 Discussion and Conclusion

The conclusions drawn from the present work are summarised below:

1. An alternative data analysis and modelling technique based on algebraic graph theoretic approach has been presented for the assessment of road traffic noise.
2. The graph theoretic (GT) approach has been illustrated with the help of two examples. In the first example, the traffic situation presented in Nicol and Wilson's work (2004) has been taken to illustrate the proposed methodology. The parameters considered in the model include traffic volume, street width, height of measuring point above street level and average speed. GT approach is applied for developing the model. A permanent noise index 'p' which consists of the effect of different traffic noise parameters and the interactions between them, is proposed and verified with the experimental data. The variation of 'p' with L_{eq} , L_{90} and L_{10} for the different measuring locations has been plotted, and equations for the three noise level descriptors and 'log p' have been formed using regression analysis. The values of multiple R and R^2 , and error (in the range -4.2 dB(A) to $+2.8$ dB(A)) for the testing dataset show good correlation between the measured and predicted values of the traffic noise level, which match fairly well. The errors are lower in the case of the 'low' point, ranging between -2.5 dB(A) to $+1.2$ dB(A). The larger errors for some values may be due to the cascading / multiple reflections in the high rise buildings, in some of the streets, and presence of horns and other extraneous noise sources, particularly in case of L_{10} values at street level.
3. The second illustrative example is based on an urban traffic noise scenario in Patiala city, India. An experimental study has been carried out at the Fountain roundabout in the city. Data related to the road traffic subsystem (consisting of four parameters traffic volume, percentage of heavy vehicles, acceleration of vehicles and road width) is collected. The permanent noise index 'p' is formulated using the GT approach and verified with the

experimental data. The values of R , R^2 and error in the predicted noise level (L_{eq} dB(A)) indicate that the results are matching fairly well.

4. It has been shown in the present work, that the value of the permanent function can be used as an index (termed as permanent noise index 'p') to compare the noise levels at different traffic scenarios within sites under consideration. This approach has the potential of taking into consideration number of parameters and their interaction effects, in a Road Traffic Subsystem, like acceleration, percentage of heavy vehicles, road gradient, horn noise etc.

5. The integration of various subsystems by using the GT approach has also been discussed. The proposed GT methodology can be applied to any existing situation by using 'p' as the index for assessment, comparison and analysis using the systems approach. A standard global predictive model might not be possible at the present stage due to differences in topography of roads and buildings, environmental conditions, vehicle types, driving conditions, regulation etc. in different countries and regions of the world.

CHAPTER 4

VEHICULAR TRAFFIC NOISE PREDICTION USING SOFT COMPUTING APPROACH

A soft computing approach for the development of vehicular traffic noise prediction models is presented in this chapter. This approach is particularly useful when the traffic noise data available is objective in nature. Some researchers have tried using techniques like Artificial Neural Networks (ANNs) (Cammarata et al., 1995, Givargis and Karimi, 2010, Kumar et al., 2014) and Genetic Algorithms (GAs) (Gundogdu et al., 2005, Rahmani et al., 2011) for developing such models, with fairly good results. The use of different soft computing techniques for developing a traffic noise prediction model for the Indian road traffic conditions seems to be a promising option and has been explored in the present work.

4.1 Introduction

In this work, four different soft computing methods have been used and compared for model development, by considering the variables: traffic volume, percentage of heavy vehicles and average speed of vehicles in Patiala city, taking it as a representative set of the traffic conditions in India. The experimental values of these variables along with the equivalent continuous sound pressure level (L_{eq}) values constitute the data set that has been used to develop and validate the models.

The different soft computing methods used in the present work are *Generalized Linear Model, Decision Trees, Neural Networks and Random Forests*. Artificial Neural Networks (ANNs) have been used for vehicular traffic noise modelling by Cammarata et al. (1995), Givargis and Karimi (2010) and Kumar et al. (2014). Genetic Algorithms (GAs) have also been used for traffic noise prediction by Gundogdu et al. (2005) and Rahmani et al. (2011). The different soft computing methods have been extensively applied for protein structure estimation (Rana *et al.*, 2015), traffic light control (Turky *et al.*, 2009), derivation of exposure-response curves for respiratory outcomes (Eliseeva *et al.*, 2013), and in many more applications.

Studies that compare multiple linear regression with ANN (Kumar et al., 2014) and some of the other soft computing methods, which show that these methods outperform linear

regression, are available. However, a comparison of the different soft computing methods with each other while developing the traffic noise models seems to be missing. Also, a study which reports the use of these methods in the development of traffic noise prediction models having higher accuracy as compared to linear regression and the potential to consider large number of variables and datasets from different locations has not been reported. An attempt has been made in the present work to apply the four different soft computing methods in the development of vehicular traffic noise prediction models in Indian road traffic conditions and compare their performance.

The chapter is structured as follows: first, an overview of the considered variables that significantly affect the road traffic noise level, the noise level descriptors, the data sets used and the different soft computing methods, is presented in section 4.2; then, the development of the prediction models using these methods for the given variables and data sets is presented in section 4.3; model evaluation, results and discussion are given in section 4.4 and finally, the conclusion is presented in section 4.5.

4.2. Materials and Methods

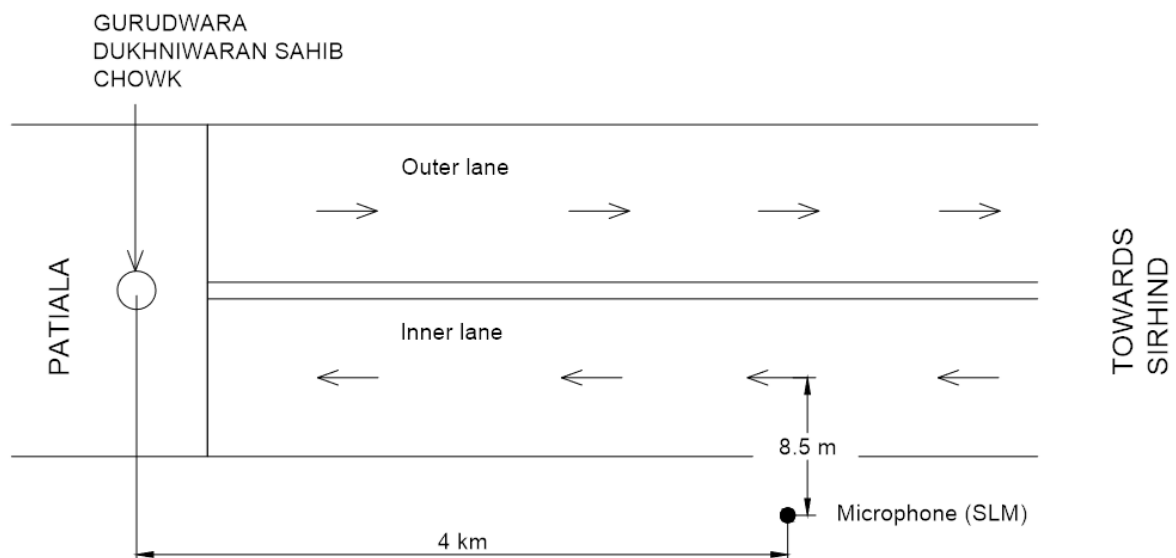
4.2.1 Assessment of Traffic Noise Level

The traffic noise is composed of many individual vehicle noise sources. The individual vehicle noise at the micro level can be attributed to its components, which can be classified into: the engine noise, exhaust noise, transmission noise, tyre road interaction noise, aerodynamics noise, body and road rattle noise. Apart from the individual vehicle noise, the different variables which contribute significantly to the overall level of traffic noise include: traffic volume (number of vehicles on the road per unit time), traffic speed (average speed of vehicles on the considered road section), traffic composition (different types of vehicles present, like cars, buses, trucks, two-wheelers), gradient of road (slope) and pavement surface. There are studies where the effects of vehicle horns (Sharma *et al.*, 2014) and acceleration/deceleration due to interrupted traffic flow conditions (Agarwal *et al.*, 2009) have also been considered.

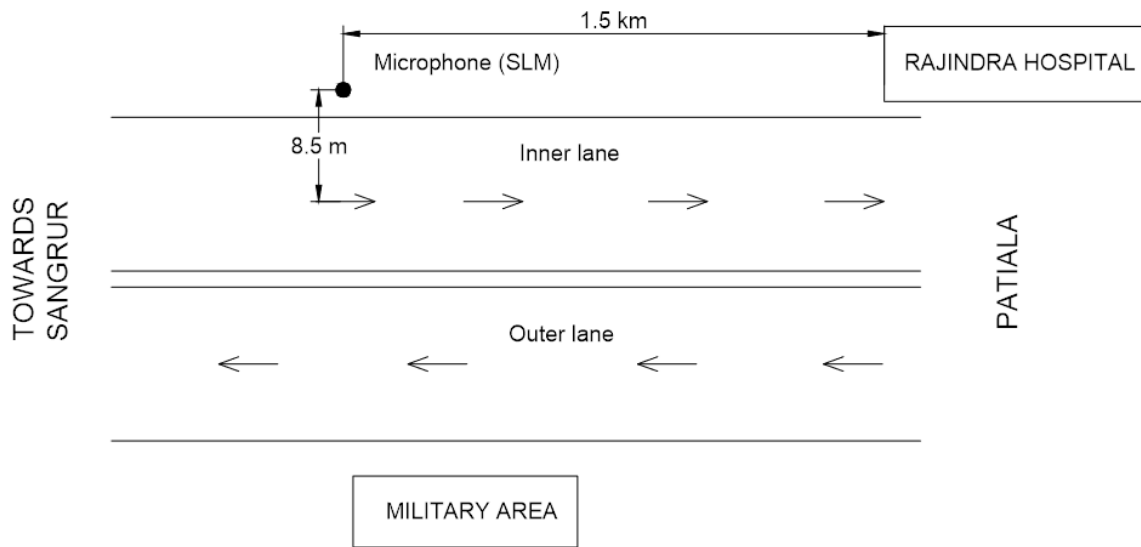
The traffic noise level at a particular location is assessed by using different descriptors. These descriptors are used to capture the time varying nature of traffic noise, because of short-term and long-term fluctuations in the noise level. L_{eq} and L_{10} are the commonly used descriptors in traffic noise assessment and abatement studies.

4.2.2 Data sets and Variables

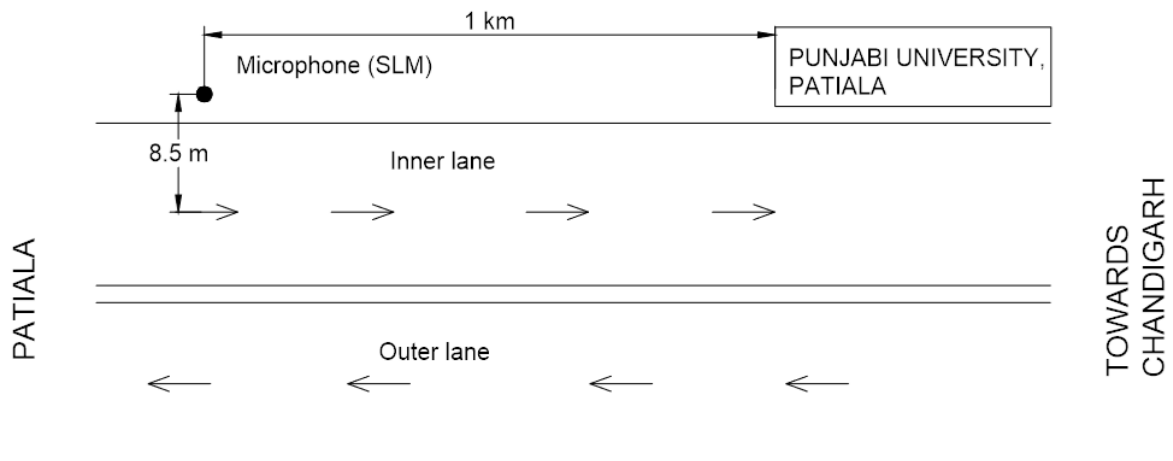
In the present work, the variables, traffic volume (Q), percentage of heavy vehicles (H_v) and average speed of vehicles (v) have been considered to develop the traffic noise prediction models. These variables are known to predominantly contribute to the overall traffic noise level, as also confirmed by the variable importance study, described later. 502 experimental data sets of these variables and the equivalent continuous sound pressure level (L_{eq}), have been extracted from the different traffic noise studies on 3 sites (Fig. 4.1), carried out in Patiala city. A total of 84 datasets were taken at the Patiala-Sirhind road; 303 datasets at the Patiala-Sangrur road; 115 datasets at the Patiala-Chandigarh road. The locations have straight and flat roads. The sound pressure level (L_{eq}) has been measured using a class 1 sound level meter (CESVA SC310 model) and other measurements were done manually. The sound level meter (SLM) was kept at a height of 1.2 m from the ground, as per standards (ISO 362-1:2015) and at a distance of 8.5 m from the center of the inner lane (Fig. 4.1). The average speed of the vehicles has been obtained by using videography. A fixed distance (50 m) was marked on the road and the time taken by a vehicle to cover this distance was noted from the video. Thus, the speed was calculated for different vehicles and then the average was taken.



(a) Site 1: Sirhind road, Patiala



(b) Site 2: Patiala-Sangrur road



(c) Site 3: Patiala-Chandigarh road

Fig.4.1 A schematic diagram of the sites for the traffic noise study in Patiala city (not drawn to scale)

The considered variables, their description and a sample data set of a few representative values taken randomly are shown in Table 4.1.

Table 4.1 Description of variables and sample dataset

Variable/Output	Description	Sample Dataset				
		1	2	3	4	5
Q	Hourly traffic volume (total number of vehicles per hour)	1086	1347	1633	1622	1670
H _v	Percentage of heavy vehicles	7.4	8	8.9	39.9	40.1
v	Average speed of vehicles (km/h)	54.9	50.1	53.7	60.1	63.9
L _{eq}	Equivalent continuous sound pressure level dB(A)	73.7	74.6	76.4	79.3	80.1

4.2.3 Approach

The approach used in the development of the traffic noise prediction model is described in Fig. 4.2. First, suitable locations are selected in the Patiala city, on the basis of significant traffic flow, and the exposure of the nearby resident population (residential houses, commercial buildings, which were 10 to 20 m from the measurement location) to the high noise levels due to the heavy traffic. Then, the data (502 sets) of hourly traffic flow (Q), percentage of heavy vehicles (H_v) and average speed of vehicles (v) is extracted, from traffic noise studies in the Patiala city. In the third stage of data purging, any incomplete or overlapping entries are cleaned-up. The importance of different variables with respect to their contribution to the noise level, was measured using a Self-adaptive Differential Evolution algorithm (SaDE). For this, an objective function (eq. 4.1) was minimized, using the evolutionary algorithm. This increases the effectiveness of the method. The four soft computing methods that have been used were trained using the data set with respective control parameters. The prediction method is shown in Fig. 4.3. In the final stage, the prediction method is evaluated using the performance criteria of coefficient of determination, mean square error and accuracy. 10-fold cross validation is done to check the stability of the most accurate method.

4.2.3.1 Self-adaptive Differential Evolution (SaDE)

Differential Evolution, which can be used for solving global optimization problems in a continuous search domain, was originally given by Storn and Price (1997). It is a very useful

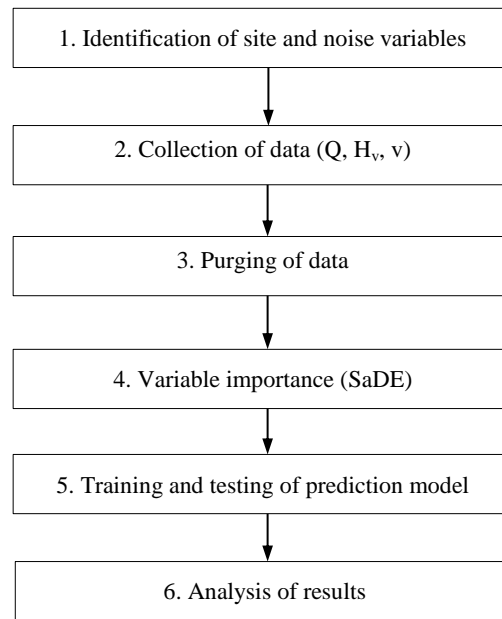


Fig.4.2 Methodology used for developing the model

tool for solving non-linear optimization problems, without the need for gradient, as required in gradient-descent methods. It belongs to the class of evolutionary algorithms like GAs (Genetic Algorithms) and PSOs (Particle Swarm Optimization) and is based on the generation of solutions from an existing population of candidate solutions, by combining existing ones according to its simple formulae and then choosing the best one on the basis of a fitness function score.

In Self-adaptive Differential Evolution (SaDE) (Qin *et al.*, 2009), the tuning of control parameters and learning strategies, which take a lot of time and computational resources, are not required to be pre-defined and are calculated or selected iteratively, using a self-adaptive evolutionary algorithm. Unlike the Differential Evolution (DE) algorithm, where the selection of trial vector generation strategy and associated control parameters is done by trial-and-error, these settings are gradually self-adapted, in SaDE, by learning from their previous experiences in generating improved solutions. Therefore, it is possible to find a better strategy along with the parameter settings in an adaptive way for the different stages of the search process.

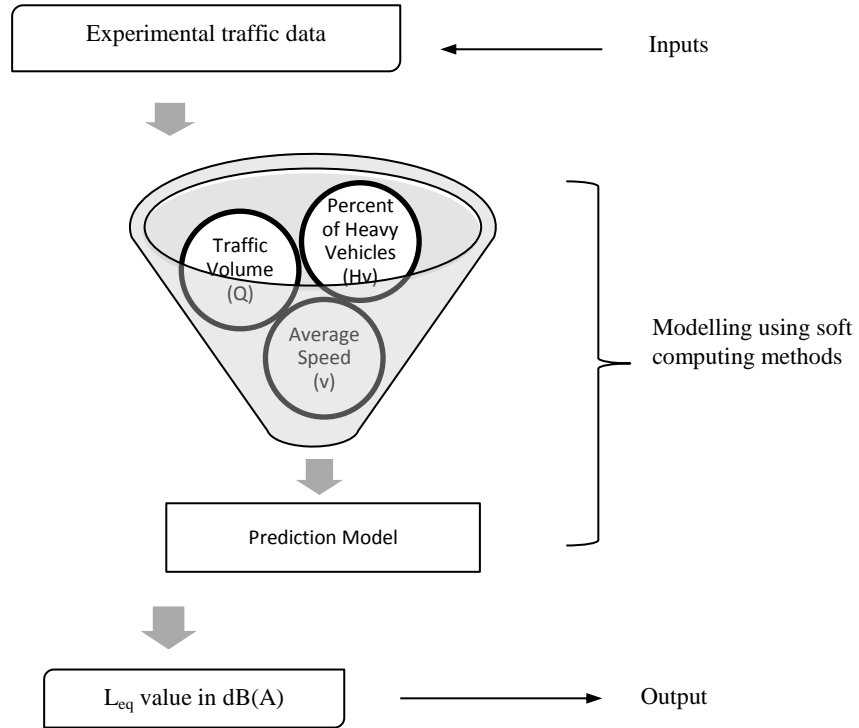


Fig. 4.3 Prediction method

The significance of SaDE lies in the fact that it identifies or confirms the importance of different variables with respect to their contribution towards the observed phenomenon, in the present case, the generation of traffic noise. Also, a ranking is provided to the variables, which provides a direction for targeting the variables in a systematic way for noise reduction measures, while using the prediction model.

4.2.3.2 Variable Importance using SaDE

Use of the self-adaptive evolutionary algorithm for the objective function, F (eq. 4.1) for L_{eq} provides an optimal score for the different variables.

$$F = \min \left(\sum_{i=1}^N \sqrt{\left(X_i - \sum_{j=1}^n s_j \cdot Z_{i,j} \right)^2} \right) \quad (4.1)$$

where N is the number of samples in the data set; X is the equivalent continuous sound pressure level, L_{eq} ; Z is the variables; n is the number of variables (3 in this case) and s is the

score for each variable. The values of the tuning parameters for mutation and crossover used during computation are given as 0.01 and 0.9 respectively (Rana et al., 2015).

After five iterations, an average score is given to each variable as shown in Table 4.2. The variables are ranked according to this average score. It is seen that the first rank is given to traffic volume (Q) and the third rank to average speed (v).

Table 4.2 Ranking of each variable using SaDE

	Input variables		
	Traffic volume	Percent of heavy vehicles	Average speed
Score using SaDE	238.64	212.98	137.96
Ranking	1	2	3

The presence of a large number of trucks and buses, which constitute the category of heavy vehicles and an overall huge traffic volume, lead to very high traffic noise levels on the considered road sections. These high noise levels have a considerable adverse effect on the health and well-being of the nearby resident population. So, measures need to be put in place to reduce the noise levels. The regulatory agencies need to take care of this adverse situation during planning and management of the road networks and traffic control. The noise prediction models can help in the assessment of the noise abatement strategies, both in the present and future environmental management policy.

4.2.3.3 Soft Computing Methods

Four different soft computing methods have been used (shown in Table 4.3) in the development of models for the prediction of sound pressure level L_{eq} . The methods are a part of the different modules of ‘Rattle’ (R) software. It is an open source software and the licensing is done under GNU General Public License. The four soft computing methods used in the present work, along with the names of the modules and the control parameters, are shown in Table 4.3.

Table 4.3 Soft computing methods used (Rana et al., 2015)

Model	Method	Name of Module	Parameters and values
Decision Trees (Quinlan, 1986)	rpart	Rpart	MinSplit=20, MaxDepth=30, MinBucket=7
Random Forests (Breiman, 2001)	rf	randomForest	mtry=500, sampling=bagging
Linear Models (Nelder and Wedderburn, 1972)	lm	glm	None
Neural Networks (Riedmiller and Braun, 1993)	neuralnet	Neuralnet	hlayers=10, MaxNWts=10000, maxit=100

(i). Decision Trees (Rpart): Decision Trees are used in data analysis and machine learning problems. Being deterministic data structures for modelling classification problems, they use a flow-chart like structure. A root node is present at the top of the tree. The branches and leaves of the tree represent certain tests that are done and the results of these tests. Ensemble methods (e.g. Random Forests) make more than one tree.

(ii). Random Forests (randomForest): Random Forests are ensembles of decision trees. This method avoids over-fitting, as happens in the decision tree method. Instead of a single deep tree, multiple shallow trees are formed, in the RF method. The output is aggregated and the errors are cancelled out, and a more accurate prediction results. RF method performs random record selection and random variable selection, while identifying patterns in data. It can be said that a group of weak models get together and form a stronger and more powerful model in this method.

(iii). Linear Models (glm): Generalized Linear Models (GLM) unify different forms of regression, e.g. linear and logarithmic (Nelder and Wedderburn, 1972). GLM can take care of different distributions e.g. log-linear and log-odds, as the response might not vary linearly and not always follow a normal distribution.

(iv). Neural Networks (Neuralnet): Artificial Neural Networks (ANNs) are originally based on the neural networks present in the human brain. They help in learning from experience by training of the neurons, by way of numeric weights which are tuned to achieve this purpose. The neural network architecture is characterized by the number of layers of input, output and

hidden layer of neurons. The historical inclination of neural networks towards biology has now been replaced by a more statistical approach.

4.2.3.4 Model Evaluation

The performance of the models developed for prediction of L_{eq} using the soft computing methods, have been evaluated using different criteria. Some of them are: correlation, accuracy, root mean squared error (RMSE), coefficient of determination etc. A brief description of these measures is given below. The L_{eq} prediction models, which contain the independent variables Q , H_v and v , and the dependent variable L_{eq} , are formulated as,

$$L_{eq} \sim f(\log Q, H_v, \log v) \quad (4.2)$$

(i) Correlation (r)

Correlation is a measure of the linear relationship between two sets of data. It is defined as:

$$r = \frac{\sum_{i=1}^n (a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum_{i=1}^n (a_i - \bar{a})^2 \sum_{i=1}^n (b_i - \bar{b})^2}} \quad (4.3)$$

where, a is the observed value, b is the predicted value, \bar{a} is the average of all the observed values, \bar{b} is the average of all the predicted values and n is the number of sample data points. The value of r lies between -1 and +1. Higher the value of r , greater is the correlation. It is also known as Pearson product-moment correlation coefficient.

(ii) Coefficient of Determination (R^2)

The coefficient of determination (R^2) is a measure of the proportion of variance of the dependent variable explained, out of the total variance, by the regression model. The value of R^2 lies between 0 and 1. It indicates how well the regression line fits the data. A perfect regression model would be indicated by an R^2 value of 1. A value of zero shows that the model does not explain any variance. The coefficient of determination is defined as follows:

$$R^2 = r * r \quad (4.4)$$

(iii) Root Mean Squared Error (RMSE)

RMSE is a measure of the difference between the measured and the predicted values. It is a sample standard deviation of the differences between the observed values and those predicted by the model. These are called residuals when the differences are calculated for the sample (called in-sample) points, that were used to make the model and prediction errors when the calculations are done for out-of-sample data points. It is calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (b_i - a_i)^2}{n}} \quad (4.5)$$

where, a is the observed value, b is the predicted value and n is the number of sample data points.

(iv) Accuracy

The accuracy (Acc) is defined as the percentage difference between the predicted and the observed values of the dependent variable, with an acceptable error, e .

$$Acc = \frac{100}{n} \sum_{i=1}^n c_i \quad (4.6)$$
$$c_i = \begin{cases} 1, & \text{if } abs(y_i - x_i) \leq e \\ 0, & \text{otherwise} \end{cases}$$

where, y is the predicted value of dependent variable, x is the observed value of dependent variable, e is the acceptable value of error and n is the total number of samples.

(v) 10-Fold Cross Validation

In this type of cross validation, generally known as k-fold cross validation, the data set is divided into k number of folds, also termed as sub-samples, which are used for separately training and testing the model for prediction error. For example, there is a data set of 100 units. In the first run, the data set is randomly split, with 80 units being used for training and the remaining 20 units for testing the model. In the next run, the 20 units testing subset of the previous run (i.e. the first run) is merged into the training subset and another, different 20 units are taken out for testing and subsequent calculation of error. This is done ten times in a ten-fold cross validation exercise. So, all the data sets are used both for training and testing,

and calculation of the prediction error. 10-fold cross validation thus provides a measure of the stability of the model.

(vi) Statistical t-test

A t-test is generally used to verify if the predicted values of the dependent variable fit well with the field data. A null hypothesis is formulated, stating that the sample means of the observed and the predicted values for the testing dataset are different. The value of t-stat is calculated and compared with t-critical. The null hypothesis is subsequently rejected or retained, depending on these values.

4.3 Results and Discussion

The results obtained by using the four soft computing methods for the prediction of equivalent sound pressure level L_{eq} , are presented below. The training datasets are used for training of the model, which is subsequently tested on the testing dataset, and the performance criteria evaluated. The four models were run using the respective control parameters (given in Table 4.3), and the output of L_{eq} obtained. The performance of the models was evaluated using the performance criteria described earlier.

The use of the linear model for the prediction of equivalent continuous sound pressure level, L_{eq} , gave the following equation:

$$L_{eq} = 22.86 \log Q + 0.08 H_v + 3.34 \log v - 3.90 \quad (4.7)$$

A sample dataset showing the observed values of L_{eq} dB(A) and the values of L_{eq} predicted by using the four methods, with the corresponding error values in dB(A), is presented in Table 4.4. It can be seen that the values of errors are least in the Random Forests method.

The testing dataset is used to evaluate the model as the training dataset, which is used to develop the model can lead to over-fitting and more optimistic results. A separate testing dataset is used for validation purpose. The partitioning, into training (70%) and testing datasets (30%) is done randomly.

Table 4.4 A sample dataset of observed vs predicted values of L_{eq}

Observed L_{eq} dB(A)	Decision Trees		Random Forests		Linear Model		Neural Networks	
	Predicted	Error	Predicted	Error	Predicted	Error	Predicted	Error
	L_{eq} dB(A)	dB(A)	L_{eq} dB(A)	dB(A)	L_{eq} dB(A)	dB(A)	L_{eq} dB(A)	dB(A)
73.7	74.8	1.1	74.4	0.7	72.0	-1.7	74.6	0.9
74.6	74.8	0.2	74.6	0.0	74.0	-0.6	74.2	-0.4
76.4	76.7	0.3	76.5	0.1	76.8	0.4	76.8	0.4
79.3	79.8	0.5	79.3	0.0	78.9	-0.4	79.3	0.0
80.1	79.8	-0.3	80.0	-0.1	79.4	-0.7	79.9	-0.2

The correlation, which shows the linear relationship between two sets of data, is calculated (equation 4.3) for all the methods, and the values are given in Table 4.5. Maximum correlation of 0.97 (training) and 0.92 (testing) in the prediction of L_{eq} is given by Random Forests.

The next measure, R^2 , also called the coefficient of determination (equation 4.4) is calculated for the four methods and the values are shown in Table 4.5. ‘Random Forests’ shows the maximum R^2 value of 0.94 (training) and 0.85 (testing) in the prediction of L_{eq} .

The RMSE value, which shows the deviation of the predicted values from the observed values, is 0.28 (training) and 0.43 (testing) in Random Forests, the lowest among all the methods. The error values for the entire testing dataset range from -1.5 dB(A) to +1.2 dB(A).

The value of accuracy (equation 4.6) shows how consistently the predicted values of the dependent variable fall within an acceptable error range. The accuracy is calculated with an acceptable error of ± 1 dB(A). In order to see the efficacy of the RF method, the accuracy was tested for a closer range of ± 0.5 dB(A) also. Table 5 shows that Random Forests has the maximum accuracy of 96.30 % (± 1 dB(A)) and 83.48 % (± 0.5 dB(A)) in training, and 88.08 % (± 1 dB(A)) and 73.51 % (± 0.5 dB(A)), in testing, in the prediction of L_{eq} .

It can be seen from Table 4.5 that ‘Random Forests’ clearly outperforms all the other methods on the different measures, and can be used to develop the traffic noise prediction models with high accuracy. RF also has some features which make it more attractive as compared to others.

Table 4.5 Comparison of results for different performance measures

Model	Training (351 datasets)					Testing (151 datasets)				
	Corr (r) ^a	R ²	RMSE	Accuracy (±1 dB(A)) ^b	Accuracy (±0.5 dB(A)) ^c	Corr (r)	R ²	RMSE	Accuracy (±1 dB(A))	Accuracy (±0.5 dB(A))
Decision Trees	0.89	0.80	0.56	88.32	56.98	0.89	0.79	0.52	86.09	62.25
Random Forests	0.97	0.94	0.28	96.30	83.48	0.92	0.85	0.43	88.08	73.51
Linear Model	0.86	0.74	0.63	81.20	55.84	0.85	0.73	0.58	84.10	61.59
Neural Networks	0.90	0.81	0.49	86.90	68.66	0.91	0.83	0.45	88.08	68.87

a. Correlation

b. Accuracy with acceptable error ±1 dB(A)

c. Accuracy with acceptable error ±0.5 dB(A)

The RF method is much faster (Breiman, 2001) and the time taken by RF to solve problems, with large number of variables and big datasets is relatively less. It can also handle missing input values, and being an ensemble method, can return a prediction despite some of the values being missing, and thus, makes it more appealing for real time predictions. Therefore, the RF method being more cost effective, accurate and faster can be used by environmental managers in forecasting and prediction modelling required for decision making in various applications.

The presented model can be used to predict the traffic noise level (L_{eq} dB(A)) for a future scenario, from the estimated values of traffic volume (Q), percentage of heavy vehicles (H_v) and average speed of vehicles (v). In the present scenario also, the prediction model can be helpful in particular cases, e.g. in assessing the reduction in noise level, when heavy vehicles are prohibited from entering into a community area. This can be useful in urban planning for taking suitable mitigation measures like re-routing of traffic, installing traffic calming measures (e.g. traffic lights), making flyovers, slip-roads and road networks. The prediction tool has the potential of assisting in environmental impact assessment studies as well. Only three significant variables that have been found to predominantly contribute to the traffic noise levels, i.e. traffic volume (Q), percentage of heavy vehicles (H_v) and average speed (v) have been considered here, but the study can be extended to include more variables like horn noise, acceleration and deceleration, street width, topology of roads, pavement surface, population increase and diverse traffic conditions in different regions of the world. Data related to these variables need to be collected and incorporated into the new model using the methodology presented in this work. It would be reflected in step 2 in Fig.4.2 and the soft

computing module in Fig. 4.3, which would be modified with the inclusion of additional variables and thus ultimately, would refine the model.

A scatter plot of the measured vs predicted values of the output variable (L_{eq}) using the four methods is given in Fig. 4.4. It shows how close these values are to the fitted regression line and also the corresponding R^2 values.

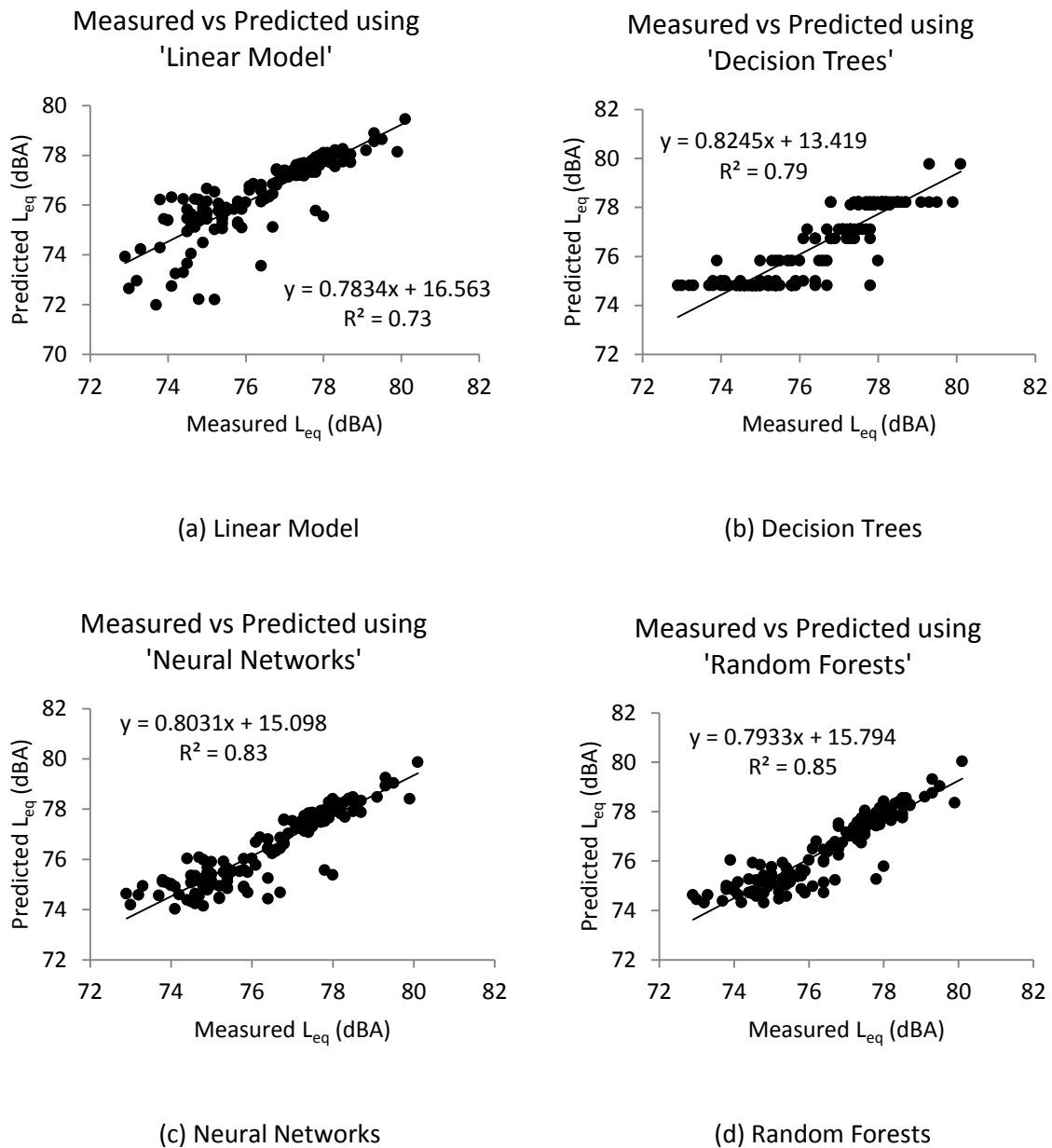


Fig.4.4 Scatter plot of L_{eq} (measured vs predicted) using Linear Model, Decision Trees, Neural Networks and Random Forests

The results of the 10-fold cross validation for the Random Forests method (the best performing method) are presented in Fig.4.5. The values of the four performance criteria remain almost same in the different iterations, indicating the stability of the model.

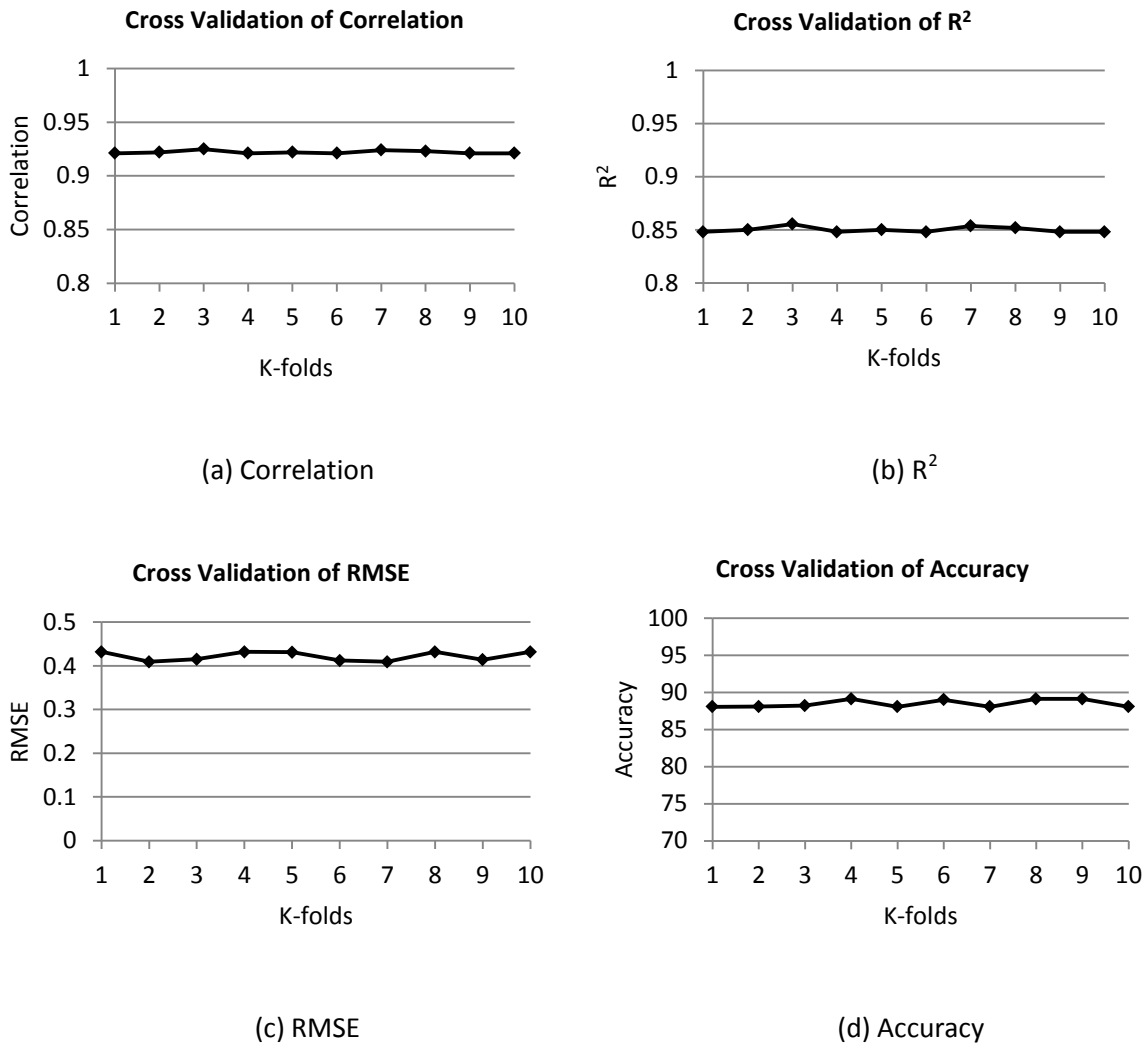


Fig. 4.5 10-fold cross-validation of Correlation, R², RMSE and Accuracy in predicting L_{eq} using the testing dataset by the Random Forests method

A t-test was performed, on the best performing model, with the null hypothesis that the sample means of the observed and the predicted L_{eq} values for the testing dataset are not different. The value of t-stat was calculated and compared with t-critical (shown in Table 4.6). The value of t-stat is less than t-critical (at a 5% significance level), indicating that the alternative hypothesis can be rejected and null hypothesis retained. These results show that the values of L_{eq} predicted using Random Forests fit well with the field data.

Table 4.6 Results of t-test (paired two sample for means) for Random Forests

Output parameter	Results of t-test	
	t-stat	t-critical
L_{eq} dB(A)	0.38	± 1.98
Number of observations	151	

* 5 % significance level ($\alpha = 0.05$)

** t-stat: test statistic calculated from sample data

t-critical: critical cut-off value, read from table of t-distribution

4.4 Conclusions

In the present work, a soft computing approach to develop vehicular traffic noise prediction models is presented. Four different soft computing methods are used in developing the models for typical road traffic conditions in the Indian city of Patiala. An overview of traffic noise parameters, the soft computing methods used and the evaluation criteria of the model performance are also presented. The traffic noise prediction models are developed, with equivalent sound pressure level, L_{eq} as the output (dependent variable) and the traffic noise variables: hourly traffic flow, percentage of heavy vehicles and average speed of vehicles, as the independent variables. The results obtained are analyzed and it is seen that the ‘Random Forests’ method excels over all the other techniques on the performance criteria of correlation, R^2 , mean square error and accuracy. The 10-fold cross validation indicates the stability of the method.

The high values of these performance measures indicate the potential of using the ‘Random Forests’ method for traffic noise problems, with accuracy and stability. Though the number of variables considered in the present work for model development is only three, the presented methodology can be extended to more number of variables, for different traffic conditions. For future work, diverse traffic conditions with the inclusion of time as a variable can be explored.

The soft computing approach for prediction modelling presented in this study has the potential of assisting the environmental managers in decision making and policy formulation, while dealing with various environmental problems. The model can also be useful in specific cases, e.g. assessing the noise level, when a certain category of vehicles is not allowed to enter into a community area or a silence zone. It can help urban planners and traffic engineers in the design of suitable mitigation measures like re-routing of traffic, installing traffic calming measures, making flyovers, slip-roads and road networks. The different methods

presented in the study can be used for predicting the future scenario by using the present data pertaining to an environmental problem of concern. The study also showcases the model which is more accurate, faster and cost-effective. It can be used by environmental managers, policy and decision makers, town planners, urban authorities and other stakeholders involved in environmental management.

CHAPTER 5

HORN NOISE – AN IMPORTANT PARAMETER IN THE INDIAN URBAN TRAFFIC SCENE

As highlighted earlier, the Indian traffic scenario is full of features/parameters that makes it quite different from many other countries in the world. One of the very important traffic noise parameters that need to be studied especially in the Indian context is horn noise. In this chapter, an experimental investigation of the effect of horn noise on the accuracy of the prediction models is presented, by taking traffic noise measurements at different locations in the Patiala city.

5.1 Introduction

Use of horns in vehicles, generally known as ‘honking’ is very common in the Indian sub-continent. This is due to heavy traffic in urban areas, lack of traffic sense, rash/aggressive driving behavior, non-compliance of traffic rules and lack of proper traffic network and infrastructure in most parts of the country.

There is a growing awareness about the adverse effects of honking. Leading national dailies, like the ‘Times of India’ and NGOs like the ‘Awaz Foundation’ have launched anti-honking campaigns in metropolitan cities like Mumbai and Delhi (*TOI sounds alarm on honking*, 2016; *Honk flu’, anti-honking campaign launched in Mumbai*, 2017). There have been some research studies on horn noise as well. Vijay *et al.* (2015) have reported an increase in L_{eq} dB(A) due to honking in the city of Nagpur, India. Kalaiselvi and Ramachandraiah (2016) have proposed a horn noise correction factor in heterogeneous traffic conditions prevalent in India. The study is based in southern city of Chennai. Studies which quantify the effect of horn noise on the accuracy of the prediction model (by considering R , R^2 and error values) seem to be missing, and form the basis of the present work.

5.2 Experimental Investigation

To study the effect of horn noise on the overall traffic noise level, an experimental investigation was carried out at five different locations in Patiala city (shown in Fig. 5.1, 5.2 and 5.3) with different levels of traffic volume and honking. The data was collected for the parameters traffic volume (with different vehicle categories), honking in 15 minutes, acoustical descriptors L_{eq} dB(A), L_{10} , L_{50} and L_{90} dB(A). The type of horns was divided into two types: normal horns (generally 90-100 dB(A)) and pressure horns (greater than 120

dB(A)). The data was collected for two days at each of the five locations. Random data was collected during day hours ranging from 10 am to 6 pm, on these days. The readings for traffic volume and horn noise were taken manually using videography.

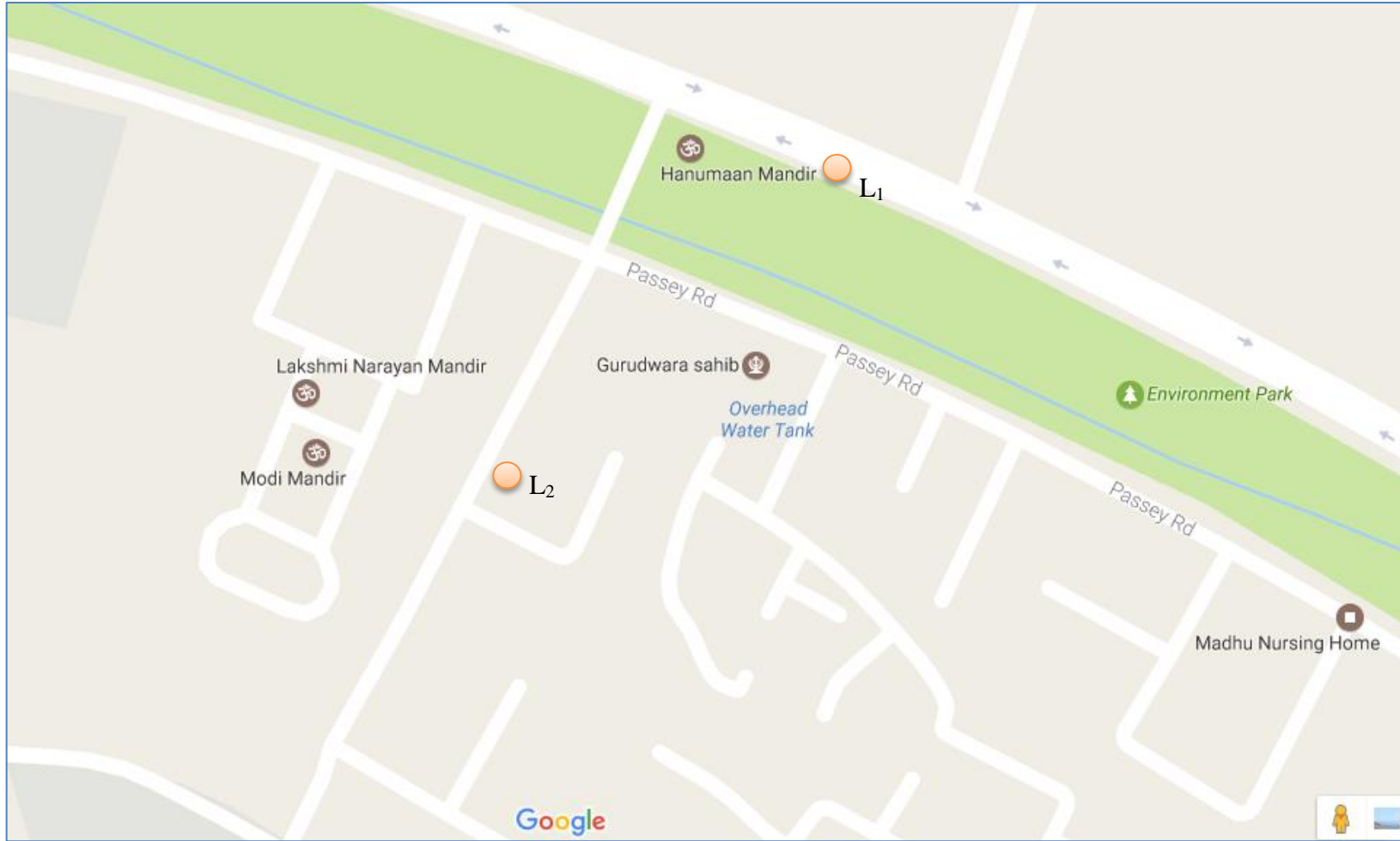


Fig. 5.1 Locations 1 and 2 (L₁ and L₂) near Modi Mandir, Passey Road, Patiala



Fig. 5.2 Locations 3 and 4 (L₃ and L₄) near Gurudwara Dukhniwaran Sahib, Patiala

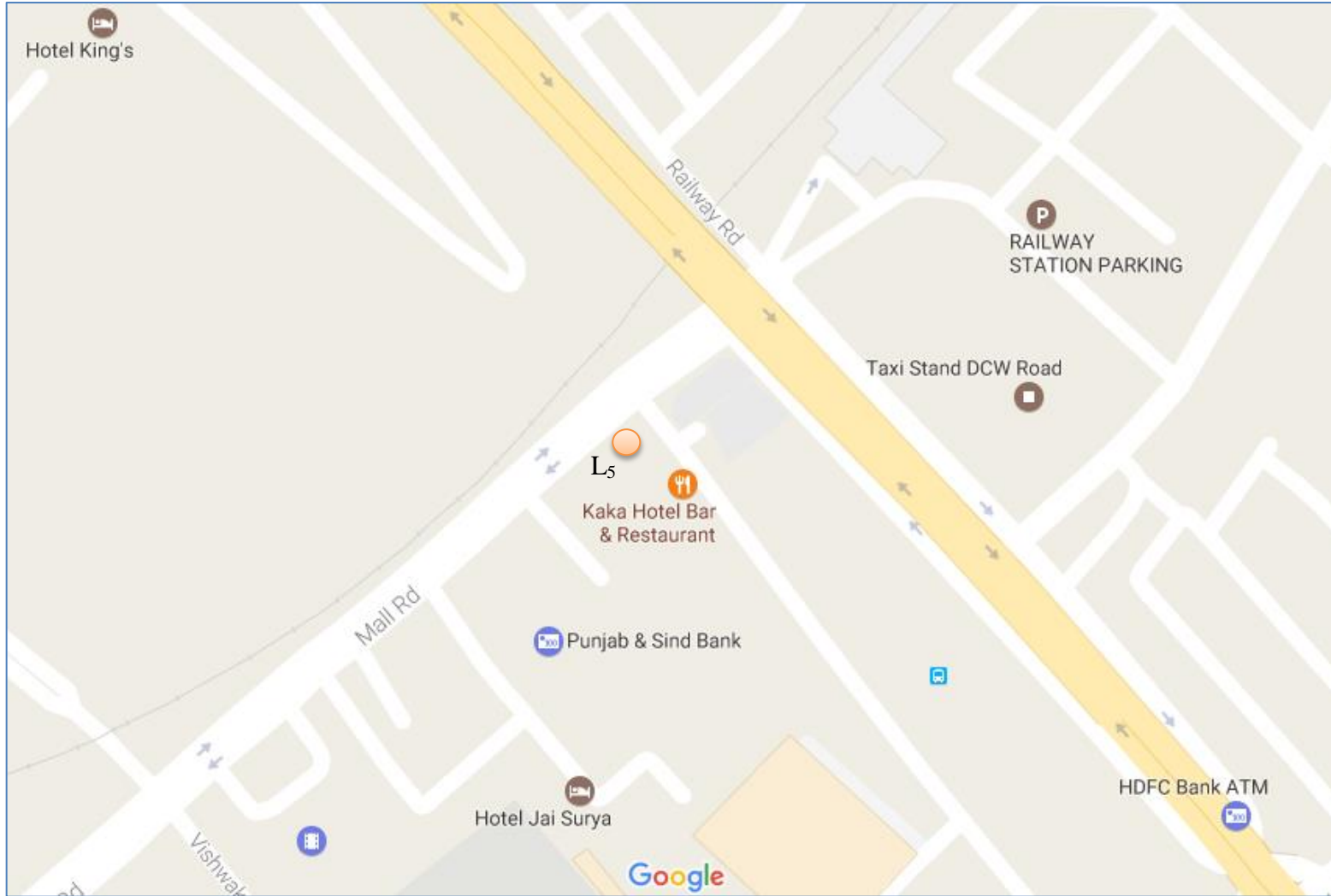


Fig. 5.3 Location 5 (L₅) near the main Bus Stand, Patiala

The traffic noise levels were measured using a class 1 sound level meter (B & K 2250) following the standard procedure (ISO 362-1:2015). The values of the collected data are shown in Table 5.1.

Table 5.1 Traffic data (for 15 mins) with noise levels at different locations in Patiala

S.No.	Location / site	Date (dd.mm.2016-17)	Heavy Vehicles	Two wheelers	Others	Total no. of Vehicles /Traffic volume (Q)	Honking frequency		Total honking frequency (H) (a + b)	L _{eq} dB(A)	L ₁₀ dB(A)	L ₅₀ dB(A)	L ₉₀ dB(A)
			Bus/truck/ tractor	Motorcycles/ Scooters	Cars, SUVs, 3- wheelers/autos		normal (90-100 dBA) (a)	pressure (>=120 dBA) (b)					
1.	L ₁	17.09.16	19	320	231	570	101	9	110	74.0	76.8	70.1	64.3
2.	L ₁	24.09.16	9	327	261	597	222	9	231	75.0	76.4	70.2	64.7
3.	L ₂	08.10.16	0	156	60	216	126	0	126	69.9	72.8	64.7	57.3
4.	L ₃	27.11.16	0	279	234	513	363	0	363	76.5	78.3	72.6	68.1
5.	L ₅	11.02.17	3	288	366	657	405	1	406	78.0	80.1	74.6	70.5
6.	L ₄	12.02.17	42	477	573	1092	177	27	204	78.7	81.1	73.7	69.6
7.	L ₂	24.02.17	0	153	93	246	90	0	90	69.8	72.6	65.4	57.6
8.	L ₄	25.02.17	42	717	618	1377	267	12	279	79.7	81.7	72.5	67.4
9.	L ₅	26.02.17	3	297	390	690	225	0	225	75.5	78.4	71.2	63.4
10.	L ₃	26.02.17	3	198	168	369	129	6	135	72.0	75.3	69.9	61.2

5.3 Results and Discussion

The graphs of the values of L_{eq} dB(A) with the corresponding traffic volume and honking frequency are given in Fig.5.4. It is generally seen that the noise level increases with an increase in the traffic volume, Q . But it can be seen in Fig. 5.4 that despite an increase in the traffic volume from 513 to 570, there is a decrease in L_{eq} dB(A). Also, the L_{eq} dB(A) decreases at another instance, when the traffic volume increases from 657 to 690. This may be due to a corresponding decrease in honking at these points. The parameter of horn noise is having an impact on the overall traffic noise levels. So, this parameter should not be ignored in the traffic noise studies, especially in typical Indian urban traffic situations. A regression analysis was further carried out in order to verify this conclusion.

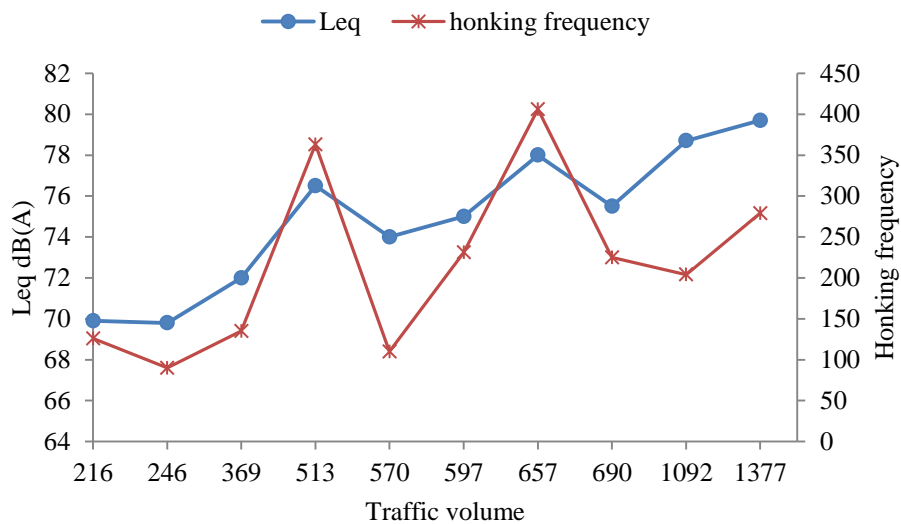


Fig.5.4 Values of L_{eq} dB(A) with the corresponding traffic volume and honking frequency

A similar trend was observed for the L_{10} dB(A) values as well, as seen in Fig. 5.5. The L_{10} values decrease at two points, despite an increase in the traffic volume. Again this may be due to a corresponding decrease in honking.

It can also be observed from Table 5.1 that the values of traffic volume, number of heavy vehicles and honking frequency of pressure horns is high (at serial no. 6 and 8), and the corresponding L_{eq} and L_{10} values are also high. This is indicating a cumulative effect of these factors on the noise level.

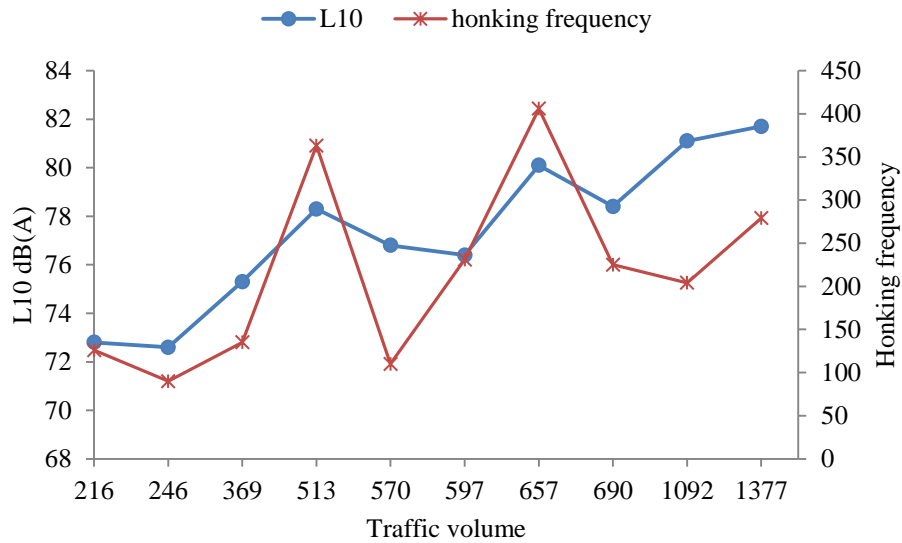


Fig.5.5 Values of L_{10} dB(A) with the corresponding traffic volume and honking frequency

Regression was done with L_{eq} and L_{10} as the dependent variables and traffic volume and honking frequency as the independent variables to see the effect of horn noise in the prediction model. The regression statistics are presented in Table 5.2 and Table 5.3.

Table 5.2 Regression statistics for L_{eq} (with traffic volume only)

L_p	Equation	Multiple R	R Square	P-value of Coefficients**	
				Intercept	'Q'
L_{eq}	$L_{eq} = 0.0086Q + 69.494$	0.88	0.78	5.86E-12	0.000644

Q – traffic volume

** confidence level is 95%

Table 5.2 presents the regression statistics for the model when only traffic volume is considered. As seen in the table, the values of R and R^2 are 0.88 and 0.78 respectively. The P-values of the coefficients indicate the statistical significance of the considered variables. A new regression analysis was done by including the experimental data related to both traffic volume and honking. The regression statistics for the same are presented in Table 5.3 below.

Table 5.3 Regression statistics for L_{eq} (with traffic volume and honking)

L_p	Equation	Multiple R	R Square	P-value of Coefficients**		
				Intercept	'Q'	'H'
L_{eq}	$L_{eq} = 0.006762 Q + 0.014884 H + 67.40317$	0.97	0.95	2.18E-12	6.89E-05	0.000951

Q – traffic volume

H – honking frequency

** confidence level is 95%

It can be seen in the above table, that the values of R and R^2 are 0.97 and 0.95. So, the inclusion of the parameter 'honking frequency' has improved the prediction model. The values of error between the predicted and measured values of L_{eq} dB(A) have also reduced, as shown in Table 5.4.

Table 5.4 Comparison between the measured and predicted values of L_{eq}

Sr. No.	L_{eq} dB(A)	L_{eq} dB(A) (without honking)		L_{eq} dB(A) (with honking)	
	Measured	Predicted	Error dB(A)	Predicted	Error dB(A)
1.	74.0	74.4	0.4	72.9	-1.1
2.	75.0	74.6	-0.4	74.9	-0.1
3.	69.9	71.3	1.4	70.7	0.8
4.	76.5	73.9	-2.6	76.3	-0.2
5.	78.0	75.1	-2.9	77.9	-0.1
6.	78.7	78.8	0.1	77.8	-0.9
7.	69.8	71.6	1.8	70.4	0.6
8.	79.7	81.3	1.6	80.9	1.2
9.	75.5	75.4	-0.1	75.4	-0.1
10.	72.0	72.7	0.7	71.9	-0.1

As seen in Table 5.4, the values of error between the measured and predicted values of L_{eq} dB(A) when the parameter 'honking frequency' (H) is not considered in the model, range from -2.9 dB(A) to +1.8 dB(A). When the parameter 'H' is included in the model the values of error decrease as shown in Table 5.4. The values of error between the measured and predicted values of L_{eq} dB(A) now range from -1.1 dB(A) to +1.2 dB(A).

Since L_{10} would be directly affected by the presence of honking, a regression model of L_{10} is pertinent for the present analysis. A regression analysis was done by taking L_{10} dB(A) as the dependent variable. The regression statistics are presented in Table 5.5 and Table 5.6.

Table 5.5 Regression statistics for L_{10} (with traffic volume only)

L_p	Equation	Multiple R	R Square	P-value of Coefficients**	
				Intercept	'Q'
L_{10}	$L_{10} = 0.0078Q + 72.359$	0.89	0.80	1.34E-12	0.000427

Q – traffic volume

** confidence level is 95%

Table 5.5 presents the regression statistics for the model (for L_{10} descriptor) when only traffic volume is considered. As seen in the table, the values of R and R^2 are 0.89 and 0.80 respectively. The P-values of the coefficients are also presented. A new regression analysis was done by including the experimental data related to both traffic volume and honking. The regression statistics for the same are presented in Table 5.6 below.

Table 5.6 Regression statistics for L_{10} (with traffic volume and honking frequency)

L_p	Equation	Multiple R	R Square	P-value of Coefficients**		
				Intercept	'Q'	'H'
L_{10}	$L_{10} = 0.0065Q + 0.0114H + 70.748$	0.96	0.93	5.13E-12	0.00026	0.009435

Q – traffic volume

H – honking frequency

** confidence level is 95%

It can be seen in the above table, that the values of R and R^2 are 0.96 and 0.93. The inclusion of the parameter 'honking frequency' has improved the prediction model. The values of error between the predicted and measured values of L_{10} dB(A) have also reduced, as shown in Table 5.7.

Table 5.7 Comparison between the measured and predicted values of L_{10}

Sr. No.	L_{10} dB(A)	L_{10} dB(A) (without honking)		L_{10} dB(A) (with honking)	
	Measured	Predicted	Error dB(A)	Predicted	Error dB(A)
1.	76.8	76.9	0.1	75.7	-1.1
2.	76.4	77.1	0.7	77.3	0.9
3.	72.8	74.1	1.3	73.6	0.8
4.	78.3	76.4	-1.9	78.2	-0.1
5.	80.1	77.5	-2.6	79.7	-0.4
6.	81.1	81.0	-0.1	80.2	-0.9
7.	72.6	74.3	1.7	73.4	0.8
8.	81.7	83.2	1.5	82.9	1.2
9.	78.4	77.8	-0.6	77.8	-0.6
10.	75.3	75.3	0.0	74.7	-0.6

As seen in Table 5.7, the values of error between the measured and predicted values of L_{10} dB(A) when the parameter ‘honking frequency’ (H) is not considered in the model, range from -2.6 dB(A) to +1.7 dB(A). When the parameter ‘H’ is included in the model the values of error decrease as shown in Table 5.7. The values of error between the measured and predicted values of L_{10} dB(A) now range from -1.1 dB(A) to +1.2 dB(A).

Similar data was also collected for the median level (L_{50}) and the background noise level (L_{90}). The L_{50} values were in the range 64.7 dB(A) to 74.6 dB(A), and the L_{90} values were in the range 57.3 dB(A) to 69.6 dB(A). The regression analysis was done and similar conclusions (as above, for L_{eq} and L_{10}) were obtained. R^2 value for L_{90} improved from 0.50 to 0.81, when honking was included. R^2 for L_{50} improved from 0.49 to 0.77.

Another point to be noted is related to the pressure horns. It can be seen in Table 5.1 that the highest noise levels in terms of L_{eq} dB(A) and L_{10} dB(A) have been observed at locations where the number of pressure horns are the highest. But, at these locations the overall traffic volume is also very high. It may be due to the busy and heavily loaded road connecting the locations to different places within and outside the city. Also, the number of pressure horns is related to the heavy vehicles and the presence of these vehicles inside the city is mostly limited. That is why the parameter of pressure horns was not considered in the regression

analysis and the overall honking frequency was taken which is relatively much higher and significant also.

It was also noticed from the spectral analysis that the horn noise events occur at higher frequencies (around 4000 Hz). It is a known fact that noise with frequency peaks at around 2,000 to 4,000 Hz cause more annoyance to human beings as compared to the continuous lower frequency noise (Rice, 1983).

5.4 Conclusion

It can be concluded from the above study that the parameter of horn noise is very significant in the Indian traffic scenario, especially in the congested urban traffic conditions. A higher accuracy in the prediction model is obtained by including this parameter, as also verified from the values of R , R^2 and error between the measured and predicted values of L_{eq} and L_{10} in the present study. It has been seen, as expected, that the overall traffic noise levels increase due to the presence of heavy honking. So, the regulatory authorities should put in place measures to take care of the horn noise. These measures can be; clearly demarcated no-honking zones and regulation in the fitment of horns in the vehicles (both in the factory and after sales retro-fitment). Pressure horns should be banned and the upper limit of noise level in the factory fitted horns should be governed. The general public should be sensitized towards the adverse effects of horn noise through awareness campaigns so that usage of horns is minimized.

CHAPTER 6

NOISE BARRIERS AS AN ABATEMENT STRATEGY

The need for acoustic barriers, different types of barriers and the acoustic design of a noise barrier for a typical urban traffic scenario is presented in this chapter. Acoustic design of a barrier has been undertaken as an illustration.

6.1 Introduction

In order to reduce the adverse effects of high traffic noise levels, the different strategies that can be followed are: decreasing the noise at the source, attenuating the noise during propagation or providing protection at the receiver. This is generally termed as the source-path-receiver concept. The traffic noise level at the source can be reduced by the automobile manufacturers. Attempts can be made to lower the engine noise, exhaust noise, tyre noise etc. by improving the design features, materials and manufacturing processes. This definitely would entail a significant amount of investment in terms of cost, time and effort. Measures like speed control, preventing the entry of heavy vehicles in sensitive zones and regulating the use of horns are also helpful.

Another approach to reduce the harmful effects of high noise level is to use protective devices like ear plugs/muffs at the receiver end (human ear).

The distance between the source (vehicular traffic) and receiver (housing) may also be increased in the newly planned projects. Increasing the distance reduces the noise level at the receiver due to the geometric spreading effects. This might not be feasible in the existing urban residential areas.

The above two noise attenuation / abatement strategies relate to the source and receiver. The third approach is to place barriers in the path of propagation of sound waves, i.e. between the source and receiver. These noise barriers are mainly of two types: artificial and natural. The artificial noise barriers are man-made walls/structures made of certain sound absorbing materials and acoustically determined dimensions. The natural barriers are usually thick vegetation belts / buffer zones of trees or plants (Tyagi *et al.*, 2006) near the edges of the road where noise abatement is required. There has been research on the effectiveness of such

barriers with some tree species having higher sound absorbing properties than others (Pathak *et al.*, 2011).

The noise barriers have been considered to be a cost-effective method for noise abatement. They have been extensively used in North America, Europe, Japan, and Australia. The principle of working of a noise barrier and some of the acoustical design considerations are given below.

6.2 Principle of a Noise Barrier

There is a reduction in the noise level due to the obstruction provided by a barrier. When a barrier is placed between a source and a receiver, the incident sound waves are either reflected back or get transmitted through the barrier. Some of the sound also reaches the other side of the barrier by diffraction. The area behind the barrier is known as the shadow zone, as the sound waves are not able to reach there. But the effectiveness of the barrier keeps on decreasing as the distance of the source or the receiver from the barrier wall increases. The effect of a barrier on the sound waves is illustrated in Fig. 6.1.

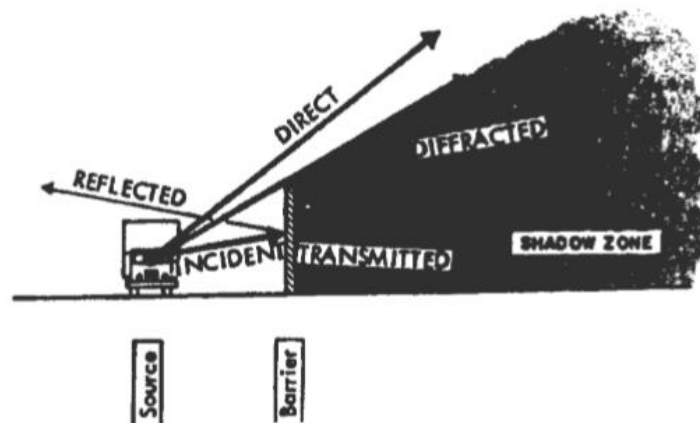


Fig. 6.1 Effect of a noise barrier (*Federal Highway Administration, 1980*)

Some acoustic terms associated with a noise barrier are given below:

1. **Insertion loss:** It is the difference in the noise level (in dB(A)) with and without the barrier at the receiver location, the noise level at the source remaining the same.

2. **Transmission loss:** The logarithm of the energy ratios in front of the barrier and behind it is termed as Transmission loss, and is expressed in dB. The transmission loss depends on the barrier material, its density and the frequency spectrum of the noise source.

3. **Thin barrier:** A thin barrier is one which attenuates the noise level by a single diffraction e.g. a solid wooden fence or a free-standing wall (Harris, 1991) as shown in Fig. 6.2.

4. **Thick barrier:** A thick barrier is one which attenuates noise level by double diffraction, e.g. a building, as shown in Fig. 6.3. If the barrier thickness, say t , is greater than 3 m, then the barrier is considered to be thick for noise of all frequencies. If t is less than 3 m, then the barrier is still considered thick for noise components whose wavelength is less than $t / 5$ (Harris, 1991).

5. **Fresnel number:** It is a dimensionless number used to represent the attenuation provided by a noise barrier. For a thin barrier, it is expressed as:

$$F = 2d / \lambda \quad (6.1)$$

where F = Fresnel number,

$$d = (A + B) - D$$

(A, B and D are the path lengths from the source to the receiver as shown in Fig. 6.2)

λ = wavelength of the sound wave (m)

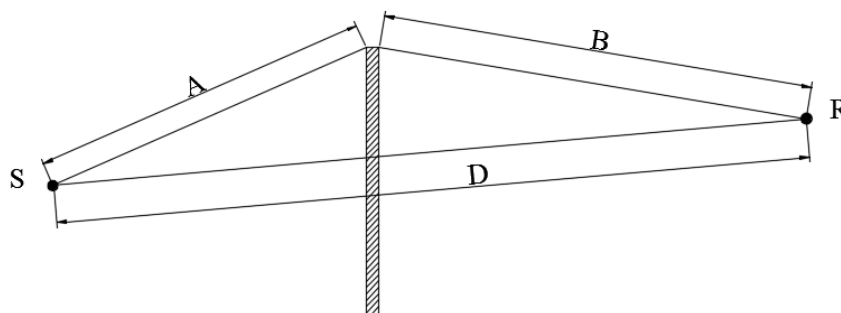


Fig. 6.2 Path lengths from the source (S) to the receiver (R) in case of a thin barrier

The Fresnel number for a thick barrier is calculated as follows:

$$F = 2d / \lambda$$

where $d = (A + t + B) - D$

t = thickness of the barrier (Fig. 6.3)

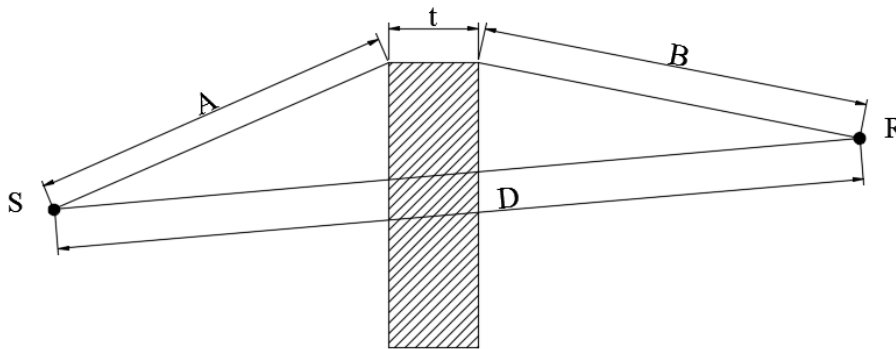


Fig. 6.3 Path lengths from the source (S) to the receiver (R) in case of a thick barrier

6.3 Materials used for Noise Barriers

Different materials are used for construction of the barriers like concrete, steel, aluminium, polycarbonate or acrylic sheets, acoustic panels, wood panels with rubber coatings, hollow walls of composite material filled with crump rubber etc. The solid barriers have been reported to be more effective as compared to vegetation belts or barriers with gaps like fences (Cowan, 1993). A few examples of barriers of various types are illustrated in Fig. 6.4 and Fig. 6.5. The places where such barriers are not possible, e.g. near airports, alternative measures like insulation of buildings or houses done by using special materials in houses walls, roof etc. or using double paned windows with special glass have been adopted. Such insulation has been done in schools, hospitals etc. in different parts of the world.

While planning a barrier at a location with high noise level, there are different aspects that need to be looked into. The following points should be considered while selecting a barrier:

- a. Effectiveness of the barrier in terms of acoustic considerations (e.g. the insertion loss)
- b. Structural strength of the barrier to withstand different loads
- c. Cost of barrier (material, labour, construction/installation, repair, maintenance)

- d. Ease of construction and maintenance
- e. Visual appeal / aesthetics, compatibility with the architecture of the place, tradition and culture.



Fig. 6.4 Examples of barriers

(source: Environmental Protection Department Highways Department Government of the Hong Kong SAR Second Issue, January 2003)

6.4 Design Considerations

The design of noise barriers needs consideration of both acoustic and non-acoustic aspects. The acoustic aspects include: material of barriers, shape and dimensions, location etc. The non-acoustic design considerations are also important. Some of them are: safety, maintainability, ease of access, structural strength, aesthetics and compatibility.

6.4.1 Acoustic Design Considerations

Acoustic design of a noise barrier implies calculating the height of a barrier based on acoustic considerations to achieve the desired attenuation at the receiver end, located at some distance.



Fig. 6.5 Traffic noise barriers at some places in India (by Ecotone Systems Pvt. Ltd., New Delhi, India)

When a noise barrier is placed between source and receiver, the sound is reflected back or it is absorbed by the barrier material (Fig. 6.6). The rest of the sound waves are transmitted through the barrier or they are diffracted from the top edge of the barrier and reach the receiver end but with a reduced acoustic energy. The noise also reaches the receiver through a diffracted path as shown in Fig. 6.6 and Fig. 6.7. The receiver is thus exposed to both the transmitted noise as well as the diffracted noise. As stated earlier, the transmitted noise depends on the barrier material and density, the diffracted noise depends on the barrier design, i.e. the shape, dimensions, location etc.

The barriers are also classified on the basis of above discussions, as reflective type, absorptive type or a combination of both. When there is a noise-sensitive region on the opposite side of the barrier (on other side of the road), then reflective type barrier is avoided or a combination of reflective and absorptive type is used, so that the noise is not reflected back towards the other end.

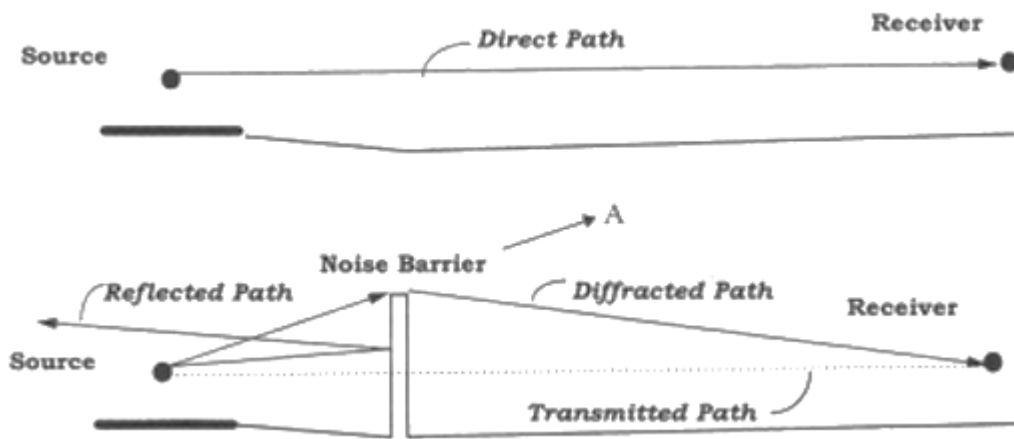


Fig. 6.6 Changes in the noise path by a barrier

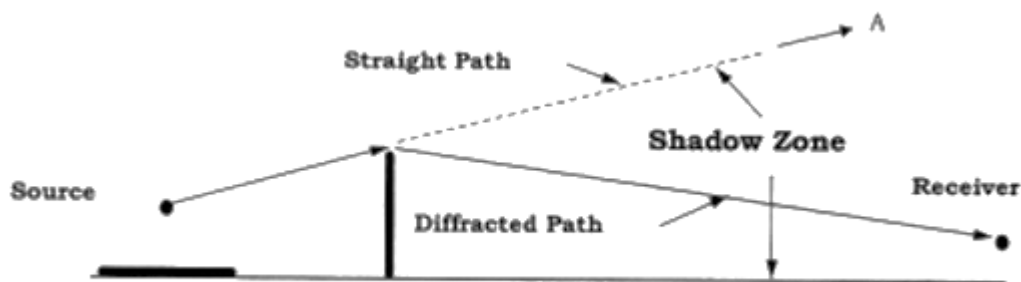


Fig. 6.7 Barrier diffraction

6.5 Acoustic Design of a Noise Barrier (Nomograph method)

Acoustic design of a noise barrier by the nomograph method implies calculating the height of the barrier to attain the desired value of attenuation (in terms of dB(A)) at the receiver end located at some distance. In order to propose the methodology for the acoustic design of the noise barrier, the nomograph method has been used and is explained in this section. A site was identified on a busy urban road near a temple in the Patiala city having high traffic noise level (with L_{eq} 75 dB(A)). The desired acceptable noise level at such sites as per the standards (Harris, 1991) is 67 dB(A). Attenuation of around 8 dB(A) is therefore required. The temple has an existing boundary wall of 1.4 m height and 17 m length with iron grills on top as shown in Fig.6.8.



Fig. 6.8 A view of the temple from outside

A schematic diagram showing the dimensions of the road site is presented in Fig. 6.9. A plan view of the proposed barrier is given in Fig. 6.10. In Fig. 6.10, it can be seen that the temple wall (17 m length line) is subtending an angle of 154° at the receiver location located inside the temple, assumed at a distance 2.0 m behind the wall.

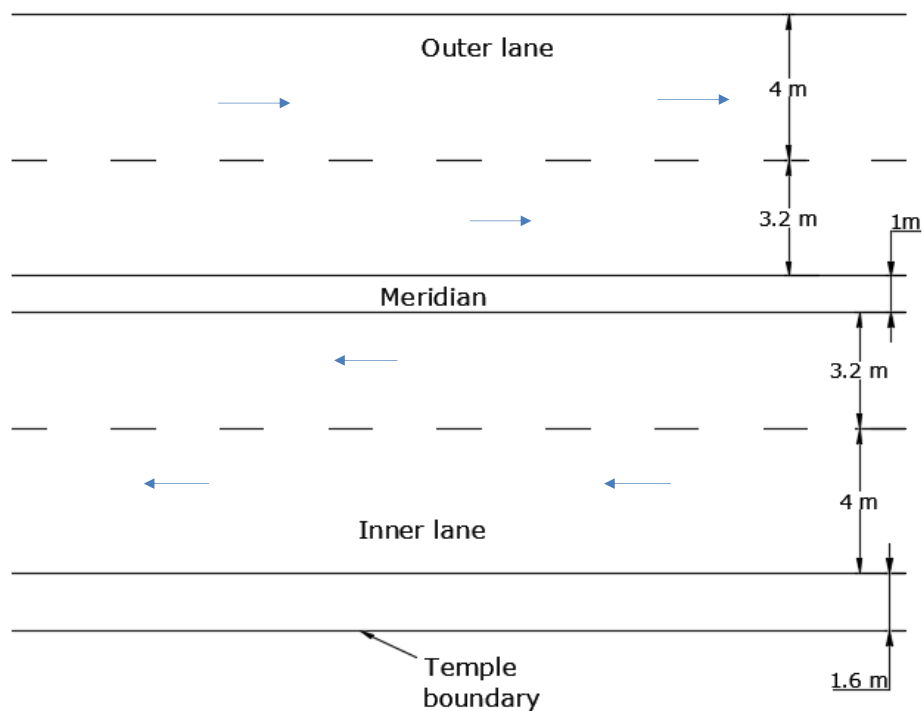


Fig. 6.9 Schematic diagram of the road segment near the temple site

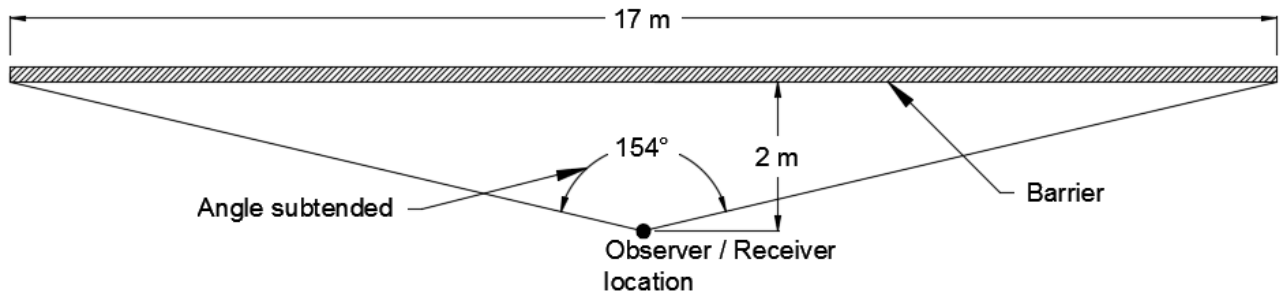


Fig. 6.10 Plan view of the barrier

In this method, a nomograph (Harris, 1991) given in Fig. 6.11 has been used to find the barrier height. The different steps that are used in this nomograph method are described below:

1. First, the desired attenuation is found by subtracting the existing traffic noise level at the site from the desirable/acceptable noise level for the category given in standards (Harris, 1991). In this standard chart/table the acceptable noise levels are defined for schools, hospitals, churches, libraries, residential areas, hotels etc.
2. From this desired barrier attenuation (upper right portion of the nomograph, Fig. 6.11), a vertical line is dropped up to the angle subtended curve (this is the angle subtended by the barrier wall at the receiver location).
3. A horizontal line is drawn from the above point to the pivot line (Fig. 6.11), meeting the pivot line at point D.
4. Then a line is drawn from the L/S line (it is the 'line of sight' line, shown in Fig. 6.12, obtained by joining the source to the receiver; the source is assumed at a height of 0.5 m from the ground, in the middle of the road, the receiver at a height of 1.2 m from the ground) to the point D (of previous step) and extended up to the Turn C line to meet at point C.
5. The corresponding point on the lower L/S line is joined with the 'barrier position' point (barrier position is the length TR in Fig. 6.12) and extended up to Turn A, meeting at point A.
6. A vertical line is drawn from point A meeting the curve from point C at point E (shown in Fig. 6.11).
7. From point E, a horizontal line is drawn up to Turn B to meet at point B.

8. The point B is connected to the corresponding point on the left L/S line, thus intersecting the barrier break line in a point. This is the required 'barrier break' value, which is further used to calculate the barrier height, using Fig. 6.12 and Fig. 6.13.

The above procedure is illustrated henceforth, with the actual measurements on the site.

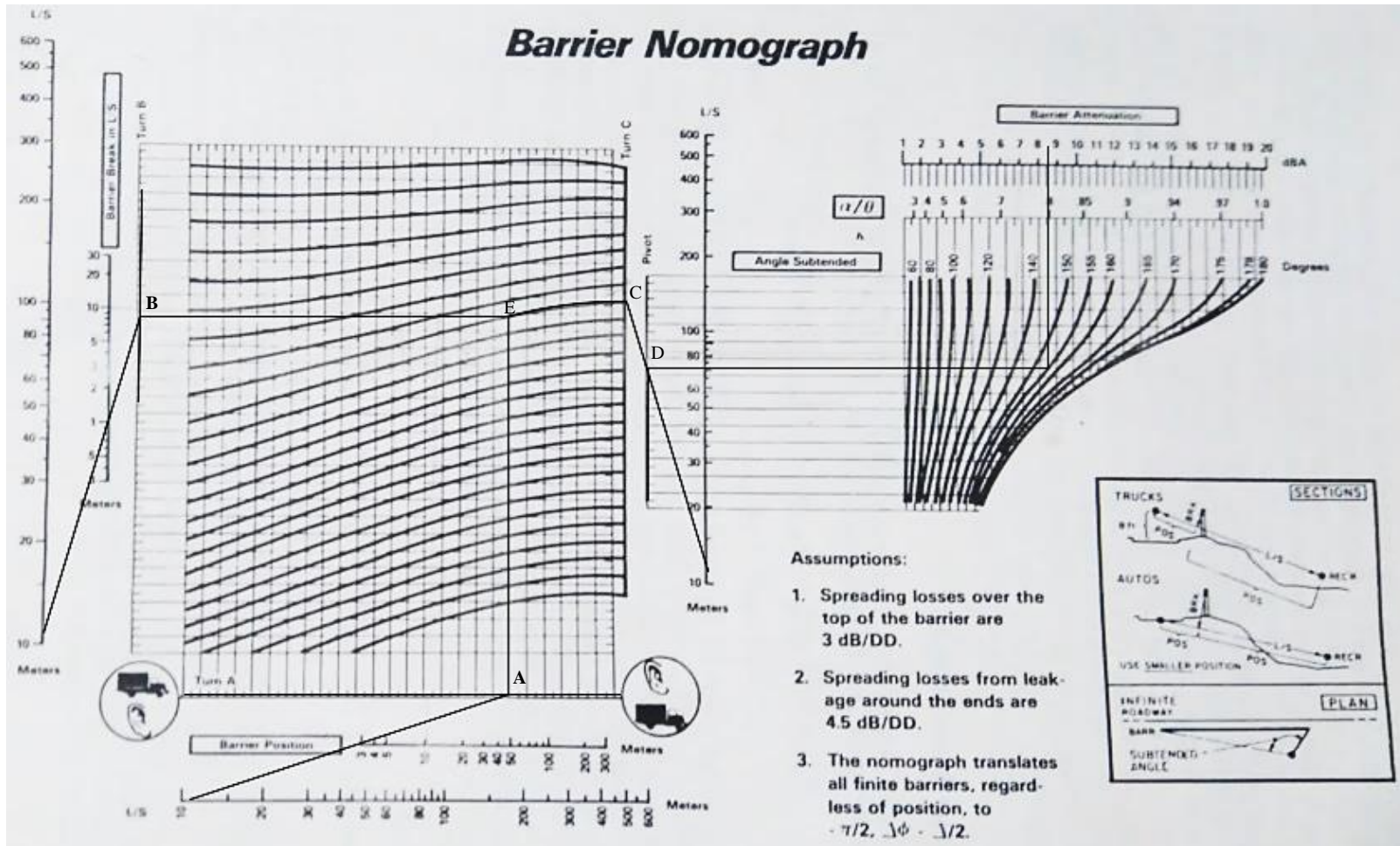
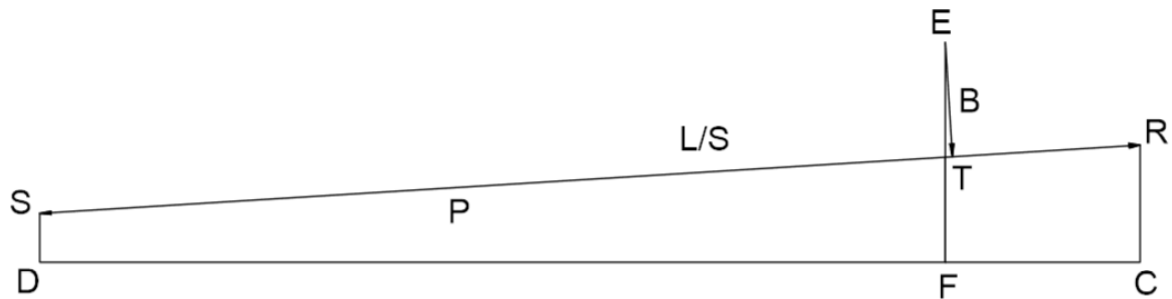


Fig. 6.11 Barrier nomograph for calculating the barrier height (Harris, 1991)

A line diagram showing the elevation view of the source, receiver and barrier is presented below.



Line of sight (L/S)	= SR	= 11.32 m
Barrier Position (P)	= TR	= 1.93 m
Height of receiver	= RC	= 1.20 m
Horizontal distance	= DC	= 11.30 m
Height of source	= SD	= 0.5 m
Break in the line of sight (B)	= ET	= 1.17 m
Barrier Height	= EF	= 2.25 m
Distance of Barrier from the centre line of 2 lane roadway	= DF	= 9.30 m

Fig. 6.12 Barrier height evaluation

In the above Fig. 6.12, the point S represents the source, assumed at a height equal to the exhaust level (generally 0.5 m). The point D is assumed to be in the middle of the road, i.e. the centre line of the meridian. The point R represents the receiver (behind the temple wall; RC is taken as 1.2 m above the ground). EF corresponds to the height of the barrier required, at the position of the existing temple boundary wall.

The general steps for calculating the barrier height from given barrier attenuation from the nomograph (shown in Fig. 6.11) are applied and illustrated below:

1. Drop a vertical line from 8.5 dB(A) barrier attenuation (upper right portion of nomograph) point to the 154° subtended angle curve.

(*8.5 dB(A) is the desired attenuation ($75 \text{ dB(A)} - 67 \text{ dB(A)}$); an extra 0.5 dB(A) is added as a safety margin or to account for any error/s).

2. From the above point (step 1), draw a horizontal line upto the pivot line, to intersect it in a point, say D.

3. Join the point corresponding to 11.32 m on the right L/S line to the point D on the pivot line and extend it up to turn C to intersect in a point, say C.

4. From the lower L/S line, join the 11.32 m point with the barrier position (P) and extend up to Turn A line in a point A.

5. Draw a vertical line from point A to meet the contour line from point C. This point is named E.

6. From E, draw a horizontal line to meet the Turn B line in point B.

7. Join the point corresponding to 11.32 m on the left L/S line to the point B. The point where this line intersects the 'Barrier break in L/S' line gives the value of 'Barrier break'. The barrier break in the present case comes out to be 1.17 m (ET in Fig. 6.12). It corresponds to a barrier height of 2.25 m. (The point E in Fig. 6.12 can be found by drawing a locus line parallel to the line SR, at a distance equal to the barrier break value. The point where this line intersects the vertical line through F, is the point E. This is illustrated in Fig. 6.13). The value of EF can be measured, which is the required barrier height). Other dimensions are given in Fig. 6.12. In the present case, the height of the temple boundary wall needs to be increased from 1.4 m (existing height) to 2.25 m to achieve the desired attenuation.

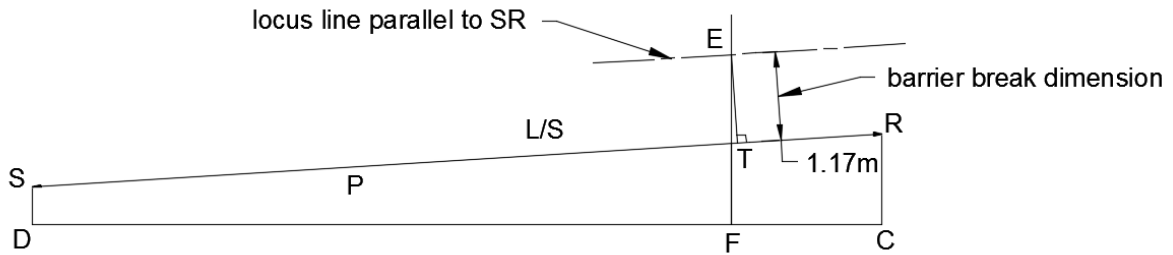


Fig. 6.13 Location of point E from barrier break

The above methodology can be used for systematically calculating the barrier height, with acoustic considerations.

Another approach that can be used either to calculate the barrier height or to verify the height obtained by the above method, is the ‘**Fresnel number**’ approach. The details of Fresnel number have already been explained in section 6.2. The application of the same in the present case is described below.

The different dimensions of the source to receiver path lengths (with the assumption of a thin barrier) are given in Fig. 6.14.

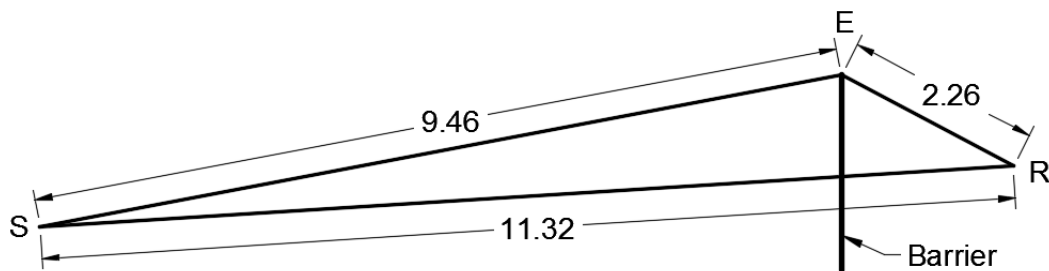


Fig. 6.14 Source to receiver path lengths

The calculations used for finding the value of the Fresnel number are presented below:

$$A = 9.46 \text{ m}$$

$$B = 2.26 \text{ m}$$

$$D = 11.32 \text{ m}$$

$$d = A + B - D = 9.46 \text{ m} + 2.26 \text{ m} - 11.32 \text{ m} = 0.40 \text{ m}$$

For a sound frequency of 500 Hz (Harris, 1991),

$$\lambda = 0.686 \text{ m}$$

$$F = \frac{2d}{\lambda} = 1.16$$

Now, the barrier attenuation that can be achieved corresponding to the above Fresnel number is looked up in a Maekawa chart (Maekawa, 1968), shown in Fig. 6.15. In this chart, the blue line shows the relationship between attenuation and Fresnel number for spherical fields and the red line represents the trend between the same for the cylindrical fields. The grey line represents the kirchoff formula for Fresnel number and insertion loss but has been reported to be quite inaccurate when compared with results in the field (Farina, 2017).

As can be seen in this chart, the attenuation that can be achieved for the given barrier, with the Fresnel number 1.16, lies between 8 dB(A) and 9 dB(A) (the red line corresponds to the cylindrical field which is generally assumed for traffic noise; the attenuation is even higher for the spherical field as can be observed from the blue line in Fig. 6.15). A frequency of 500 Hz has been considered for the present calculations. The attenuation achieved is higher for higher frequencies, as can be observed from the formulas and the standard charts.

So, it can be observed that the results obtained by both the methods (i.e. Nomograph and Fresnel number approach) are matching fairly well, and may be used independently or simultaneously to gain a fair deal of confidence to get started with the initial design of the barrier with acoustic considerations.

After ascertaining the height of the barrier, attention can be turned to decide the other design considerations like the barrier material, surface finish, aesthetics etc. The civil engineering design which also takes into consideration the load calculation and the composition of material which is required to construct the barrier wall can be further taken up. The construction of the barrier must ensure that it does not have any cracks or gaps and the surface mass is atleast 10 kg/m^2 (Harris, 1991).

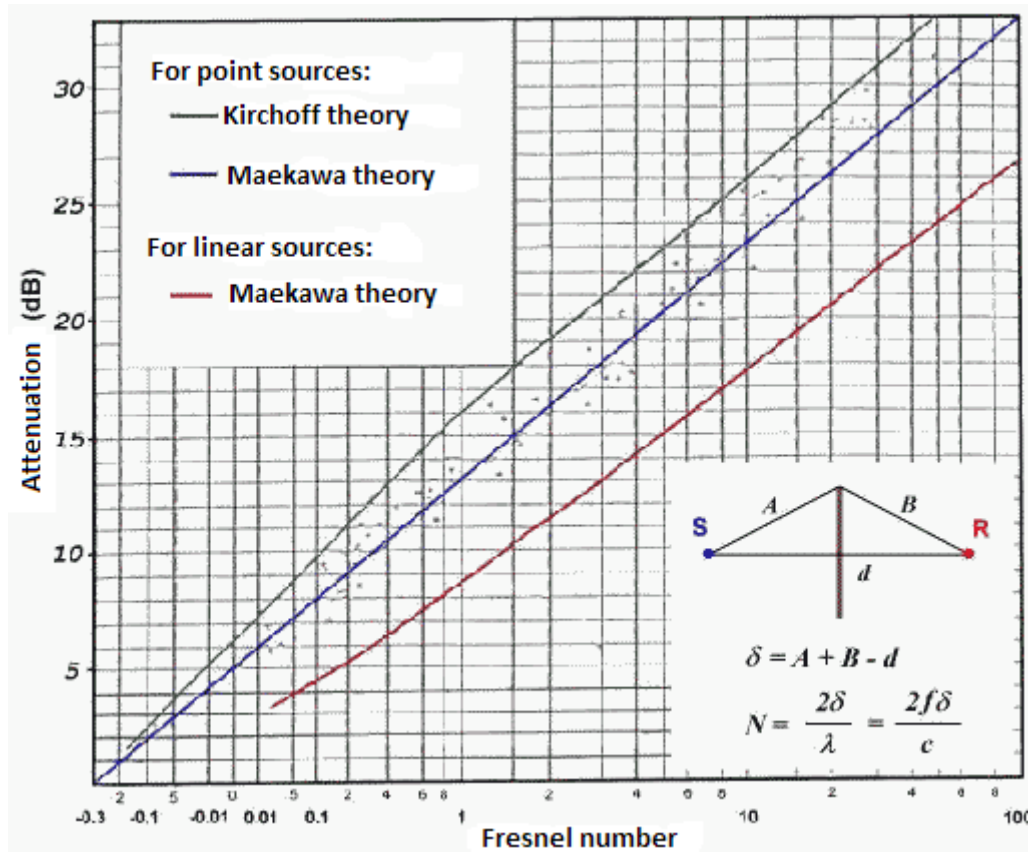


Fig. 6.15 Maekawa chart for finding the barrier attenuation for a given Fresnel number (Maekawa, 1968)

In the present work, the design of the noise barrier is limited to determining the height of barrier to achieve a desired attenuation based purely on acoustic considerations. The literature indicated the scope was limited to addressing the issue of adhocism that is adopted while making the barriers with some hit and trial approach, especially in the Indian traffic scene. The barriers are generally constructed or installed, and then the attenuation is measured. Sometimes, even that measurement does not happen. So, a systematic and scientific procedure to design the noise barriers based on acoustic considerations is necessary. The presented approach addresses this aspect of the barrier design.

CHAPTER 7

CONCLUSIONS AND SCOPE FOR FUTURE WORK

The present chapter discusses the different conclusions drawn from the work carried out and presented in the previous chapters. The key contribution to knowledge in the field of vehicular traffic noise and scope for future work are also given.

In the present work, different issues related to vehicular traffic noise have been addressed. The focus, in line with the identified objectives, has been on traffic noise prediction modelling and barrier as a noise abatement measure. A study of the relevant literature led to the formulation of objectives in this area. Work was carried out in the assessment of traffic noise levels at different locations in the Patiala city, taking it as a representative set of the traffic conditions in India. Experimental data collected at these locations revealed that the noise levels are very high with respect to the prescribed noise limits. The adverse health effects of these high noise levels have been very clearly documented in literature. Steps need to be taken to curb the high noise levels in the urban areas.

7.1 Conclusions

The findings from the present work and the conclusions drawn are summarised below:

1. The measurements of the traffic noise levels at different locations in the Patiala city have revealed that the existing noise level in terms of L_{eq} dB(A) is in the range 70 dB(A) to 75 dB(A) in residential areas and 75 dB(A) to 80 dB(A) in busy urban areas with traffic congestion (during day time) whereas the prescribed noise limits are 55 dB(A) in residential areas and 65 dB(A) in commercial areas (*Noise pollution*, 2000).
2. There have been numerous attempts across the globe, which have tried to find methods to study, predict and mitigate the road traffic noise levels. In order to address the urban traffic noise problem, an attempt has been made in the present work to develop a **Graph Theory (GT)** based traffic noise model. An Urban Traffic Noise System (UTNS) has been proposed, which consists of the subsystems: road traffic subsystem, human subsystem, environment subsystem, traffic network subsystem and urban prosperity subsystem. The first subsystem (road traffic subsystem) has been studied in detail in the present work. One of the benefits of this approach is that it is a systems approach, in

which the interdependencies or interactions between different subsystems are taken into account. All real life systems behave in an integrated and interactive way. The GT approach is very appropriate from this perspective, as the interactions between different subsystems are considered explicitly, being an integral part of this technique. The existing traffic noise models do not seem to take care of this aspect. A large number of contributing factors can be considered using the GT approach and the complete Urban Traffic Noise System (UTNS) can be analyzed in a holistic and systematic manner.

3. The permanent function based GT approach has been applied probably for the first time in the urban traffic noise system in the present work. The different steps involved in the formulation of a traffic noise model have been illustrated. 'Permanent function' in the form of a composite noise index ('p') has been formulated and its calculation and correlation (in terms of 'log p') with the existing noise level descriptors like L_{eq} , have been illustrated with examples.
4. In the first example, the traffic situation presented in Nicol and Wilson's work (2004) has been taken to establish and illustrate the proposed methodology. The parameters considered in the model are traffic volume, street width, height of measuring point above street level and average speed. GT approach is applied for developing the model. A permanent noise index 'p' which takes into account the effect of different traffic noise parameters and the interactions between them, is proposed and verified with the experimental data. The variation of 'p' with L_{eq} , L_{90} and L_{10} for the different measuring locations has been plotted, and equations for the three noise level descriptors and 'log p' have been formed using regression analysis. The values of multiple R and R^2 , and error (in the range - 4.2 dB(A) to + 2.8 dB(A)) for the testing dataset show good correlation between the measured and predicted values of the traffic noise level, which match fairly well. The R^2 values range from 0.76 for L_{10} (street) to 0.96 for L_{eq} (low) points. The errors are lower in the case of the 'low' point, ranging between -2.5 dB(A) to +1.2 dB(A). The larger errors for some values may be due to the cascading / multiple reflections in the high rise buildings, in some of the streets, and presence of horns and other extraneous noise sources, particularly in case of L_{10} values at street level.
5. The second illustrative example is that of an urban traffic noise scenario in Patiala city, India. An experimental study has been carried out at the Fountain roundabout in the city in order to further validate the methodology developed using the GT approach. Data related to the road traffic subsystem (consisting of four parameters traffic volume, percentage of heavy vehicles, acceleration of vehicles and road width) has been collected.

The permanent noise index 'p' is formulated using the GT approach and verified with the experimental data. The values of R, R^2 and error in the predicted noise level (L_{eq} dB(A)) indicate that the results are matching fairly well. The highest and lowest value of the Permanent Noise Index (PNI) is 2.75 and 0.90, corresponding to the L_{eq} value of 80.1 dB(A), and 66.2 dB(A), respectively. The value of R^2 is 0.83. The error between the measured and predicted values of L_{eq} for the testing dataset lies between 0.2 dB(A) and 1.6 dB(A).

6. Another gap that was identified from a study of the literature was the use of **soft computing** methods in traffic noise modelling only in a limited way. Genetic algorithms (GAs) and artificial neural networks (ANNs) seem to have been used so far for the modelling purpose. There are many other state-of-the-art methods/techniques which intuitively are felt to have a potential of application in this area. Four different soft computing methods (*Generalized Linear Model, Decision Trees, Neural Networks and Random Forests*) have been explored and used in developing the models for typical road traffic conditions in Patiala. An overview of traffic noise parameters, the soft computing methods used and the evaluation criteria of the model performance have been presented. The traffic noise prediction models are developed, with equivalent sound pressure level, L_{eq} as the output (dependent variable) and the traffic noise variables: hourly traffic flow, percentage of heavy vehicles and average speed of vehicles, as the independent variables. The results obtained are analyzed and it is seen that the 'Random Forests' method excels over all the other techniques on the performance criteria of correlation, R^2 (coefficient of determination), RMSE (root mean square error) and accuracy.

The correlation, which shows the linear relationship between two sets of data, is calculated for all the methods. Maximum correlation of 0.97 (training) and 0.92 (testing) in the prediction of L_{eq} is given by Random Forests.

R^2 (coefficient of determination) is also calculated for the four methods. 'Random Forests' shows the maximum R^2 value of 0.94 (training) and 0.85 (testing) in the prediction of L_{eq} .

The RMSE (root mean square error) value, which shows the deviation of the predicted values from the observed values, is 0.28 (training) and 0.43 (testing) in Random Forests,

the lowest among all the methods. The error values for the entire testing dataset range from -1.5 dB(A) to +1.2 dB(A).

The accuracy is calculated with an acceptable error of ± 1 dB(A). In order to see the efficacy of the RF method, the accuracy was tested for a closer range of ± 0.5 dB(A) also. Random Forests has the maximum accuracy of 96.30 % (± 1 dB(A)) and 83.48 % (± 0.5 dB(A)) in training, and 88.08 % (± 1 dB(A)) and 73.51 % (± 0.5 dB(A)), in testing, in the prediction of L_{eq} .

The 10-fold cross validation further indicates the stability of the method.

7. To study the effect of **horn noise** on the overall traffic noise level, an experimental investigation was carried out at five different locations in Patiala city with different levels of traffic volume and honking. The data was collected for the parameters traffic volume (with different vehicle categories), honking in 15 minutes and acoustical descriptors L_{eq} dB(A), L_{10} , L_{50} and L_{90} dB(A). The type of horns was divided into two types: normal horns (generally 90-100 dB(A)) and pressure horns (greater than 120 dB(A)). The study revealed that the parameter of horn noise is very significant in the Indian traffic scenario, especially in the congested urban traffic conditions. A higher accuracy in the prediction model is obtained by including this parameter, as also verified from the values of R, R^2 and error between the measured and predicted values of L_{eq} and L_{10} in the present study. It has been seen, as expected, that the overall traffic noise levels increase due to the presence of heavy honking. Though it is quite obvious, but some quantification of the effect of the horn noise was required, which has been addressed. Also, the improvement in the model by including the honking effect has been validated in an objective way.

The values of R and R^2 for the L_{eq} regression equation were 0.88 and 0.78 respectively, when only traffic volume was considered in the model. The values of R and R^2 increased to 0.97 and 0.95 when the parameter of honking was included in the model. The values of error between the measured and predicted values of L_{eq} dB(A) when the parameter 'honking frequency' (H) was not considered in the model, ranged from -2.9 dB(A) to +1.8 dB(A). When the parameter 'H' was included in the model the values of error

decreased and ranged from -1.1 dB(A) to +1.2 dB(A). Therefore, it can be concluded that the inclusion of the parameter 'honking frequency' improved the prediction model.

Since L_{10} would be directly affected by the presence of honking, a regression model of L_{10} was also developed and analysed. When only traffic volume was considered, the values of R and R^2 were 0.89 and 0.80 respectively. The inclusion of the parameter 'honking frequency' improved the prediction model and the values of R and R^2 increased to 0.96 and 0.93. The values of error between the measured and predicted values of L_{10} dB(A) when the parameter 'honking frequency' (H) was not considered in the model, ranged from -2.6 dB(A) to +1.7 dB(A). When the parameter ' H ' was included in the model the values of error decreased. The values of error between the measured and predicted values of L_{10} dB(A) ranged from -1.1 dB(A) to +1.2 dB(A).

Similar data was also collected for the median level (L_{50}) and the background noise level (L_{90}). The L_{50} values were in the range 64.7 dB(A) to 74.6 dB(A), and the L_{90} values were in the range 57.3 dB(A) to 69.6 dB(A). To get a feel of the effect of honking on the background noise level, L_{90} and the median noise level, L_{50} , the regression analysis was also done and similar conclusions (as above, for L_{eq} and L_{10}) were obtained. R^2 value for L_{90} improved from 0.50 to 0.81, when honking was included. R^2 for L_{50} improved from 0.49 to 0.77.

It was also noticed from the spectral analysis that the horn noise events occur at higher frequencies (around 4000 Hz). It is a known fact that this high frequency noise causes more annoyance to human beings as compared to the continuous lower frequency noise (Rice, 1983). It therefore seems necessary to include this honking parameter to obtain a better realistic model which can be indicative of overall annoyance caused by traffic noise.

8. Finally, a systematic and scientific procedure to design **noise barriers** based on acoustic considerations is presented. The design methodology proposed is useful for determining the height of a barrier to achieve the desired attenuation based purely on acoustic considerations. In order to illustrate this, a site was identified on a busy urban road near a temple in the Patiala city having high traffic noise level (with L_{eq} 75 dB(A)). Attenuation of around 8 dB(A) can be achieved at this site with the help of a noise barrier, whose height has been calculated using the proposed methodology.

It is hoped that the work presented can be useful to urban town planners, pollution control bodies/authority, civil engineers working on road and infrastructure projects, acoustic engineers and officials working on environment impact assessment (EIA) studies with an objective of vehicular traffic noise prediction and abatement.

7.2 Key Contribution to Knowledge

The contribution to knowledge in the field of vehicular traffic noise, which can also be applied in other domains, is given below:

1. A graph theoretic approach has been proposed for vehicular traffic noise prediction in urban traffic conditions.
2. The proposal of a new traffic noise descriptor, permanent noise index (PNI) has been formulated using a systems approach. It takes into account the interactions and interdependencies between different subsystems/parameters of the urban traffic noise system.
3. Different soft computing methods have been proposed for traffic noise prediction modelling. The application of a novel method, 'Random Forests' has been presented and shown to have higher accuracy than some of the existing techniques. This approach has an exciting potential in the area of traffic noise prediction modelling.
4. The effect of honking on traffic noise prediction models has been analysed in an objective way. A comparison between the models with and without the honking parameter has been presented.
5. A systematic procedure for the acoustic design of a noise barrier has been proposed that uses the nomograph method and is verified with the Maekawa approach and Fresnel number. The adhoc-ism used while making and installing the barriers should be replaced with the proposed systematic method.

7.3 Scope for Future Work

The work carried out and presented in this thesis has dealt with different aspects of vehicular traffic noise modelling and abatement. It certainly has a lot of scope for further work in the future and can be extended in different directions as outlined below:

1. More subsystems of the Urban Traffic Noise System (UTNS) can be studied using the GT approach and integrated to develop an improved traffic noise prediction model.
2. A recent data in the Indian capital city, Delhi mentions the ratio of the kind of vehicles termed as two-wheelers; motorcycles, scooters and mopeds plying in the city to be 63% of the total vehicle population. It would be important to include them as separate, independent parameters in the prediction models.
3. Different types of horns (e.g. normal horns, pressure horns etc.) can be included as separate parameters in the models.
4. Different soft computing methods like bio-inspired computation (e.g. 'ant colony optimization', 'particle swarm optimization'), 'decision stump', 'cubist' etc. can be used and their effectiveness compared with the methods used in the present work.
5. Spectral analyses can be done and used for selecting a barrier material with suitable absorption coefficient.
6. Civil engineering design and construction of noise barriers with different materials can be attempted.

LIST OF PUBLICATIONS

1. Singh, D., Nigam, S. P., Agrawal, V. P. and Kumar, M. (2016) 'Modelling and Analysis of Urban Traffic Noise System Using Algebraic Graph Theoretic Approach', *Acoustics Australia*, 44(2), pp. 249-261. doi: 10.1007/s40857-016-0058-3.
(Special issue, Part 1 – 'Road Traffic Noise')
Status: *Published*
Publisher: Australian Acoustical Society / Springer
Impact Factor: 0.604
Category: SCI
2. Singh, D., Nigam, S. P., Agrawal, V. P. and Kumar, M. (2016) 'Vehicular traffic noise prediction using soft computing approach', *Journal of Environmental Management*, 183(1), pp. 59-66. doi: 10.1016/j.jenvman.2016.08.053.
Status: *Published*
Publisher: Elsevier
Impact Factor: 4.010
Category: SCI
3. Singh, D., Nigam, S. P., Agrawal, V. P. and Kumar, M. (2017) 'Modelling of urban traffic noise using a systems approach', *Proceedings of the Institution of Civil Engineers: Transport*. doi: 10.1680/jtran.16.00094
Status: *Published (online)*
Publisher: Institution of Civil Engineers, UK
Impact Factor: 0.402
Category: SCI

References

- Aballea, F. E., Lissek, H., Utz, S., Rene, P. J. and Martin, P. (2009) 'Update of the Swiss source model for road traffic noise', in *16th International Congress on Sound and Vibration*.
- Abbott, P., Taylor, M. and Layfield, R. (1997) 'The effects of traffic calming measures on vehicle and traffic noise', *Traffic Engineering Control*, 38(9), pp. 447–453.
- Agarwal, S. and Swami, B. L. (2011) 'Comprehensive approach for the development of noise prediction model for Jaipur city, India', *Environ. Monit. Asses*, 19(20), pp. 113–120.
- Agarwal, S., Swami, B. L. and Gupta, A. B. (2009) 'Development of a noise prediction model under interrupted traffic flow conditions: A case study for Jaipur city', *Noise and health*. Medknow Publications, 11(45), p. 189.
- Avsar, Y., Saral, A., Gönüllü, M. T., Arslankaya, E. and Kurt, U. (2004) 'Neural network modelling of outdoor noise levels in a pilot area', *Turkish Journal of Engineering and Environmental Sciences*. The Scientific and Technological Research Council of Turkey, 28(3), pp. 149–156.
- Babisch, W. (2003) 'Stress hormones in the research on cardiovascular effects of noise', *Noise and health*. Medknow Publications, 5(18), p. 1.
- Banerjee, D. (2012) 'Research on road traffic noise and human health in India: Review of literature from 1991 to current', *Noise and Health*. Medknow Publications, 14(58), p. 113.
- Banerjee, D., Chakraborty, S. K., Bhattacharyya, S. and Gangopadhyay, A. (2008) 'Modeling of road traffic noise in the industrial town of Asansol, India', *Transportation Research Part D: Transport and Environment*. Elsevier, 13(8), pp. 539–541.
- Barry, T. M. and Reagan, J. A. (1978) *FHWA highway traffic noise prediction model*.
- Bolt, R. H., Lukasik, S. J., Nolle, A. W. and Frost, A. D. (1952) 'Handbook of Acoustic Noise Control, Vol I, *Physical Acoustics*, pp. 52–204.
- Breiman, L. (2001) 'Random forests', *Machine learning*. Springer, 45(1), pp. 5–32.

- Brookhouser, P. E., Worthington, D. W. and Kelly, W. J. (1992) 'Noise-induced hearing loss in children', *The Laryngoscope*. John Wiley & Sons, Inc., 102(6), pp. 645–655. doi: 10.1288/00005537-199206000-00010.
- Burgess, M. A. (1977) 'Noise prediction for urban traffic conditions - related to measurements in the Sydney Metropolitan Area', *Applied Acoustics*, 10(1), pp. 1–7. doi: 10.1016/0003-682X(77)90002-0.
- Calvo, J. A., Álvarez-Caldas, C., San Román, J. L. and Cobo, P. (2012) 'Influence of vehicle driving parameters on the noise caused by passenger cars in urban traffic', *Transportation Research Part D: Transport and Environment*. Elsevier, 17(7), pp. 509–513.
- Cammarata, G., Cavalieri, S. and Fichera, A. (1995) 'A neural network architecture for noise prediction', *Neural Networks*. Pergamon, 8(6), pp. 963–973.
- Can, A., Leclercq, L., Lelong, J. and Defrance, J. (2008) 'Capturing urban traffic noise dynamics through relevant descriptors', *Applied Acoustics*. Elsevier, 69(12), pp. 1270–1280.
- Cannelli, G. B. (1974) 'Traffic noise pollution in Rome', *Applied Acoustics*. Elsevier, 7(2), pp. 103–115.
- Chakrabarty, D., Chandra Santra, S., Mukherjee, A., Roy, B. and Das, P. (1997) 'Status of road traffic noise in Calcutta metropolis, India', *The Journal of the Acoustical Society of America*. ASA, 101(2), pp. 943–949.
- Chevallier, E., Leclercq, L., Lelong, J. and Chatagnon, R. (2009) 'Dynamic noise modeling at roundabouts', *Applied Acoustics*. Elsevier, 70(5), pp. 761–770.
- Chew, C. H. (1995) 'The influence of inclined buildings on road traffic noise', *Applied Acoustics*. Elsevier, 45(1), pp. 29–46.
- Cho, D. S. and Mun, S. (2008) 'Development of a highway traffic noise prediction model that considers various road surface types', *Applied Acoustics*, 69(11), pp. 1120–1128. doi: 10.1016/j.apacoust.2007.06.004.
- Cirianni, F. and Leonardi, G. (2011) 'Road traffic noise prediction models in the metropolitan area of the Strait of Messina', in *Proceedings of the Institution of Civil Engineers-*

- Transport*. Thomas Telford Ltd, pp. 231–239.
- Clayden, A. D., Culley, R. W. D. and Marsh, P. S. (1975) ‘Modelling traffic noise mathematically’, *Applied Acoustics*. Elsevier, 8(1), pp. 1–12.
- De Coensel, B., De Muer, T., Yperman, I. and Botteldooren, D. (2005) ‘The influence of traffic flow dynamics on urban soundscapes’, *Applied acoustics*. Elsevier, 66(2), pp. 175–194.
- CoRTN Calculation of Road Traffic Noise, Department of Transport, London: Her Majesty’s Stationery Office (HMSO) (1988).*
- Cowan, J. P. (1993) *Handbook of environmental acoustics*. John Wiley & Sons.
- Crocker, M. J. (2007) *Handbook of noise and vibration control*. John Wiley & Sons.
- Cross, N. (1989) *Engineering design methods*. Wiley New York.
- Delany, M. E., Harland, D. G., Hood, R. A. and Scholes, W. E. (1976) ‘The prediction of noise levels L_{10} due to road traffic’, *Journal of Sound and Vibration*. Elsevier, 48(3), pp. 305–325.
- Deo, N. (2004) *Graph Theory with Applications to Engineering and Computer Science*. Prentice-Hall of India (Prentice-Hall series in automatic computation).
- Dutilleul, G., Defrance, J., Ecotièrre, D., Gauvreau, B., Bérengier, M., Besnard, F. and Duc, E. Le (2010) ‘NMPB-ROUTES-2008: the revision of the French method for road traffic noise prediction’, *Acta Acustica united with Acustica*. S. Hirzel Verlag, 96(3), pp. 452–462.
- El-Sharkawy, A. I. and Aboukhashaba, A. A. (1983) ‘Traffic noise measurement and analysis in Jeddah’, *Applied Acoustics*. Elsevier, 16(1), pp. 41–49.
- Eliseeva, E., Hubbard, A. E. and Tager, I. B. (2013) ‘An application of machine learning methods to the derivation of exposure-response curves for respiratory outcomes’, *U.C. Berkeley Division of Biostatistics Working Paper Series. Working Paper 309*. bepress. Available at: <http://biostats.bepress.com/ucbbiostat/paper309>.
- Farina, A. (2017) *Acoustics course documents*. Available at:

pcfarina.eng.unipr.it/Public/Acoustics-Course/DOC-2012/08_ghiacci_222030.doc

(Accessed: 13 May 2017).

Federal Highway Administration, Fundamentals and Abatement of Highway Traffic Noise—Textbook and Training Course. FHWA, Washington, D.C. (1980).

FHWA Traffic Noise Model (1998) US Department of Transportation. Available at: https://www.fhwa.dot.gov/Environment/noise/traffic_noise_model/ (Accessed: 7 June 2015).

Frei, P., Mohler, E. and Rösli, M. (2014) ‘Effect of nocturnal road traffic noise exposure and annoyance on objective and subjective sleep quality’, *International journal of hygiene and environmental health*. Elsevier, 217(2), pp. 188–195.

Gaja, E., Gimenez, A., Sancho, S. and Reig, A. (2003) ‘Sampling techniques for the estimation of the annual equivalent noise level under urban traffic conditions’, *Applied Acoustics*. Elsevier, 64(1), pp. 43–53.

Galloway, W. J., Clark, W. E. and Kerrick, J. S. (1969) ‘Highway noise measurement, simulation, and mixed reactions’, *NCHRP report*, (78).

Gandhi, O. P., Agrawal, V. P. and Shishodia, K. S. (1991) ‘Reliability analysis and evaluation of systems’, *Reliability Engineering & System Safety*, 32(3), pp. 283–305. doi: 10.1016/0951-8320(91)90004-Q.

Garg, N. and Maji, S. (2014) ‘A critical review of principal traffic noise models: Strategies and implications’, *Environmental Impact Assessment Review*, 46, pp. 68–81. doi: 10.1016/j.eiar.2014.02.001.

Garg, N., Mangal, S. K., Saini, P. K., Dhiman, P. and Maji, S. (2015) ‘Comparison of ANN and analytical models in traffic noise modeling and predictions’, *Acoustics Australia*. Springer, 43(2), pp. 179–189.

Genaro, N., Torija, A., Ramos-Ridao, A., Requena, I., Ruiz, D. P. and Zamorano, M. (2010) ‘A neural network based model for urban noise prediction’, *The Journal of the Acoustical Society of America*. ASA, 128(4), pp. 1738–1746.

Gerlough, D. L. and Huber, M. J. (1975) ‘Traffic flow theory: a monograph’.

- Givargis, S. and Karimi, H. (2010) 'A basic neural traffic noise prediction model for Tehran's roads', *Journal of Environmental Management*, 91(12), pp. 2529–2534. doi: 10.1016/j.jenvman.2010.07.011.
- Givargis, S. and Mahmoodi, M. (2008) 'Converting the UK calculation of road traffic noise (CORTN) to a model capable of calculating LAeq, 1h for the Tehran's roads', *Applied Acoustics*. Elsevier, 69(11), pp. 1108–1113.
- Gorai, A. K., Maity, S. and Pal, A. K. (2007) 'Development of the path model in road traffic noise annoyance of Dhanbad township', *Noise & Vibration Worldwide*. SAGE Publications Sage UK: London, England, 38(3), pp. 17–22.
- Goswami, S. (2009) 'Road traffic noise: A case study of Balasore town, Orissa, India', *International Journal of Environmental Research*, 3(2), pp. 309–318.
- Guarnaccia, C. (2013) 'Advanced Tools for Traffic Noise Modelling and Prediction', *WSEAS TRANSACTIONS on SYSTEMS*, 12(2), pp. 121–130.
- Guarnaccia, C., Quartieri, J., Barrios, J. M. and Rodrigues, E. R. (2014) 'Modeling environmental noise exceedances using non-homogeneous Poisson processes', *The Journal of the Acoustical Society of America*. Acoustical Society of America, 136(4), pp. 1631–1639.
- Gulliver, J., Morley, D., Vienneau, D., Fabbri, F., Bell, M., Goodman, P., Beevers, S., Dajnak, D., J Kelly, F. and Fecht, D. (2015) 'Development of an open-source road traffic noise model for exposure assessment', *Environmental Modelling & Software*, 74, pp. 183–193. doi: 10.1016/j.envsoft.2014.12.022.
- Gündoğdu, Ö., Gökdağ, M. and Yüksel, F. (2005) 'A traffic noise prediction method based on vehicle composition using genetic algorithms', *Applied Acoustics*, 66(7), pp. 799–809. doi: 10.1016/j.apacoust.2004.11.003.
- Hammad, R. N. S. and Abdelazeez, M. K. (1987) 'Measurements and analysis of the traffic noise in Amman, Jordan and its effects', *Applied Acoustics*. Elsevier, 21(4), pp. 309–320.
- Harman, D. M. and Burgess, M. A. (1973) 'Traffic noise in an urban situation', *Applied Acoustics*. Elsevier, 6(4), pp. 269–276.

- Harris, C. M. (1991) *Handbook of acoustical measurements and noise control*. McGraw-Hill New York.
- Heutschi, K. (2004) ‘SonRoad: New Swiss road traffic noise model’, *Acta Acustica united with Acustica*. S. Hirzel Verlag, 90(3), pp. 548–554.
- ‘Honk flu’, anti-honking campaign launched in Mumbai (2017) *TheTimes of India*. Mumbai. Available at: <http://m.timesofindia.com/videoshow/55312718.cms>.
- Hood, R. A. (1987) ‘Accuracy of calculation of road traffic noise’, *Applied Acoustics*. Elsevier, 21(2), pp. 139–146.
- Iannone, G., Guarnaccia, C. and Quartieri, J. (2011) ‘Noise fundamental diagram deduced by traffic dynamics’, *Recent Researches in Geography, Geology, Energy, Environment and Biomedicine*. EMESEG’11, Corfù Island, Greece, pp. 14–16.
- IEC 61672-1: 2002, *International Electrotechnical Commission (2002) Electroacoustics–Sound Level Meters–Part 1*.
- Ingle, S. T., Pachpande, B. G., Wagh, N. D. and Attarde, S. B. (2005) ‘Noise exposure and hearing loss among the traffic policemen working at busy streets of Jalgaon urban centre’, *Transportation Research Part D: Transport and Environment*. Pergamon, 10(1), pp. 69–75.
- ISO 362-1:2015 *Measurement of noise emitted by accelerating road vehicles - Engineering method - Part 1: M and N categories*.
- ISO 9613-2:1996 *Acoustics - Attenuation of sound during propagation outdoors - Part 2: General method of calculation*. Available at: <https://www.iso.org/standard/20649.html>.
- Johnson, D. R. and Saunders, E. G. (1968) ‘The evaluation of noise from freely flowing road traffic’, *Journal of Sound and vibration*. Elsevier, 7(2), p. 287-309.
- Jurkat, W. B. and Ryser, H. J. (1966) ‘Matrix factorizations of determinants and permanents’, *Journal of Algebra*. Elsevier, 3(1), pp. 1–27.
- Kalaiselvi, R. and Ramachandraiah, A. (2016) ‘Honking noise corrections for traffic noise prediction models in heterogeneous traffic conditions like India’, *Applied Acoustics*.

- Elsevier, 111, pp. 25–38.
- Kephalopoulos, S., Paviotti, M., Anfosso-Lédée, F., Van Maercke, D., Shilton, S. and Jones, N. (2014) ‘Advances in the development of common noise assessment methods in Europe: The CNOSSOS-EU framework for strategic environmental noise mapping’, *Science of The Total Environment*, 482–483, pp. 400–410. doi: 10.1016/j.scitotenv.2014.02.031.
- Koh, D. and Jeyaratnam, J. (1998) ‘Occupational health in Singapore’, *International Archives of Occupational and Environmental Health*, 71(5), pp. 295–301. doi: 10.1007/s004200050284.
- Kragh, J., Plovsing, B., Storeheier, S. Å., Taraldsen, G. and Jonasson, H. G. (2002) ‘Nordic Environmental Noise Prediction Methods, Nord2000-Summary report. General Nordic Sound Propagation Model and Applications in Source-Related Prediction Methods’, *DELTA Acoustics & Vibration Report*, 1719(1).
- Kumar, K. and Jain, V. K. (1994) ‘A study of noise in various modes of transport in Delhi’, *Applied Acoustics*. Elsevier, 43(1), pp. 57–65.
- Kumar, K., Katiyar, V. K., Parida, M. and Rawat, K. (2011) ‘Mathematical modeling of road traffic noise prediction’, *Int. J. of Appl. Math and Mech*, 7(4), pp. 21–28.
- Kumar, K., Parida, M. and Katiyar, V. K. (2012) ‘Road traffic noise prediction with neural networks-a review’, *An International Journal of Optimization and Control*. Balikesir University, Faculty of Engineering Department of Industrial Engineering, 2(1), p. 29.
- Kumar, P., Nigam, S. P. and Kumar, N. (2014) ‘Vehicular traffic noise modeling using artificial neural network approach’, *Transportation Research Part C: Emerging Technologies*, 40, pp. 111–122. doi: 10.1016/j.trc.2014.01.006.
- Lam, K.C. and Ma, W.C. (2012) ‘Road traffic noise exposure in residential complexes built at different times between 1950 and 2000 in Hong Kong’, *Applied Acoustics*. Elsevier, 73(11), pp. 1112–1120.
- Lamure, C. (1965) ‘Niveaux de bruit au voisinage des autoroutes’, in *Proc. Fifth International Congress on Acoustics*.
- Lee, E. Y., Jerrett, M., Ross, Z., Coogan, P. F. and Seto, E. Y. W. (2014) ‘Assessment of

- traffic-related noise in three cities in the United States', *Environmental research*. Elsevier, 132, pp. 182–189. doi: <https://doi.org/10.1016/j.envres.2014.03.005>.
- Li, B., Tao, S. and Dawson, R. W. (2002) 'Evaluation and analysis of traffic noise from the main urban roads in Beijing', *Applied Acoustics*. Elsevier, 63(10), pp. 1137–1142.
- Maekawa, Z. (1968) 'Noise reduction by screens', *Applied acoustics*. Elsevier, 1(3), pp. 157–173.
- Makarewicz, R. (1997) 'Influence of ground effect and refraction on road traffic noise', *Applied Acoustics*. Elsevier, 52(2), pp. 125–137.
- Marcus, M. and Minc, H. (1965) 'Permanents', *The American Mathematical Monthly*. Mathematical Association of America, 72(6), pp. 577–591. doi: 10.2307/2313846.
- Marcus, M. and Newman, M. (1962) 'Inequalities for the Permanent Function', *Annals of Mathematics*. Annals of Mathematics, 75(1), pp. 47–62. doi: 10.2307/1970418.
- Mohan, M., Gandhi, O. P. and Agrawal, V. P. (2003) 'Systems modelling of a coal-based steam power plant', *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*. SAGE Publications Sage UK: London, England, 217(3), pp. 259–277.
- Naish, D. A., Tan, A. C. C. and Nur Demirbilek, F. (2013) 'Speech interference and transmission on residential balconies with road traffic noise', *The Journal of the Acoustical Society of America*. ASA, 133(1), pp. 210–226.
- Nelder, J. A. and Wedderburn, R. W. M. (1972) 'Generalized linear models.', *J.R. Statist. Soc A*, 135(3), pp. 370–384.
- Nickson, A. F. (1965) 'Can community reaction to increased traffic noise be forecast', in *Proceedings of the Fifth International Congress on Acoustics*.
- Nicol, F. and Wilson, M. (2004) 'The effect of street dimensions and traffic density on the noise level and natural ventilation potential in urban canyons', *Energy and Buildings*, 36(5), pp. 423–434. doi: 10.1016/j.enbuild.2004.01.051.
- Nirjar, R. S., Jain, S. S. and Parida, M. (2003) 'A study of transport related noise pollution in

- Delhi'. *Journal of the Institution of Engineers (India)*.
- Noise pollution (regulation and control) rules (2000). *Central Pollution Control Board, Ministry of Environment and Forests, Government of India*. Available at: http://cpcb.nic.in/divisionsofheadoffice/pci2/noise_rules_2000.pdf (Accessed: 10 March 2016).
- Number of registered vehicles (2017) *Global Health Observatory (GHO) data, World Health Organization*. Available at: http://www.who.int/gho/road_safety/registered_vehicles/number/en/ (Accessed: 27 May 2016).
- Öhrström, E. (1995) 'Effects of low levels of road traffic noise during the night: a laboratory study on number of events, maximum noise levels and noise sensitivity', *Journal of sound and vibration*. Elsevier, 179(4), pp. 603–615.
- Öhrström, E., Hadzibajramovic, E., Holmes, M. and Svensson, H. (2006) 'Effects of road traffic noise on sleep: Studies on children and adults', *Journal of environmental psychology*. Elsevier, 26(2), pp. 116–126.
- Padhy, P. K. and Padhi, B. K. (2008) 'Assessment of noise quality in Bolpur-Santiniketan areas (India)', *Journal of Environmental Research And Development Vol*, 3(1).
- Pamanikabud, P., Tansatcha, M. and Brown, A. L. (2008) 'Development of a highway noise prediction model using an L eq 20s measure of basic vehicular noise', *Journal of sound and vibration*. Elsevier, 316(1), pp. 317–330.
- Pamanikabud, P. and Vivitjinda, P. (2002) 'Noise prediction for highways in Thailand', *Transportation Research Part D: Transport and Environment*. Elsevier, 7(6), pp. 441–449.
- Pandey, G., Dubey, S. and Tripathi, S. (2011) 'Traffic noise assessment at National Highway 28 in India using FHWA model', *International Journal of Vehicle Noise and Vibration*. Inderscience Publishers Ltd, 7(1), pp. 37–50.
- Pathak, V., Tripathi, B. D. and Mishra, V. K. (2011) 'Evaluation of Anticipated Performance Index of some tree species for green belt development to mitigate traffic generated noise',

- Urban forestry & urban greening*. Elsevier, 10(1), pp. 61–66.
- Paviotti, M. and Vogiatzis, K. (2012) ‘On the outdoor annoyance from scooter and motorbike noise in the urban environment’, *Science of the Total Environment*. Elsevier, 430, pp. 223–230.
- Prabhakaran, R. T. D., Babu, B. J. and Agrawal, V. P. (2006) ‘Structural Modeling and Analysis of Composite Product System: A Graph Theoretic Approach’, *Journal of Composite Materials*. SAGE Publications Ltd STM, 40(22), pp. 1987–2007. doi: 10.1177/0021998306061318.
- Qin, A. K., Huang, V. L. and Suganthan, P. N. (2009) ‘Differential evolution algorithm with strategy adaptation for global numerical optimization’, *IEEE transactions on Evolutionary Computation*. IEEE, 13(2), pp. 398–417.
- Quinlan, J. R. (1986) ‘Induction of decision trees’, *Machine learning*. Springer, 1(1), pp. 81–106.
- Rahmani, S., Mousavi, S. M. and Kamali, M. J. (2011) ‘Modeling of road-traffic noise with the use of genetic algorithm’, *Applied Soft Computing*, 11(1), pp. 1008–1013. doi: 10.1016/j.asoc.2010.01.022.
- Rajakumara, H. N. and Mahalinge Gowda, R. M. (2009) ‘Road Traffic Noise Prediction Model under Interrupted Traffic Flow Condition’, *Environmental Modeling & Assessment*, 14(2), pp. 251–257. doi: 10.1007/s10666-008-9138-6.
- Ramirez, A. and Dominguez, E. (2013) ‘Modeling urban traffic noise with stochastic and deterministic traffic models’, *Applied Acoustics*, 74(4), pp. 614–621. doi: 10.1016/j.apacoust.2012.08.001.
- Rana, P. S., Sharma, H., Bhattacharya, M. and Shukla, A. (2015) ‘Quality assessment of modeled protein structure using physicochemical properties’, *Journal of bioinformatics and computational biology*. Imperial College Press, 13(2), p. 1550005.
- Rao, P. R. and Rao, M. G. S. (1991) ‘Prediction of LA10T traffic noise levels in the city of Visakhapatnam, India’, *Applied Acoustics*. Elsevier, 34(2), pp. 101–110.
- Ratha, D. and Agrawal, V. P. (2015) ‘A digraph permanent approach to evaluation and

- analysis of integrated watershed management system', *Journal of Hydrology*, 525, pp. 188–196. doi: 10.1016/j.jhydrol.2015.03.046.
- Rice, C. (1983) 'CEC joint research on annoyance due to impulse noise: laboratory studies', in *Noise as a Public Health Problem: Proceedings of the Fourth International Congress*, pp. 1073–1084.
- Riedmiller, M. and Braun, H. (1993) 'A direct adaptive method for faster backpropagation learning: The RPROP algorithm', in *Neural Networks, 1993., IEEE International Conference on*. IEEE, pp. 586–591.
- Sato, T., Yano, T., Björkman, M. and Rylander, R. (1999) 'Road traffic noise annoyance in relation to average noise level, number of events and maximum noise level', *Journal of Sound and Vibration*. Elsevier, 223(5), pp. 775–784.
- Sharma, A., Bodhe, G. L. and Schimak, G. (2014) 'Development of a traffic noise prediction model for an urban environment', *Noise and Health*. Medknow Publications, 16(68), p. 63.
- Singh, D., Nigam, S. P., Agrawal, V. P. and Kumar, M. (2016a) 'Modelling and Analysis of Urban Traffic Noise System Using Algebraic Graph Theoretic Approach', *Acoustics Australia*, 44(2), pp. 249–261. doi: 10.1007/s40857-016-0058-3.
- Singh, D., Nigam, S. P., Agrawal, V. P. and Kumar, M. (2016b) 'Vehicular traffic noise prediction using soft computing approach', *Journal of Environmental Management*, 183(1), pp. 59–66. doi: 10.1016/j.jenvman.2016.08.053.
- Sousanis, J. (2011) *World Vehicle Population Tops 1 Billion Units*, *WardsAuto*. Available at: <http://wardsauto.com/news-analysis/world-vehicle-population-tops-1-billion-units> (Accessed: 26 May 2016).
- Steele, C. (2001) 'A critical review of some traffic noise prediction models', *Applied Acoustics*, 62(3), pp. 271–287. doi: 10.1016/S0003-682X(00)00030-X.
- Stoilova, K. and Stoilov, T. (1998) 'Traffic noise and traffic light control', *Transportation Research Part D: Transport and Environment*. Elsevier, 3(6), pp. 399–417.
- Storn, R. and Price, K. (1997) 'Differential evolution—a simple and efficient heuristic for

- global optimization over continuous spaces’, *Journal of global optimization*. Springer, 11(4), pp. 341–359.
- Subramani, T., Kavitha, M. and Sivaraj, K. P. (2012) ‘Modelling of traffic noise pollution’, *International Journal of Engineering Research and Applications*, 2(3), pp. 3175–3182.
- Sy, H. K., Ong, P. P., Tang, S. H. and Tan, K. L. (1985) ‘Traffic noise survey and analysis in Singapore’, *Applied Acoustics*. Elsevier, 18(2), pp. 115–125.
- Tachibana, H. and Sasaki, M. (1994) ‘ASJ prediction methods of road traffic noise’, in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Institute of Noise Control Engineering, pp. 283–288.
- Tandel, B., Macwan, J. and Ruparel, P. N. (2011) ‘Urban corridor noise pollution: A case study of Surat city, India’, in *International Conference on Environment and Industrial Innovation*, pp. 144–148.
- Tang, S. K. and Tong, K. K. (2004) ‘Estimating traffic noise for inclined roads with freely flowing traffic’, *Applied Acoustics*. Elsevier, 65(2), pp. 171–181.
- Tansatcha, M., Pamanikabud, P., Brown, A. L. and Affum, J. K. (2005) ‘Motorway noise modelling based on perpendicular propagation analysis of traffic noise’, *Applied Acoustics*. Elsevier, 66(10), pp. 1135–1150.
- Thorsson, P. J. and Ögren, M. (2005) ‘Macroscopic modeling of urban traffic noise–influence of absorption and vehicle flow distribution’, *Applied Acoustics*. Elsevier, 66(2), pp. 195–209.
- TOI sounds alarm on honking* (2016) *The Times of India*. New Delhi. Available at: <http://timesofindia.indiatimes.com/city/delhi/TOI-sounds-alarm-on-honking / articleshow / 53677400.cms>.
- Total Number of Registered Motor Vehicles in India* (2016) *Open Govt. Data (OGD) platform, Ministry of Road Transport and Highways, India*. Available at: <https://data.gov.in/catalog/total-number-registered-motor-vehicles-india> (Accessed: 27 May 2016).
- Turky, A. M., Ahmad, M. S. and Yusoff, M. Z. M. (2009) ‘The use of genetic algorithm for

- traffic light and pedestrian crossing control', *International Journal of Computer Science and Network Security*, 9(2), pp. 88–96.
- Tyagi, V., Kumar, K. and Jain, V. K. (2006) 'A study of the spectral characteristics of traffic noise attenuation by vegetation belts in Delhi', *Applied Acoustics*. Elsevier, 67(9), pp. 926–935.
- Venkatasamy, R. and Agrawal, V. P. (1997) 'A Digraph Approach to Quality Evaluation of an Automotive Vehicle', *Quality Engineering*. Taylor & Francis, 9(3), pp. 405–417. doi: 10.1080/08982119708919060.
- Vijay, R., Sharma, A., Chakrabarti, T. and Gupta, R. (2015) 'Assessment of honking impact on traffic noise in urban traffic environment of Nagpur, India', *Journal of environmental health science and engineering*. BioMed Central, 13(1), p. 10.
- Voelcker, J. (2014) *1.2 Billion Vehicles On World's Roads Now, 2 Billion By 2035: Report, Green Car Reports*. Available at: http://www.greencarreports.com/news/1093560_1-2-billion-vehicles-on-worlds-roads-now-2-billion-by-2035-report (Accessed: 4 June 2016).
- Wang, B. and Kang, J. (2011) 'Effects of urban morphology on the traffic noise distribution through noise mapping: A comparative study between UK and China', *Applied Acoustics*. Elsevier, 72(8), pp. 556–568.
- Watts, G. (2005) 'Harmonoise models for predicting road traffic noise', *Acoustics Bulletin*. Institute of Acoustics, 30(5), p. 19.
- Win, K. N., Balalla, N. B. P., Lwin, M. Z. and Lai, A. (2015) 'Noise-Induced Hearing Loss in the Police Force', *Safety and Health at Work*, 6(2), pp. 134–138. doi: <http://dx.doi.org/10.1016/j.shaw.2015.01.002>.
- Yamamoto, K. (2010) 'Road traffic noise prediction model "ASJ RTN-Model 2008": report of the research committee on road traffic noise', *Acoustical Science and Technology*. Acoustical Society of Japan, 31(1), pp. 2–55.
- Yeow, K. W., Popplewell, N. and MacKay, J. F. W. (1977) 'Method of predicting Leq created by urban traffic', *Journal of sound and vibration*. Elsevier, 53(1), pp. 103–109.
- Yoon, K. and Hwang, C.-L. (1981) *Multiple attribute decision making: methods and*

applications. Springer-Verlag Berlin.

Yoshida, T., Osada, Y., Kawaguchi, T., Hoshiyama, Y., Yoshida, K. and Yamamoto, K. (1997) 'Effects of road traffic noise on inhabitants of Tokyo', *Journal of sound and Vibration*. Elsevier, 205(4), pp. 517–522.

Yu, B. and Lu, Q. (2013) 'Bayesian model for tyre/asphalt pavement noise', in *Proceedings of the Institution of Civil Engineers-Transport*. Thomas Telford Ltd, pp. 241–252.

Zhao, J., Ding, Z., Hu, B., Chen, Y. and Yang, W. (2015) 'Assessment and improvement of a highway traffic noise prediction model with L_{eq} (20s) as the basic vehicular noise', *Applied Acoustics*. Elsevier, 97, pp. 78–83.